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Title Page

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 tracking global, regional, and national carbon budgets, which in turn help predict future rates of climate change and help define potential solutions for mitigation. Here we update a long-term (1850-2020) series of annual, national carbon emissions 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 (Faostat, 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 forests is greater than the net gain in croplands and pastures, and we explore three alternative interpretations of this apparent forest conversion, one of which is shifting cultivation. We note that LULUCF is not equivalent to LULCC (Land-Use and Land-Cover Change), and suggest that the difference between "land use" and "land cover" may contribute to variation among independent estimates of emissions. The calculated emissions of carbon based on LULUCF approximate the anthropogenic component of terrestrial carbon emissions, but carbon management opportunities exist for unmanaged lands as well.

1. Introduction

The annual 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., terrestrial ecosystem responses to environmental change) (Grassi et al., 2018; Friedlingstein et al., 2022). The net emissions of carbon from direct anthropogenic effects are often referred to as emissions from Land Use, Land-Use Change, and Forestry (LULUCF) and/or Land-Use and Land-Cover Change (LULCC). However, the two definitions of direct anthropogenic effects are not equivalent.

Here we update an earlier analysis of emissions from LULUCF by Houghton and Nassikas (2017). The update 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 the latest Forest Resources Assessment of the FAO (Fra, 2020).

Incorporating the recent data required more than adding the most recent five years because the latest data on land use from Faostat (2021) included revisions to earlier years. Third, we explicitly accounted for the conversion of tropical forests to lands other than permanent pastures and croplands, as reported by FAOSTAT. We argue that this conversion includes some combination of temporary deforestation, increases in degraded lands, and shifting cultivation, and we calculated the potential emissions for all three 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.

2. Methods

Two variables control the emissions of carbon from LULUCF: changes in land use (ha/yr), including wood harvest (MgC/yr), and changes in the amount of carbon held in biomass, soils, slash, and wood products (MgC/ha/yr) as a result of LULUCF.

2.1. Changes in land use (rates of conversion (ha/yr) and rates of wood harvest (m3/yr))

In keeping with data from FAOSTAT, we considered four major types of land use: croplands, pastures, forests, and other lands. The areas in "other lands" were estimated as the difference between total country land area and the combined areas of forests, crops and pastures. We also considered forest management (i.e., harvest of industrial and fuel wood). In the United States we considered changes in fire management.

We reconstructed historical changes in land use starting with the most recent information and working backwards in time. From 1990-2020 we used data from the FAO (Faostat, 2021; Fra, 2020) to define national areas in forests, croplands, and pastures. From 1961 to 1990 we used data from FAOSTAT for croplands and pastures. Before 1961 (for crops and pastures) and before 1989 (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 (Houghton and Nassikas, 2017).

The areas in croplands are better documented through history than other land uses. Areas in pastures or grazing lands are less consistently defined, in large part because many lands that are grazed (rangelands) are not pastures. We assumed, conservatively, that pastures were converted from natural grasslands unless data suggested they were converted from forests. Sometimes it was clear from data in FAOSTAT that new pastures came from forests.

With few exceptions (United States, Europe, South and Southeast Asia), national areas of forest are not well documented historically. Thus, we generally reconstructed or extrapolated historical changes in forest areas backwards from the oldest available data into the past. We started the model in 1700 but report emissions only after 1850 to avoid artificial emissions resulting from spin-up of the model (i.e., time lags associated with buildup of decay pools and forest age classes).

2.2. Changes in the carbon content of terrestrial ecosystems (MgC/ha/yr)

We generally used the data from Houghton and Nassikas (2017) to assign to the model changes in carbon density (MgC ha^{-1} yr^{-1} in vegetation and soils) that follow a change in land use or wood harvest. The starting (1700) biomass and soil carbon densities for ecosystems or ecozones were also the same as those used by Houghton and Nassikas (2017).

2.3. Updates included in this work

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

1. Improved calculation of carbon emissions from wood harvest.
2. Updated and revised input to accommodate new data from FRA2020/FAOSTAT 2021 (this step included some historical adjustments as well)
3. Treated the apparent conversion of forests to other lands with three alternative assumptions. We also estimated the historical trajectory of this conversion so that there was not an abrupt change in 1990 when FAO data on forest area first became available (Fra, 1990).
4. Included other effects of management (peat drainage and burning in Southeast Asia and northern lands)

Each of these steps is elaborated below.

2.3.1. Adjustments to the bookkeeping model for wood harvest

Two adjustments, partially off-setting, were made for the original code used by Houghton and Nassikas (2017). The first resulted in a more accurate simulation of harvested wood products. We had overestimated harvest by failing to account for the fact that some harvested forest biomass becomes slash rather than wood product. This adjustment reduced the amount of wood harvested to match data from FAOSTAT and other data sources. The second adjustment increased the areas of secondary forests or plantations harvested because the intensity of harvest (MgC/ha removed) is generally lower in secondary forests than in primary forests. Thus a larger area of secondary forests was harvested in the improved version to obtain the same volume of wood. The larger area harvested led to a greater gross uptake of carbon by recovering forests and, thus, lower net emissions from wood harvest than estimated by Houghton and Nassikas (2017).

2.3.2. Incorporation of new data from the FAO

We used two data sources from the FAO to update the analyses to 2020. Every five years since 1990 the FAO publishes a Forest Resources Assessment (FRA), the latest being FRA2020. The FRAs report the areas and biomass/carbon stocks of forests, country by country. Every year since 1960 FAOSTAT reports the national areas of forests, croplands, pastures, and other lands. It also reports annual rates of harvest of industrial wood and fuelwood. We used data from the most recent FAOSTAT2021, thereby accounting not only for additional years but also for revisions to earlier estimates. Revised data from FRA2020 and FAOSTAT2021 often required that we revise pre-1990 estimates in order to avoid abrupt changes. We assumed that rates reported by the FAO 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. 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 FAOSTAT2021. Then, after 2007 croplands were again expanded 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 FAOSTAT2021. These departures from

FAOSTAT were similar to those used by Houghton and Nassikas (2017). For 15 other countries we adjusted pasture areas (mostly) to accommodate a discontinuity in FAOSTAT data in 1990.

2.3.3. Alternative interpretations of forest conversion to other lands

Annual estimates of national areas in croplands, pastures, and forests from the FAO have been used for nearly 40 years to infer net changes in land use and, thereby, to calculate annual emissions of carbon associated with those changes (Houghton et al., 1983). The approach is based on documented changes in carbon stocks (vegetation and soils) that follow the conversion of native ecosystems to agricultural lands. However, the three classes of land use (croplands, pastures, and forests) do not account for all land areas, and a fourth class, other lands, has been used by the FAO to insure that the total area in all four classes adds up to a country's total land area. Other lands include any lands that are not classified as cropland, pasture, or forest. They can include un-grazed grasslands, shrublands, and deserts as well as anthropogenic lands, such as urban lands, degraded lands, and anything else that does not match the definitions of croplands, pastures, and forests. The challenge is to determine how changes in the area of these other lands affect the amount of carbon stored on land. For example, if the area of forest is reduced one year, and the areas of croplands, pastures, and other lands all increase, what were the changes in carbon that resulted from the conversion of forests to other lands?

Clearly, the changes in area determined with this approach are net changes; the gross changes might be quite different. For example, forests might be converted to croplands, and an equivalent area of croplands might be abandoned to other land, yielding a net loss of forest, a net gain in other land, and no net change in cropland area. More complicated conversions can be easily imagined for any combination of net changes in area. Our use of net changes represented the simplest interpretation for conversions among the four cover types.

