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Annual emissions of carbon from land use, land-use change, and forestry 1850-2020

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Abstract

Estimates of the annual emissions of carbon from Land Use, Land-Use Change, and Forestry (LULUCF) are important for constructing global, regional, and national carbon budgets, which in turn help predict future rates of climate change and help define potential strategies for mitigation. Here we update a long-term (1850-2020) series of annual, national carbon emissions resulting from LULUCF (Houghton and Nassikas, 2017), based largely, after 1960, on statistics of land use from the Food and Agriculture Organization (FAO) of the United Nations (FAO, 2021). Those data suggest that rates of deforestation in the tropics (and thus net emissions of carbon) have decreased over the last ten years (2011-2020). The data also indicate that the net loss of tropical forest area was greater than the net gain in agricultural lands, and we explore four alternative explanations for this apparent forest conversion, one of which is shifting cultivation. We also discuss how opposing trends in recent estimates of tropical deforestation (and emissions) might be reconciled. The calculated emissions of carbon attributable to LULUCF approximate the anthropogenic component of terrestrial carbon emissions, but limiting national carbon accounting to the anthropogenic component may also limit the potential for managing carbon on land.

1. Introduction

The annual net exchanges of carbon between land and atmosphere are represented by two terms in the global carbon budget: one term for direct anthropogenic effects (i.e., management) and the second term for natural effects and indirect anthropogenic effects (e.g., the response of terrestrial ecosystems to environmental change) (Grassi et al., 2018; Friedlingstein et al., 2022). Quantifying the emissions for these two processes and separating them are important for determining whether indirect effects are changing, perhaps as a result of feedbacks between climate change and terrestrial carbon storage. Estimates of the emissions of carbon from both of these two processes, however, are variable and uncertain.

One surrogate for the emissions of carbon attributable to management is based on Land Use, Land-Use Change, and Forestry (LULUCF) (Watson et al., 2000). However, there are at least two different approaches for determining these emissions. The original approach was based on bookkeeping models (e.g., (Houghton and Nassikas, 2017; Hansis et al., 2015; Gasser et al., 2020), which calculated the emissions resulting from conversion of native ecosystems to agriculture (croplands and pastures) and from harvest of wood from forests. They did not include all the effects of management because they generally neglected the emissions from different management practices within agriculture (e.g., no-till cultivation, irrigation, erosion and redeposition of sediments (Naipal et al., 2018; Wang et al., 2017) and forestry (e.g., tree breeding, fertilizer use, non-timber use of forests (Erb et al., 2013)). The results from these bookkeeping models have been used to define the role of land management (E_{LUC}) in the global carbon budget (Friedlingstein et al., 2022).

A second approach for estimating the emissions from LULUCF is the approach used by countries to define their national greenhouse gas inventories (NGHGIs) (Grassi et al., 2022). The approach was developed because of the difficulty of separating direct anthropogenic effects (e.g., land use) from indirect and natural effects (i.e., environmental effects). The approach is based on the so-called Managed Land Proxy (MLP). Countries count all of the emissions from land defined as managed, and count none of the emissions from unmanaged lands. Thus, instead of separating processes (direct and indirect effects), the approach separates areas (managed and unmanaged lands). Unfortunately, while there are no direct anthropogenic effects on unmanaged lands (by definition), there are indirect effects on managed lands. That is, environmental factors affect both managed and unmanaged lands. And because indirect effects are currently responsible for a net removal of carbon from the atmosphere, the NGHGI approach produces lower estimates of emissions from LULUCF than the first, or original, approach.

The analysis described here is based on the first of these approaches. We update and improve an earlier analysis of emissions attributable to LULUCF (Houghton and Nassikas (2017). It is important to note that the “improvements” described in this work have no objective benchmark against which to verify that “improvement”. There are no large-scale independent observations of the effects of direct anthropogenic management. We have improved the bookkeeping model (to be more consistent with harvesting practices, for example) and used more recent data for the calculations, but the true effects of management are not known.

The update and improvements consists of four steps. First, we improved the bookkeeping model's simulation of fuelwood and industrial wood harvest. Then we extended the period of analysis to 2020, based largely on national data on land use from FAO (2021). Incorporating the recent data required more than adding the most recent five years (2016-2020) because FAOSTAT (FAO, 2021) incorporated data from the latest Forest Resources Assessment (FAO, 2020), which included revisions back to 1990. Third, we explicitly accounted for the apparent conversion of tropical forests to non-agricultural lands (i.e., lands that were neither crops, nor meadows and permanent pastures), as reported by FAOSTAT (FAO, 2021). This apparent conversion represents either an error in land-use statistics, a real change in land use, or both. Possibilities of real change include temporary deforestation, increases in degraded (low carbon) lands, and shifting cultivation, none of which is explicitly recognized as a land use by FAOSTAT (FAO, 2021). We calculated the emissions for all four of these alternative interpretations. Finally, we included newly published and updated estimates of the carbon emissions from peatlands in northern lands (Qiu et al., 2021) and in Southeast Asia (Randerson, 2013; Hooijer et al., 2010; Randerson et al., 2018).

2. Methods

Annual emissions of carbon from LULUCF were calculated with a bookkeeping model based on two types of data: activity data (rates of wood harvest and rates of land-use change) (Section 2.2) and per hectare effects of land-use change and harvest on carbon stocks (MgC ha^{-1} yr^{-1}) (Section 2.3).

2.1. Bookkeeping model

We used a bookkeeping model (Houghton and Nassikas, 2017) to calculate the annual net and gross emissions of carbon to and from the atmosphere as a result of LULUCF. Note that *land use* includes forestry and, to a limited extent, fire management. It does not include changes in agricultural management practices, except when new croplands and pastures are converted from native ecosystems. *Land-use change* includes the conversion of native ecosystems to crops, pastures, and other non-forest lands, and the reversion of these land uses back to native ecosystems following abandonment.

The model is non-spatial. It uses national LULULCF data and calculates emissions for individual countries, but it does not use gridded data. Rather the input data are annual rates of land-use change per country and m^3 wood harvested per country.

The overall purpose of the bookkeeping model is to track changes in carbon on every hectare of land affected by land use, land-use change, and forestry. Only lands experiencing LULUCF are included in the calculations. The effects of environmental change on lands either managed or unmanaged are excluded to the extent possible.

Each year a new age class of hectares is created in the model for each type of land use or land-use change in each type of ecosystem. Age classes either lose carbon annually (cropland newly converted from forest) or gain carbon annually (growing forest) until they reach a minimum soil carbon (croplands) or a maximum biomass carbon (mature forest) (Fig. 1).

The changes in carbon stocks that take place as a result of land use and land-use change are prescribed in the model with response curves (Fig. 1) (Section 2.3) for each type of ecosystem and each type of land use and land-use change. The prescribed, or fixed, nature of these per hectare changes is what distinguishes this bookkeeping model from models based on physiological or ecological processes. Four pools of carbon are tracked: biomass (above and belowground); slash (debris left on site at the time of management: twigs, branches, stumps, roots); wood products (fuelwood, paper, pulp, lumber); and soil organic carbon. Not all of the carbon lost to the atmosphere as a result of deforestation is lost in the year of deforestation, but occurs over decades as a result of decay. Likewise, growing forests accumulate carbon for a century or more (see Section 2.3). Net and gross emissions of carbon to the atmosphere (and removals from the atmosphere) were calculated annually by summing the emissions from each hectare of each age class.

Burning and decay of organic matter as a result of LULUCF accounted for annual gross emissions of carbon, while growing forests recovering from harvest or agricultural abandonment removed carbon from the atmosphere. The model simulated annual age classes until an age class reached a new equilibrium, when no further loss of carbon occurred (e.g., in cultivated land) or no further gain of carbon occurred (e.g., in a mature forest).

The bookkeeping model was developed to calculate only direct anthropogenic effects, ignoring the effects of environmental change on stocks of carbon. That is, rates of forest growth and rates of decay (MgC ha^{-1} yr^{-1}) varied for different types of land use and land-use change and for different ecosystem types (the model included 20 ecosystem types), but they did not vary through time. The same rates of growth and decay applied in 1850 and 2020. Thus, the model calculated emissions from LULUCF as though the environment was constant. The approach could not completely eliminate the effects of environmental change because field data used to define changes in vegetation and soil (Section 2.3) were collected at different times during the last 50 years or so, and thus included indirect effects. For example, increased rates of growth as a result of CO_2 fertilization, led the model to overestimate rates of forest growth in the past and to underestimate them in recent years.

Emissions of carbon from organic soils (burning and decay of peatlands as a result of management) were not explicitly included in the bookkeeping model, but were added to the results based on independent studies (Randerson et al., 2018; Qiu et al., 2021).

We ran the model starting in 1700 but report emissions only after 1850 to avoid artificial emissions resulting from spin-up of the model. For example, it took several decades for the pools of carbon in wood products and slash to reach equilibrium (inputs equal outputs). Similarly, it took approximately 150 years for the pools of carbon in age classes of growing forests to reach equilibrium. Rather than initializing the model with pool sizes and age classes specified in 1850, we “spun-up” the model from 1700 so that these pools were in existence and approximately of the appropriate magnitude by 1850.

2.2. Changes in land use (rates of conversion (ha yr^{-1}) and rates of wood harvest (m^3 yr^{-1}))

We considered the four major types of land use FAOSTAT (FAO, 2021) reports: crops, permanent meadows and pastures (hereafter referred to as pastures), forest land, and other land. “Other land” includes all lands that are neither in agriculture nor forest land. Examples include urban lands, settlements, grasslands that were not grazed, rock, ice, and lands denuded by mining. The sum of areas in all four categories is equal to the total land area of a country, and other land is calculated as a residual to reach that total. We assumed that changes in these land uses from one year to the next are directly anthropogenic (i.e., a consequence of management decisions). We discuss below possible exceptions to, and implications of, that general assumption.

We also considered forest management as a land use (i.e., annual harvest of industrial wood and fuel wood (FAO, 2021). In the United States we included fire exclusion as an aspect of forest management that affects the carbon stocks of forests. Areas burned by wildfires were obtained, not from the FAO, but from USDA (1926-1990). Fire management has been and is practiced elsewhere, but quantitative data detailing changes through time were not available for other countries, with the exception of peatland burning in Southeast Asian countries and northern countries.

We reconstructed historical changes in land use for each country starting with the most recent information and working backwards in time. From 1990-2020 we used data from the (FAO, 2020) for national areas in forest land, crops, pastures, and other land. From 1961 to 1990 we used the same data for crops and pastures, but data on forest area were not available from that source. Before 1961 (for crops and pastures) and before 1990 (for forests) we used national statistics or the literature, where available, to quantify areas in different types of land use. In the absence of such information, we extrapolated rates of change into the past in proportion to population growth. Thus, uncertainties in rates of LULUCF were greater before 1990 and greater still before 1961. Ironically, the variation among emissions estimates appears less in the past (*less* uncertainty?) than in recent years, in part because rates of land-use change were lower in the past, and in part because different studies presumably used similar assumptions in the absence of data (Houghton and Nassikas, 2017; Houghton, 2010).

Calculating rates of land-use change from FAOSTAT (FAO, 2021) data on land use was not a trivial exercise. We used changes in land area from one year to the next to determine rates of conversion among categories. For example, if forest area decreased by one ha and crop area increased by one ha, then we assigned one ha as converted from forest to crop. It is possible, however, that two ha were deforested and one ha converted from crop to forest, thus yielding the same *net* change: one ha from forest to cropland. We underestimated the gross emissions and removals of carbon that would have resulted from gross changes in land use. The effect on net emissions is unclear, but some effect is likely as the emissions and removals associated with gross changes in land use are not necessarily symmetrical in time. For example, the rate of emissions from a hectare burned at the time of forest clearing is higher than the rate of carbon removal in forest growth.

The cross-walk between annual changes in land-use categories (FAOSTAT (FAO, 2021) and rates of conversion between one category and another (land-use change) becomes more complex when net changes in area are reported for more than two categories. For example, if both forest and other land each decreased by one ha while crop and pasture each increased by one ha, it was unclear how much forest area was converted to crop as opposed to pasture, and how much other land was converted to either. Thus, we developed a series of rules to determine the translation of FAOSTAT data to annual rates of land-use change.

With these rules, a loss of forest was preferentially converted to crop, then to pasture, and finally to other land to the extent that these categories increased in area. We explore the apparent conversion of forest to other land in more detail below (Section 2.4.3). We also smoothed annual rates with a five-year running average to avoid large year-to-year variations in rates of land-use change. For example, large back-and-forth shifts between croplands and pastures were assumed to be artifacts of reporting.

The areas in croplands are better documented through history than other land uses. Areas in permanent meadows and pastures are less consistently defined, in large part because many lands that are grazed (rangelands) are neither meadows nor pastures.

With few exceptions (United States, Europe, South and Southeast Asia), national accounting of forest areas is not well documented historically. Thus, we generally reconstructed or extrapolated historical changes in forest areas backwards from the oldest available data into the past. Because the areas of different land uses is least well known for years before 1961, we adjusted the starting areas (1700) so as to end in 2020 with the areas of land use reported by FAOSTAT.

2.3. Changes in carbon per hectare as a result of LULUCF (Response Curves)

The stocks of carbon in vegetation and soils of different types of natural ecosystems were initially compiled from ecological and forestry literature. These values were assigned to modeled ecosystems in 1700. Houghton and Nassikas (2017) then adjusted those starting values of biomass so that the average forest biomass simulated in 2015 matched the estimates of average forest biomass per country reported by FAO (2015). We did not change those starting values. Median values of biomass by ecosystem type are shown in Appendix 1.

Average soil carbon densities for the top meter of soil were assigned to natural ecosystem types so as to give regional averages that were consistent with regional variation as described by Schlesinger (1984); Zinke et al. (1986) for major types of vegetation (Appendix 1).

The changes in carbon stocks that took place as a result of land use and land-use change were prescribed in the model for each type of ecosystem and each type of land use and land-use change (Fig. 1). Rates of forest growth included a fast initial rate, followed by a slower rate that continued until the biomass was “recovered” to its original level, after which growth stopped. These response curves of two linear rates were meant to approximate the declining rate of biomass accumulation during forest growth. The lower rate applied until about 75% of the original biomass had recovered. Forests in the model were preferentially harvested at this 75% recovery.

