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The key role of forests in meeting climate targets requires science for credible mitigation

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Forest-based climate mitigation may occur through conserving and enhancing the carbon sink and through reducing greenhouse gas emissions from deforestation. Yet the inclusion of forests in international climate agreements has been complex, often considered a secondary mitigation option. In the context of the Paris Climate Agreement, countries submitted their (Intended) Nationally Determined Contributions ((I)NDCs), including climate mitigation targets. Assuming full implementation of (I)NDCs, we show that land use, and forests in particular, emerge as a key component of the Paris Agreement: turning globally from a net anthropogenic source during 1990–2010 (1.3 ± 1.1 $GtCO_2e\,yr^{-1}$) to a net sink of carbon by 2030 (up to −1.1 ± 0.5 $GtCO_2e\,yr^{-1}$), and providing a quarter of emission reductions planned by countries. Realizing and tracking this mitigation potential requires more transparency in countries' pledges and enhanced science-policy cooperation to increase confidence in numbers, including reconciling the ≈3 $GtCO_2e\,yr^{-1}$ difference in estimates between country reports and scientific studies.

In December 2015, 195 countries adopted the Paris Climate Agreement[1] at the twenty-first Conference of Parties (COP-21) of the United Nations Framework Convention on Climate Change (UNFCCC). As part of the process, 187 countries, representing more than 96% of global net emissions in 2012[2], submitted their Intended National Determined Contributions[3] (INDCs, which become NDCs with the ratification of the Paris Agreement[4]). The NDCs are the basis for implementing actions under the Agreement, and the vast majority include commitments in the land-use sector.

Land use, including agriculture and forests, accounts for about 10% of global greenhouse gas (GHG) emissions as CO_2, and nearly a quarter including CH_4 and N_2O (refs 5–9). Also, about one-third of the current anthropogenic CO_2 emissions are removed by terrestrial ecosystems, mainly forests. While deforestation is estimated to be the main GHG source in many tropical countries, forest sinks are important globally with net sinks dominating in temperate and boreal countries[10].

Including land use in the UNFCCC process has been long and complex. For forests, uncertainties of GHG estimates and methodological issues such as additionality (that is, showing that proposed mitigation efforts go beyond Business-as-Usual (BAU) and separation of non-anthropogenic effects) and leakage (displacement of land-use activities to other areas) have often led to controversies and compromises[11].

The UNFCCC requires that all countries report GHG inventories of anthropogenic emissions and removals using methodologies developed by the Intergovernmental Panel on Climate Change (IPCC) and adopted by the UNFCCC[12]. Developed countries report annual GHG inventories[13], using mandatory and voluntary land-use activities towards meeting their emission reduction targets where applicable under the Kyoto Protocol[14]. Developing countries' GHG inventories have historically been reported less frequently[15], although biennial updates are now required[16], and these countries may undertake voluntary mitigation activities, notably through the REDD+ process (Reducing Emissions from Deforestation, forest Degradation, and other forest activities).

The Paris Agreement is a potential game changer for land-use mitigation. It calls explicitly for all countries to make use of a full range of land-based mitigation options, and to take action on REDD+.

Based on country information, this analysis quantifies the expected GHG mitigation role of the land-use sector in the (I)NDCs to the year 2030, including activities conditional on finance, technology and capacity-building support. It does not assess specific country policies. It focuses on CO_2 emissions and removals and non-CO_2 emissions from Land Use, Land-Use Change and Forestry (LULUCF, primarily deforestation and forest management), encompassing most of the land-use sector identified in (I)NDCs. Harvested wood products are included for most developed countries. Non-CO_2 emissions from agriculture are not included.

Country mitigation targets are expressed in different ways

Countries express their (I)NDC targets with different combinations of the following elements[17–19] (Supplementary Tables 1 and 2), reflecting different national circumstances, that is:

- Quantifier—Targets are expressed as either an absolute quantity, for example, amount of GHG reduction in tonnes of CO_2 equivalent (tCO_2e), or as a change in the emission intensity, for example, China and India express a reduction of emission intensity per unit of GDP.
- Reference point—Emissions in the target year (for example, 2025 or 2030) are compared with either a historic base year (for example, 1990, 2005) or with the target year in a BAU scenario. The BAU scenario assumes either no mitigation activity, or some existing mitigation activity.
- Conditionality—While developed country (I)NDC targets are unconditional, most developing countries expressed at least part of their targets as conditional on finance, technology or capacity-building support.

The (I)NDCs vary in the way they include LULUCF. It may be fully included as part of the overall target like other sectors,

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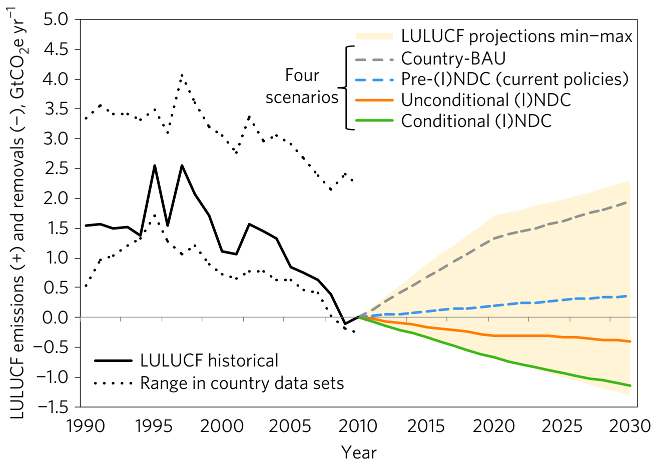

Figure 1 | Global LULUCF net GHG flux for the historical period and future scenarios based on analyses of countries' documents and mitigation pledges ((I)NDCs). The LULUCF historical data (black solid line) reflect the following countries' documents (in order of priority): data submitted to UNFCCC ((I)NDCs[3], 2015 GHG Inventories[13], recent National Communications[15,20]); other official countries' documents; FAO-based data sets, that is, FRA 2015[22] for forest (as elaborated by ref. 8) and FAOSTAT[23] for non-forest land-use emissions. The future four scenarios reflect official countries' information (mostly (I)NDCs, complemented by Biennial Update Reports[16] and National Communications[15,20]), and show: the BAU scenario as defined by the country (country-BAU); the trend based on pre-(I)NDC levels of activity (current policies); the unconditional (I)NDC scenario assuming that all countries implement their unconditional targets in their (I)NDCs; the conditional (I)NDC scenario assuming that all countries implement the unconditional and conditional targets in their (I)NDCs. The unconditional target holds irrespective of actions of other countries, whereas for the conditional, more ambitious, target, certain conditions regarding receiving external support have to be met. The shaded area indicates the full range of countries' available projections (min–max), expressing the available countries' information on uncertainties beyond the specific scenarios shown (see Methods for details). The uncertainty of historical and future data may be analysed through two different perspectives. First, the range of historical country data sets (dotted lines) reflects differences between alternative selections of country sources, that is, GHG inventories for developed countries complemented by FAO-based data sets (upper range) or by data in National Communications (lower range) for developing countries (see Methods for details). Similarly, the range of future scenarios gives an order of magnitude of the impact of different assumptions by countries. Secondly, on the basis of available information from countries' reports to UNFCCC complemented by expert judgement, we estimated the uncertainties (at 95% confidence interval) for LULUCF GHG emission levels over time and for the associated trends (see text and Supplementary Section 3).