The question is What are the new densities of carbon in the vegetation and soils of other lands generated by deforestation? We explored the effects of three different interpretations of this apparent forest conversion to other land. In one case we assumed that the conversion represented *degraded land*; i.e., low carbon stocks. We assumed that forests were converted to new permanent croplands, while worn-out, degraded croplands were abandoned yet did not recover to forests. Instead, they remained with low densities of carbon in vegetation and soils (i.e., degraded). In this interpretation there is a net loss of forest area, perhaps no change in cropland area, and an increase in other (degraded) land area.

In a second, *recovering* scenario we assumed, again, that forests were converted to croplands, but in this case the abandoned croplands began growing back to forests after an interval of 15 years. The resulting areas of forests were, therefore, greater than reported by the FAO but, perhaps, within the error of reporting. For example, while the conversion of forests to non-forest lands is abrupt and clear, the conversion of non-forest to forest is more difficult to identify and may be overlooked in the short term of 15 or so years. In this *recovering* interpretation the loss of forest (and the gain in other land) was temporary. By one definition, this temporary loss of forest is not deforestation at all, but similar to wood harvest in that the land remains forest. This *recovering* scenario was the one used Houghton and Nassikas (2017).

The third interpretation was that forests apparently converted to other lands were converted to *shifting cultivation*. Lands that are temporarily (less than five years) in crops are not classified as permanent croplands by FAOSTAT, but the loss of forests to such lands are, nevertheless, counted as deforestation. Thus, the loss of forest area that exceeded the gain in cropland and pasture was assumed to represent an increase in the area of shifting cultivation. This interpretation has been described previously (Houghton and Nassikas, 2018) (Houghton and Hackler, 2006). Given that shifting cultivation generally includes some tree cover and a period of fallow during which trees grow, one can argue that clearing for shifting cultivation is not really deforestation (as wood harvests are not deforestation) but, instead, forest degradation. The land remains forest, but its average biomass is lower than in an untouched forest. Whether to call that conversion deforestation or degradation is discussed below.

We refer to all three of these interpretations as “forests converted to other lands” (FCO). Negative values represented the return of other land to forest. We estimated areas and changes in areas as follows.

First, when the annual loss of forest 1990-2020 according to FRA2020 (Fra, 2020) was greater than the annual increase in croplands plus pasture (from FAOSTAT 2021), the “additional” loss of forests was assigned to “forests converted to other land” (FCO).

Second, the rates obtained from FRA2020 for the period 1990-2020 were extrapolated backwards to 1980. We compared the resulting area of FCO in 1980 with a country's total area in the fallow of shifting cultivation in 1980 (Fao/Unep, 1981). In many countries our estimate of FCO was large enough to accommodate the FAO/UNEP's area of fallow. But in other tropical countries the 1980 estimate of fallow area was larger than the area we found in FCO. In these cases, we lowered the fallow area given by (Fao/Unep, 1981) to match the land area we categorized as FCO. FCO was constrained by the 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 FCO between 1990 and 2020 were determined from annual increases (or decreases) in the conversion of forest to other land. A decrease in FCO represented an increase in forest area that did not come from croplands or pastures (Faostat, 2021). As discussed above, these data refer only to net changes in land use. The gross changes are likely higher and involve any combination of conversions among forest, cropland, pasture, and other land areas.

Finally, we extrapolated the observed rate of change between 1980 and 1990 back to 1945, and then at a declining rate back to 1700. A more reliable 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 whether shifting cultivation was increasing or decreasing before 1970.

Shifting cultivation is a special case of cropland, where, first, tree cover is present and, second, the time in fallow is longer than the time in crops. 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/forests to partially recover and 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.

https://doi.org/10.5194/essd-2022-351
Preprint. Discussion started: 27 October 2022

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 as recently as the 1970s (Van Vliet et al., 2012). 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).

2.3.4. The draining and burning of peatlands

Because our bookkeeping model does 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, and the emissions from draining peatlands reported by Hooijer et al. (2010). The approach was the same as reported by Houghton and Nassikas (2017).

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

3. Results

Because of offsetting effects of these model improvements and revisions to data, the net global emissions of carbon from changes in land use over the period 1850-2020 appear generally similar to the results presented five years ago (Houghton and Nassikas, 2017)(Fig. 1) (Table 1). Below, we present the results of the four steps outlined in the Methods (Table 1).

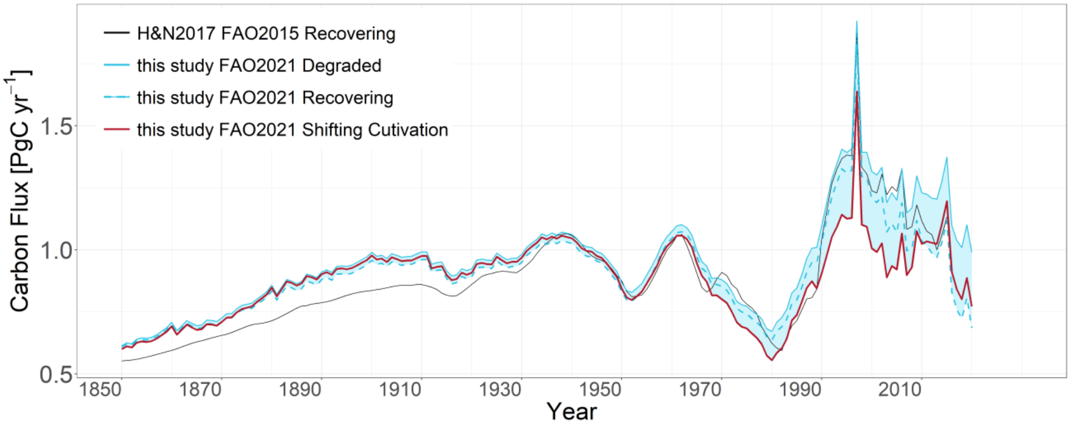

Figure 1. Annual net emissions of carbon from LULUCF. The red line refers to the analysis including shifting cultivation. The shaded area indicates the range of emissions from alternative interpretations of forest loss in the tropics (see 3.3, below). The black line refers to Houghton and Nassikas (2017).

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)

[PgC]		based on FAOSTAT2015		based on FAOSTAT2015		based on FAOSTAT2021			
		H&N2017 recovering		**this study** recovering		**this study** degraded	**this study** recovering	**this study** shifting cultivation	peat - 2020
region	time period	with SSEA peat	no peat	with SSEA peat	no peat	no peat			SSEA + Norhtern Countries
GLOBAL	1850-2015	145.5	139.1	117.8	111.4	123.4	115.9	112.5	34.4
GLOBAL	1850-2020					127.0	118.0	115.1	36.1
NONTROPICS	1850-2015	43.4	43.4	25.5	25.5	25.2	24.8	24.4	28.0
NONTROPICS	1850-2020					23.6	23.2	22.7	28.5
TROPICS	1850-2015	102.0	95.6	92.3	85.9	98.2	91.1	88.1	6.4
TROPICS	1850-2020					103.4	94.9	92.4	7.6

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 product and (2) the larger area required for secondary forests to provide the same volumes of

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harvested wood as primary forests had offsetting effects, but together the adjustments led to lower emissions (Fig. 2). Accounting for slash increased the emissions from harvest, but harvesting 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: 111.4 PgC after adjustment, compared to the original total of 139.1 PgC (not counting peat emissions) (Houghton and Nassikas, 2017)(Table 1).