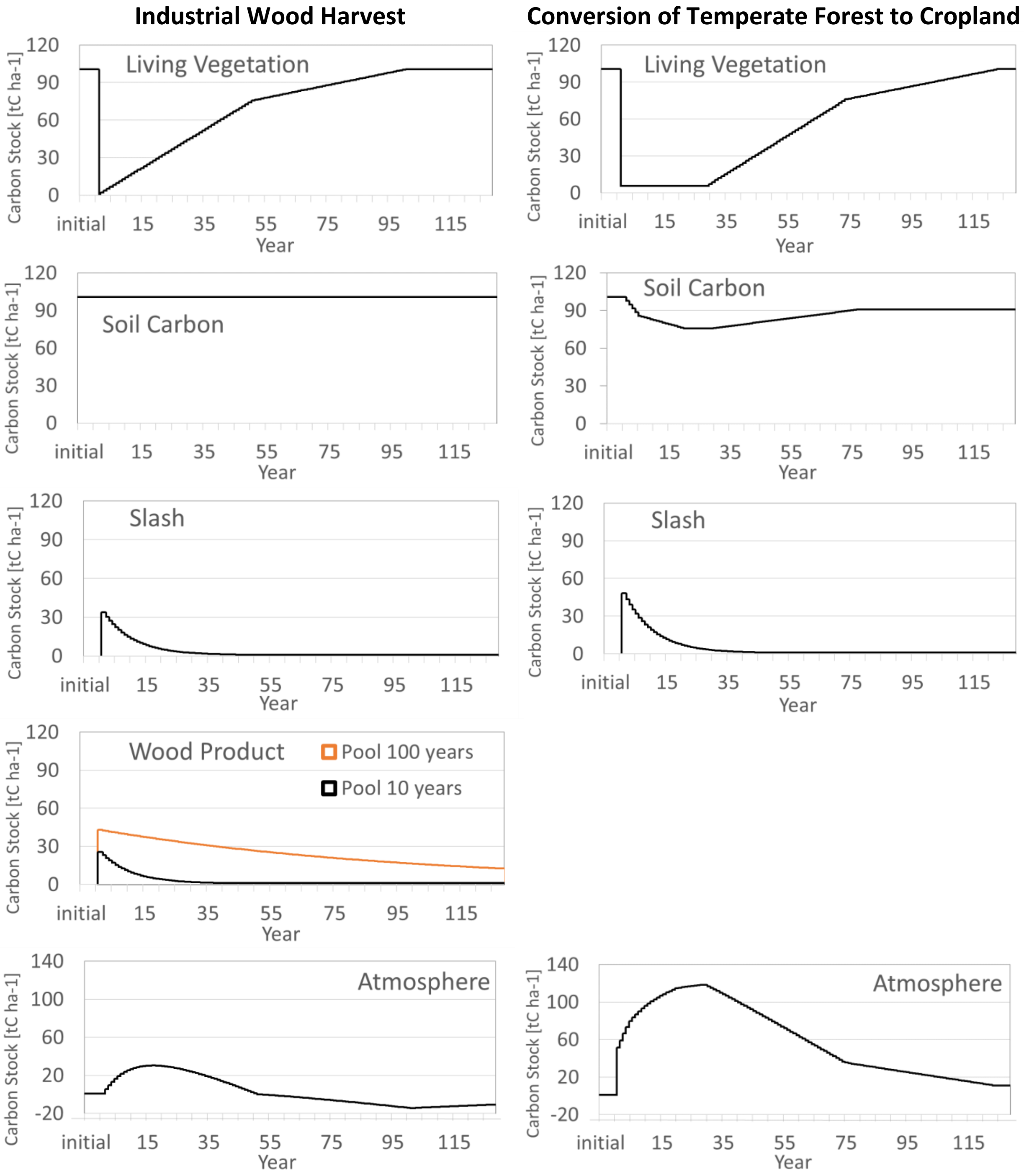

Figure 1. Response curves. Per hectare changes in vegetation, soils, slash and wood products as a result of management, in this case industrial wood harvest (left) and conversion of temperate

forest to cropland (right), followed by abandonment. Change in soil carbon was not included in the harvest response curves because direct measurements are too variable to assign a reliable or consistent change. The bottom panels show the emissions of carbon to the atmosphere as a result of annual changes in the four pools.

Similar response curves were used to define the rates of loss and accumulation of soil organic carbon following cultivation of native soils and abandonment of agriculture, respectively. Approximately 25% of the organic carbon in the top meter of soil is lost with cultivation in a two stage process approximating exponential decay (Detwiler, 1986; Schlesinger, 1986; Davidson and Ackerman, 1993; Post and Kwon, 2000; Johnson and Curtis, 2001; Guo and Gifford, 2002; Murty et al., 2002).

In addition to changing the carbon in vegetation and soil, management also generates slash (branches, twigs, leaves, stumps and roots left on site after harvest and forest conversion) and wood products. Slash was assigned exponential decay rates in the model that varied with ecosystem type, and wood products were assigned to pools that decayed at rates of 1 yr^{-1}, 0.1 yr^{-1}, or 0.01 yr^{-1}, corresponding roughly to fuelwood, paper & pulp, and lumber, respectively, which were obtained from FAOSTAT (FAO, 2021).

A set of four response curves defined the annual changes in carbon for each hectare cultivated, abandoned, or harvested. A different set of response curves was assigned for each type of land use and land-use change on each type of ecosystem. Twenty types of ecosystems were included.

2.4. Updates included in this work

We incorporated changes to Houghton and Nassikas (2017) in four steps.

Step 1: Improved calculation of carbon emissions from wood harvest, using data from FAOSTAT (FAO, 2015) (Houghton and Nassikas, 2017).

Step 2: Updated and revised input to accommodate new data from FAOSTAT (FAO, 2021) (this step included some historical adjustments as well)

Step 3: Treated the apparent conversion of forests to other land with four alternative assumptions. We also estimated the historical trajectory of this conversion before 1990 so that there was not an abrupt change when FAO data on forest area first became available (FRA, 1990).

Step 4: Included other effects of management (peat drainage and burning in Southeast Asia and peatland use northern lands)

Each of these steps is elaborated below.

2.4.1 Adjustments to the bookkeeping model for wood harvest – Step1

Two adjustments were made for the original code used by Houghton and Nassikas (2017). First, the code did not deliver the appropriate volume of wood products (from FAOSTAT (FAO, 2021)) because some of the annual production had been assigned to slash. In the improved version, the total amount of wood products harvested was the amount specified by FAO, and an additional amount of carbon was converted from biomass to slash.

The second adjustment reduced harvest intensity (MgC ha^{-1}) for secondary forests to account for the lower biomass in these forests. Harvests were thereby more representative of harvest practices. The improvement increased the areas of secondary forests harvested, thereby increasing the annual gross uptake of carbon in recovering forests.

2.4.2 Incorporation of new data from the FAO – Step 2

We used two data sources from the FAO to update the analyses to 2020. Every five years since 1990 the FAO has published a Forest Resources Assessment (FRA), the latest being FRA2020 (FAO, 2020). The FRAs report the areas and biomass/carbon stocks of forests, country by country. Every year since 1960 FAOSTAT reports the national areas of croplands and pastures. It also reports annual rates of harvest of industrial wood and fuelwood. We used data from the most recent FAOSTAT (FAO, 2021), thereby accounting not only for additional years but also for revisions to earlier estimates. Table A1 provides more specific references for the FAO data we used. Revised data from FRA2020 and FAOSTAT (FAO, 2021) sometimes required that we revise pre-1990 estimates in order to avoid abrupt changes. Areas in forest land are reported every five years since 1990, and we used five-year running averages to smooth rates of land-use change reported by the FAO (2021). We also assumed that the rates for 2015-2019 continued in 2020.

For a few countries, we used sources of data other than from the FAO. For example, for China we used cropland areas from Liu and Tian (2010) from 1961 to 1995, after which we used data from FAO. Appendix B shows the differences between the two sources of data. For Russia, Ukraine, and Belarus we used arable land from Schierhorn et al. (2013) to simulate a much larger abandonment of cropland after 1990 than reported by FAOSTAT (FAO, 2021). Then, after 2007 we expanded the area in croplands as reported by Bartalev et al. (2016) and Prishchepov et al. (2012). For Kazakhstan we used arable land from Kraemer et al. (2015), increasing it after 2000 until it matched data reported in FAOSTAT (FAO, 2021) (See Appendix B). These departures from FAOSTAT were the same as those used by Houghton and Nassikas (2017).

2.4.3 Alternative interpretations of forest conversion to other land – Step 3

As discussed above (section 2.2) the FAOSTAT (FAO, 2021) reports national areas in crops, permanent meadows and pastures, and forest land, annually since 1990. However, the three classes of land use do not account for all land areas, and a fourth class, other land, has been used by the FAO to account for other land uses and to insure that the total area in all four classes adds up to a country's total land area. Other land includes any lands that are not classified as crop, permanent meadows and pasture, or forest. It can include un-grazed grasslands, shrublands, and deserts as well as anthropogenic lands, such as settlements and urban lands, lands affected by mining and energy extraction, and anything else that does not match the definitions of the first three categories. The problem with other land, from a carbon perspective, is that, without further information, its carbon density is unknown. This ambiguity creates a problem for carbon accounting when forests are converted to other land, or when other land is converted to crops. Actually, it is a potential problem even if the area of other land does not change. If shrublands were converted to urban areas, for example, the area reported to be in other land would not change, yet the carbon stocks would. We did not deal with this potential problem.

We were particularly concerned here with the observation that in many tropical countries, net losses in forest area exceeded net gains in agricultural area. Forests were declining while other land was increasing. We explored the effects of four different interpretations of this apparent Forest Conversion to Other land (FCO). Note that FCO is not a term reported in FAOSTAT (FAO, 2021). Rather, it was inferred from the rules we applied to FAO data on land use to calculate annual rates of land-use change. This investigation of FCO became a major focus of this analysis.

The first interpretation of FCO was that the apparent loss of forest to other land was a statistical or accounting error. The data reported by countries are total areas of crops, permanent meadows and pastures, forests, and other land. It is quite possible that areas were revised in one category without adjusting the others. There are two possibilities for error: first, that the loss of forest might be overestimated, and in reality no forests were converted to other land. This error seems unlikely because FAOSTAT incorporates forest data from the latest FRA, which is systematically carried out and up to date. The second possibility is that the error might be in assigning deforestation to other land, when in reality it was for agricultural land. For this interpretation, we implemented the reported deforestation rates but assigned deforestation to cropland rather than to other land.

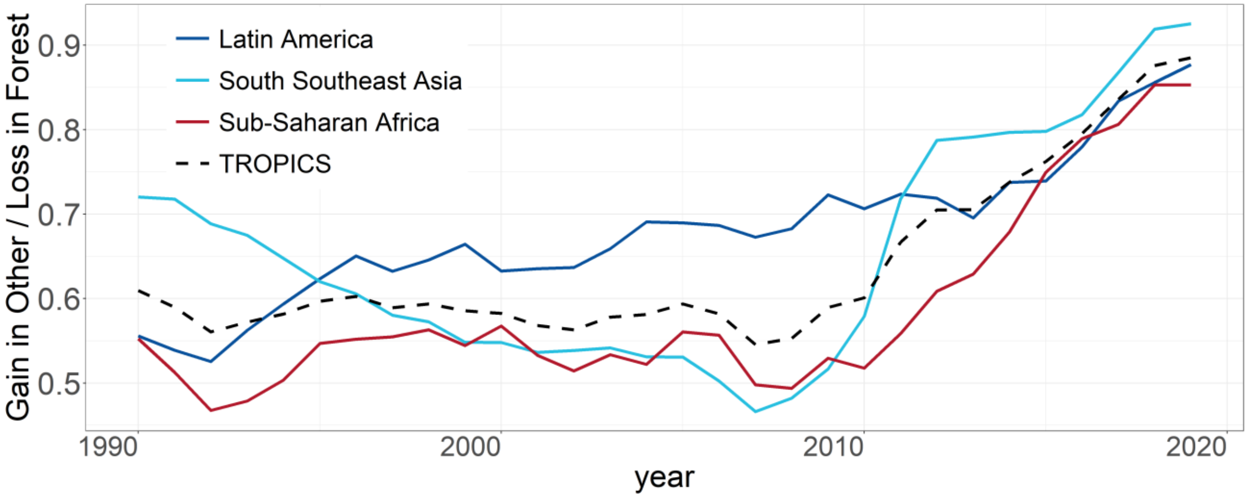

Figure 2. The fraction of tropical deforestation that was apparently a conversion to other land (FCO). Data shown are 5-year running averages.

What if FCO, or at least some fraction of it, represented a real change in land use? FCO has accounted for more tropical deforestation than agriculture, about 90% of it after 2010 (Fig. 2). Furthermore, our estimate of FCO is minimal because our rules for handling FAO data on land use assumed that forests were converted to croplands and pastures before they were converted to other land. Could errors really be that large and that biased (nearly always in the same direction)?

We explored the effect of three alternative interpretations of FCO in addition to error. The rationale for considering that the reported change might be real was based, not only on its relative magnitude (Fig. 2), but on the observation that changes in the areas under shifting cultivation, country by country (Heinimann et al., 2017), were (qualitatively) correlated with our calculation of FCO (as inferred from FAOSTAT (FAO, 2021)). Tropical countries with increasing areas of shifting cultivation in the years 2000-2015 matched those countries with high values of FCO, while countries with less change or negative changes in the area of shifting cultivation matched countries with low or negative FCO. Only 21 countries were evaluated by Heinimann et al. (2017), but the changes in shifting cultivation were consistent with the sign of FCO. The match seemed worth exploring.

Thus, the first interpretation of FCO as real was that forests apparently converted to other land were converted to *shifting cultivation*. FAO (2021) does not recognize “shifting cultivation” in its classifications of land; rather, it is included in cropland. Here we considered it a particular type of cropland. We have used the interpretation previously (Houghton and Nassikas, 2018; Houghton and Hackler, 2006).

Traditional shifting cultivation is a special case of cropland, where the time in fallow is longer than the time in crops, and where some tree cover persists. Typical fallow lengths are 2 to 25 years (Snedaker and Gamble, 1969; Harris, 1972; Betts et al., 2004; Turner et al., 1977), long enough for trees to recover, at least partially, and to accumulate carbon before the land is cleared again for cropping. We used fallow lengths between 2 and 15 years, including the cropping that occurs in the first few years of each cycle.

