1   Title Page

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

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12 **Abstract**

13 Estimates of the annual emissions of carbon from Land Use, Land-Use Change, and Forestry

14 (LULUCF) are important for tracking global, regional, and national carbon budgets, which in

15 turn help predict future rates of climate change and help define potential solutions for mitigation.

16 Here we update a long-term (1850-2020) series of annual, national carbon emissions from

17 LULUCF (Houghton and Nassikas, 2017), based largely, after 1960, on statistics of land use

18 from the Food and Agriculture Organization (FAO) of the United Nations (Faostat, 202 Those

19 data suggest that rates of deforestation in the tropics (and thus net emissions of carbon) have

20 decreased over the last ten years (2011-2020). The data also indicate that the net loss of tropical

21 forests is greater than the net gain in croplands and pasture nd we explore three alternative

22 interpretations of this apparent forest conversion, one of which is shifting cultivation. We note

23 that LULUCF is not equivalent to LULCC (Land-Use and Land-Cover Change), and suggest that

24 the difference between "land use" and "land cover" may contribute to variation among

25 independent estimates of emissions. The calculated emissions of carbon based on LULUCF

26 approximate the anthropogenic component of terrestrial carbon emissions, but carbon

27 management opportunities exist for unmanaged lands as well.

28 **1. Introduction**

29 The annual exchanges of carbon between land and atmosphere are represented by two terms in

30 the global carbon budget: one term for direct anthropogenic effects (i.e., management) and the

31 second term for natural effects and indirect anthropogenic effects (e.g., terrestrial ecosystem

32 responses to environmental change) (Grassi et al., 2018; Friedlingstein et al., 2022). The net

33 emissions of carbon from direct anthropogenic effects are often referred to as emissions from

34 Land Use, Land-Use Change, and Forestry (LULUCF) and/or Land-Use and Land-Cover

35 Change (LULCC) wever, the two definitions of direct anthropogenic effects are not

36 equivalent.

37 Here we update an earlier analysis of emissions from LULUCF by Houghton and Nassikas

38 (2017). The update consists of four steps. First, we improved the bookkeeping model's

39 simulation of fuelwood and industrial wood harvest. Then we extended the period of analysis to

40 2020, based largely on the latest Forest Resources Assessment of the FAO (Fra, 2020

41   Incorporating the recent data required more than adding the most recent five years because the

42   latest data on land use from Faostat (2021) included revisions to earlier years. Third, we

43   explicitly accounted for the conversion of tropical forests to lands other than permanent pastures

44   and croplands, as reported by FAOSTAT. We argue that this conversion includes some

45   combination of temporary deforestation, increases in degraded lands, and shifting cultivation,

46   and we calculated the potential emissions for all three of these alternative interpretations. Finally,

47   we included newly published and updated estimates of the carbon emissions from peatlands in

48   northern lands (Qiu et al., 2021) and in Southeast Asia.

49   **2. Methods**

50   Two variables control the emissions of carbon from LULUCF: changes in land use (ha/yr),

51   including wood harvest (MgC/yr), and changes in the amount of carbon held in biomass, soils,

52   slash, and wood products (MgC/ha/yr) as a result of LULUCF.

53   2.1. Changes in land use (rates of conversion (ha/yr) and rates of wood harvest (m3/yr))

54   In keeping with data from FAOSTAT, we considered four major types of land use: croplands,

55   pastures, forests, and other lands. The areas in "other lands" were estimated as the difference

56   between total country land area and the combined areas of forests, crops and pastures. We also

57   considered forest management (i.e., harvest of industrial and fuel wood). In the United States we

58   considered changes in fire management.

59   We reconstructed historical changes in land use starting with the most recent information and

60   working backwards in time. From 1990-2020 we used data from the FAO (Faostat, 2021; Fra,

61   2020) to define national areas in forests, croplands, and pastures. From 1961 to 1990 we used

62   data from FAOSTAT for croplands and pastures. Before 1961 (for crops and pastures) and

63   before 1989 (for forests) we used national statistics or the literature where available to quantify

64   areas in different types of land use. In the absence of such information, we extrapolated rates of

65   change into the past in proportion to population growth (Houghton and Nassikas, 2017).

66   The areas in croplands are better documented through history than other land uses. Areas in

67   pastures or grazing lands are less consistently defined, in large part because many lands that are

68 grazed (rangelands) are not pasture. We assumed, conservatively, that pastures were converted

69 from natural grasslands unless data suggested they were converted from forests. Sometimes it

70 was clear from data in FAOSTAT that new pastures came from forests.