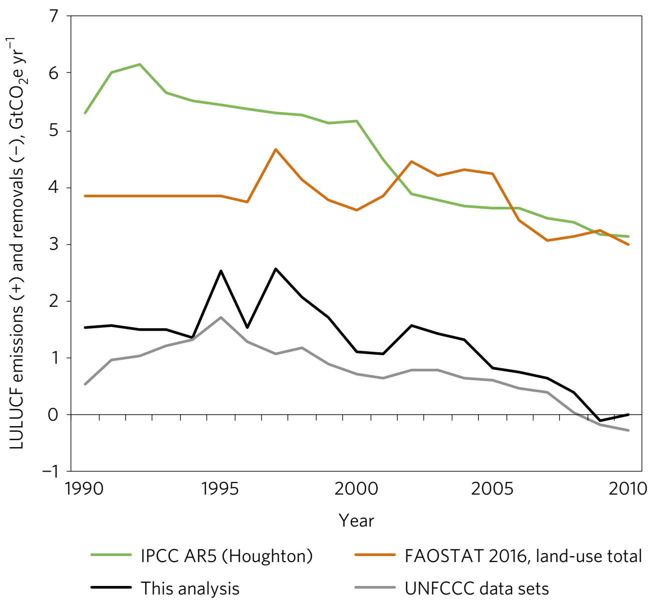

Figure 2 | Comparison of historical LULUCF net GHG flux from this analysis and other key global LULUCF data sets. (1) Net GHG flux from latest country reports to UNFCCC[13,15,16,20] (grey line); (2) net GHG flux from FAOSTAT[23] (orange line); and (3) net land-use sector CO_2 anthropogenic flux included in IPCC AR5[5,6] using data from the Houghton bookkeeping model[27,50] (green line). This analysis (black line) uses a combination of GHG data from the following countries' sources (in order of priority): data submitted to UNFCCC ((I)NDCs[3], 2015 GHG Inventories[13], recent National Communications[15,20]); other countries' official documents; FAO-based data sets, that is, FRA 2015[22] for forest (as elaborated by ref. 8) and FAOSTAT[23] for non-forest land-use emissions. Given the small share of non-CO_2 gases in the total LULUCF GHG budget (which excludes non-CO_2 GHG emissions from agriculture—see Methods for details), the different coverage on non-CO_2 gases does not represent an important reason for discrepancy between data sets. Whereas for all data sets emissions are decreasing over time, the slopes of the linear trends are different between this analysis, the IPCC AR5 and FAOSTAT (95% confidence interval).

partially included through different accounting rules to reflect the additional impact of human actions or considered separately with special mitigation actions. Consequently, evaluating the expected effect of LULUCF on the (I)NDC mitigation targets is complex.

Our analysis is based on information provided on LULUCF in the (I)NDCs[3], and also (in order of priority) other country reports to UNFCCC[13,15,16,20,21], other official country documents, and Food and Agriculture Organization (FAO)-based data sets for forest[8,22] and for other land uses[23] (Supplementary Tables 4 and 5). Given the Paris Agreement context of our analysis, we prioritized (I)NDCs and those country reports that are formally reviewed or technically assessed by the UNFCCC, with FAO-based data sets used for gap filling, allowing global estimates covering 195 countries (see Methods). We found sufficient information to analyse the LULUCF mitigation contribution for 68 countries (or 41 (I)NDCs, with the EU's NDC representing 28 countries), corresponding to around 78% of global net emissions in 2012[2] and 83% of the global forest area[22]. For the remaining countries, where LULUCF is not expected to offer a large mitigation potential (Supplementary Section 1), the future LULUCF mitigation contribution was assumed to be zero.

Historical and projected forest emissions and removals

Figure 1 shows, for all 195 UNFCCC countries, historical and future anthropogenic LULUCF emissions and removals from this analysis, based on official country data. Supplementary Sections 2 and 3 provide, respectively, additional country-specific assessments and an analysis of uncertainties for the absolute level of net emissions and their trend[24,25], based on information from countries' reports. While country information on uncertainty up to 2030 is not available, we conservatively assumed that the uncertainty estimated for historical net emissions would also hold for the future.

Historically, global LULUCF net emissions decreased from $1.54 \pm 1.06\ GtCO_2e\ yr^{-1}$ (95% CI) in 1990 to $0.01 \pm 0.86\ GtCO_2e\ yr^{-1}$ in 2010 (slope of linear trend: $-0.08\ GtCO_2e\ yr^{-1}$). The trend and the inter-annual variability over this period are influenced by: (i) deforestation in Brazil, with peak years in 1995 and 2002–2004 followed by a steep reduction of emissions by about $-1.3\ GtCO_2e\ yr^{-1}$ until 2010; (ii) high deforestation rates (1997–1999) and peak years in peat fire emissions (for example, 1997) in Indonesia; (iii) an increasing sink in managed temperate and boreal forests, of about