Our definition of shifting cultivation is broad and includes more than traditional shifting cultivation. It refers to the repeated use of forests for temporary agriculture. Shifting cultivation, or swidden, was the most prevalent type of agriculture in the tropics “…well into the second half of the 20th century” (Van Vliet et al., 2012). It remains widespread today and was observed (around 2015) in 62% of the 1° x 1° cells investigated with high-resolution satellite imagery in the humid and sub-humid tropics (Heinimann et al., 2017). Most of it (nearly 80%) was observed in the Americas and Africa. At present the area of shifting cultivation is increasing in some regions, and decreasing or remaining stable in others (Van Vliet et al., 2012). Changes in both directions may occur within a single country (Heinimann et al., 2017).

For this *shifting cultivation* interpretation, we estimated areas and changes in areas as follows. First, we compared each country’s area of other land in 1980 (based on our extrapolation of FAOSTAT data) with that country’s area of forest fallow (shifting cultivation) in 1980 as reported by FAO/UNEP (1981) (FAO/UNEP, 1981). The FAO/UNEP (1981) was an earlier Forest Resources Assessment but is not consistent with recent (1990-2020) assessments and, thus, is of greater uncertainty. The latest FRA assessments no longer report changes in forest area before 1990. Nevertheless, these estimates of forest fallow represent one of the only tropicswide estimates of shifting cultivation in existence. In our comparison of other land with forest fallows in 1980, many countries had areas in other land that were large enough to accommodate the fallow areas, and thus we were able to assign a land area to shifting cultivation. In other tropical countries the 1980 estimate of fallow area was larger than the area in other land. In these cases, we lowered the fallow area given by (FAO/UNEP, 1981) to match the area of other land. The area in other land was constrained by changes in forests, croplands, and pastures, and, thus, could not be increased. With this approach we obtained a fallow area of 277 x 10^6 ha in 1980, somewhat more than half of the (FAO/UNEP, 1981) estimate of 456 x 10^6 ha, but within the range from previous studies (260 to 450 million ha (Silva et al., 2011; Van Vliet et al., 2012; Heinimann et al., 2017; FAO/UNEP, 1981; Lanly, 1982).

Annual increases (or decreases) in shifting cultivation were based on FCO between 1990 and 2020 and were estimated to remain a constant fraction of other land for prior years (1700 to 1980). A less uncertain reconstruction is difficult because the areas are not well known. A greater number of people might be supported either by a larger area in shifting cultivation or by a shortened the length of fallow; but neither of these variables is known for most regions (Ickowitz, 2006). We used the qualitative estimates of experts (in Heinimann et al. (2017)) to help define where shifting cultivation was increasing or decreasing before 1970. Negative values of FCO indicated an abandonment of shifting cultivation to forest.

For the second interpretation of FCO as real, we assumed that it represented the conversion of forests to new croplands, and, at the same time, the abandonment of an equivalent area of croplands to other land (in this case unproductive or degraded croplands). The abandoned croplands had low amounts of carbon in vegetation and soils, and did not accumulate more after they were abandoned. In this interpretation, labeled *degraded*, there was a net loss of forest area, no change in cropland area, and an increase in other land. The increase in other land could just as well include mining or energy extractive activities as well as degradation of croplands. Note that this “degraded” cropland is not a term used by FAOSTAT (FAO, 2021); it is simply our label for identifying a possible interpretation of FCO, which we inferred from FAO data (FAOSTAT

(FAO, 2021). Note also that this interpretation has effectively the same effect on carbon storage as attributing FCO to an error in the reported area of croplands.

In a third, *recovering*, interpretation we assumed, again, that forests were converted to croplands, and an equivalent area of croplands was abandoned, but in this case the abandoned croplands began growing back to forests after an interval of 15 years. The value of 15 was arbitrarily chosen to represent a long fallow. This *recovering* scenario was the one used by Houghton and Nassikas (2017) instead of shifting cultivation. We note that it is inconsistent with data from FAOSTAT because the area of forests increases after 15 years of abandonment.

To summarize, the *degraded*, *shifting cultivation*, and *recovering* interpretations of FCO may be described as alternatives leading to high, medium, and low emissions, respectively, based on their long-term effects on biomass (Fig. 3). As mentioned above, the possibility that FCO is a statistical error is essentially the same as the degraded interpretation; i.e., forest converted to cropland. Thus, there are four interpretations yet only three estimates reported here.

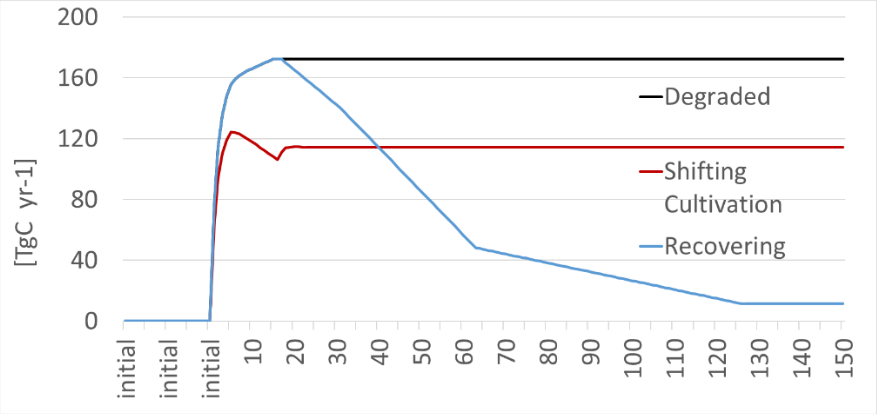

Fig. 3. Cumulative net emissions of carbon on a hectare of land under three different changes in land use: forest converted to degraded cropland (Degraded), forest converted to shifting cultivation (Shifting Cultivation), and forest converted to cropland for 15 years and then allowed to recover (Recovering).

2.4.4 The draining and burning of peatlands – Step 4

Because our bookkeeping model did not calculate the changes in peatland soils from the use, draining, and burning of peat, we used published estimates to supplement the fluxes calculated here. In the tropics we used the emissions from burning peatlands reported in GFED-4 (Randerson, 2013; Randerson et al., 2018), and the emissions from draining peatlands reported by Hooijer et al. (2010) and extrapolated to the present. The approach was the same as reported by Houghton and Nassikas (2017). That is, the draining and burning of peatlands was not significant before 1980 and has increased in importance since then (Hooijer et al., 2010; Hooijer et al., 2012; Field et al., 2009).

Outside the tropics we used the estimates of carbon loss from peatland use and draining reported recently by Qiu et al. (2021).

We note that the FAO also reports national emissions of carbon from drained and burned peatlands (Conchedda and Tubiello, 2020; Rossi et al., 2016). We did not use these estimates because they begin only in 1990 and because they differed so much, country by country, from the estimates by Qiu et al. (2021). It is beyond the scope of this study to explore reasons for this variability, but clearly these emissions are a major uncertainty in emissions from LULUCF.

3. Results

The four steps to revising the model and input data produced estimates of global emissions from LULUCF over the period 1850-2015 that were surprisingly similar to the results reported five years ago (Houghton and Nassikas, 2017) (Fig. 4) (Table 1). The similarity, however, resulted from offsetting differences from the revisions. Below, we present, one at a time, the effects of the four steps outlined in the Methods. We do it cumulatively such that the results from each step are incorporated into subsequent steps.

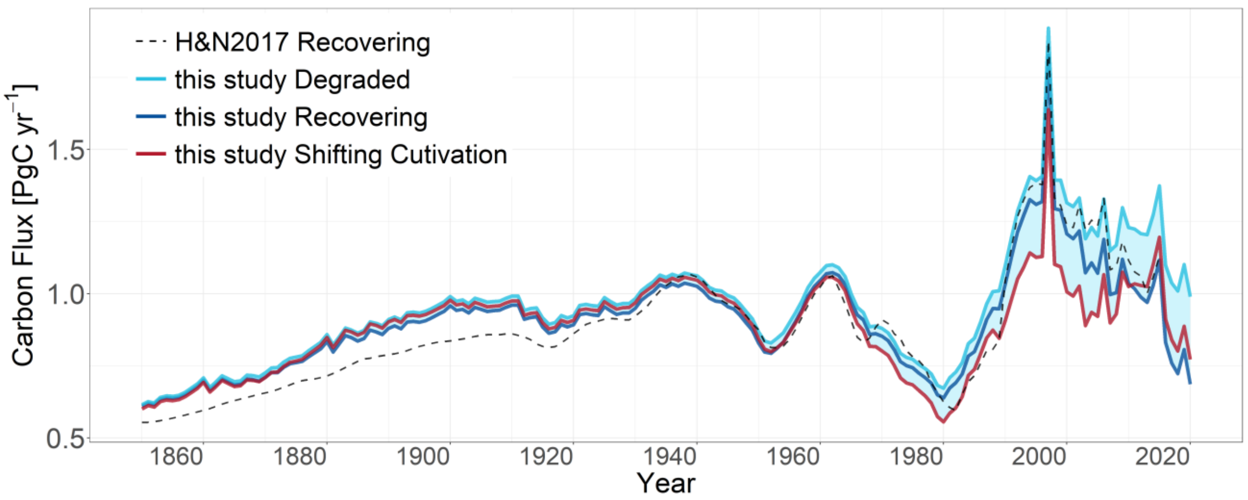

Figure 4. Annual net emissions of carbon from LULUCF including emissions from peatlands. The red line refers to the analysis including shifting cultivation. The shaded area indicates the range of emissions from alternative interpretations of forest loss to other land in the tropics (see Section 3.3, below). The black line refers to Houghton and Nassikas (2017). This Figure incorporates the results from all four steps or revisions, using the shifting cultivation interpretation of FCO.

Table 1: Total net emissions from LULUCF for the globe, the non-tropics and the tropics for the period 1850 to 2020 (or to 2015 for comparison with H&N2017). Note that H&N2017 did not include shifting cultivation but did include what is here called “recovering”.

[PgC]		**H&N2017** recovering		**This study Step1** recovering		**This study Step 2** recovering	**This study Step 3** degraded	**This study Step 3** shifting cultivation	**Step 4** Emissions of peat alone
region	time period	includes SSEA peat	no peat	includes SSEA peat	no peat	no peat			SSEA + Norhtern Countries
GLOBAL	1850-2015	145	139	118	112	116	123	113	34
GLOBAL	1850-2020					118	127	115	37
NONTROPICS	1850-2015	43	43	26	26	25	25	24	28
NONTROPICS	1850-2020					23	24	23	29
TROPICS	1850-2015	102	96	92	86	91	98	88	6
TROPICS	1850-2020					95	103	92	8

3.1.Adjustments to the bookkeeping model for wood harvest

Adjustments to the code to account for (1) the fraction of harvest that becomes slash instead of wood product and (2) the larger area required for secondary forests to provide the same volumes of harvested wood as primary forests had offsetting effects, but together the adjustments led to lower emissions (Fig. 5). Accounting for slash increased the emissions from harvest, but harvesting a greater area of secondary forests had a greater effect on increasing the area of secondary forests and, thereby, the gross sinks. The adjustments lowered the net flux throughout the period 1850-2015: 112 PgC after adjustment, compared to the original total of 139 PgC (not counting peat emissions) (Houghton and Nassikas, 2017) (Table 1).

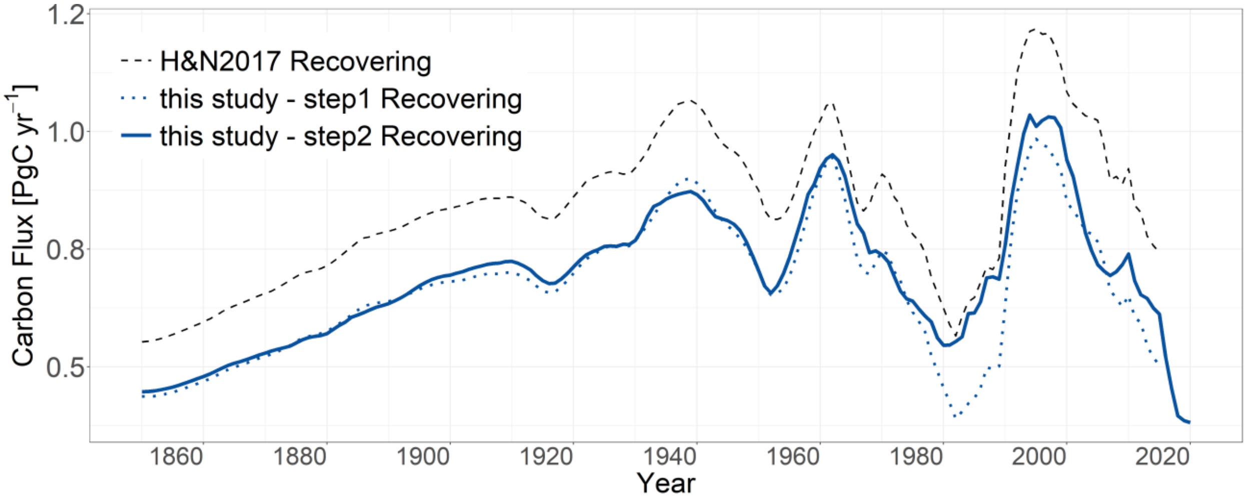

Figure 5. Annual net emissions of carbon from LULUCF, excluding emissions from peatlands. Improvements to the model (step 1) (dotted line) lowered estimated emissions from those reported by Houghton and Nassikas (2017). Updated data from FAOSTAT (FAO, 2021) (step 2) (solid line) increased emissions slightly. All analyses were based on the "recovering" interpretation of FCO for comparison with Houghton and Nassikas (2017).

3.2.Incorporation of new data from the FAOSTAT (FAO, 2021)

The "new" data from the FAOSTAT (FAO, 2021) were largely land-use data for the last 5 years (2016-2020), but included some revisions before 2016. Furthermore, we included revisions we made to estimated areas of land use before 1990 in order to avoid abrupt transitions in rates of land-use change. Use of these new and revised data increased the cumulative net emissions little: from 112 Pg to 116 PgC for the period 1850-2015 (Table 1). The addition of the last 5 years added another 2 PgC to this total (118 PgC 1850-2020, not counting emissions from peatlands). The greatest effect of incorporating new data from the FAOSTAT (FAO, 2021) occurred in the tropics, increasing net emissions during 1980s-1990s (Fig. 5).

3.3. Alternative interpretations of the conversion of forest to other land

As discussed above, the annual loss of forest area in many tropical countries exceeded the gain in agricultural lands and resulted in a gain in “other land” area (FAO, 2021). We called this apparent conversion “forests converted to other land” (FCO). We calculated the emissions for four alternative interpretations of this new other land: (1) error in reported cropland area, (2) shifting cultivation, including fallow, (3) degraded land, and (4) recovering forest.