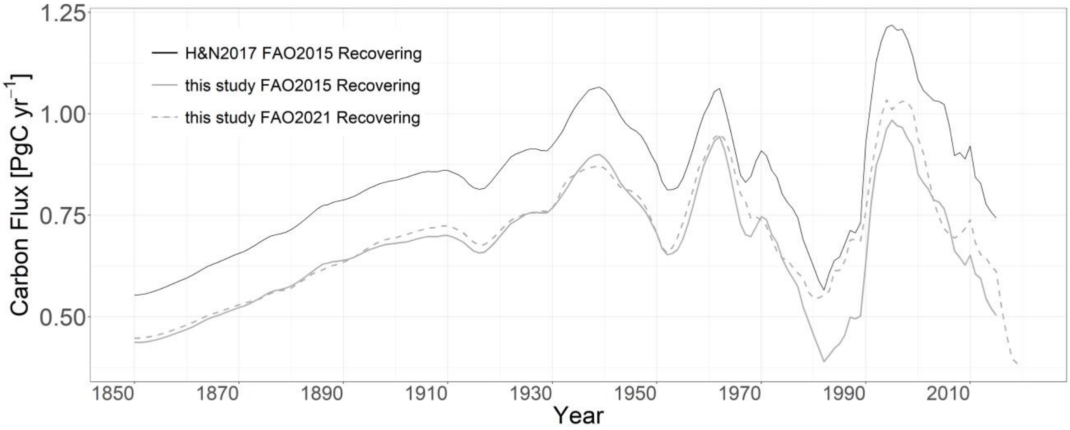

Figure 2. Annual net emissions of carbon from LULUCF. Gray line: improvements to model in this analysis. Dashed gray line: updated data from FAOSTAT2021. Black line: Houghton and Nassikas (2017). All analyses are based on the "recovering" analysis for comparison.

3.2.Incorporation of new data from the FAO

Use of the new data from FAO (Faostat, 2021; Fra, 2020) increased the estimated net emissions little: from 111.4 Pg to 115.9 PgC for the period 1850-2015 (Table 1). The addition of the last 5 years added another 2.1 PgC to this total (118.0 PgC 1850-2020, not counting emissions from peatlands. The greatest impact from revisions to data in FAO2021 occurred in the tropics, increasing net emissions during 1980s-1990s and lowering them after 2015 (Fig. 2).

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 croplands and pastures and resulted in a gain in "other land" area (Faostat, 2021). We called this gain "forests converted to other land" (FCO) to distinguish it from the FAO's category "other land". We calculated the emissions for three alternative interpretations of this new other land: (1) degraded land, (2) recovering forest, and (3) shifting cultivation, including fallow.

The area involved was large. If all conversions of tropical forests to other lands 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 these other lands were in the 1990s (Fig. 3).

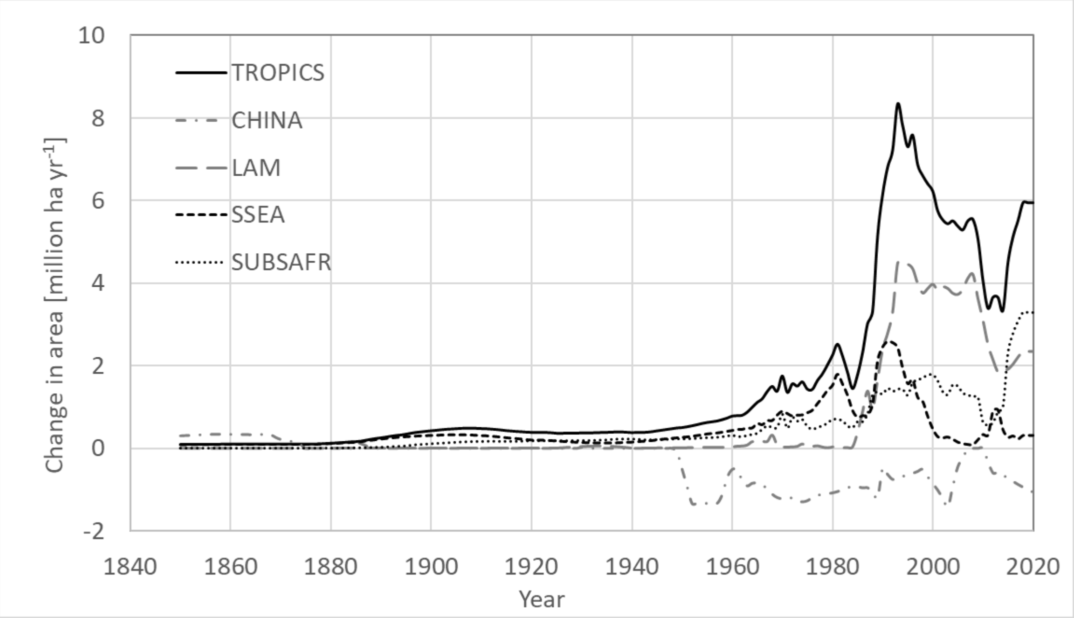

Figure 3. Rates at which forests appeared to be converted to other lands (FCO). Negative values indicate the conversion of other lands to forests.

The qualitative results from the three alternatives were as expected if run to equilibrium. Forests converted to degraded lands emitted the most carbon, while those that returned to forests generally emitted the least. However, because of the 15-year delay in the "recovering" interpretation, the ranking of the recovering and shifting cultivation interpretations varied over time (Fig. 4) (Table 1). For example, when the rate of "FCO" was increasing (1950-2010), emissions from shifting cultivation were lowest; while during more constant conditions, the expected ranking held. Total emissions 1850-2015 were 123.4, 115.9, and 112.5 Pg C for degraded, recovering, and shifting cultivation interpretations, respectively (Table 1). To 2020, total emissions from FCO were higher (127.0, 118.0, 115.1 Pg C, respectively).

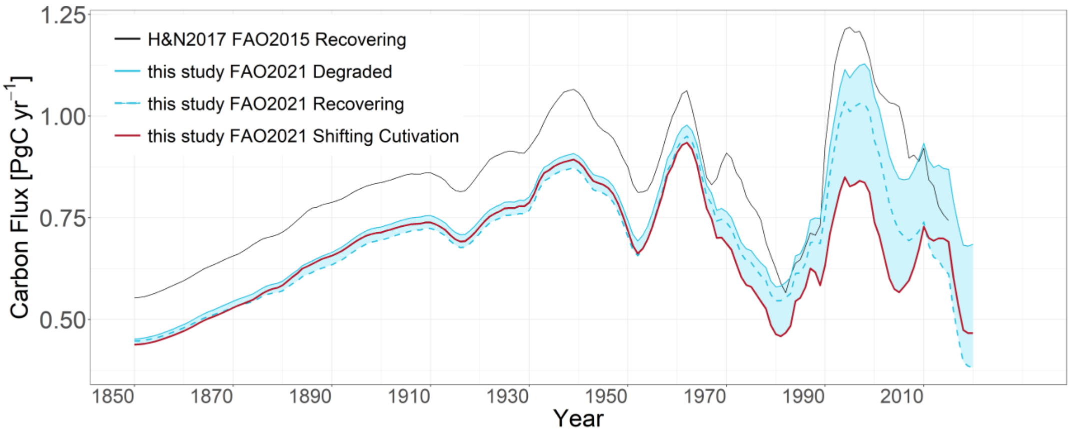

Figure 4. Annual net emissions of carbon from LULUCF. Red line includes shifting cultivation. Shaded area represents range of FCO interpretations. Black line: Houghton and Nassikas (2017).

If the current rates of deforestation for new other land were to continue until the emissions reached a steady state, the three interpretations (counting no other uses of land) would yield emissions of 0.789, 0.126, 0.537 PgC yr^{-1} for degraded lands, recovering forests, and shifting cultivation, respectively. Thus, not only are the emissions from this conversion large, but the uncertainty is large as well.