71 With few exceptions (United States, Europe, South and Southeast Asia), national areas of forest

72 are not well documented historically. Thus, we generally reconstructed or extrapolated historical

73 changes in forest areas backwards from the oldest available data into the past. We started the

74 model in 1700 but report emissions only after 1850 to avoid artificial emissions resulting from

75 spin-up of the model (i.e., time lags associated with buildup of decay pools and forest age

76 classes).

77   2.2. Changes in the carbon content of terrestrial ecosystems (MgC/ha/yr)

78 We generally used the data from Houghton and Nassikas (2017) to assign to the model changes

79 in carbon density (MgC ha^{-1} yr^{-1} in vegetation and soils) that follow a change in land use or wood

80 harvest. The starting (1700) biomass and soil carbon densities for ecosystems or ecozones were

81 also the same as those used by Houghton and Nassikas (2017).

82   2.3. Updates included in this work

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

84   1. Improved calculation of carbon emissions from wood harvest.

85   2. Updated and revised input to accommodate new data from FRA2020/FAOSTAT 2021

86   (this step included some historical adjustments as well)

87   3. Treated the apparent conversion of forests to other lands with three alternative

88   assumptions. We also estimated the historical trajectory of this conversion so that there

89   was not an abrupt change in 1990 when FAO data on forest area first became available

90   (Fra, 1990).

91   4. Included other effects of management (peat drainage and burning in Southeast Asia and

92   northern lands)

93 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

123 FAOSTAT were similar to those used by Houghton and Nassikas (2017). For 15 other countries

124 we adjusted pasture areas (mostly) to accommodate a discontinuity in FAOSTAT data in 199

2.3.3. Alternative interpretations of forest conversion to other lands

126 Annual estimates of national areas in croplands, pastures, and forests from the FAO have been

127 used for nearly 40 years to infer net changes in land use and, thereby, to calculate annual

128 emissions of carbon associated with those changes (Houghton et al., 1983). The approach is

129 based on documented changes in carbon stocks (vegetation and soils) that follow the conversion

130 of native ecosystems to agricultural lands. However, the three classes of land use (croplands,

131 pastures, and forests) do not account for all land areas, and a fourth class, other land, has been

132 used by the FAO to insure that the total area in all four classes adds up to a country's total land

133 are Other lands include any lands that are not classified as cropland, pasture, or forest. They

134 can include un-grazed grasslands, shrublands, and deserts as well as anthropogenic lands, such as

135 urban lands, degraded lands, and anything else that does not match the definitions of croplands,

136 pastures, and forests. The challenge is to determine how changes in the area of these other lands

137 affect the amount of carbon stored on land. For example, if the area of forest is reduced one year,

138 and the areas of croplands, pastures, and other lands all increase, what were the changes in

139 carbon that resulted from the conversion of forests to other lands?

140 Clearly, the changes in area determined with this approach are net changes; the gross changes

141 might be quite different. For example, forests might be converted to croplands, and an equivalent

142 area of croplands might be abandoned to other land, yielding a net loss of forest, a net gain in

143 other land, and no net change in cropland area. More complicated conversions can be easily

144 imagined for any combination of net changes in area. Our use of net changes represented the

145 simplest interpretation for conversions among the four cover types

146 The question is What are the new densities of carbon in the vegetation and soils of other lands

147 generated by deforestation We explored the effects of three different interpretations this

148 apparent forest conversion to other land. In one case we assumed that the conversion represented

149 *degraded land* i.e., low carbon stocks. We assumed that forests were converted to new

150 permanent croplands, while worn-out, degraded croplands were abandoned yet did not recover to

151 forest Instead, they remained with low densities of carbon in vegetation and soils (i.e.,

152 degraded). In this interpretation there is a net loss of forest area, perhaps no change in cropland
153 area, and an increase in other (degraded) land area.