The cumulative area in this FCO category was large. If all conversions of tropical forests to other land were assumed to be for shifting cultivation, the area was 450 million ha in 2020, up from 239 million ha in 1850 according to our assumptions. The highest rates of conversion to other land were in the 1990s (Fig. 6).

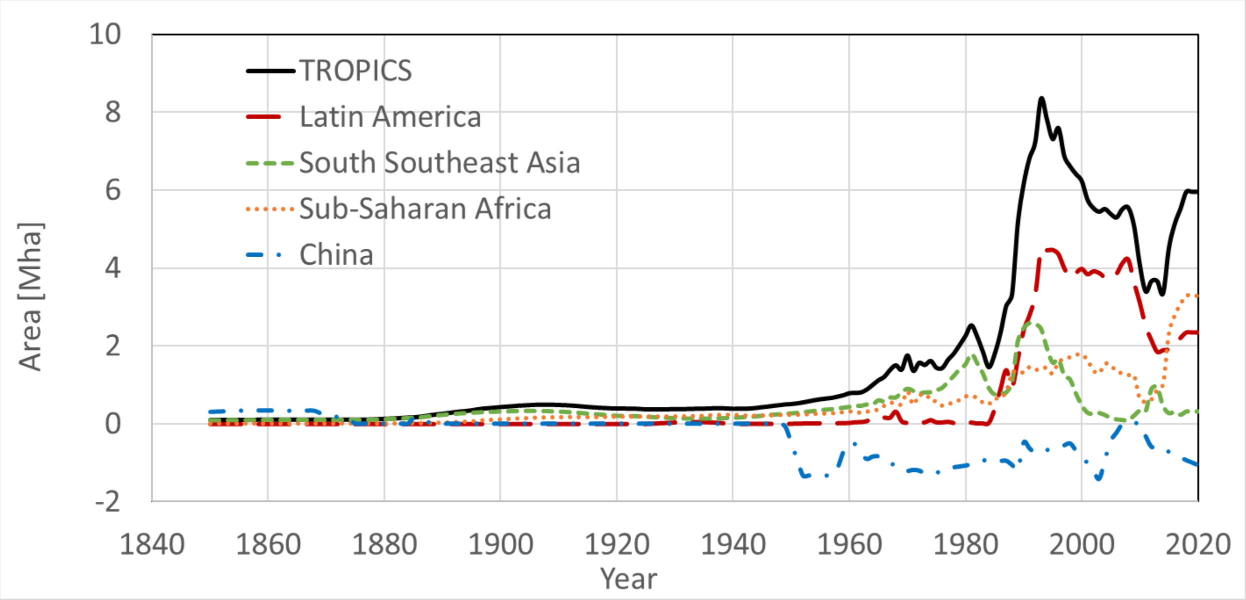

Figure 6. Rates at which forests appeared to be converted to other land (FCO), defined by forest area loss exceeding agricultural gain (FAO, 2021). Negative values indicate the conversion of other land to forest land.

Because grown forests have the highest carbon densities in biomass, while crops have the lowest densities and shifting cultivation is intermediate, emissions would be expected to be highest for the degraded interpretation, intermediate for shifting cultivation, and lowest for the recovering interpretation (Fig. 3). However, because in the "recovering" interpretation forest growth was delayed for 15 years, while in the shifting cultivation interpretation regrowth of fallow began after one year, the emissions from the recovering and shifting cultivation interpretations were not always as predicted from their respective end states (Table 1, Fig. 3). Over the period 1850-2015 total emissions were 123, 116, and 113 Pg C for degraded, recovering, and shifting cultivation interpretations, respectively (Table 1), and it was only in the last decade or so that the shifting cultivation interpretation was intermediate (Fig. 7).

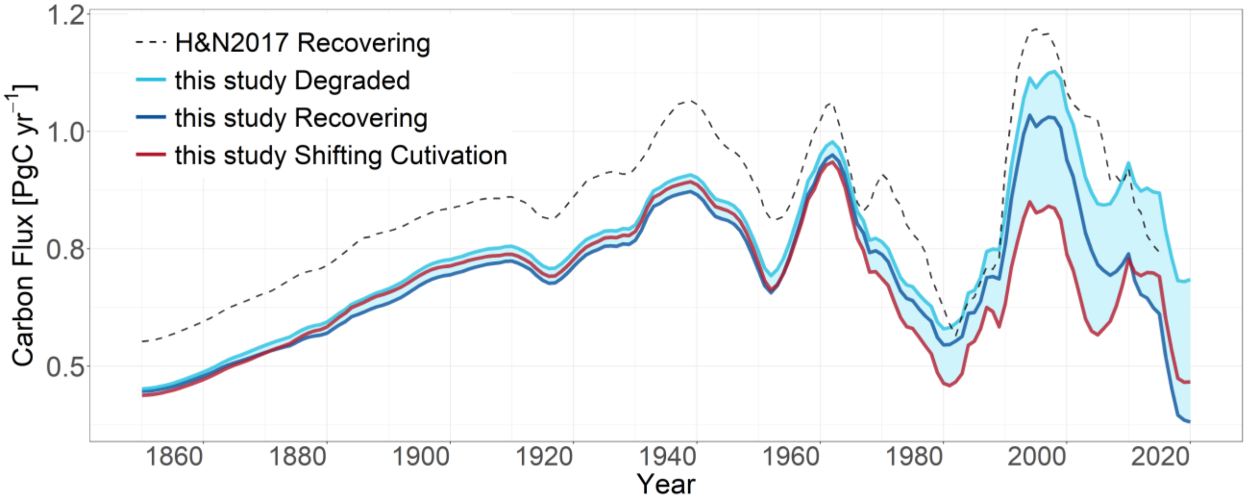

Figure 7. Annual net emissions of carbon from LULUCF (peatland emissions excluded). Red line includes shifting cultivation. Shaded area represents range of FCO interpretations. Black dashed line: Houghton and Nassikas (2017). This figure incorporates the results from steps 1 through 3, as described in Section 2.4.

The uncertainty in emissions is large, but the range is undoubtedly an overestimate because each interpretation is treated as if it explained all of FCO. In reality, the true explanation for FCO is likely to include a mixture of these interpretations, and more. Furthermore, the uncertainty is higher than a more detailed analysis might find because expertise within the FAO would likely provide the appropriate explanation for FCO for any country and time. Those details were not used in this analysis.

3.4.The draining and burning of peatlands

Over the 170-year period 1850-2020 the emissions from use of peatlands added 8 PgC to emissions from countries in Southeast Asia and 29 PgC to countries in the northern mid-latitudes (Qiu et al., 2021) (Table 1) (Fig. 8). The emissions from northern peatlands were not included in Houghton and Nassikas (2017), and including them here largely offset the lowered emissions that resulted from improvements in the model's simulation of wood harvest (Fig. 5) (Table 1).

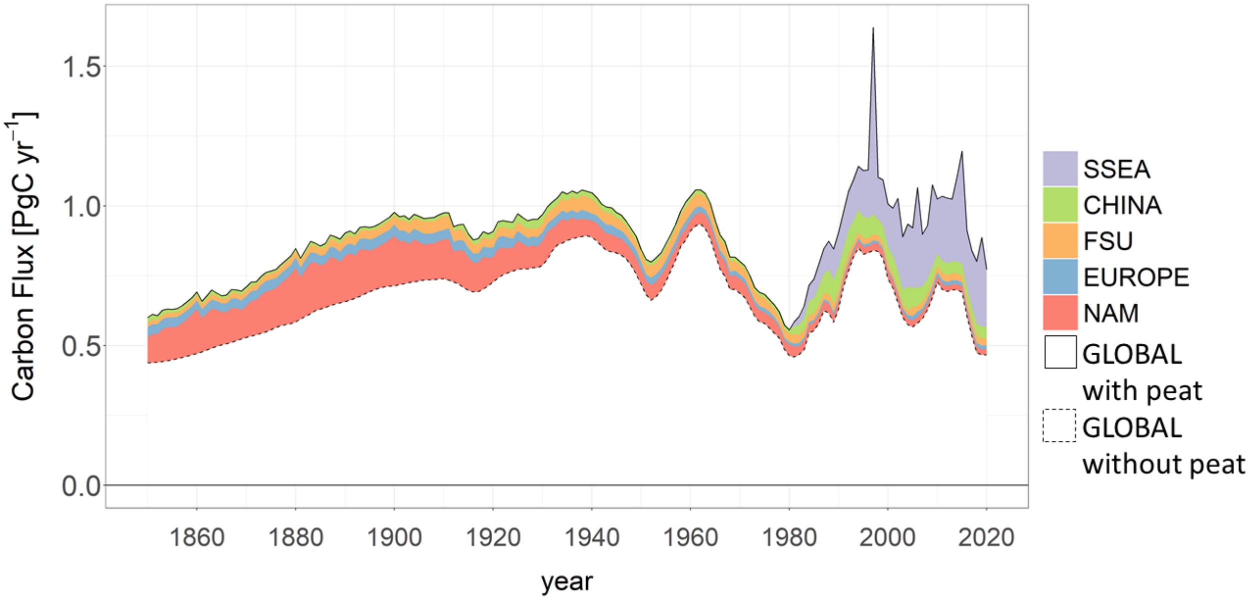

Figure 8. Annual emissions of carbon from use of peatlands, shown here above the global annual net emissions from the shifting cultivation alternative. A list of the countries in each region is given in Table A2.

3.5. Overall results from the revised analysis

The results presented above addressed sequentially the four revisions to the model and input data. Below we report the results of the complete update (all four revisions steps). Unless otherwise specified, the estimates given below refer to the shifting cultivation interpretation of FCO.

3.5.1.Net and gross emissions

Global net emissions of carbon from LULUCF increased from about 0.6 PgC yr^{-1} in 1850 to about 1 PgC yr^{-1} in the 1930s and never got much higher (except in 1997 as a result of unusually high emissions from peatlands in Southeast Asia) (Fig. 9). The emissions were far from constant after 1930, however. Rather, emissions peaked around 1960, in the 1990s, and around 2015, with declines during the 1940s, the 1970s and 1980s, and after 2015.

The largest net emissions in the last ten years (2011-2020) were from the three tropical regions (a mean of 0.500, 0.411, 0.308 PgC yr^{-1} for South and Southeast Asia, SubSaharan Africa, and Latin America, respectively) (Table 2), while four regions (Europe, North America, Former Soviet Union (FSU), and China) showed net sinks of about -0.094, -0.073, -0.052, -0.025 PgC yr^{-1}, respectively. The net negative emissions (carbon sinks) for individual regions first appeared in the 1920s (Fig. 9), reached about -0.3 PgC yr^{-1} in the 1970s, and remained nearly constant thereafter, although the sink seems to have declined slightly since 2005. Interestingly, the four regions with the largest net negative emissions currently had the highest net positive emissions in the 19th and early 20th centuries.

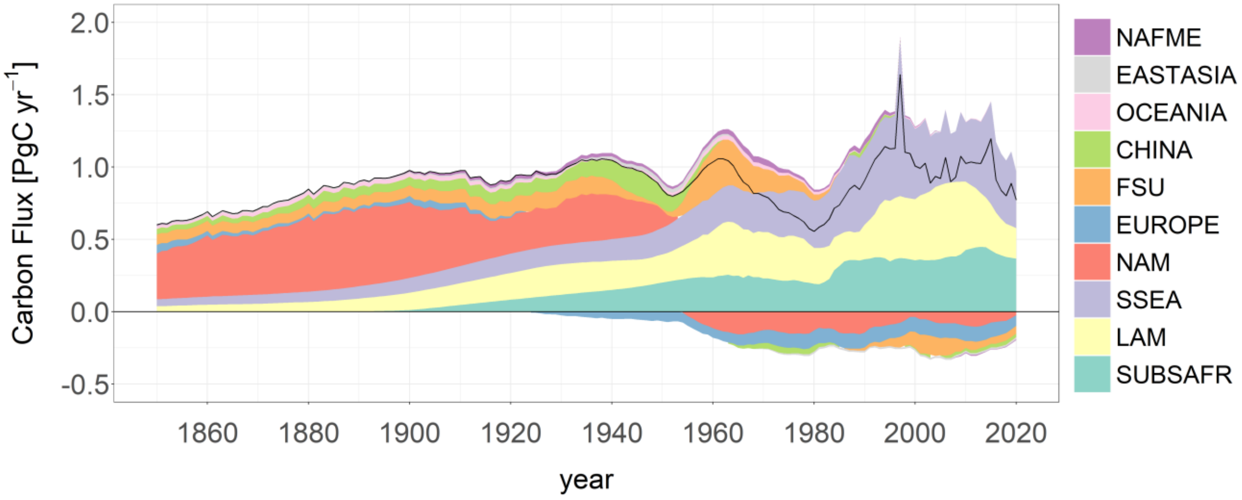

Figure 9. Net annual emissions of carbon from LULUCF for major world regions. The black line represents the global net annual emissions. Net negative emissions are removals of carbon from the atmosphere (sinks). A list of the countries in each region is given in Table A2.

Table 2. Average annual net emissions from LULUCF for the globe and major regions for the period 2011 to 2020

	[PgC yr^{-1}] (2011 to 2020)	**This study** step 4			
		degraded	recovering	shifting cultivation	Emissions from peatlands alone
		include peatlands emissions			SSEA + Norhtern Countries
	GLOBAL	1.15	0.89	0.96	0.36
	NONTROPICS	-0.26	-0.25	-0.26	0.10
	TROPICS	1.41	1.14	1.22	0.26
TROPICS	Latin America	0.413	0.352	0.308	0
	Sub-Saharan Africa	0.477	0.395	0.411	0
	South Southeast Asia	0.518	0.389	0.500	0.26
NON TROPICS	North America	-0.021	-0.073	-0.025	0.02
	Europe		-0.094		0.01
	China		-0.010		0.04
	Former Soviet Union		-0.052		0.03
	Oceania		0.001		0
	North Africa – Midle East		-0.005		0
	East Asia		-0.011		0

In the period 2011-2020 global gross emissions (3.38 PgC yr^{-1}) were more than three times higher than net emissions (0.96 PgC yr^{-1}), while gross removals averaged 2.42 PgC yr^{-1} (Fig. 10) (Table 3). High gross emissions and removals result from rotational uses of land, such as harvest of wood and shifting cultivation, where the emissions are largely offset by the removals in forest recovery or fallows.