Table 2. Average annual net emissions from LULUCF for the globe and major regions for the period 2011 to 2020 (or to 2015 for comparison with H&N2017).

[PgC yr^{-1}]			based on FAOSTAT2021			
			this study degraded	**this study** recovering	**this study** shifting cultivation	peat - 2020
	region	time period	with Peat			SSEA + Norhtern Countries
	GLOBAL	2011-2020	1.152	0.893	0.960	0.357
	NONTROPICS	2011-2020	-0.255	-0.244	-0.259	0.102
	TROPICS	2011-2020	1.407	1.137	1.219	0.255
Tropics	LAM	2011-2020	0.413	0.352	0.308	0.000
	SUBSAFR	2011-2020	0.477	0.395	0.411	0.000
	SSEA	2011-2020	0.518	0.389	0.500	0.255
Non Tropics	NAM	2011-2020	-0.021	-0.073	-0.025	0.020
	EUROPE	2011-2020		-0.094		0.014
	CHINA	2011-2020		-0.010		0.043
	FSU	2011-2020		-0.052		0.025
	OCEANIA	2011-2020		0.001		0.000
	NAFME	2011-2020		-0.005		0.000
	EASTASIA	2011-2020		-0.011		0.000

3.4.The draining and burning of peatlands

Over the 170-year period 1850-2020 the emissions from use of peatlands added 7.6 Pg to emissions from countries in Southeast Asia and 28.5 PgC to countries in the northern mid-latitudes (Qiu et al., 2021) (Table 1) (Fig. 5). 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. 2) (Table 1).

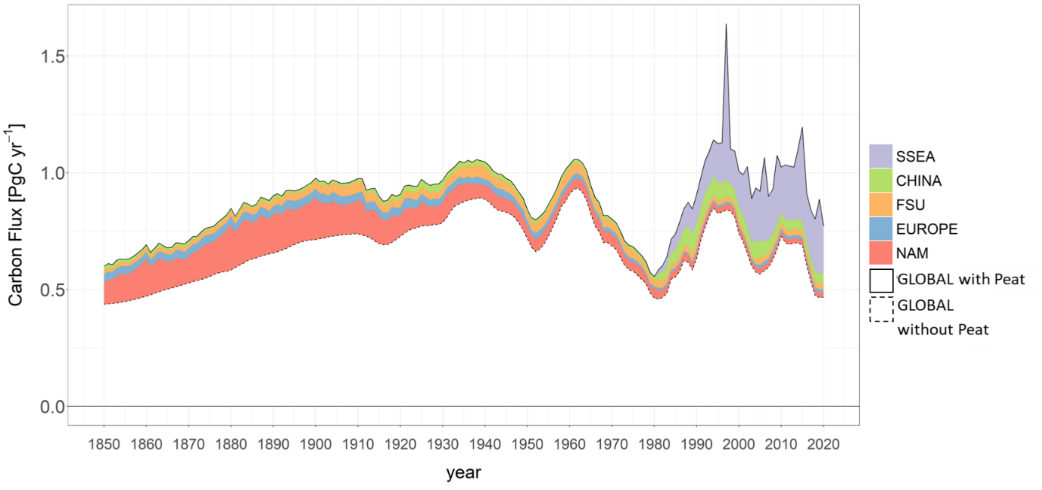

Figure 5. Annual emissions of carbon from use of peatlands, shown here above the annual net emissions from the shifting cultivation alternative.

3.5.Overall

Unless otherwise specified, the estimates described below refer to the shifting cultivation interpretation of forests converted to other lands (FCO). Global net emissions of carbon from LULUCF increased from about 0.6 PgC yr^{-1} in 1850 to about 1.0 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. 6). 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. 6), 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.

https://doi.org/10.5194/essd-2022-351
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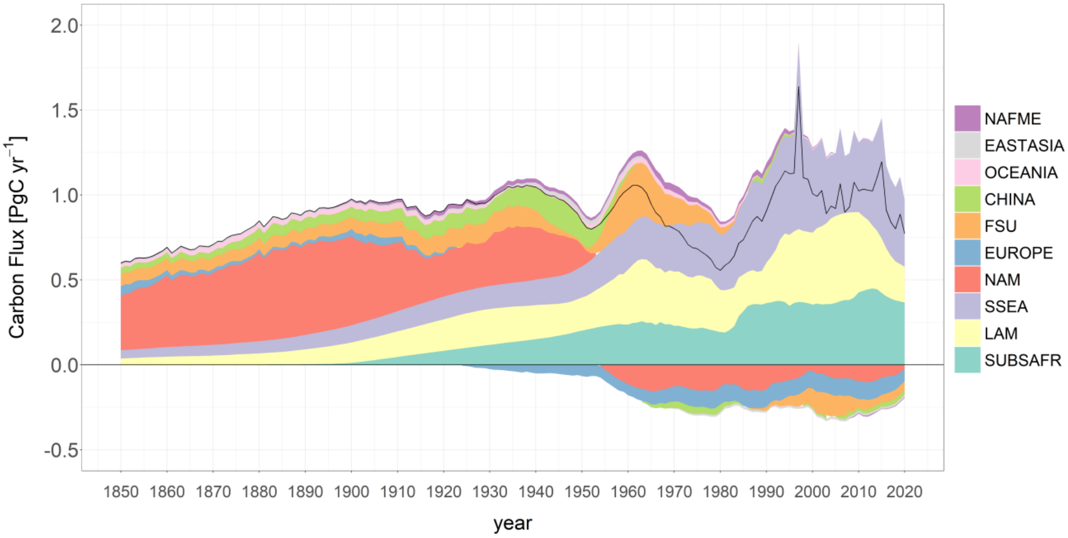

Figure 6. Net annual emissions of carbon from regions. The black line represents the global net annual emissions.

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. 7) (Table 3).

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 difference is largely attributable to the higher rates of deforestation in the tropics. In contrast to deforestation, rotational uses of land, such as shifting cultivation and the harvest of wood, have much lower net emissions because gross emissions and removals (due to forest regrowth) are largely offsetting.

The offset is not simultaneous, however, and has implications for mitigation. Because most emissions happen rapidly, while most removals occur over a longer time, a reduction in shifting cultivation or wood harvest 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 of the potential for mitigation than net fluxes are (compare Fig. 6 and Fig. 7). As discussed above, actual gross emissions and removals are larger than estimated here because rates of land-use change are based on *net* changes in area as reported by FAOSTAT.

Table 3. Average net and gross emissions of carbon from LULUCF for the period 2011-2020.