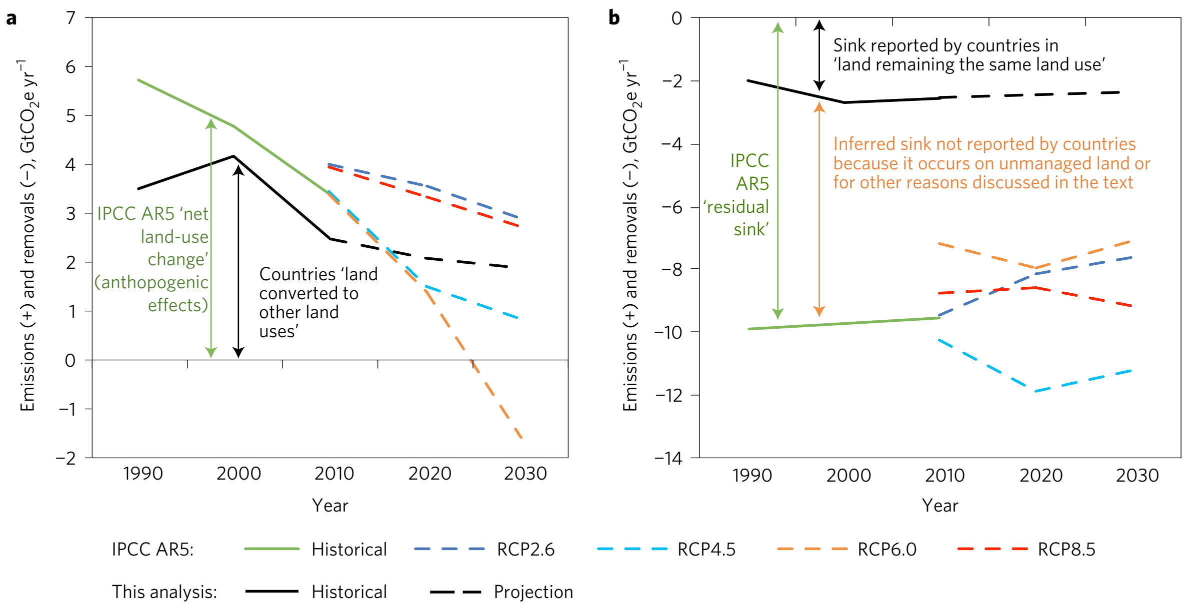

Figure 3 | Comparison of historical and projected land fluxes from this analysis (based on country reports, including conditional (I)NDCs) and IPCC AR5 (based on global models and the projections of the four Representative Concentration Pathways (RCP) scenarios). a,**b**, For this figure we have disaggregated between fluxes undoubtedly considered 'anthropogenic', that is, anthropogenic CO_2 fluxes according to IPCC AR5 ('net land-use change'[5], or 'Forestry and Other Land Uses'[6]), dominated by changes in land cover (but including also some forms of forest management, see text for details) versus country GHG fluxes from this analysis separated out to show only net flux from 'land converted to other land uses' (**a**) and fluxes where the attribution between 'anthropogenic' and 'natural' effects differs at least in part, that is, residual terrestrial sink of CO_2 according to IPCC AR5[5,6] (considered largely 'natural') versus country GHG fluxes from this analysis separated out to show only net flux from managed 'land remaining the same land use' (assumed 'anthropogenic') (**b**). To make estimates more easily comparable with IPCC AR5, projections from this analysis were averaged over 10 yr (2010 = average 2005–2014). For the separation of 'land converted to other land uses' from 'land remaining under the same land use', see Methods. Historical anthropogenic flux data in IPCC AR5[5,6] are from Houghton's bookkeeping model[27,50], with the residual sink data as presented in WGI table 6.1 and WGIII table 11.2. The RCP data come from ref. 51 (Tables AII.2.1.b and AII.3.1a). Given the small share of non-CO_2 gases in the total LULUCF GHG budget (which excludes non-CO_2 GHG emissions from agriculture—see Methods for details), the different coverage on non-CO_2 gases does not represent an important reason for discrepancy between data sets.

$-0.8\ GtCO_2e\ yr^{-1}$ from 1990 to 2010. By splitting the 1990–2010 period (average emissions: $1.28 \pm 1.15\ GtCO_2e\ yr^{-1}$) into four sub-periods, we conclude that the historical trend is statistically significant after 2000 (Supplementary Section 3).

The wide range of future LULUCF net emissions depends on policy scenarios (Fig. 1). The 'country-BAU' scenario foresees a marked increase in global net emissions (Supplementary Table 6), reaching $1.94 \pm 1.53\ GtCO_2e\ yr^{-1}$ in 2030. This is because several developing countries assumed BAU to be a no-measures scenario, for example, ignoring the existing policies to reduce deforestation. Under the 'pre-(I)NDC scenario', that is, considering policies in place prior to COP-21 (including the earlier Copenhagen pledges[21]), global net emissions increase moderately, up to $0.36 \pm 0.94\ GtCO_2e\ yr^{-1}$ in 2030. For the 'unconditional (I)NDC scenario' the global net emissions slightly decrease, reaching a sink of $-0.41 \pm 0.68\ GtCO_2e\ yr^{-1}$ in 2030. An additional reduction of net emissions is estimated for the 'conditional (I)NDC' scenario, leading to a sink of $-1.14 \pm 0.48\ GtCO_2e\ yr^{-1}$ in 2030.

The analysis of the emission trend over the entire period shows that the difference between the 1990–2010 average and the net emissions in 2030 is not significant for the pre-(I)NDC scenario, but is significant (95% CI) for both the unconditional and the conditional (I)NDC scenarios (Supplementary Fig. 3b). This indicates that the reduction of net emissions assumed by the (I)NDCs relative to the historical period, if achieved, is statistically robust.

Comparison with global data sets

Figure 2 compares the historical LULUCF trend from our analysis with three other well-known global LULUCF data sets: (i) latest country reports to UNFCCC (refs 13,15,16,20); (ii) FAOSTAT for all land uses[23]; and (iii) IPCC Fifth Assessment Report (AR5) Working Groups (WG) I[5] and III[6] data used for the global carbon budget.

The difference between this analysis and the UNFCCC country reports is because several (I)NDCs updated past data sets, and because we used FAO-based data for gap filling, instead of pre-2010 National Communications.

Differences between this analysis and FAOSTAT include the definition of forest (UNFCCC versus FAO); coverage of areas and of carbon pools; and differing estimation methods by reporting agencies[8] (see Methods).

There is a large difference of about $3\ GtCO_2e\ yr^{-1}$ between this analysis, based on country reports following the IPCC Guidelines for National GHG Inventories[25,26] (IPCC GL), and the scientific studies summarized by the IPCC AR5[5,6], For the period 2000–2009, the level of net emissions is on average $0.90 \pm 1.11\ GtCO_2e\ yr^{-1}$ (95% CI) in our analysis and $4.03 \pm 2.93\ GtCO_2e\ yr^{-1}$ (90% CI, reflecting both methodological and terminological choices[27–29]) in IPCC AR5 (Fig. 2). The above differences are linked to different scopes of the two IPCC work streams[30]: the GL focus on internationally agreed methodologies for national anthropogenic GHG estimation, recognizing different countries' definitions and technical capabilities, whilst the AR5 focuses on assessing the state of the science on the global carbon budget using globally applied data, definitions and modelling methods.