Gross emissions were predominantly (69%) in the three tropical regions (Latin America, tropical Africa, and South and Southeast Asia), while the gross sink was distributed nearly equally between tropical (46%) and non-tropical (54%) regions. The higher net emissions from the tropics were attributable to the higher rates of deforestation there.

The offset of gross emissions and gross removals is not simultaneous and has implications for mitigation. Because most gross emissions happen rapidly, while most gross removals occur over a longer time, a reduction in shifting cultivation would result in a rapid reduction in (gross) emissions, while the (gross) removals (in re-growing forests) would continue for decades. Hence, gross fluxes are more indicative than net fluxes of the potential for mitigation. Furthermore, our estimates of gross fluxes are underestimated because rates of land-use change were based on *net* changes in area as reported by FAOSTAT.

Table 3. Average net and gross emissions of carbon from LULUCF by region for the period 2011-2020. Emissions from burning and draining of peatlands are included.

	[PgC yr^{-1}] (2011-2020)	This study - step4		
		Net flux	Gross sink	Gross Source
		Shifting Cultivation Interpretation		
	GLOBAL	0.96	-2.42	3.38
	NONTROPICS	-0.26	-1.30	1.04
	TROPICS	1.22	-1.12	2.34
TROPICS	Latin America	0.308	-0.373	0.681
	Sub-Saharan Africa	0.411	-0.384	0.796
	South Southeast Asia	0.500	-0.364	0.864
NON TROPICS	North America	-0.073	-0.404	0.331
	Europe	-0.094	-0.306	0.211
	China	-0.025	-0.204	0.179
	Former Soviet Union	-0.052	-0.295	0.243
	Oceania	0.001	-0.030	0.031
	North Africa – Midle East	-0.005	-0.028	0.024
	East Asia	-0.011	-0.030	0.018

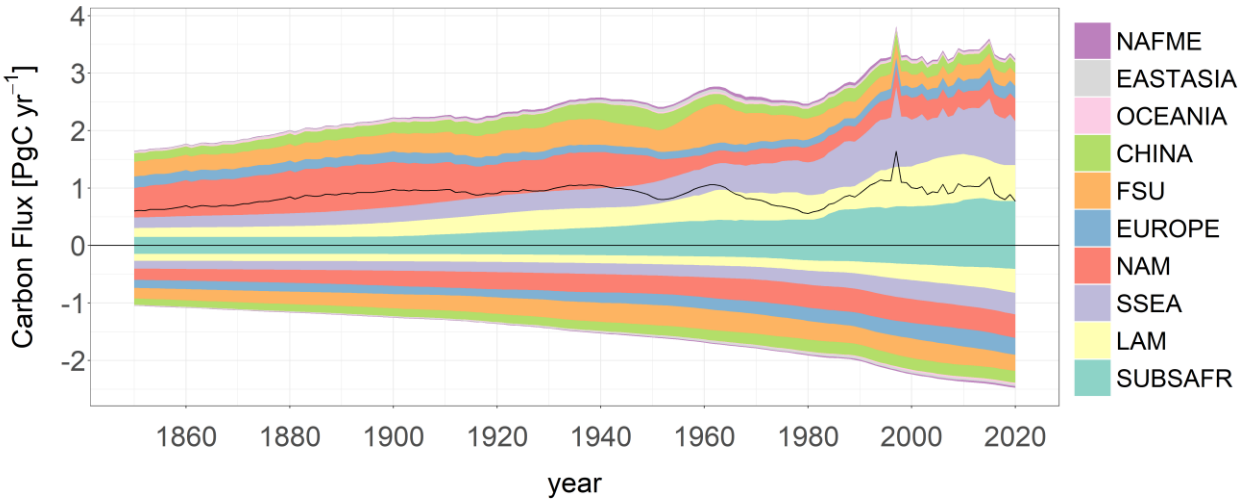

Figure 10. Annual gross emissions and removals of carbon from LULUCF by region. The black line represents global net emissions. A list of the countries in each region is given in Table A2.

3.5.2.Emissions by country

Over the last decade (2011-2020), according to the analysis based on the shifting cultivation interpretation of FCO, three countries (Indonesia, Brazil and DRC) accounted for 54% of the global net emissions, and 20 countries accounted for 86% (Fig. 11). Seven countries offset 18% of the total emissions, while about 80 countries with negative emissions offset 26% of total net emissions from LULUCF. The total net removal (sum of all net removal countries) (0.34 PgC yr^{-1}) was less than the emissions from Indonesia (0.38 PgC yr^{-1}). Indonesia alone accounted for 30% of all emissions from LULUCF in this last 10 years, with 56% of those emissions from the burning and draining of peatlands.

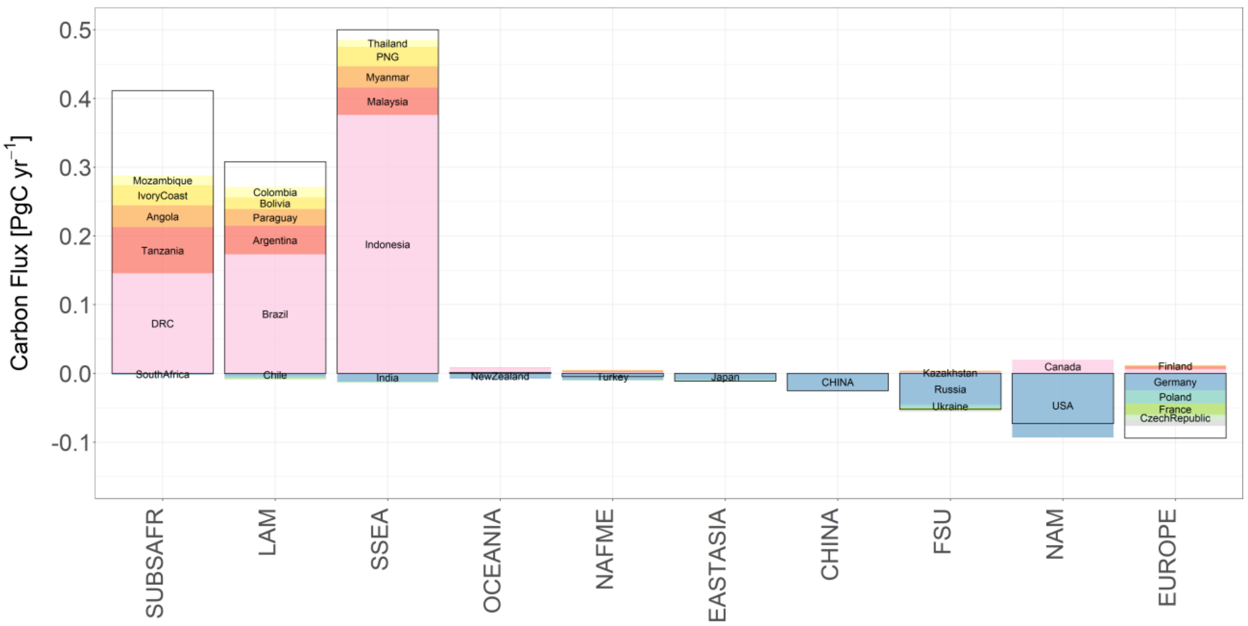

Figure 11. Regions and countries with the largest net annual emissions and removals, including emissions from use of peatlands (average for 2011-2020). The white portions of the columns represent the contribution of all other countries in the corresponding regions.

3.5.3.Emissions by type of land use or land-use change

Land uses with the greatest emissions or removals of carbon varied among regions and over time (Fig. 12). The expansion of croplands generally accounted for the greatest emissions everywhere except in Oceania where pastures were the dominant source of carbon before 1950. Shifting cultivation was important in the three largely tropical regions. Emissions from the use of peatlands were most noticeable, historically, in North America and Europe and, more recently, in South and Southeast Asia and China. Removals of carbon resulting from agricultural abandonment, establishment of tree plantations, and declining rates of harvest were dominant in Europe, FSU, China, and North America (-0.108, -0.077, -0.068, -0.093 PgC yr^{-1} in the last 10 years) (Table 4).

The net US sink was -0.109 PgC yr^{-1} when the history of fire suppression was included. We included wildfires in the US because fire management (fire suppression or exclusion) was a part of forest management. According to the wildfire statistics, the area burned nationally was greatly reduced after the 1930s, and this reduction led to a significant sink in regrowing forests. Other countries have also practiced fire management and might be expected to have larger sinks than calculated here, but data were not available for this study.

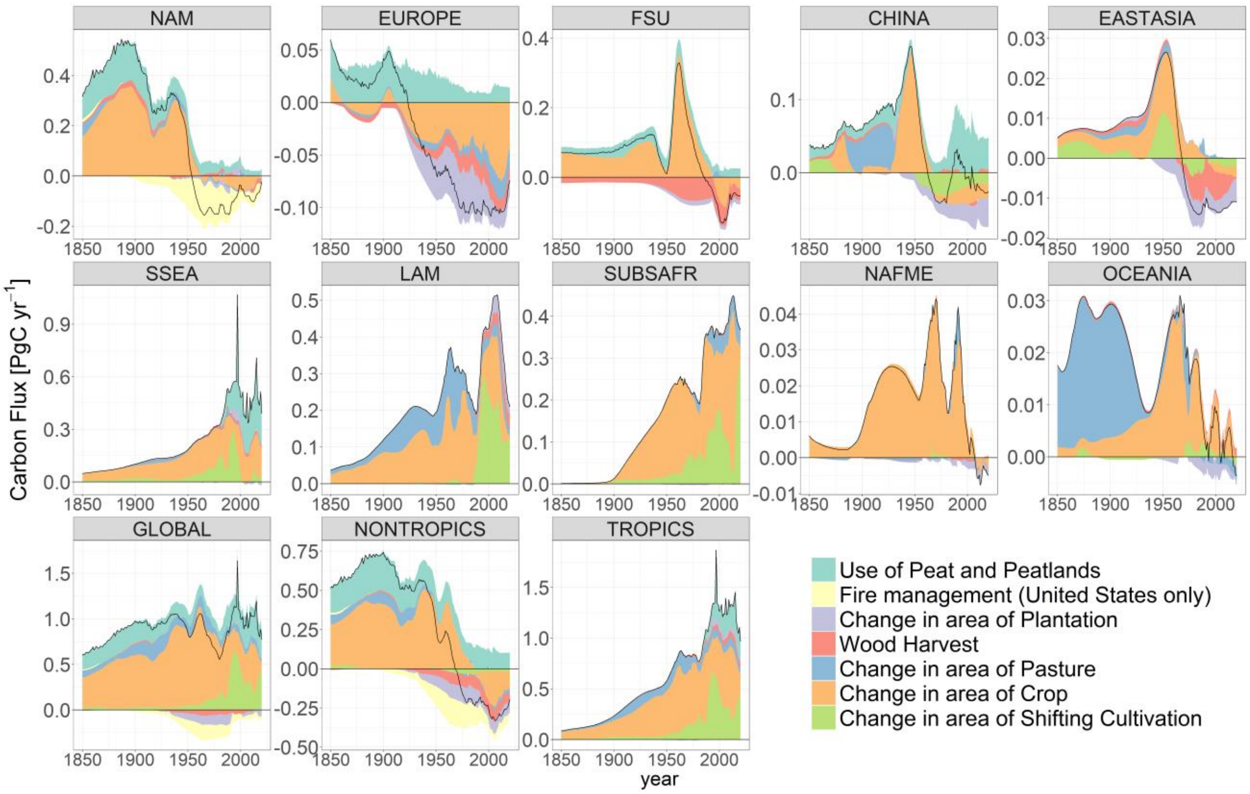

Figure 12. Net emissions from LULUCF attributed to different types of land use and land-use change. The emissions attributed to pasture, crop, and shifting cultivation result from changes in area (land-use change), not to management practices.

Table 4. Annual net emissions of carbon attributable to different land uses and land-use changes by region, averaged over the last decade (2011-2020). The emissions attributed to pasture, crop, and shifting cultivation result from changes in area (land-use change), not to management practices.

	Net Flux [PgC yr^{-1}] (2011-2020)	Net Flux with peat	Net Flux without peat	Wood Harvest	Crop	Pasture	Shifting Cutivation	Plantation	Peat	Fire
	GLOBAL	0.960	0.603	-0.003	0.344	0.060	0.298	-0.044	0.357	-0.051
	NONTROPICS	-0.259	-0.361	-0.061	-0.133	-0.023	-0.016	-0.077	0.102	-0.051
	TROPICS	1.219	0.964	0.058	0.476	0.083	0.314	0.033	0.255	-
TROPICS	Latin America	0.308	0.308	0.039	0.063	0.039	0.123	0.044	-	-
	Sub-Saharan Africa	0.411	0.411	0.003	0.212	0.044	0.153	-0.001	-	-
	South Southeast Asia	0.500	0.245	0.016	0.201	0	0.038	-0.010	0.255	-
NON TROPICS	North America	-0.073	-0.093	-0.017	-0.023	-0.002	0.001	0	0.020	-0.051
	Europe	-0.094	-0.108	-0.011	-0.063	-0.018	0.001	-0.018	0.014	-
	China	-0.025	-0.068	0.005	-0.020	0	-0.015	-0.038	0.043	-
	Former Soviet Union	-0.052	-0.077	-0.037	-0.026	0	0	-0.014	0.025	-
	Oceania	0.001	0.001	0.001	0.004	-0.002	-0.001	-0.001	-	-
	North Africa – Midle East	-0.005	-0.005	0	-0.002	0	0	-0.002	-	-
	East Asia	-0.011	-0.011	-0.002	-0.002	0	-0.002	-0.005	-	-

3.5.4.Emissions by carbon pool

The annual, global net flux of 0.96 PgC yr^{-1} to the atmosphere for the period 2011-2020 was composed of gross emissions of 3.38 PgC yr^{-1} from burning of live vegetation, decay of dead vegetation (slash), oxidation of wood products, and oxidation of soil carbon as a result of cultivation, including peatland emissions. Annual, global gross removals were -2.42 PgC yr^{-1} as a result of vegetation and soil recovering from wood harvest and agricultural abandonment (Table 5).

Table 5. Annual emissions (+) and removals (-) of carbon by ecosystem component 2011-2020 (in PgC yr^{-1}).