	[PgC yr^{-1}]		based on FAOSTAT2021		
			Net flux	Gross sink	Gross Source
	region	time period	Shifting Cultivation		
	GLOBAL	2011-2020	0.960	-2.420	3.380
	NONTROPICS	2011-2020	-0.259	-1.297	1.038
	TROPICS	2011-2020	1.219	-1.122	2.341
Tropics	LAM	2011-2020	0.308	-0.373	0.681
	SUBSAFR	2011-2020	0.411	-0.384	0.796
	SSEA	2011-2020	0.500	-0.364	0.864
Non Tropics	NAM	2011-2020	-0.073	-0.404	0.331
	EUROPE	2011-2020	-0.094	-0.306	0.211
	CHINA	2011-2020	-0.025	-0.204	0.179
	FSU	2011-2020	-0.052	-0.295	0.243
	OCEANIA	2011-2020	0.001	-0.030	0.031
	NAFME	2011-2020	-0.005	-0.028	0.024
	EASTASIA	2011-2020	-0.011	-0.030	0.018

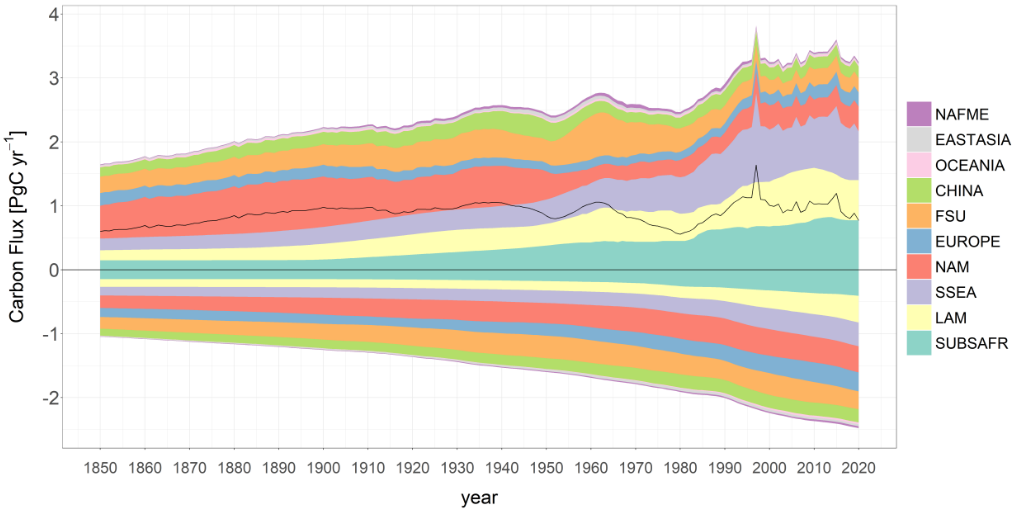

Figure 7. Annual gross emissions and removals of carbon from regions. The black line represents global net annual emissions.

3.5.1. 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 85.7% (Fig. 8). Seven countries offset 18.1% of the total emissions, while about 80 countries with negative emissions offset 26.3% of total net emissions from LULUCF. The total net removal (sum of all net removal countries) (3.41PgC yr^{-1}) was less than the emissions from Indonesia (3.76 PgC yr^{-1}). Indonesia alone accounted for 30% of all emission in this last 10 years, with 56% of those emissions from burning and draining of peatlands.

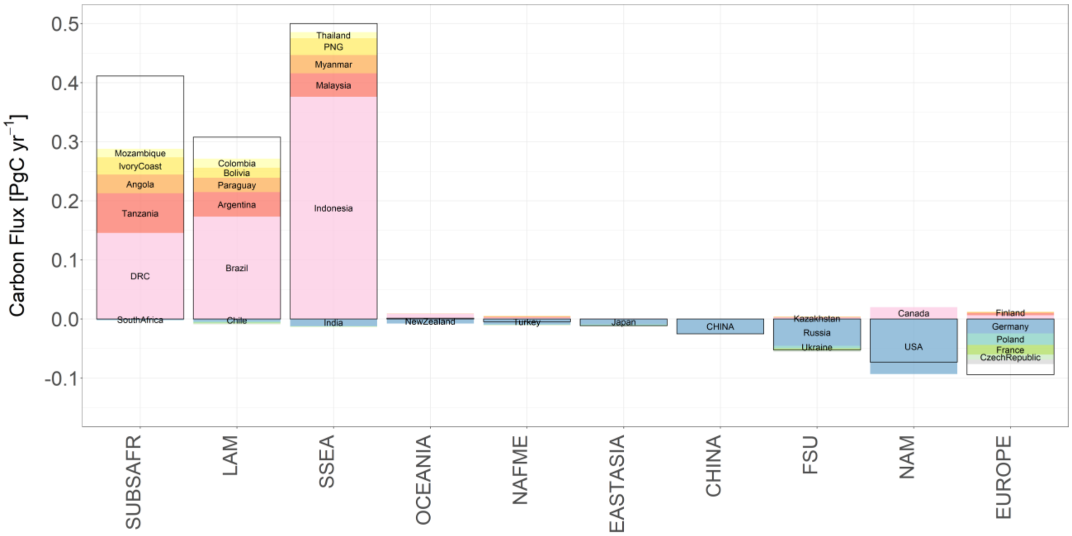

Figure 8. Regions and countries with the largest net annual emissions and removals, including emissions from use of peatlands (average for 2011-2020). The white portions of the columns represent the contribution of all other countries in the corresponding regions.

3.5.2. Emissions by land use

Land uses with the greatest emissions or removals of carbon varied among regions and over time (Fig. 9). 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 greatest in the three largely tropical regions. Emissions from the use of peatlands

https://doi.org/10.5194/essd-2022-351
Preprint. Discussion started: 27 October 2022

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, -0.109 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.

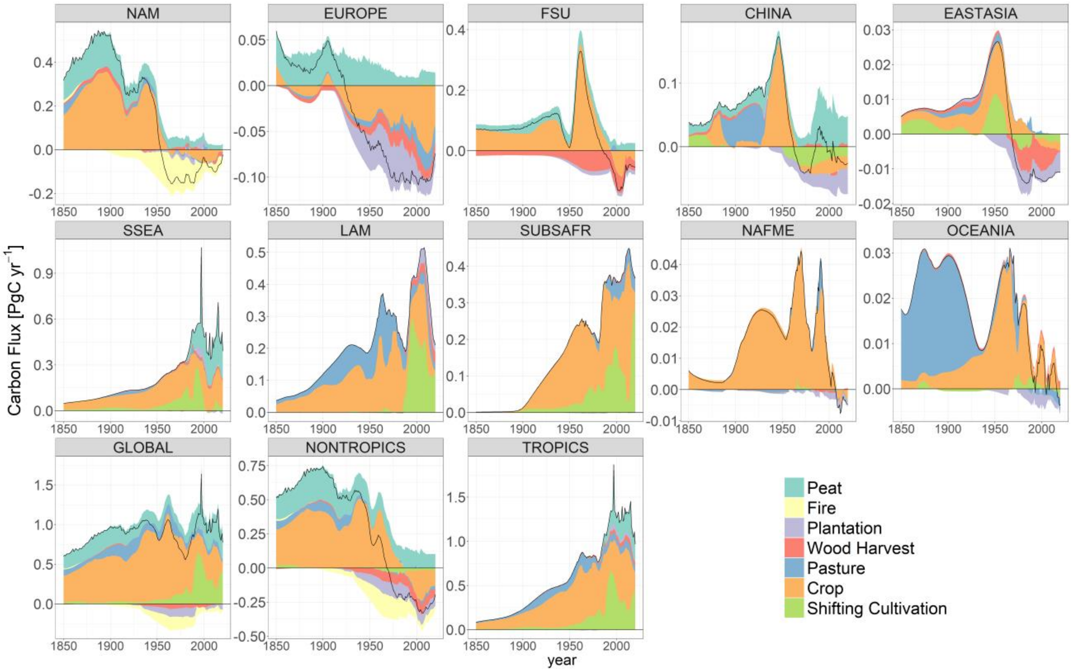

Figure 9. Net emissions from LULUCF attributed to different types of land use

https://doi.org/10.5194/essd-2022-351
Preprint. Discussion started: 27 October 2022

Table 4. Annual net emissions by land use by region, averaged over the last decade (2011-2020).