Specifically, LULUCF in the IPCC GL includes estimates of GHG emissions and removals from all land uses, reported under either a stable or changed land-use status (typically in the last 20 years), for example, 'forest remaining forest' or 'forest converted to cropland' (or vice versa). There is a large scientific challenge of

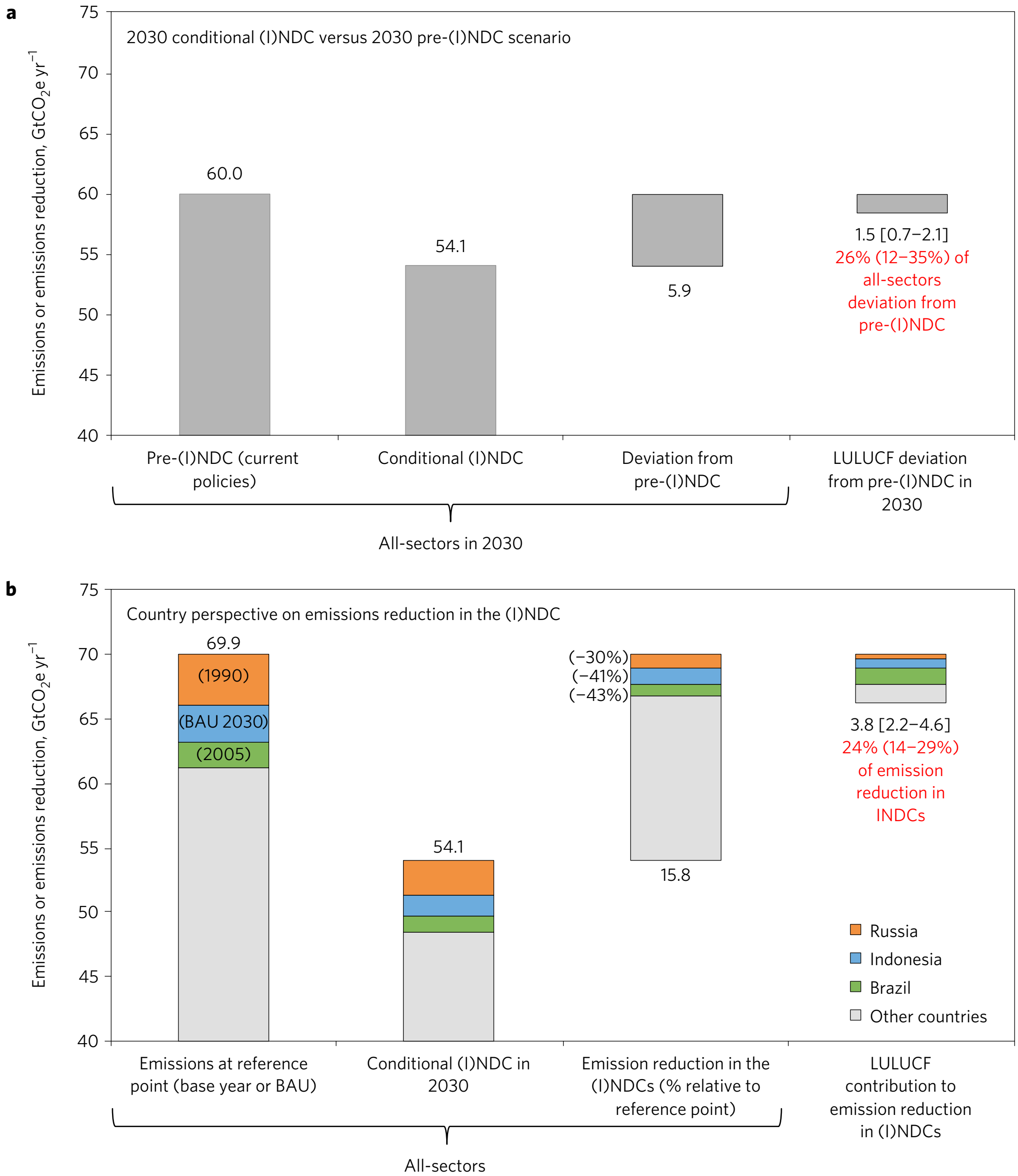

Figure 4 | Contribution of mitigation in the LULUCF sector to total GHG mitigation across all sectors according to countries' (I)NDCs. Levels of mitigation shown here assume a full implementation of the (I)NDCs (that is, conditional (I)NDCs), including the more ambitious conditional targets based on receipt of external support. **a**,**b**, The (I)NDC mitigation is shown on the basis of two perspectives of calculating the (I)NDC contribution: 2030 mitigation expected in (I)NDC versus 2030 pre-(I)NDC scenario based on current policies in place (perspective B in the text) (**a**), and country perspective on emissions reduction in the (I)NDC (perspective C in the text) (**b**). All-sectors 'pre-(I)NDC' (in **a**) and conditional (I)NDC scenario (in both **a** and **b**) are from the United Nations Environment Programme (UNEP)[35]. Data for all-sectors emissions at 'Reference point' (in **b**) are from country sources (except for the BAU estimates for China and India[18], see Methods for details) and reflects the way countries define their (I)NDC (relative to historical base years or BAU scenario year). Total numbers (in $GtCO_2e\ yr^{-1}$) are shown next to each column. The LULUCF contributions include the best estimate, based on country's official information, and a range expressing the main uncertainties when interpreting this information (for example, on projections or accounting rules) plus the uncertainties estimated in this analysis for the conditional (I)NDC case (see Supplementary Section 3). In **b**, three country examples are shown, selected both because they are representative of different (I)NDC targets in 2030 (−30% relative to 1990 for Russia, −41% relative to BAU 2030 for Indonesia and −43% relative to 2005 for Brazil) and because they are the most relevant countries in terms of the magnitude of the LULUCF contribution.

providing a practicable methodology to factor out direct human-induced mitigation action from indirect human-induced and natural effects[31,32], such as the natural ageing of forests, natural disturbances and environmental change (for example, climate change, extended growing seasons, fertilizing effects of increased $[CO_2]$ and nitrogen deposition). Therefore, the IPCC GL[25,26] use the category of 'managed land' as a default first-order approximation of 'anthropogenic' emissions and removals, based on the rationale that the preponderance of anthropogenic effects occurs on managed land[32]. The GHG inventories should report all emissions and removals for managed land, while GHG fluxes from unmanaged land are excluded. What is included in 'managed land' varies from country to country, although the countries' definition must be applied consistently over time.