[PgC yr^{-1}] (2011-2020)	Net flux emission with peat	Gross sink	Gross Emission with peat
Living vegetation	-1.53	-2.24	0.71
Slash	1.14		1.14
Wood products	0.78		0.78
Soil and Peatlands	0.57	-0.18	0.75
Total	0.96	-2.42	3.38

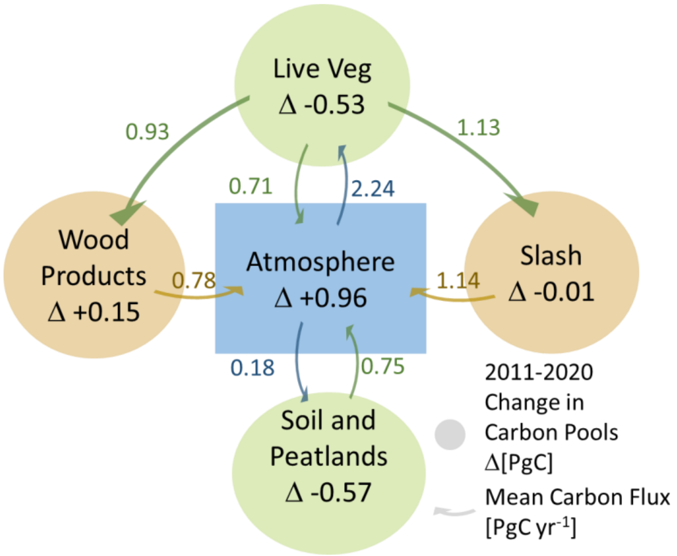

Figure 13. Global transfers of carbon (PgC yr^{-1}) among components of the terrestrial carbon cycle during the last 10 years (2011-2020) and average annual changes in pool sizes in the same decade.

The annual transfers of carbon among pools for the period 2011-2020 are shown in (Fig. 13). By far the largest flux was from the atmosphere to growing vegetation (2.24 PgC yr^{-1}). As discussed above, this gross removal of carbon by growing forests would continue for many decades even if emissions were reduced by stopping deforestation and forest degradation. Hence, the potential for mitigation is significant as long as changes in climate do not affect rates of regrowth. Fluxes half that magnitude were into and out of slash each year, and smaller still were the flows into and out of wood products.

Wood products accumulated carbon over this decade (Fig. 13), but whether that accumulation is considered a sink or not depends on definition (i.e., changes in pool size or exchanges with the atmosphere). The sum of all exchanges with the atmosphere (0.96 PgC yr^{-1}) is equivalent to the sum of all annual changes in pools (0.96 PgC yr^{-1}) when peatlands are included (Fig. 13).

Forests accounted for nearly all emissions (99%) for the decade 2011-2020 if emissions from peatlands were excluded. It is unclear whether the emissions from peatlands in northern regions were from forests or not. Emissions from peatlands (0.36 PgC yr^{-1}) were 37% of the total global net flux in this decade, while emissions from mineral soils were 22% (0.22 PgC yr^{-1}).

4. Discussion

We limit the discussion, below, to three general topics. First, what is the likely explanation for “forest converted to other land” (FCO)? Second, how do these new estimates of emissions compare with other recent studies, including recent estimates of forest degradation? And, third, how can we reconcile reduced emissions of carbon from LULUCF in the tropics with increased rates of deforestation reported in the literature (Wiltshire et al., 2022; Van Marle et al., 2022; Feng et al., 2022; Prodes, 2021)?

4.1.Forests converted to other land

Four interpretations were initially proposed to explain the apparent conversion of tropical forests to other land. “Apparent” is used here because the conversion is inferred from the areas of land reported by the FAO (2021) between 1990 and 2020. When the loss of forest area exceeded the gain in agricultural areas, the excess forest loss appeared as “other land”.

If FCO is an error in assigning newly deforested land to other land rather than to agricultural land, the emissions would be essentially the same as from the degradation interpretation. Both of them increase the area of cropland, rather than other land. The recovering interpretation is the least consistent with FAO data because it leads to a greater area of forest than reported by the FAO and is inconsistent with FRA2020. Thus, either shifting cultivation or degradation seems more likely if FCO is a real change in land use.

According to the FAO shifting cultivation is included in cropland. Are the areas in crops (FAO, 2021) large enough to include the areas in shifting cultivation calculated here? The answer seems to be yes for tropical Asia and SubSaharan Africa, where shifting cultivation might account for as much as 23% and 38% of total cropland area (Table 6). For Latin America, however, where the area calculated here to be in shifting cultivation is nearly as large as the total area in crops, either our estimate for shifting cultivation is too large or total cropland area is not large enough. Clearly, Latin America has large areas in crops that are not under shifting cultivation. In any case, if shifting cultivation (and fallows) were included in croplands, then we are left with the question of what changes in other land represent.

Table 6. Total areas in crops (from FAOSTAT, (FAO, 2021)) and in shifting cultivation (calculated here)

Year 2020	Crop Area	Shifting Cultivation Area	Shift. Cult. as fraction of total area
	[Mha]	[Mha]	[%]
Latin America	163	159	49%
South Southeast Asia	325	99	23%
Sub-Saharan Africa	232	141	38%
TROPICS	720	400	36%

Based on these arguments, the most reasonable interpretations for FCO seem to be the conversion of forest either to shifting cultivation or to new agricultural land, mistakenly called other land or offset by abandonment of old agricultural land that does not return to forest. By comparison, the recovering interpretation departs from FAOSTAT (FAO, 2021) because it results in a larger area of forest than reported.

It is important to recognize that these interpretations include more than their labels suggest. For example, the degradation interpretation applies to more than the conversion of forest to croplands and simultaneous abandonment of croplands. It includes the conversion of forest to any low carbon ecosystems (e.g., urban lands, settlements, roads, mining and energy extraction operations. It also includes the emissions that would result from an error in classification if the deforestation had been for new agricultural land instead of other land. The shifting cultivation interpretation includes the conversion of forest to ecosystems of intermediate carbon stocks. And the recovering interpretation represents temporary deforestation followed by forest recovery (Fig. 3).

Note that the more reasonable interpretations (shifting cultivation and degradation) are those with higher emissions. We use the shifting cultivation interpretation as our preferred estimate. It has the advantage of including shifting cultivation explicitly, although it is likely an overestimate. In the discussion below we compare our estimates of area under shifting cultivation with other estimates. We also discuss the importance of shifting cultivation for gross emissions of carbon and, finally, whether shifting cultivation accounts for much of the uncertainty associated with emissions from forest degradation.

Trends in the area of shifting cultivation are uncertain (Van Vliet et al., 2012; Heinimann et al., 2017). Van Vliet et al. (2012) found that the area of shifting cultivation was declining in 55% of their case studies, while the other 45% showed either an increase or no change in area. Where the areas of shifting cultivation were declining, they were most often being converted to more permanent croplands (no longer including fallows) rather than being allowed to return to forest. Curtis et al. (2018) found that shifting agriculture accounted for as much temporary loss of forest cover, globally, as fire and logging. Regionally, it was sometimes a dominant cause of forest cover loss. For example, Samndong et al. (2018) found shifting cultivation to have been the main cause of deforestation in the Democratic Repubic of Congo (DRC). In contrast, De Sy et al. (2015) found that shifting cultivation was a minor contributor to deforestation in South America, and Fantini et al. (2017) reported the end of swidden-fallow agriculture within the Brazilian Atlantic rainforest.

We evaluated changes in shifting cultivation using an independent approach inferred from land-use data from FAOSTAT (FAO, 2021). We acknowledge that this approach is hypothetical, but it is broadly consistent yet independent of other estimates of shifting cultivation, and it offers one explanation for FCO (Section 2.2). The rate at which Forests were Converted to Other land (FCO) increased in Latin America and Africa but declined in tropical Asia (Fig. 6). In China the area in other land actually declined.

If we assume that FCO was driven entirely by the expansion of shifting cultivation, and that fallows are counted as “other land”, then we calculate the total area in shifting cultivation to have been 277 x 10^6 ha in 1980 and 450 x 10^6 ha in 2020. These estimates are probably high because we assumed in this calculation that *all* of the increase in other land was attributable to shifting cultivation rather than to other land uses. For example, a recent analysis and review by Heinimann et al. (2017), based in part on satellite data for the period 2000-2014, estimated an area of 260 x 10^6 ha in shifting cultivation. As those authors acknowledge, however, the area is uncertain. Previous estimates have ranged between 260 and 450 million ha (Silva et al., 2011; Van Vliet et al., 2012; Heinimann et al., 2017; FAO/UNEP, 1981; Lanly, 1982).

Overall, the uncertainty remains, affecting both rates of land-use change and emissions of carbon. For example, in the last 10 years the “degradation” interpretation emitted about 0.260 PgC yr^{-1} more than the “recovery “interpretation, a difference that was greater than the annual emissions from any country except Indonesia. The unknown fate of FCO lands (degraded, recovering or shifting cultivation) contributed an uncertainty of about 13% to global net emissions from LULUCF. If the emissions from peatlands are ignored, the uncertainty for FCO accounted for about 20% of these global net emissions.

All of these interpretations have the implicit assumption that FCO is anthropogenic. Another possible interpretation for FCO is that the loss of forest to other land might not be directly anthropogenic but, instead, the result of increasing droughts, fires, or storms (Section 4.3.4, below). The loss of forest area to such indirect effects is not thought to be important (Tyukavina et al., 2022) because forests generally recover from such disturbances. However, indirect effects are responsible for carbon losses through forest degradation, which may rival the losses from deforestation (Lapola et al., 2023). Furthermore, savannization in Africa and in Amazonia, which *would* reduce the area of forest, is a distinct possibility with further changes in climate (Cochrane et al., 1999; Beckett et al., 2022), and increasing droughts in the tropics may already be changing the dynamics of fires and forests (Brando et al., 2019; Uribe et al., 2023). To the extent that FCO is driven by indirect effects, the emissions from LULUCF reported here are overestimates. Some of those emissions should be attributed to environmental effects instead.

4.1.1 Gross emissions and removals

The greatest difference between shifting cultivation and the two other interpretations of tropical forest loss is the effect they have on gross fluxes of carbon. Aside from wood harvest and agricultural abandonment, both of which include forest recovery, there are few other land uses that generate gross fluxes of carbon. Shifting cultivation accounted for 30% of the global gross emissions of carbon over the period 2011-2020 in our analysis. Gross emissions and removals for shifting cultivation, alone, were 1.02 and -0.72 PgC yr^{-1} in comparison to total gross emissions and removals were 3.38 and -2.42 PgC yr^{-1}, respectively (Table 3). And these gross fluxes are probably conservative because, as mentioned above, the changes in land use reported by FAOSTAT are *net* changes within a country. If data on gross changes in land use were available, they would presumably yield higher gross fluxes. The higher gross fluxes resulting from LULUCF in other bookkeeping models (BLUE and OSCAR), for example, reflect the fact that those models use gross rates of land-use change (Hansis et al., 2015; Gasser et al., 2020; Chini et al., 2021).

4.1.2 Is shifting cultivation deforestation or forest degradation?

Carbon may be lost to the atmosphere through either deforestation (a change in the area of forests) or forest degradation (a reduction in forest carbon stocks without a change in forest area). Estimates of the carbon emitted from forest degradation vary widely, from nearly zero to greater than the emissions from deforestation (Baccini et al., 2017; Lapola et al., 2023; Federici et al., 2015). We suggest that the relative proportions of deforestation and degradation to carbon emissions may depend on whether shifting cultivation is identified as degraded forest or agriculture; and that that identification may depend on resolution of measurement. As discussed above, FAO does not have a specific classification for shifting cultivation, but includes it as agricultural land. However, analyses of changes in aboveground biomass based on satellite data (e.g., Baccini et al., 2017) may interpret the effects of shifting cultivation as forest degradation. And at intermediate resolution (~1 km), degradation and deforestation may be inseparable (Baccini et al., 2017).

In this analysis the relative contributions of deforestation and degradation to the net carbon emissions from the tropics were 69% and 5%, respectively, for the period 2011-2020 (Fig. 14). Another 21% resulted from burning and draining of peatlands, and 5% resulted from non-forest land uses. But if we include shifting cultivation as forest degradation, then the relative contributions are more nearly equal (42% and 32%, for deforestation and degradation respectively), and in some years the emissions from degradation were more than 50% (Fig. 14). Thus, the dynamic nature of shifting cultivation, and how it is measured, may account for some of the variation in estimates of forest degradation.

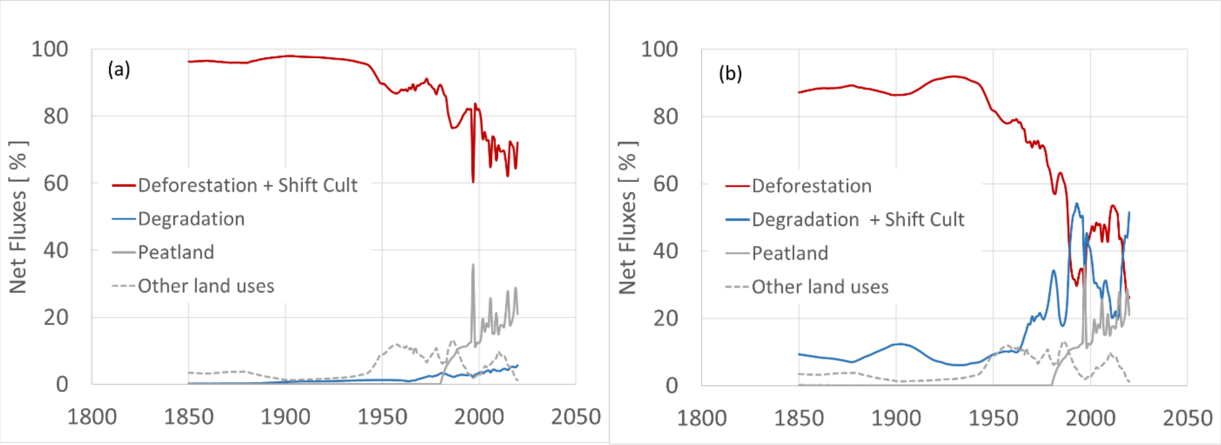

Figure 14. Emissions from deforestation and forest degradation if conversion of forests to shifting cultivation is deforestation (a) and if conversion of forests to shifting cultivation is

degradation of forests (b). In the latter case, the emissions from degradation and deforestation are comparable.

4.2.How do these estimates of emissions compare with other recent studies?

Given that most of the data used in this analysis came from the FAO, one might expect the calculated emissions to agree with those reported by the FAO (Tubiello et al., 2021), or at least with their estimates for deforestation (Table 7).

Table 7. Average annual emissions of carbon from deforestation, globally.