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

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

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

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

180   Second, the rates obtained from FRA2020 for the period 1990-2020 were extrapolated

181   backwards to 1980. We compared the resulting area of FCO in 1980 with a country's total area

182   in the fallow of shifting cultivation in 1980 (Fao/Unep, 1981). In many countries our estimate of

183   FCO was large enough to accommodate the FAO/UNEP's area of fallow. But in other tropical

184   countries the 1980 estimate of fallow area was larger than the area we found in FCO. In these

185   cases, we lowered the fallow area given by (Fao/Unep, 1981) to match the land area we

186   categorized as FCO. FCO was constrained by the changes in forests, croplands, and pastures,

187   and, thus, could not be increased. With this approach we obtained a fallow area of 277 x 10^6 ha

188   in 1980, somewhat more than half of the (Fao/Unep, 1981) estimate of 456 x 10^6 ha, but within

189   the range from previous studies (260 to 450 million ha (Silva et al., 2011; Van Vliet et al., 2012;

190   Heinimann et al., 2017; Fao/Unep, 1981; Lanly, 1982).

191   Annual increases (or decreases) in FCO between 1990 and 2020 were determined from annual

192   increases (or decreases) in the conversion of forest to other land. A decrease in FCO represented

193   an increase in forest area that did not come from croplands or pastures (Faostat, 2021). As

194   discussed above, these data refer only to net changes in land use. The gross changes are likely

195   higher and involve any combination of conversions among forest, cropland, pasture, and other

196   land areas.

197   Finally, we extrapolated the observed rate of change between 1980 and 1990 back to 1945, and

198   then at a declining rate back to 1700. A more reliable reconstruction is difficult because the areas

199   are not well known. A greater number of people might be supported either by a larger area in

200   shifting cultivation or by a shortened the length of fallow; but neither of these variables is known

201   for most regions (Ickowitz, 2006). We used the qualitative estimates of experts (in Heinimann et

202   al. (2017)) to help define whether shifting cultivation was increasing or decreasing before 1970.

203   Shifting cultivation is a special case of cropland, where, first, tree cover is present and, second,

204   the time in fallow is longer than the time in crop. Typical fallow lengths are 2 to 25 years

205   (Snedaker and Gamble, 1969; Harris, 1972; Betts et al., 2004; Turner et al., 1977) long enough

206   for trees/forests to partially recover and accumulate carbon before the land is cleared again for

207   cropping. We used fallow lengths between 2 and 15 years, including the cropping that occurs in

208   the first few years of each cycle.

209 Our definition of shifting cultivation is broad and includes more than traditional shifting

210 cultivation refers to the repeated use of forests for temporary agriculture. Shifting cultivation,

211 or swidden, was the most prevalent type of agriculture in the tropics as recently as the 1970s

212 (Van Vliet et al., 2012). At present the area of shifting cultivation is increasing in some regions,

213 and decreasing or remaining stable in others (Van Vliet et al., 2012). Changes in both directions

214 may occur within a single country (Heinimann et al., 2017)

2.3.4. The draining and burning of peatlands

216 Because our bookkeeping model does not calculate the changes in peatland soils from the use,

217 draining, and burning of peat, we used published estimates to supplement the fluxes calculated

218 here. In the tropics we used the emissions from burning peatlands reported in GFED-4, and the

219 emissions from draining peatlands reported by Hooijer et al. (2010). The approach was the same

220 as reported by Houghton and Nassikas (2017)

221 Outside the tropics we used the estimates of carbon loss from peatland use and draining reported

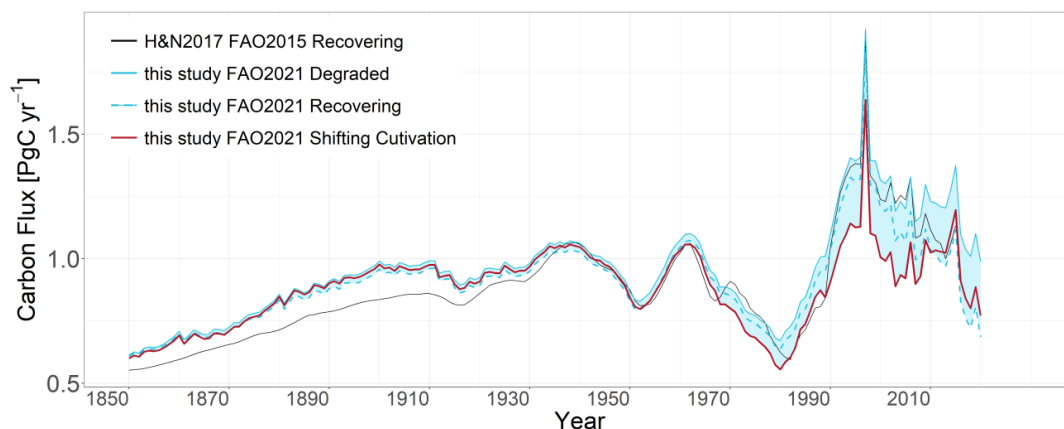
222 recently by Qiu et al. (2021)

3. Results

224 Because of offsetting effects of these model ~~improvement~~ and revisions to data, the net global

225 emissions of carbon from changes in land use over the period 1850-2020 appear generally

226 similar to the results presented five years ago (Houghton and Nassikas, 2017)(Fig. 1) (Table 1).