In contrast, global models such as those used in IPCC AR5 and the Global Carbon Project take a different approach to separate anthropogenic from natural effects. Anthropogenic fluxes (referred to as 'net land-use change'[5,9], or 'Forestry and Other Land Uses'[6]) are estimated by a bookkeeping model[27] or by dynamic global vegetation models[9] based on changes in land cover (that is, between forest and agriculture), forest regrowth and, depending on the modelling capability, some forms of management (wood harvest and shifting cultivation). The difference between this modelled 'anthropogenic' flux and the estimated total net flux of CO_2 between the land and atmosphere[9] is the 'residual terrestrial sink'[5,6,9], which is generally assumed to be a natural response of primary or mature regrowth forests to environmental change[9,27].

The above methodological differences are reflected in the net emissions from developed countries, where most of the $\approx$3 $GtCO_2e\,yr^{-1}$ difference between our analysis and IPCC AR5 occurs for the period 2000–2009: while these countries report a substantial 'anthropogenic' sink (-1.9 $GtCO_2e\,yr^{-1}$ in 'UNFCCC Annex 1' countries), the bookkeeping model (IPCC AR5) finds a small net source (0.1 $GtCO_2e\,yr^{-1}$, 'OECD' in Fig. 1.7 of ref. 6). This difference lies essentially in whether the large sinks in areas designated by countries as 'managed forest' (following IPCC GL), well documented in forest inventories[10], are attributed to 'anthropogenic' (in the GHG inventories) or to 'natural' fluxes (in IPCC AR5).

To explore, at least in part, the impact of these different attribution methods, Fig. 3a compares what is considered undisputedly 'anthropogenic' by both IPCC AR5 (land-use change) and the country reports (land converted to other land uses). These estimates, both predominated by tropical deforestation, are of similar magnitude, especially after 2000. The other fluxes, where the attribution differs more between IPCC AR5 and the countries, are shown in Fig. 3b. Thus, much of the sink that countries report under 'forest remaining forest', the global models consider part of the natural flux. This disaggregation suggests that the residual sink is at least partly influenced by management practices not captured by global carbon models[33], but also that countries consider anthropogenic what is partly influenced by environmental change and by recovery from past disturbances.

There are many reasons for the lower sink reported by countries in Fig. 3b compared with the residual sink from IPCC AR5[30], including the fact that countries do not report sinks for unmanaged lands (for example, a large sink in tropical and boreal unmanaged forests[10]) and their reporting for managed land may be incomplete, that is, ignoring fluxes (for example, sink in grasslands, wetlands or forest regrowth) or carbon pools. There would be other factors to consider, including treatment of legacy fluxes from past land-use and other definitional and methodological differences. These would require a more detailed analysis, which is outside the scope of this paper.

Finally, the projections from this analysis can be compared with RCP scenarios used in IPCC AR5 up to 2030 (Fig. 3, dashed lines). For the undoubtedly 'anthropogenic' fluxes (Fig. 3a), our country data analysis falls broadly within the IPCC AR5 scenarios, supporting previous qualitative findings[34].

Overall, our analysis shows (1) that various global LULUCF data sets may be more consistent than apparent at first glance, (2) unless the scientific and GHG inventory community appreciate these definitional and methodological issues, conflicting numbers and messages are likely to appear in the coming years, and (3) that several reasons for the differences among data sets can be further reconciled in collaboration between the two communities, which would be a very useful contribution to science and policy.

Different perspectives on forest mitigation contribution

To reflect the complexity of approaches to (I)NDCs, this analysis assesses three different perspectives on LULUCF mitigation:

(A) 2030 (I)NDC versus 2005, that is, the expected impact of full (I)NDC implementation. The year 2005 is chosen as historically reliable in terms of data. Figure 1 shows that the global LULUCF net emissions to the atmosphere would transition from an estimated net anthropogenic source of $+0.8$ $GtCO_2e\,yr^{-1}$ in 2005 to a net sink of -0.4 $GtCO_2e\,yr^{-1}$ (unconditional (I)NDCs) or -1.1 $GtCO_2e\,yr^{-1}$ (conditional (I)NDCs) in 2030.

(B) 2030 (I)NDC versus 2030 alternative scenarios: country-BAU or pre-(I)NDC, that is, the additional LULUCF contribution relative to alternative scenarios (Fig. 1). The magnitude of the difference between country-BAU and pre-(I)NDC (1.6 $GtCO_2e\,yr^{-1}$) may raise concerns about the expected results-based payments under REDD+, which should be based on credible baselines and not on a no-measures scenario. Clarification of the role of REDD+ in (I)NDCs should therefore be seen as a priority by countries. Compared with the estimated pre-(I)NDC scenario, net emissions in 2030 are lower by 0.8 $GtCO_2e\,yr^{-1}$ or 1.5 $GtCO_2e\,yr^{-1}$ for unconditional and conditional (I)NDCs, respectively. For the 'conditional (I)NDC versus 2030 pre-(I)NDC' scenario (Fig. 4a), this LULUCF contribution of 1.5 $GtCO_2e\,yr^{-1}$ (Fig. 4a, last column) represents 26% of the total mitigation expected from all GHG sectors (5.9 $GtCO_2e\,yr^{-1}$ (ref. 35), Fig. 4a, third column). The countries contributing most to LULUCF mitigation under this perspective are Brazil and Indonesia, followed by other countries focusing either on avoiding carbon emissions (for example, Ethiopia, Gabon, Mexico, DRC, Guyana and Madagascar) or on promoting the sink through large afforestation programmes (for example, China and India).

(C) Country perspective on emissions reduction in the (I)NDC, that is, what each country might consider its 'LULUCF contribution to the overall (I)NDC', as part of its mitigation package; for example, if a country commits to reduce its all-sectors emissions by x% relative to y (reference point: base year or BAU scenario), what fraction of x is attributable to LULUCF? This approach looks at the way countries define their (I)NDCs (for example, reference point) and the way LULUCF is included within the (I)NDC (as any other sector or with special accounting rules). Globally, under this perspective the LULUCF contribution is 3.1 $GtCO_2e\,yr^{-1}$ (unconditional) or 3.8 $GtCO_2e\,yr^{-1}$ (conditional). The latter case (Fig. 4b, last column) corresponds to 24% of total all-sectors emission reduction relative to the reference point (that is, 15.8 $GtCO_2e\,yr^{-1}$, Fig. 4b, third column).