[PgC yr^{-1}]	Tubiello et al., 2021	This study*	This study**	Peatlands Only	Soil Carbon (no peat)
1991-2000	1.17	1.11	1.13	0.33	0.22
2001-2010	1.01	0.95	0.98	0.35	0.20
2011-2015	0.90	0.86	1.08	0.38	0.23
2016-2020	0.79	0.79	0.84	0.33	0.20

* To make our estimates comparable with the estimates from Tubiello et al. (2021), we report the emissions from the degradation interpretation, excluding non-forests, the effects of wood harvest, soils and peatlands.

** For comparison, we report here the results of the shifting cultivation interpretation, including all emissions, including peatlands.

When we exclude the emissions from soils, peatlands, non-forest conversions, and wood harvests, our estimates for deforestation, alone, (Table 7, column 2) are nearly identical with those reported by Tubiello et al. (2021). When we include all emissions (column 3), the results of the two studies are also close, but in that case the similarity is misleading, because net sinks in regions without deforestation (Fig. 9) are offset by emissions from peatlands.

It is perhaps worth noting that the different methods used for computing emissions had little effect on the estimates (Table 7). The bookkeeping model tracked the delayed emissions of carbon from deforested biomass left on site (slash), while Tubiello et al. (2021) reported all the (committed) emissions in the year of deforestation. The nearly constant differences from one period to the next suggest that accounting for time lags in emissions from deforestation had negligible effects over this period.

As noted earlier the emissions calculated here were not very different (1850-2015) from those reported by Houghton and Nassikas (2017), although the similarity was more the result of offsetting differences than of identical data and assumptions. Houghton and Nassikas (2017) did not include shifting cultivation explicitly, but they did include the conversion of forest to other land by using the “recovering” interpretation described here. More importantly, Houghton and Nassikas (2017) considered this conversion of forest to other land only in the years following 1990, when the FAO began their consistent reporting of changes in forest area. In the analysis reported here, we extrapolated FCO into the past based on earlier FAO estimates in FAOSTAT (FAO, 2021) and qualitative expert opinion reported in Heinimann et al. (2017). Thus, although the results of the two studies are similar, those reported here are more comprehensive and up to date.

The net and gross emissions reported here are lower than the emissions calculated by BLUE (Hansis et al., 2015) and OSCAR (Gasser et al., 2020), two other bookkeeping models used by the Global Carbon Project (GCP) (Friedlingstein et al., 2022). The difference may be explained by lower values of biomass in the model of Houghton and Nassikas (2017) (Bastos et al., 2021). Other differences may to attributed to different definitions of land use (Pongratz et al., 2014), different data sets (Gasser et al., 2020), as well as different model parameters and assumptions (Bastos et al., 2021).

Overall, the variation in estimates among bookkeeping models is small in comparison to other recent estimates of terrestrial carbon emissions (Harris et al., 2021; Xu et al., 2021; Tubiello et al., 2021). The reason is largely understood (Grassi et al., 2018; Grassi et al., 2022;

Schwingshackl et al., 2022). Bookkeeping models calculate higher emissions because they exclude the indirect effects of environmental change on carbon emissions (Friedlingstein et al., 2022). Thus, we could compare our results with the deforestation emissions of Tubiello et al. (2021) but not with their emissions from forest land. For the same reasons, emissions calculated by bookkeeping models are higher than those reported for managed lands in national greenhouse gas inventories (Grassi et al., 2018; Grassi et al., 2022).

Finally, we consider our estimates relative to two recent studies that have documented forest degradation (Kan et al., 2023; Lapola et al., 2023). We explicitly considered wood harvest as contributing to forest degradation (lower carbon stocks), and we considered the consequences of attributing shifting cultivation to forest degradation. But there are other factors leading to forest degradation, not considered by FAOSTAT (FAO, 2021) and not considered in this analysis. For example, Kan et al. (2023) attributed most of the loss (degradation or fragmentation) of intact forest landscapes to non-agricultural activities (forestry and mining and energy extraction, including the associated road networks). These losses were attributed to degradation, not deforestation, and thus the work does not help explain FCO, but it does suggest that forest degradation is important and directly anthropogenic. In contrast, degradation of the Amazon forest, attributed to fire, edge effects, timber extraction, and/or extreme drought (Lapola et al., 2023), is a mixture of both direct and indirect anthropogenic effects. If these two studies are accurate and representative, our estimates are likely biased toward the low end because we failed to account for a host of anthropogenic processes degrading forests. On the other hand, forest inventories suggest that the world’s forests are gaining biomass, not losing it (Pan et al., 2011; Tubiello et al., 2021). Clearly, the issue of forest degradation needs more attention, and separating direct and indirect effects on forest land is likely to be more challenging than it is for deforestation

4.3.Are emissions from LULUCF declining?

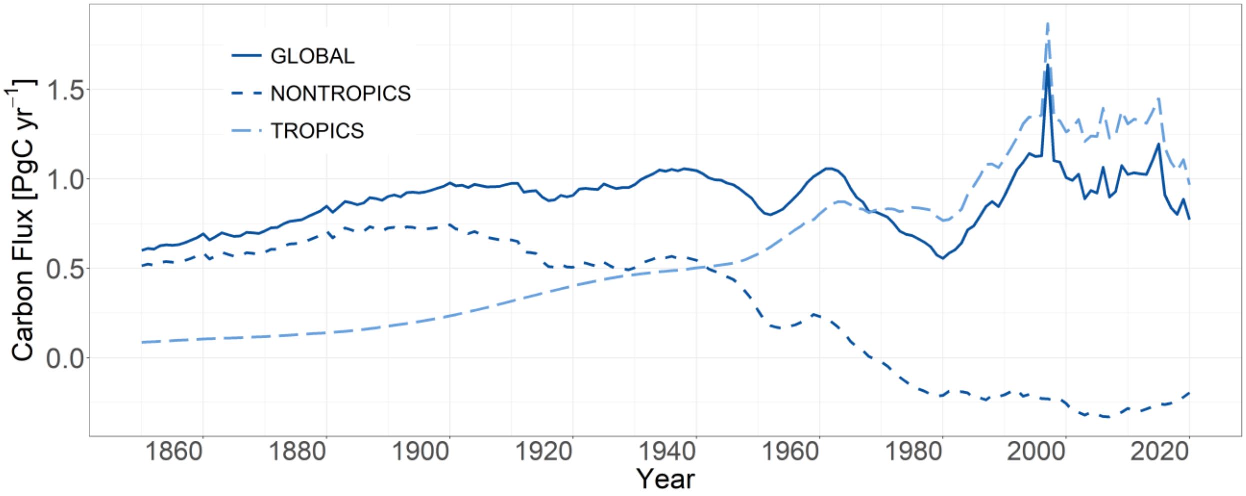

Figure 15. Net annual emissions of carbon from LULUCF for the globe, tropical regions, and non-tropical regions. The estimates are based on the shifting cultivation interpretation, including peatlands.

The recent decline in LULUCF emissions reported here (Fig. 15) was documented earlier by the FAO's Forest Resources Assessment (FAO, 2020) (Tubiello et al., 2021). The decline is consistent with the two other bookkeeping models (BLUE and OSCAR) used by the Global Carbon Project (Carbonbrief, 2021), but more precipitous. The decline in tropical emissions was new in the 2021 GCP budget (Friedlingstein et al., 2022) and represented a notable revision to global emissions (Carbonbrief, 2021). The emissions from the bookkeeping models BLUE (Hansis et al., 2015) and OSCAR (Gasser et al., 2020) were based on land use data from LUH2-GCB2021 (Hurtt et al., 2017; Hurtt et al., 2020; Chini et al., 2021), which, in turn, used data on land-use change from FAO and the HYDE3.3 dataset (Klein Goldewijk et al., 2017b; Klein Goldewijk et al., 2017a). Thus, the data on land-use change used in all three bookkeeping models were based, at least in part, on rates of land-use change from FAOSTAT. Despite the use of this common data set, differences among the estimated emissions still remain, perhaps because national statistics differ from those reported by FAOSTAT. Analyses by Kondo et al. (2022) and

(Yu et al., 2022) provide recent examples of discrepancies in reported rates of land-use change in Southeast Asia and China, respectively.

In contrast to the declining emissions calculated from FAO data on land use, Feng et al. (2022), using high-resolution satellite data to document changes in forest area in the tropics, reported a near doubling of emissions between 2001-2005 (average emissions of 0.97 PgC yr^{-1}) and 2015-2019 (1.99 PgC yr^{-1}). Interestingly, the emissions reported for the first period are in agreement with both our estimates and those reported by Tubiello et al., (2021) (Table 7). For the second period (2015-2019), however, Feng et al. (2022) reported emissions two times higher than those based on FAO rates of deforestation.

None of our simulations showed the increase in emissions that Feng et al. (2022) showed although they were qualitatively similar in identifying the regions and countries with declining and increasing rates of deforestation. In both studies, emissions were increasing in Africa and Southeast Asia and declining in Latin America (Fig. 16). In our analysis, the recent decline in emissions was led by Brazil and Argentina. An analysis comparing changes between 2001-2005 and 2015-2019 (similar to the comparison by Feng et al. (2022)) did not change the results appreciably from those shown in Fig. 16.

The trends in rates of tropical deforestation and associated emissions are strikingly different between the FAO and Feng et al. (2022). Can the difference be explained? Below, we consider three possible explanations for how the two studies might be reconciled.

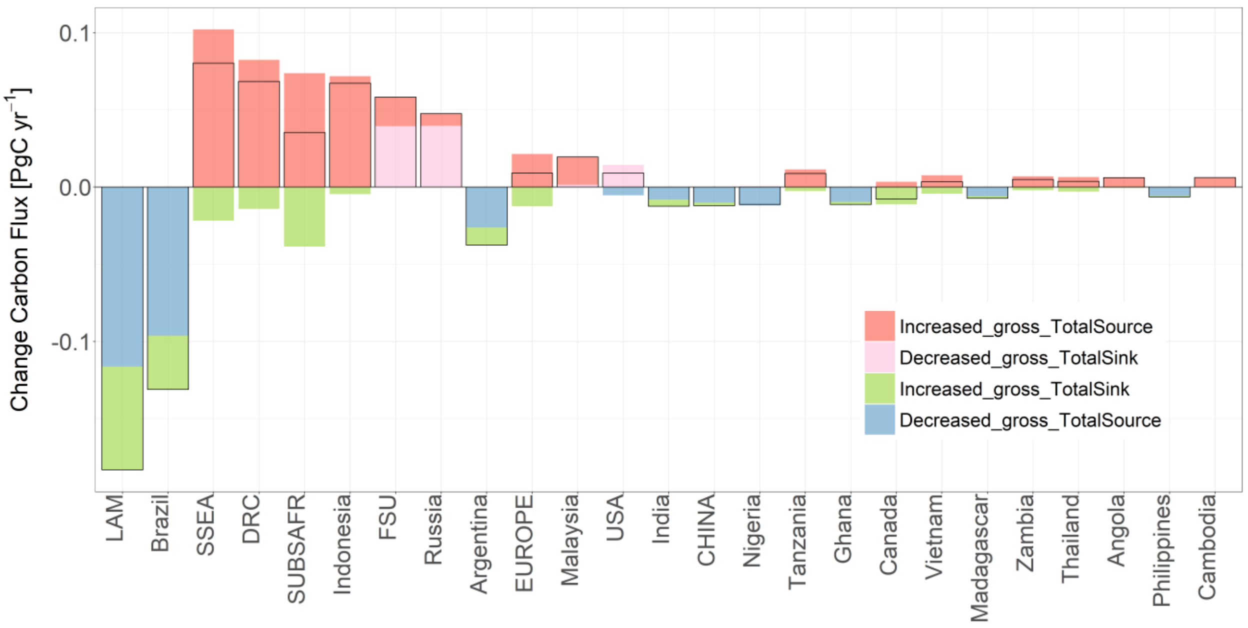

Figure 16. Changes in the sources and sinks of carbon between the first and second decades of the 21st century. Changes in the net source/sink are shown by black horizontal lines. Negative values indicate reduced emissions in second decade.

4.3.1 Are the emissions from deforestation gross or net emissions?

When a hectare is deforested, net and gross emissions of carbon are identical. But when FAOSTAT (FAO, 2021) reports a loss of forest area for a country, that loss is a net loss; and it is possible that high-resolution data from satellites record gross rates of forest loss that are partially offset by gross rates of forest gain within that country. In such a case, the net/gross emissions from gross losses in forest area would be greater than the net/gross emissions from net losses of forest area. It is possible that the higher estimates of deforestation (and emissions) from Feng et al. (2022) result from gross deforestation, while the lower estimates from FAOSTAT result from net deforestation.

4.3.2 Deforestation versus forest loss.

Another possible explanation for different rates of deforestation is related to the definition of deforestation. The UNFCCC and IPCC define deforestation as the conversion of forest to another land use, i.e., cropland, pasture, or other land. The temporary loss of forests as a result of harvests, fire, or other disturbances, even if directly anthropogenic, is not deforestation by this definition because the disturbed forest is expected to recover. The land is still defined as forest even if it is temporarily without trees. Some estimates of deforestation, particularly those from satellite data (e.g., Feng et al., 2022), may include temporary losses of forest that are not deforestation by this definition. Such estimates of deforestation would be higher than those reported by FAOSTAT and used here to calculate anthropogenic emissions.

4.3.3 Re-clearing of fallows already in shifting cultivation.

A third possible explanation for different deforestation rates and associated emissions is that the re-clearing of fallows in shifting cultivation may be attributed to deforestation. The term deforestation is appropriate the first time a forest is converted to shifting cultivation, but subsequent re-clearing of fallow is not deforestation (unless the recovery of forest in the fallows is identified as an increase in forest area). The cropped areas of shifting cultivation have tree cover and may be mistakenly identified as forests with remote sensing. Older fallows are even more forest-like, although perhaps recognizable as degraded forest.

If only a small fraction of the re-clearing of fallows is counted as deforestation by Feng et al. (2022), the rate of deforestation would be inflated. According to our analysis, the area in shifting cultivation was 450 x 10^6 ha in 2020. More importantly, the annual re-clearing of these lands was 25.7 x 10^6 ha in 2020. This rate is large in comparison to tropical deforestation rates of 10 x 10^6 ha inferred from FAOSTAT (FAO, 2021).