227 Below, we present the results of the four steps outlined in the Methods (Table 1).

228

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

233 Table 1: Total net emissions from LULUCF for the globe, the non-tropics and the tropics for the
234 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

235

236 3.1.Adjustments to the bookkeeping model for wood harvest

237 Adjustments to the code to account for (1) the fraction of harvest that becomes slash instead of

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

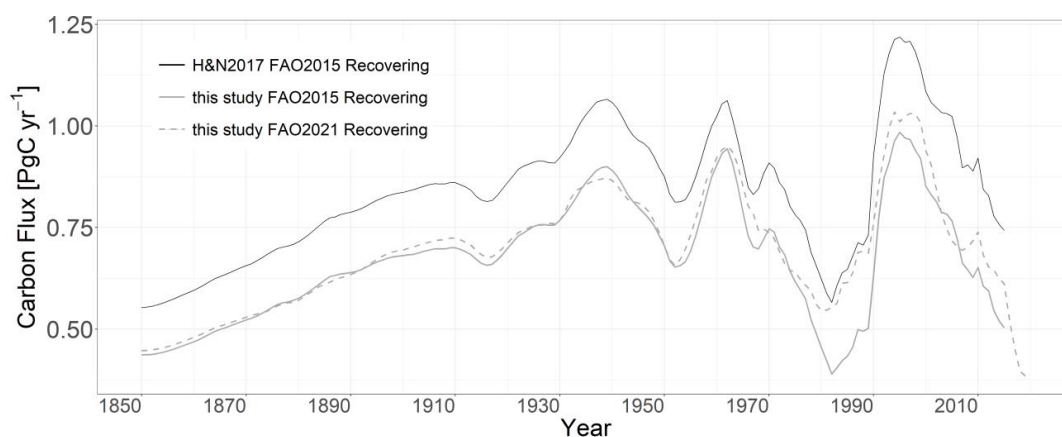
239   harvested wood as primary forests had offsetting effects, but together the adjustments led to

240   lower emissions (Fig. 2). Accounting for slash increased the emissions from harvest, but

241   harvesting secondary forests had a greater effect on increasing the area of secondary forests and,

242   thereby, the gross sinks. The adjustments lowered the net flux throughout the period 1850-2015:

243   111.4 PgC after adjustment, compared to the original total of 139.1 PgC (not counting peat

244   emissions) (Houghton and Nassikas, 2017)(Table 1).

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246   Figure 2. Annual net emissions of carbon from LULUCF. Gray line: improvements to model in

247   this analysis. Dashed gray line: updated data from FAOSTAT2021. Black line: Houghton and

248   Nassikas (2017). All analyses are based on the "recovering" analysis for comparison.

249   3.2. Incorporation of new data from the FAO

250   Use of the new data from FAO (Faostat, 2021; Fra, 2020) increased the estimated net emissions

251   little: from 111.4 Pg to 115.9 PgC for the period 1850-2015 (Table 1). The addition of the last 5

252   years added another 2.1 PgC to this total (118.0 PgC 1850-2020, not counting emissions from

253   peatlands. The greatest impact from revisions to data in FAO2021 occurred in the tropics,

254   increasing net emissions during 1980s-1990s and lowering them after 2015 (Fig. 2).

255   3.3. Alternative interpretations of the conversion of forest to other land

256   As discussed above, the annual loss of forest area in many tropical countries exceeded the gain in

257   croplands and pastures and resulted in a gain in "other land" area (Faostat, 2021). We called this

258   gain "forests converted to other land" (FCO) to distinguish it from the FAO's category "other