The emission reductions from a country perspective (Fig. 4b) are greater than the deviation from the pre-(I)NDC scenario (Fig. 4a), because countries' choices of reference point in their (I)NDCs tend to maximize the accounted mitigation; that is, countries that already reduced emissions used a historical base year, whereas countries expecting a future increase of emissions used a future BAU scenario. This is evident under perspective C, where nearly one-third of the contribution comes from Brazil, followed by Indonesia and Russia (Fig. 4b, last column). In Brazil, where total emissions have declined after 2004 due to successful implementation of policies to reduce deforestation[36], the NDC target (-43%) is relative to 2005. Our analysis suggests that in Brazil the LULUCF contribution to NDC is greater than the all-sectors NDC target for 2030; that is, the NDC allows emissions from other sectors to increase. In Indonesia, the conditional NDC target (-41%) is relative to the BAU scenario in 2030. LULUCF represents about 65% of current (2010) total emissions and is expected to contribute nearly two-thirds of the NDC emission reduction (relative to BAU) foreseen in 2030. Brazil and Indonesia are representative examples of GHG emission trends in developing countries: with an expanding and industrializing economy, the currently high LULUCF emissions are expected to decrease, and be superseded by growing emissions from the energy sector. The INDC target of Russia (-30%) is relative to 1990, with LULUCF contributing about two-fifths to this emission reduction. Russia is more important in perspective C than in B because its specific accounting method for LULUCF gives prominence to the contribution of the current forest sink to climate mitigation.

The (I)NDCs of the three countries above may be assessed also in terms of clarity and trust of information provided (see Supplementary Section 2). Overall, Brazil's NDC is transparent on the land-use sector and the underling GHG estimates are based on a well-developed monitoring system. The recent relevant upward revision of historical deforestation emissions in Brazil opens new questions on the implementation of the NDC target and on how and when data consistency between NDC, REDD+ and National Communications will be ensured. The relative ambiguity of Indonesia's NDC on how it would address land-use emissions is improved by the information in more recent documents. Furthermore, recent monitoring efforts have improved the GHG emission estimates, especially from peatland drainage and from forest degradation, whereas emissions from peat fires remain very uncertain. These improvements are mainly due to the REDD+ process, which in many developing countries is triggering unprecedented monitoring efforts. The challenge is increasingly to transfer these improvements into the NDC process, and to clarify the often uncertain relationship between the financially supported REDD+ activities and the NDCs. For Russia, transparency of mitigation efforts will crucially depend on clarifying the accounting method chosen for LULUCF. In addition, credible GHG estimates will require reconciling or explaining the currently large difference in the forest sink between the reports submitted by Russia to UNFCCC and to FAO.

In summary, the full implementation of (I)NDCs would turn LULUCF globally from a net source during 1990–2010 (1.3 ± 1.1 $GtCO_2e\,yr^{-1}$) to a net sink by 2030 (up to -1.1 ± 0.5 $GtCO_2e\,yr^{-1}$). The accounted LULUCF mitigation contribution in 2030 is very different depending on the way that mitigation is calculated, ranging from 0.8 to 3.1 $GtCO_2e\,yr^{-1}$ for unconditional (I)NDCs and from 1.5 to 3.8 $GtCO_2e\,yr^{-1}$ for conditional (I)NDCs (Supplementary Table 3). However, in relative terms, LULUCF would provide about a quarter of total emission reductions planned in countries' (I)NDCs irrespective of the approach to calculating mitigation.

Whereas a similar trend of decreasing LULUCF net emissions with full (I)NDCs implementation has been suggested also by other analyses[34,37], the absolute level of net emissions differs significantly: for example, ref. 37 reports net emissions about 3 $GtCO_2e\,yr^{-1}$ higher than ours, due to the 'harmonization' of different data sets (country projections and (I)NDCs were aligned to historical FAOSTAT data). By contrast, our study is the first so far showing a global picture of country-based LULUCF net emissions that is consistent between historical and projected periods, including discussing the differences with other global data sets and different mitigation perspectives.

Science can help to keep the forest mitigation promise

Several studies suggest a theoretical mitigation potential from land use[6,35,38] higher than in this analysis; others suggest limits posed by ecological and socio-economic constraints (including land availability)[39,40]. Irrespective of the potential, in the past UNFCCC negotiations the LULUCF sector has often been treated separately and considered as a secondary mitigation option, largely due to its complexity and limited trust in data.

Our analysis shows a wide range of future LULUCF net emissions, depending on policy scenarios. Through the implementation of (I)NDCs, countries (especially developing ones) expect a key contribution from LULUCF in meeting their (I)NDC targets, with a clear focus on forests. Achieving this will require increasing the credibility of LULUCF mitigation, through more transparency in commitments and more confidence in estimates. To this regard, the Paris Agreement includes a 'Framework for transparency of actions', key for its credibility[41], aimed at providing clarity on GHG estimates and tracking of progress toward achieving countries' individual targets.

More transparent commitments mean that future updates of the NDCs should provide more details on how LULUCF mitigation is calculated towards meeting the target and how the financially supported REDD+ activities contribute to the pledges. More confidence in LULUCF estimates will require improving the country GHG inventories in terms of transparency, accuracy (including information on uncertainties), consistency, completeness and comparability[42], especially in developing countries.

This is a challenge and an opportunity for the scientific community. Supporting country GHG estimation includes regular reviews of the latest science (for example, ref. 43), expanding the scope of the operational methods in the IPCC guidance, as has been done for REDD+ (ref. 44), and incorporating opportunities offered by emerging satellite data[45,46] available through highly accessible products[47]. More confidence also requires independent checks of the transparency and reliability of data, for example, by reproducing and verifying countries' GHG estimates. According to IPCC guidance[25], verification of GHG inventories is key to improve scientific understanding and to build confidence on GHG estimates and their trends. This can be achieved by comparing GHG inventories with scientific studies using partially or totally independent data sets and/or different methods (for example, ref. 48), including greater integration of modelling and measurement systems of land-use-related net emissions[9]. Meaningful verification requires improving mutual understanding and cooperation between the scientific community and the developers of national GHG inventories.