Although any of these three explanations might help explain why satellite-based data would provide higher rates of forest loss than ground surveys, none of them explains why the disagreement between FAOSTAT (FAO, 2021) and Feng et al. (2022) was only for the second period, and not the first. The two studies report changes in emissions of opposite sign. It would appear that one of them is simply wrong.

4.3.4 What if some deforestation is not directly anthropogenic?

Aragão et al. (2018) reported that the emissions from deforestation (directly anthropogenic) in Brazilian Amazonia were declining while the emissions from drought-related fires (indirectly anthropogenic) were increasing. The authors reported this finding despite the observation that many fires in Amazonia were arguably the direct effect of human activities (deliberate burning to clear forests). The finding raises the possibility that some deforestation may not be directly anthropogenic, but rather a consequence of indirect effects (e.g., changes in climate, fires, storms) (Gatti et al., 2021). This possibility does not help explain the difference between Feng et al. (2022) and FAOSTAT because they both reported forest loss and did not distinguish anthropogenic from non-anthropogenic loss.

Nevertheless, the question of causality (directly versus indirectly anthropogenic) is important because globally the net effect of environmental change, so far, has been to increase carbon storage on land. But changes in the environment (indirect effects) may result in gross emissions as well as sinks. It may be that terrestrial sinks are decreasing (or emissions from indirect effects are increasing) (Aragão et al. (2018)). Fire-induced savannization of tropical forests has long been recognized as a potential consequence of climate change (Cochrane et al., 1999; Beckett et al., 2022). Perhaps such a transition is beginning.

The broader issue is whether changes in land use and land cover are directly anthropogenic or not. We assumed that changes in land *use* reported by FAOSTAT were indeed directly anthropogenic. Clearly, crops and pastures are land uses (directly anthropogenic). Forestry is also anthropogenic, but forests and other land are not land uses; they are land covers and, if changes in “other land” result not only from changes in land use but also from indirect effects, then FCO may not be anthropogenic, as assumed here. The distinction between directly and indirectly anthropogenic is important because emissions from indirect effects offer clues to whether the terrestrial carbon sink may be changing. If land-use data from the FAO include indirect, as well as direct effects, then those data may no longer help define or constrain direct effects.

The distinction between direct and indirect effects has some similarities with the distinction between land use and land cover. Land use is clearly anthropogenic; land cover may or may not be. Hence, the two commonly used acronyms to describe terrestrial carbon emissions, LULUCF and LULCC [(Land Use, Land-Use Change, and Forestry) and (Land-Use and Land-Cover Change), respectively] are not the same. LULUCF is a UNFCCC and IPCC term and concerns direct anthropogenic changes in land *use*. In contrast, LULCC, a term used by NASA and generally based on satellite data, concerns changes in land *cover*. The terms have been used interchangeably but perhaps ought not to be. LULUCF is generally assumed to be anthropogenic, while LULCC includes land-*cover* change, which need not be anthropogenic. If some deforestation is driven by changes in climate (droughts, fires, storms), it should be attributed to indirect effects.

Indirect effects are believed responsible for a land sink that is larger than the net emissions from management (Friedlingstein et al., 2022). That does not mean, however, that all indirect effects remove carbon from the atmosphere. Some may drive emissions, as well. Amazonia may be an example where indirect effects are leading to additional emissions instead of, or as well as, sinks of carbon. The possibility would help explain why the global land sink seems to have shifted from the tropics to boreal regions after the 1980s (Ciais et al., 2019).

Our use of data from FAOSTAT assumed that changes in land use/cover were directly anthropogenic. On the contrary, changes in forest land and other land, in particular, could include both direct and indirect effects. Most scholars think that droughts, fires, and storms have so far been minor in replacing forests with other land cover. In other words, deforestation has been largely anthropogenic to date. The same is not true for forest degradation, which is driven by both direct and indirect effects. Separation of the emissions attributable to these effects is important because mistaken attribution could mask a declining land sink. Indeed, declining emissions from LULUCF, given a generally constant airborne fraction, suggest the land and/or ocean sinks are also declining (Van Marle et al., 2022). Documentation of such a decline is crucial.

Overall, one would expect satellite-based changes in land use to be more consistent (the same approach used everywhere) and, perhaps, more accurate (less potential for cheating) than changes reported to the FAO by individual countries using varied methods for determining change. Sadly, however, if the conditions described above account for the divergent trends in rates of deforestation and reported emissions, then data from satellites may not provide an easy resolution. The “advantage” of satellite data’s being more consistent may not be an advantage if, for example, shifting cultivation is not consistently practiced in different countries. Furthermore, anthropogenic versus non-anthropogenic disturbances are difficult to distinguish with any kind of measurement, and the fate of disturbed lands (including both land use and carbon density) may remain uncertain for years following a disturbance. The recent disagreement between satellite-based and ground-based rates of wood harvest in Europe provides an example of the limitations of satellite-based measures of land-use (Palahí et al., 2021; Ceccherini et al., 2020; Picard et al., 2021; Wernick et al., 2021).

On the other hand, forest degradation, as opposed to deforestation, may be better documented with satellite data than with tabular data because it seems to be widespread and caused by a variety of different agents and processes (Kan et al., 2023; Lapola et al., 2023). Satellites with Lidar or Radar sensors are especially promising for estimating changes in aboveground biomass (Baccini et al., 2017; Brandt et al., 2018), although not necessarily for assigning cause.

One further advantage of satellite data (as opposed to tabular data) is their explicit geographic specificity. If the spatial resolution is fine enough, maps of changes in area can be overlaid on maps of biomass to determine the biomass of the forests actually deforested (Harris et al., 2021). And knowing where deforestation has occurred may help identify what the deforestation was for (i.e., what other land is) and what caused it. Ground surveys may provide more detail and accuracy, but the magnitude and distribution of change, globally, clearly require a combination of ground and space-based observations.

Data availability

Annual emissions of carbon from Land Use, Land-Use Change, and Forestry (LULUCF) as reported in this analysis (Houghton and Castanho, XXXX) are available through Harvard Dataverse (https://dataverse.harvard.edu/privateurl.xhtml?token=09ee9f75-3b93-4755-8be6-9da7ac06dd60, final DOI to be updated during publication process). The tabular data include both net and gross annual fluxes of carbon globally and regionally from 1850 to 2020, as well as a list of the countries included in each region. The emissions were calculated with a bookkeeping model using the shifting cultivation interpretation of land-use change, inferred from data from FAOSTAT (FAO, 2021). Estimates include the emissions from peatlands in both Southeast Asia and northern regions. Further breakdown of the data may be obtained directly from the authors (rhoughton@woodwellclimate.org, acastanho@woodwellclimate.org).

5. Conclusions

A major objective in quantifying the emissions of carbon from terrestrial ecosystems is to separate the emissions resulting from management (direct anthropogenic activities) from those resulting from the effects of environmental change (indirect effects). Those resulting from management can, in theory, be controlled, while those resulting from environmental change are more difficult to control. The estimated emissions of carbon from LULUCF calculated in this analysis approximate the emissions resulting from management, but they are not complete. They do not include the effects of agricultural management practices (for example, irrigation), but only the effects of converting lands from one use to another. They also include the major effects of forestry (i.e., wood harvest). Despite the difficulties and uncertainties apparent throughout this effort, quantifying the terrestrial emissions of carbon that are directly anthropogenic is important, both for predicting future rates of climate change and for identifying land-based solutions for mitigation.

However, the separation of emissions into those caused by direct, as opposed to indirect, effects of human activity may not be necessary for national reporting of emissions and, further, it may be limiting. Carbon credits and debits are now limited to anthropogenic emissions, defined by the emissions from managed lands (Ogle et al., 2018; Grassi et al., 2018; Grassi et al., 2022). But the emissions from managed land include indirect effects as well. It would be much simpler in practice, consistent with observations, and would provide the appropriate incentives for mitigation if countries were credited and debited for *all* emissions and removals of carbon on *all* lands. Penalties for emissions resulting from droughts, fires, and natural disturbances might seem unfair, but the same unfairness applies equally to current rewards for carbon removals (the land sink). At present, at a global scale, the non-anthropogenic land sink is greater than the net emissions attributable to anthropogenic activities. Policies that rewarded countries for maintaining and enhancing that sink would provide a greater opportunity for slowing climate change than policies rewarding only reductions in anthropogenic emissions.

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Appendix A

Table A1: Detailed reference for each property downloaded from FAOSTAT (FAO, 2021) in October 2021 (FAO, 2021)

FAOSTAT domain	FAO file name	FAO Property Name	units
https://www.fao.org/faostat/en/#data/GF	Emissions_Land_Use_Forests_E_All_Data.csv	Forestland [area]	Mha
https://www.fao.org/faostat/en/#data/RL	Inputs_LandUse_E_All_Data.csv	Country [area]	Mha
		Land [area]	Mha
		Cropland [area]	Mha
		Land under perm. meadows and pastures [area]	Mha
		Planted Forest [area]	Mha
https://www.fao.org/faostat/en/#data/FO	Forestry_E_All_Data.csv	Wood Fuel [volume]	m3
		Industrial roundwood [volume]	m3

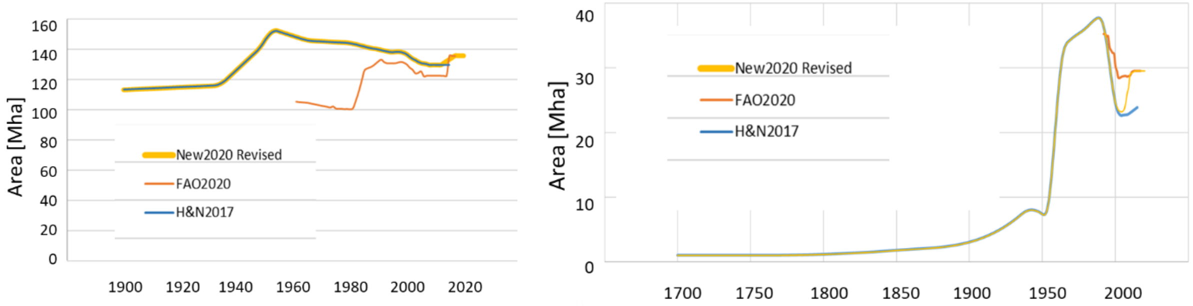
Table A2: List of countries per region

TROPICS			NON TROPICS						
SUBSAFR	**LAM**	**SSEA**	**NAM**	**EUROPE**	**FSU**	**CHINA**	**NAFME**	**EASTASIA**	**OCEANIA**
Subsaharan Africa	Latin America	South South East Asia	North America	Europe	Former Soviet Union	China	North Africa and Midle East	East Asia	Oceania
Angola	Argentina	Bangladesh	Canada	Albania	Armenia	China	Afghanistan	Japan	Australia
Benin	Bahamas	Bhutan	USA	Andorra	Azerbaijan		Algeria	Mongolia	CookIslands
Botswana	Barbados	Brunei		Austria	Belarus		Bahrain	North Korea	Fiji
BurkinaFaso	Belize	Cambodia		Belgium	Estonia		Cyprus	South Korea	French Polynesia
Burundi	Bolivia	India		Bosnia	Georgia		Egypt		Micronesia
Cameroon	Brazil	Indonesia		Bulgaria	Kazakhstan		Iran		New Caledonia
Central African Republic	British Virgin Islands	Laos		Croatia	Kyrgyzstan		Iraq		New Zealand
Chad	Chile	Malaysia		Czech Republic	Latvia		Israel		Niue
Congo	Colombia	Myanmar		Denmark	Lithuania		Jordan		Samoa
Djibouti	CostaRica	Nepal		Finland	Moldova		Kuwait		Solomon Islands
Democratic Republic Congo	Cuba	Pakistan		France	Russia		Lebanon		Tonga
Equatorial Guinea	Dominica	Philippines		Germany	Tajikistan		Libya		Vanuatu
Eritrea	Dominican Republic	Papua New Guinea		Greece	Turkmenistan		Morocco		
Ethiopia	Ecuador	Singapore		Hungary	Ukraine		Oman		
Gabon	ElSalvador	Sri Lanka		Iceland	Uzbekistan		Qatar		
Gambia	FrenchGuiana	Thailand		Ireland			Saudi Arabia		
Ghana	Guadeloupe	Timor Leste		Italy			Syria		
Guinea	Guatemala	Vietnam		Liechtenstein			Tunisia		
Guinea Bissau	Guyana			Luxembourg			Turkey		
Ivory Coast	Haiti			Macedonia			United Arab Emirates		
Kenya	Honduras			Malta			Western Sahara		
Lesotho	Jamaica			Montenegro			Yemen		
Liberia	Martinique			Netherlands					
Madagascar	Mexico			Norway					
Malawi	Nicaragua			Poland					
Mauritania	Panama			Portugal					
Mali	Paraguay			Romania					
Mozambique	Peru			Serbia					
Namibia	StLucia			Slovakia					
Niger	StVincent			Slovenia					
Nigeria	Suriname			Spain					
Rwanda	TrinidadandTobago			Sweden					
South Sudan	Uruguay			Switzerland					
Senegal	Venezuela			United Kingdom					
Sierra Leone	PuertoRico								
Somalia									
South Africa									
South Sudan									
Swaziland									
Tanzania									
Togo									
Uganda									
Zambia									
Zimbabwe									

Table A3: Median Carbon Densities (Primary Vegetation and Soil in MgC ha^{-1}) for 20 types of ecosystems (ranges include the variation among different countries with the same ecosystem type)

FRA2000 Ecozone Class	Median Carbon Density of Primary Vegetation [MgC ha^{-1}]	Carbon Density of Undisturbed Soils [MgC ha^{-1}]
Tropical rain forest	190	120
Tropical moist deciduous	78	100
Tropical dry	39	40
Tropical shrub	36	35
Tropical desert	10	58
Tropical mountain	62	75
Subtropical humid	148	120
Subtropical dry	57	80
Subtropical steppe	25	50
Subtropical desert	7	58
Subtropical mountain	80	120
Temperate oceanic	252	220
Temperate continental	150	200
Temperate steppe	25	80
Temperate desert	8	60
Temperate mountain	101	150
Boreal coniferous	67	206
Boreal tundra	21	206
Boreal mountain	46	206
Polar	4	150

Appendix B



(a) (b)

Figure B1: Cropland areas revised in this study (in yellow) compared to cropland area in FAOSTAT (FAO, 2021) (in orange) and Houghton and Nassikas (2017) (in blue), for China (a) and Kazakhstan (b).

Author contributions

Both RAH and AC participated in all aspects of the analysis and writing.

Competing interests

The authors declare that they have no conflict of interest.

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