	Net Flux [PgC yr-1] (2011-2020)	Net Flux with peat	Net Flux without peat	Wood Harvest	Crop	Pasture	Shifting Cutivation	Plant	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**	0.000
Tropics	LAM	**0.308**	**0.308**	**0.039**	**0.063**	**0.039**	**0.123**	**0.044**	0.000	0.000
	SUBSAFR	**0.411**	**0.411**	0.003	**0.212**	**0.044**	**0.153**	-0.001	0.000	0.000
	SSEA	**0.500**	**0.245**	**0.016**	**0.201**	0.000	**0.038**	-0.010	**0.255**	0.000
Non Tropics	NAM	**-0.073**	**-0.093**	**-0.017**	**-0.023**	-0.002	0.001	0.000	**0.020**	**-0.051**
	EUROPE	**-0.094**	**-0.108**	-0.011	**-0.063**	**-0.018**	0.001	**-0.018**	0.014	0.000
	CHINA	**-0.025**	**-0.068**	0.005	**-0.020**	0.000	**-0.015**	**-0.038**	**0.043**	0.000
	FSU	**-0.052**	**-0.077**	**-0.037**	**-0.026**	0.000	0.000	-0.014	**0.025**	0.000
	OCEANIA	0.001	0.001	0.001	0.004	-0.002	-0.001	-0.001	0.000	0.000
	NAFME	-0.005	-0.005	0.000	-0.002	0.000	0.000	-0.002	0.000	0.000
	EASTASIA	-0.011	-0.011	-0.002	-0.002	0.000	-0.002	-0.005	0.000	0.000

3.5.3. Emissions by carbon pool

The annual net flux of 0.960 PgC yr^{-1} to the atmosphere for the period 2011-2020 was composed of gross emissions of 3.380 PgC yr^{-1} from burning of live vegetation, decay of dead vegetation, oxidation of wood products, and soil as a result of cultivation, including peatland emissions; and gross removals of -2.420 PgC yr^{-1} by 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	Gross sink	Gross emission
Living vegetation	-1.529	-2.238	0.709
Slash	1.137		1.137
Wood products	0.780		0.780
Soil carbon	0.572	-0.182	0.397+Peat 0.357
Total	0.960	-2.420	3.380

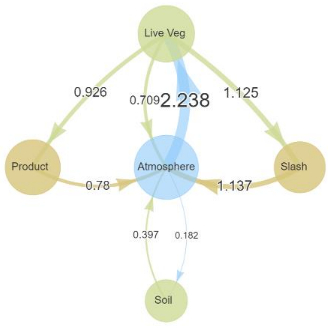

Figure 10. Global transfers of carbon (PgC yr^{-1}) among components of the terrestrial carbon cycle during the last 10 years (2011-2020). Peatlands (not included) would add another 0.357 PgC yr^{-1} to soil emissions.

The annual transfers of carbon among pools for the period 2011-2020 are shown in (Fig. 10). By far the largest flux was from the atmosphere to growing vegetation (2.238 PgC yr^{-1}). As discussed above, this gross removal of carbon by growing forests will continue for many decades even if emissions are reduced through management. 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.

It is unclear whether the emissions of carbon from peatlands in northern regions were from forests or not. Ignoring peatlands, global forests accounted for nearly all emissions (99%) for the decade 2011-2020. Emissions from peatlands were 37% of the total global net flux, and some of those emissions were probably from forested lands, as well.

4. Discussion

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

4.1. Are emissions from LULUCF in the tropics declining?

Perhaps the most surprising result of these revisions and updates was the apparent sharp decline in LULUCF emissions since 2015 (Fig. 11). The decline was even greater for tropical countries than the global decline because countries outside the tropics showed a small reduction in carbon sinks (although we note that a recent analysis of land use in China found a larger sink in recent decades than reported here (Yu, in press)).

https://doi.org/10.5194/essd-2022-351
Preprint. Discussion started: 27 October 2022

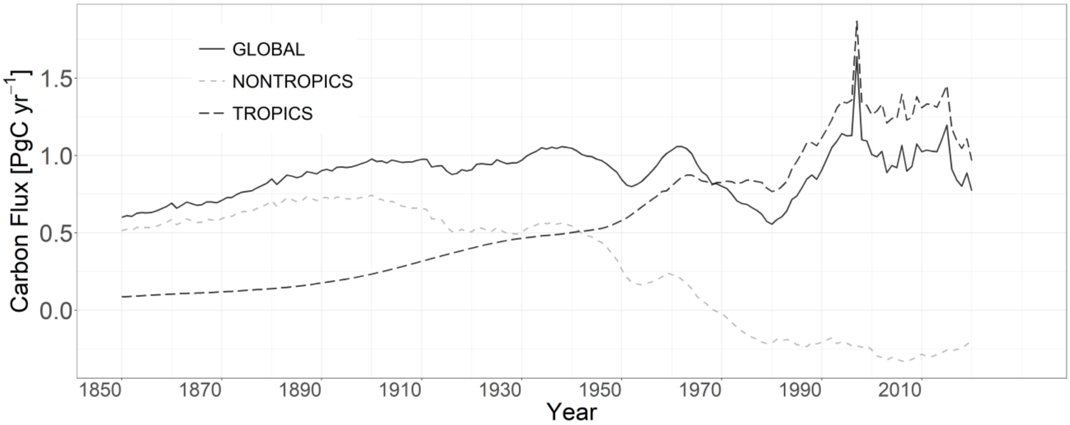

Figure 11. Net annual emissions of carbon from LULUCF for the globe, tropical regions, and non-tropical regions.

The decline in emissions reported here over the last decade is consistent with other bookkeeping models used by the Global Carbon Project (Carbonbrief, 2021), but more precipitous. The decline in tropical emissions was new in the 2020 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 HYDE (History Database of the global Environment) (Klein Goldewijk et al., 2017), which are semi-independent of the data reconstructed here. That is, all the land-use data used in the three analyses were based on rates of land-use change from FAOSTAT, but the data sets varied in their mapping of those changes (See Kondo et al. (2022), for a more detailed example of differences among data sets for Southeast Asia.).

In contrast to the declining emissions driven by FAO data, 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}), respectively. Their estimates were based on committed emissions; that is, assuming all the carbon lost from vegetation and soils was released to the atmosphere at the time of deforestation. When we calculated emissions similarly (gross emissions from deforestation alone), our estimates were 1.9 and 1.8 PgC yr^{-1} for the same intervals. Our estimates and those of Feng et al. (2022) were similar for the period 2015-2019 and very different for the first period. Did Feng et al. (2022) underestimate deforestation rates and emissions in the earlier period, or did FAO overestimate deforestation then? Including shifting cultivation and emissions from peat increased our estimated gross emissions from the tropics to about 2.4 PgC yr^{-1} for both intervals.

None of our simulations showed the increase in emissions that Feng et al. (2022) did. Interestingly, although not evident from the 2015-2019 mean, Feng et al. (2022) show a reduction in rates of forest loss after 2016, similar to the pattern reported by FAOSTAT2021. Furthermore, despite the absolute differences, our analysis and that of Feng et al. (2022) 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. 12). In our analysis, the recent decline in emissions was led by Brazil and Argentina. An analysis comparing changes between 2001-2005 and 2015-2019 did not change the results appreciably from those shown in Fig. 12.