Finally, increasing trust in proposed LULUCF mitigation options will require reconciling the current $\approx$3 $GtCO_2e\,yr^{-1}$ difference in global LULUCF net emissions between country reports and scientific studies (as reflected in IPCC reports). Among the many possible reasons for these differences[30,49], we suggest that what is considered 'anthropogenic sink' is key and deserves further analyses. While recognizing differences in scopes among these communities, reconciling differences in estimates is a necessity, as the 'Global stocktake', that is, the foreseen five-yearly assessment of the collective progress toward achieving the long-term goals of the Paris Agreement, will be based on both country reports and IPCC reports. Without speaking the same language, the 'balance between anthropogenic GHG emissions by sources and removals by sinks in the second half of this century'[1], needed to reach the ambitious 'well-below 2 °C' target, cannot be properly assessed.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Acknowledgements

Author Jim Penman passed away recently. Jim Penman was the UK and EU negotiator on LULUCF for many years, coordinator of key IPCC methodological reports and credited as one of the key architects of the LULUCF process under the UNFCCC. He was awarded an OBE (Order of the British Empire) for his work. He was an outstanding scientist and negotiator, who strived always towards a better world.

Author contributions

G.G. conceived the analysis on (I)NDCs, executed the calculations and drafted the paper. J.H., F.D., M.d.E. and J.P. contributed to the analysis and to the writing of the paper. S.F. provided data from FAO FRA 2015 and contributed to the analysis. J.H. was supported by the Leverhulme Foundation and EU FP7 through project LUC4C (GA603542).

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Disclaimer: The views expressed are purely those of the writers and may not in any circumstances be regarded as stating an official position of the European Commission. Correspondence and requests for materials should be addressed to G.G.

Competing financial interests

The authors declare no competing financial interests.

Methods

This analysis quantifies the mitigation role of Land Use, Land Use Change and Forestry (LULUCF, mainly forests), based on the (I)NDCs[3,4] submitted by Parties in the context of the Paris Climate Agreement[1], complemented with information from other countries' official documents. This analysis does not aim to assess specific country policies or the quality of country data in comparison with independent sources.

Our analysis of LULUCF net emissions over time covered all 195 UNFCCC countries, with assumptions necessary in some cases (that is, using the latest historical data where no (I)NDC projection was available, see below). However, due to constraints, our estimation of the LULUCF mitigation contribution was possible only for 68 countries (41 (I)NDCs), covering 83% of global forest area (based of FAO FRA 2015[22]). Other countries were not included either because LULUCF was not clearly included in the target or because the LULUCF contribution was not entirely clear or directly quantifiable (see Supplementary Section 1 and Supplementary Information).

Our analysis is based on countries' documents submitted up to February 2016. However, the most relevant recalculations made by countries after that date and before December 2016 (for example, Brazil, Indonesia and USA) are briefly discussed in Supplementary Section 2.

Information used in this analysis. The methodological approach applied in this analysis required collecting information on:

- *Countries' historical data and projections up to 2030* (for all 195 UNFCCC countries), using countries' documents submitted up to end of February 2016, with the following priority: (I)NDCs[3]; other country data submitted to UNFCCC (2015 GHG Inventories[13] (GHGI) for developed counties, and GHGIs included in recent National Communications[15,20] (NC) and in Biennial Update Reports[16] (BUR) for developing countries); other official countries' documents (for example, ref. 21); FAO-based data sets (for forests[8,22] and non-forest emissions[23]). Despite gaps in country reports (especially for non-forest land uses in developing countries), this priority is justified by the fact that country reports to UNFCCC are formally reviewed or technically assessed by UNFCCC (GHGIs of developed countries are formally reviewed annually, with biennial technical assessment for developing country inventories), and are the means by which countries assess their progress towards targets. Furthermore, FAO FRA reports[22] are not primarily for reporting CO_2 emissions and removals, while UNFCCC country reports specifically address emissions and removals. The range of historical country data sets (dotted line in Fig. 1) reflects alternative selections of country sources, that is, GHGIs for developed countries (selected for both the lower and the upper range), plus FAO-based data sets (upper range) or NCs (lower range) for developing countries. This alternative selection assumes a high reliability of GHGIs for developed countries, while providing an idea of the impact of choosing only NCs (including old NCs) versus FAO-based data sets for developing countries. See Supplementary Table 4 for an overview of historical data sets used.
- For historical data, GHGIs with a time series from 1990 to 2013 were available for all developed countries, in most cases including Harvested Wood Products. For developing countries, data are from BURs when available or from latest NCs, typically not including Harvested Wood Products. When only few years were available (typically at least two between 1990 and 2010), 5- or 10-year averages were used. Sometimes, especially for older NCs, data from NCs contain ambiguities, or are not fully comparable across countries (for example, while most countries implicitly report only emissions and removals from 'managed forests', in accordance with the recent IPCC guidance, a few countries include the sink from apparently unmanaged forests). To reduce the risk of using old or inappropriate data, the more recent FAO data sets were used instead of NCs prior to 2010. Net emissions from forests (for example, sink from forest management and emissions from deforestation) usually dominate the LULUCF fluxes in country reports, although in some cases emissions from croplands and grasslands (rarely reported by developing countries) are also relevant, especially from organic soils.
- On the basis of available information from countries' reports to UNFCCC complemented by expert judgement, we performed an analysis of the uncertainties for LULUCF absolute GHG net emissions (level) and for the associated trends (see Supplementary Section 3, Supplementary Table 7 and Supplementary Figs 2 and 3).
- The FAO-based data sets include country data on forest carbon stock change from the Forest Resource Assessment (FRA 2015[22], as elaborated by ref. 8) and FAOSTAT[23] data on country-level non-forest land-use emissions (CO_2, CH_4 and N_2O from biomass fires, including peatland fires, and from drainage of organic soils). The overall small difference between the FRA 2015 forest carbon stock data used in our analysis (based on ref. 8) and the FRA 2015 forest carbon stock data included in FAOSTAT[23] is that the gap-filling methods differ (although for the biomass pools such difference does not impact the total net CO_2 emissions/removals across the time series), and that we include both living biomass (above- and below-ground) and dead organic matter if reported by countries, while FAOSTAT considers only living biomass. Overall, for the historical period we used only FAO-based data sets to fill the gaps for a relative large number (60), but typically rather small developing countries (covering 11% of global forest area). The significant difference between this analysis and FAOSTAT (Fig. 2 of the paper) is due to several factors, including higher non-forest land-use emissions in FAOSTAT for developing countries (especially in Indonesia, Sudan and Zambia) and higher forest land-use emissions in FAOSTAT for both developing countries (for example, Colombia, Liberia, Madagascar, Myanmar, Nigeria, Philippines and Zimbabwe) and developed ones (USA and Russia).
- For projections, data from (I)NDCs (with some expert-judgement interpretation when needed) or NCs[20] were available for almost all developed countries. For developing countries, if no projection was available in the (I)NDCs, BURs or NCs, FRA 2015 country projections[8,22] were used in a few cases. Where no projection was available, the latest historical country data available were used (that is, continuing the recent estimates).
- While almost no country provided formal information on uncertainties in their projections, in the analysis of uncertainties (see Supplementary Section 3) we conservatively assumed that the uncertainties estimated for the past will hold for the future. In addition, the different scenarios that our analysis identified up to 2030 (Fig. 1) may also give an order of magnitude of the uncertainties. The range 'LULUCF projections min–max' shown in Fig. 1 is slightly broader than the various scenarios (by about 500 $MtCO_2e\,yr^{-1}$, or 0.5 $GtCO_2e\,yr^{-1}$, in 2030) because in a few cases countries provide a range of projections and not all the various projections can be associated with the four scenarios analysed. The overall difference of about 500 $MtCO_2e\,yr^{-1}$ is essentially due to the range of projections from the US (the difference between the 'high' and a 'low' sequestration scenario in their latest National Communication amounts to 370 $MtCO_2e\,yr^{-1}$ in 2030), and due to Russia (the difference between the various sequestration scenarios in their latest National Communication amounts to about 150 $MtCO_2e\,yr^{-1}$ in 2030).
- With regards to the GHGs considered, this paper focuses on CO_2 emissions and removals and on available data on non-CO_2 emissions (CH_4 and N_2O), based on the information included in countries' documents. National GHGIs are required to report on all GHGs, but in some developing countries the information on non-CO_2 gases is incomplete. On the basis of available information, and excluding agricultural emissions, the importance of non-CO_2 gases is typically small relative to the total GHG fluxes (see ref. 30 for details), representing about 2–3% of total CO_2-equivalent forest flux, with slightly higher values found where forest fires are important in the overall GHG budget. This suggests that, when comparing different data sets (Fig. 2), the possible different coverage in the (I)NDCs and other documents of non-CO_2 gases does not represent a major reason for discrepancy.
- *Type of mitigation target elaborated in each countries' (I)NDC* (Supplementary Table 1), that is, change in absolute emissions or intensity, either relative to a base year or to a BAU scenario (that is, 2025 or 2030 scenario year); target 'unconditional' or 'conditional' (that is, related to the provision of finance, technology or capacity-building support). (I)NDCs expressing only 'policies and measures' (without quantitative targets) were not taken into account.
- *Modality of inclusion of LULUCF within each countries' (I)NDC* (Supplementary Table 1), that is, it may be treated in the same way as other sectors (fully included as part of the overall target), or partially included (only forest activities), or considered separately with special mitigation actions and/or accounting rules. Some additional expert evaluation was included where necessary.

(I)NDC cases. The (I)NDCs were classified into four '(I)NDC cases' (Supplementary Table 2). Based on the availability of country LULUCF information, enough information was found to assign 68 countries to these different '(I)NDC cases', and to quantify directly the expected LULUCF mitigation. These 68 countries include all countries with a major forest coverage and correspond to 78% of global emissions in 2012 (including LULUCF emissions and international aviation and marine emissions)[2].

Different mitigation perspectives. The quantification of the mitigation role of LULUCF has been undertaken using different approaches, reflecting different perspectives, according to the questions addressed (Supplementary Table 3).

Estimation of LULUCF mitigation. Whereas estimates for perspective A (LULUCF net emissions over time) could be made for all 195 UNFCCC countries, the information needed for the LULUCF mitigation contribution under perspectives B ((I)NDC compared with alternative future scenarios) and C (country perspective on calculating emissions reduction (I)NDC) was available only for the 68 countries (41 (I)NDCs) included in Supplementary Table 1. For the remaining countries, the additional mitigation in perspectives B and C was assumed to be zero relative to other sectors. This assumption is probably conservative (see Supplementary Section 1).

Based on the four (I)NDC cases (Supplementary Table 2), and using the available country information (generally with limited expert judgement), this analysis quantified the LULUCF mitigation perspectives (Supplementary Table 3) following the method illustrated in Supplementary Fig. 1. In the very few cases where the target is expressed for 2025, we assumed that the same target applies to 2030, allowing us to sum up all the countries' contribution to 2030.

Contribution of the land sector to mitigation activity across all sectors. The LULUCF mitigation perspectives B and C were compared with the expected (I)NDC mitigation efforts across all sectors, for each country and at a global level. The global-level all-sectors 'pre-(I)NDC' and '(I)NDC unconditional + conditional' are taken from UNEP[35]. All-sector emissions at the 'reference point' (that is, base year or BAU scenario for target year 2025 or 2030) are from: (i) countries or (ii) from ref. 18 (for the BAU estimates for China and India). These two sources of information were sufficient for countries representing 87% of global GHG emission in 2012. Emissions for the remaining countries were approximated by assuming the same ratio of emissions at reference point (that is, estimates from available sources were multiplied by 100/87).

Comparison of this analysis with IPCC AR5. To make a meaningful comparison of country data (this analysis) with IPCC AR5[5,6], we disaggregated country data between 'land converted to another land use' and 'land remaining under the same land use'. While this disaggregation was directly available in all developed country reports, and was largely available for the most important developing countries (for example, Brazil, Indonesia, India, China and Mexico), for the remaining developing countries information was generally available only for deforestation. In these cases, unless specified otherwise, the other emissions and removals were assigned to 'land remaining under the same land use'.

Data availability. This study is primarily based on countries' (I)NDCs[3,4] and other GHG reports submitted to UNFCCC[13,15,16,20,21], complemented by FAO-based data sets[8,22,23]. A large part of elaborated data used to support our findings are available in the Supplementary Information, including:

- *Country-specific information* for 68 countries (41 (I)NDCs), in terms of general features of the (I)NDCs (Supplementary Tables 1 and 2) and of data and sources of information of LULUCF net emissions for the historical period 1990–2010 and for 2030, as expected for unconditional and conditional (I)NDC targets (Supplementary Table 5).
- *Aggregated information* on uncertainties (Supplementary Figs 2 and 3), on LULUCF mitigation perspectives (Supplementary Table 3) and on LULUCF net emissions (Supplementary Table 6).

Any other raw or elaborated data used in this study are available from the corresponding author on request.