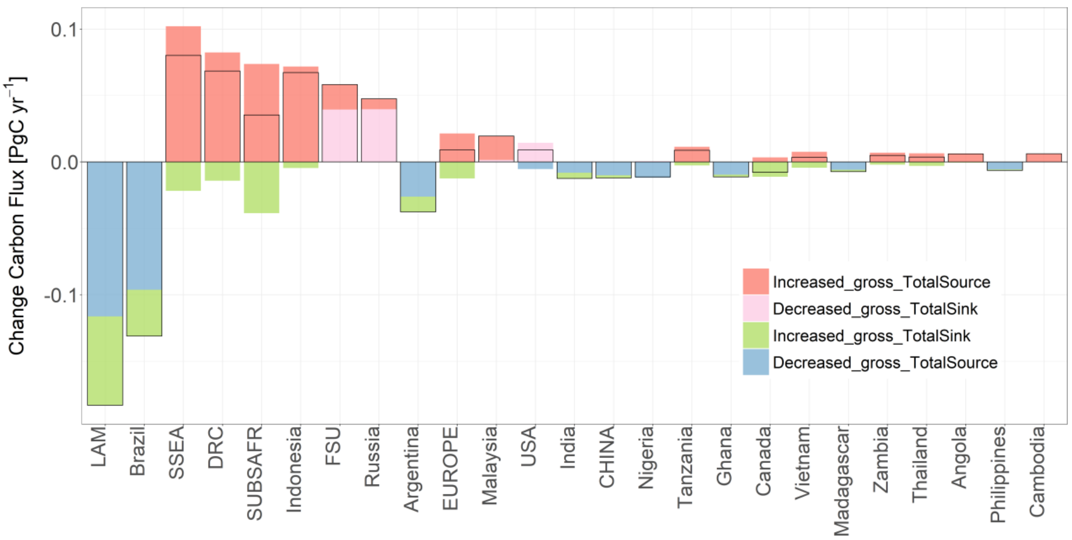

Figure 12. Changes in the sources and sinks of carbon between the first and second decades of the 21st century. Changes in the net source/sink are shown by black horizontal lines. Negative values indicate reduced emissions in second decade.

Why do tropical deforestation rates reported by FRA2020 (Fra, 2020) and Feng et al. (2022) *differ?* Many countries do not have the means to measure changes in forest area, and thus rates of deforestation may be out of date. Even Brazil, which may be unique in its ability to monitor deforestation, may underreport recent rates of deforestation. In Amazonia rates of deforestation declined greatly between 2004 and 2012 but seem to have been increasing since 2014 (Wiltshire et al., 2022). In contrast, FAO estimates of deforestation for all Brazil show a pattern similar to Legal Amazonia but with no increase after 2014 (Fra, 2015, 2020) .Thus, the FAO may lag somewhat in reporting the uptick in deforestation for Amazonia and Brazil.

The lag may result from the uncertain fate of deforested lands. In Amazonia, for example, forests may be burned years before they show up on the books as cattle pasture or cropland. We note that this time lag may explain the nearly constant rates of deforestation reported in recent years by FAO. The lag could also explain an increase in "other land" in FAOSTAT, suggesting that new agricultural lands may account for the emissions and not shifting cultivation, as assumed here.

Overall, deforestation rates in Brazil have not fallen as sharply as reported by FAOSTAT, and perhaps they have increased in recent years. Thus, emissions may not have declined as sharply as calculated in this study. However, the regions showing the greatest increases in emissions, according to Feng et al. (2022), were Africa and Southeast Asia, not Latin America. Thus, Feng et al. (2022) are most different from FAOSTAT2021 in Africa and Southeast Asia. If Feng et al. (2022) are correct, the decline in tropical emissions reported by all bookkeeping models would seem to be wrong. On the other hand, it may be that the analysis by Feng et al. (2022) is flawed (Hansen, 2022). The disagreement is a major uncertainty.

However, the possibility exists that both studies are correct, and that the disagreement can be explained by definitional and methodological issues.

Are changes in land cover anthropogenic? One possible explanation is to recognize that some deforestation is not directly anthropogenic, not a part of LULUCF, but rather a consequence of indirect effects (e.g., changes in climate, fires, storms) (Gatti et al., 2021). If Feng et al. (2022) counted all deforestation, while FAOSTAT counted only anthropogenic deforestation, the difference might represent environmental effects. For example, Aragão et al. (2018) found that the emissions from deforestation in Brazilian Amazonia were declining while the emissions from drought-related fires were increasing. The authors reported this finding despite the observation that many fires in Amazonia are arguably the direct effect of human activities (deliberate burning to clear forests) and, thus, part of LULUCF. Is the difference between Feng et al. (2022) and FAOSTAT explained by an increase in environmentally-driven disturbances?

The broader issue is whether changes in land *cover* are anthropogenic or not. If they are not directly anthropogenic, but rather driven by climate change, for example, then Land-Use and *Land-Cover Change* (LULCC) is different from Land Use, Land-Use Change, and Forestry (LULUCF). The terms are generally used interchangeably but perhaps ought not to be. LULCC includes land-cover change; LULUCF does not. We previously attributed the calculated fluxes to LULCC (Houghton et al., 2012; Houghton and Nassikas, 2017), but the more precise attribution is LULUCF because we focus on direct anthropogenic effects exclusively (clearing, planting, cultivating, harvesting) and do not assume that changes in land cover are necessarily anthropogenic. Examples of non-anthropogenic changes in land cover include droughts, wildfires, storms, natural disturbances. The issue is whether a change in land cover represents direct anthropogenic activity or is, instead, attributable to indirect (environmental) effects (Grassi et al., 2018). Globally, indirect effects are responsible for a land sink that is larger than the net emissions from management. But 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).

Deforestation versus forest loss. Another possible explanation for declining emissions despite increasing deforestation is related to the definition of deforestation. FAOSTAT defines 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 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, may include temporary losses of forest resulting from disturbance. Such estimates of deforestation would be higher than those reported by the FAOSTAT and used here to calculate emissions.

Re-clearing of fallows already in shifting cultivation. A third possible explanation for declining emissions despite increasing deforestation rates 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 (unless the recovery of forest in the fallows is identified as an increase in forest area). Even the cropped areas of shifting cultivation have tree cover and may be mistakenly identified as forests. Older fallows are even more forest-like, although perhaps recognizable as degraded forest.

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 reported by the FAO (Fra, 2020; Faostat, 2021). If only a small fraction of re-clearing is counted as deforestation, it would inflate the rate reported.

If any of these three possible explanations is correct, the net effect is to overestimate anthropogenic emissions and, thereby, overestimate the (non-anthropogenic) land sink as well (if the land sink is determined from the global carbon budget). Such a mistaken attribution could mask a declining land sink. Indeed, declining emissions, given a generally constant airborne fraction, suggest that land and/or ocean sinks are declining (Van Marle et al., 2022).

Overall, one would expect satellite-based changes in land use to be more accurate than changes reported to the FAO by individual countries using varied methods for determining change. Sadly, however, if the distinctions described above account for the divergent trends between rates of deforestation and reported emissions, then data from satellites may not provide an easy resolution. Anthropogenic versus non-anthropogenic disturbances are difficult to distinguish with any kind of measurement, and the fate (both land use and carbon density) of disturbed lands may remain uncertain for years following a disturbance. The recent disagreement between satellite-based and ground-based rates of wood harvest in Europe provides another recent example of the limitations of satellite-based measures of land-use change (Palahí et al., 2021; Ceccherini et al., 2020; Picard et al., 2021; Wernick et al., 2021).

4.2. Forests converted to other lands

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 emissions of carbon from shifting cultivation should be attributed to forest degradation or to deforestation.

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 permanent croplands 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.

As an alternative approach to evaluating changes in shifting cultivation, we used changes in "other land" reported by FAOSTAT. The rate at which forests were converted to other lands (FAOSTAT, 2021) increased in Latin America and Africa but declined in tropical Asia (Fig. 3). In China the area in other lands actually declined. An alternative explanation for the apparent conversion of forests to other lands (FCO) is that the fate of forest loss is unknown when it occurs and temporarily assigned to other land. Only later is it assigned to cropland, pasture, or forest. The subsequent revision of other land to one of these other land uses would reduce the emissions we attribute to shifting cultivation, but our alternative interpretations regarding forest conversion to other lands should include the range of possible emissions (Fig. 4). Nevertheless, 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) introduced an uncertainty of about 13% in global net emission from LULUCF. If the emissions from peatlands are ignored, the uncertainty for FCO was about 20% of global net emissions.

If we assume that the apparent conversion of forests to other lands (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 lands was attributable to shifting cultivation rather than to degraded lands or forests. By comparison, 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).

4.2.1. 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 1.016 and -0.718 PgC yr^{-1} in comparison to total gross emissions and removals were 3.379 and -2.420 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.

4.2.2. Is shifting cultivation deforestation or forest degradation?

Estimates of the emissions from degradation vary widely, from nearly zero (Xu et al., 2021) to greater than the emissions from deforestation (Baccini et al., 2017). Xu et al. (2021) reported little degradation, perhaps to avoid double counting it in the other drivers considered: forest clearing, forest fire, and non-forest fire. Baccini et al. (2017) found that degradation accounted for more carbon loss from the tropics than deforestation. Rappaport et al. (2018) reported degradation in Amazonian forests due to fire and logging, but it is unclear whether shifting cultivation was counted in either the fire or the logging data.

https://doi.org/10.5194/essd-2022-351
Preprint. Discussion started: 27 October 2022

Aside from issues of measurement, the relative proportions of deforestation and degradation to carbon emissions may depend on where the emissions from shifting cultivation are counted. If the emissions of carbon from shifting cultivation are attributed to deforestation, the relative contributions of deforestation and degradation to the net emissions from the tropics were 68.8% and 4.8%, respectively, for the period 2011-2020 (Fig. 13). The fraction of emissions attributed to neither deforestation nor degradation was largely from burning and draining of peatlands. Most of the degradation, or lowering of biomass, resulted from harvest of wood. But if we include shifting cultivation as forest degradation, arguing that fallows may be identified as forests by some definitions, then the relative contributions were more nearly equal (41.7% and 31.9%, for deforestation and degradation respectively), and in some years the emissions from degradation were more than 50% (Fig. 13).

Counting shifting cultivation as degradation rather than deforestation suggests a lower rate of deforestation than reported by the FAO (FAOSTAT 2021). Of the three interpretations of FCO, only the "degraded" interpretation represents the rate FAO reports. Both the "recovered" and the "shifting cultivation" interpretations are only temporary losses of forest, not deforestation as defined by FAOSTAT.

Whether the emissions and removals of carbon by shifting cultivation are attributed to deforestation or to degradation may depend on observations and their resolution. If changes in aboveground biomass can be determined, for example at fine resolution with Lidar, then degradation may be quantified. But at the intermediate resolution of MODIS, degradation and deforestation may be inseparable (Baccini et al., 2017), and at coarser resolution, or with measurements based on land cover alone, degradation may be missed altogether.

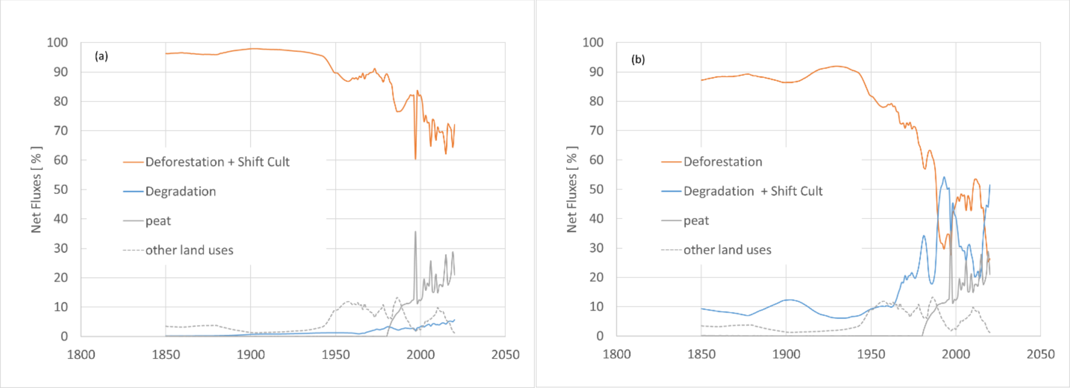

Figure 13. Emissions from deforestation and forest degradation if conversion of forests to shifting cultivation is deforestation (a) and if conversion of forests to shifting cultivation is degradation of forests (b). In the latter case, the emissions from degradation and deforestation are comparable.

4.3.Comparisons with other studies

Houghton and Nassikas (2017) interpreted FCO to represent the replacement of old croplands with new ones (from forests), with an equivalent area of old croplands abandoned. These abandoned croplands began gaining carbon after 15 years (the same as the *recovered* interpretation). Thus, while Houghton and Nassikas (2017) did not include shifting cultivation explicitly, they did include the conversion of forest to other land. 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 (Fao, 1980) and qualitative expert opinion reported in Heinimann et al. (2017).

As discussed above, the three bookkeeping models used by the Global Carbon Project (GCP) have all shown declining emissions from land-use and land-cover change over the last decade (Friedlingstein et al., 2022), although the net emissions estimated by Houghton and Nassikas (2017) were lower than the emissions calculated by BLUE (Hansis et al., 2015) and OSCAR (Gasser et al., 2020). The difference may be explained by lower values of biomass in the model of Houghton and Nassikas (2017) (Bastos et al., 2021) or, as suggested here, by changes in land cover that are not directly anthropogenic. That is, the HYDE data set uses LULCC rather than LULUCF to drive deforestation. 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). We would add to this list the difference between land use and land cover, discussed above.

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) in large part because the latter were based on total changes in forest carbon and not just those changes attributable to LULUCF. These estimates included the effects of both management (LULUCF) *and* environment, while we (and other bookkeeping models) have tried to estimate only the effects of management (i.e., land-use change). Because the total net flux of carbon from terrestrial ecosystems has been a net sink greater than the net emissions from LULUCF, including both processes generates a net sink, rather than a source, globally.

Second, we considered all ecosystems, not only forests. These non-forests accounted for about 4% of net emissions in 2011 and (as a sink) for about 6% of the net emissions in 2020.

Third, neither slash, harvested wood products, nor soils were included in the emissions determined by the other studies cited. Their results were based on changes in the biomass and area of forests. Table 5 shows the additional emissions from slash, harvested wood products, and soils. And fourth, the approach reported here considered the delay in emissions from wood products, soil, and dead organic matter, and the delay in removals of carbon in forest growth. In contrast, most recent studies have assumed that observed reductions in aboveground carbon storage are emitted to the atmosphere instantaneously. The differences may be significant if rates of land-use change are increasing or decreasing.

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 FAOSTAT2021. 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).

Conclusions

The estimated emissions of carbon from LULUCF calculated in this analysis approximate the emissions resulting from direct anthropogenic activities; that is, management. They are not equivalent to total net terrestrial emissions because the total includes sources and sinks resulting from natural and indirect anthropogenic effects, such as climate change and rising CO_2 levels. Separating terrestrial emissions of carbon into those directly anthropogenic (LULUCF) and those either natural or indirectly anthropogenic (environmental) is important, both for predicting future rates of climate change and for identifying land-based solutions for mitigation. But the separation may not be necessary for policy 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, in press). 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 from droughts, fires, and natural disturbances would seem unfair, but the same unfairness applies equally to 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 (i.e., LULUCF). 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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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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