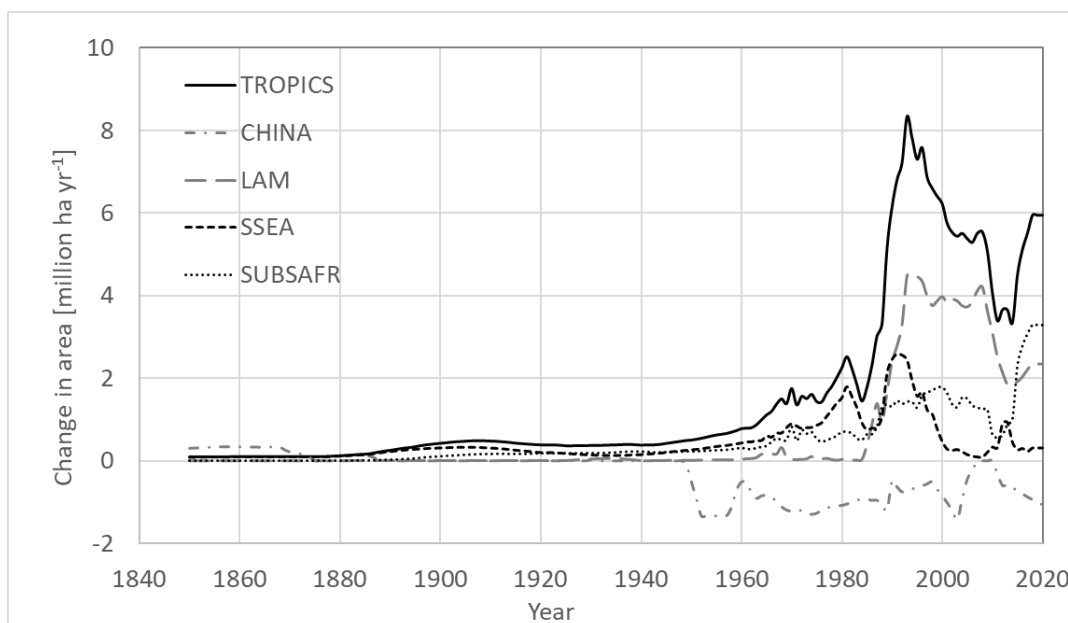
259   land". We calculated the emissions for three alternative interpretations of this new other land: (1)

260   degraded land, (2) recovering forest, and (3) shifting cultivation, including fallow.

261   The area involved was large. If all conversions of tropical forests to other lands were assumed to

262   be for shifting cultivation, the area was 450 million ha in 2020, up from 239 million ha in 1850

263   according to our assumptions. The highest rates of conversion to these other lands were in the

264   1990s (Fig. 3).

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

268   The qualitative results from the three alternatives were as expected if run to equilibrium. Forests

269   converted to degraded lands emitted the most carbon, while those that returned to forests

270   generally emitted the least. However, because of the 15-year delay in the "recovering"

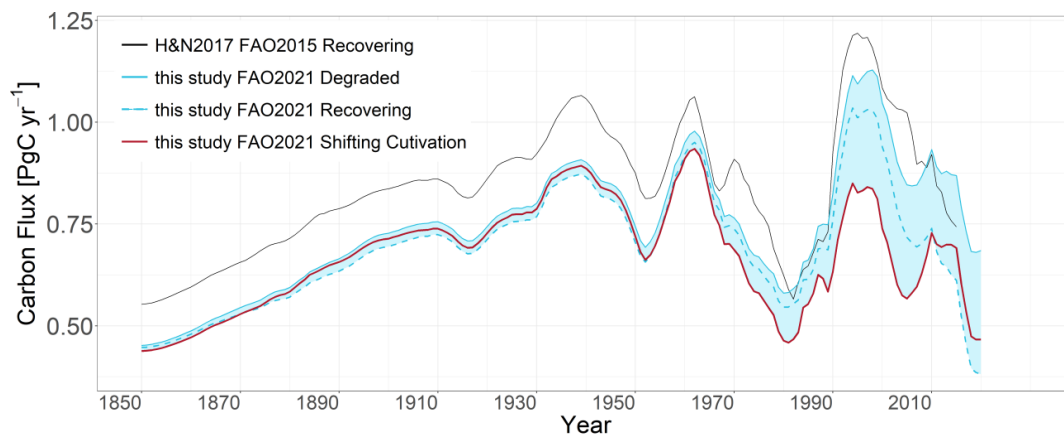
271   interpretation, the ranking of the recovering and shifting cultivation interpretations varied over

272   time (Fig. 4) (Table 1). For example, when the rate of "FCO" was increasing (1950-2010),

273   emissions from shifting cultivation were lowest; while during more constant conditions, the

274   expected ranking held. Total emissions 1850-2015 were 123.4, 115.1, and 112.5 Pg C for

275   degraded, recovering, and shifting cultivation interpretations, respectively (Table 1). To 2020,

276   total emissions from FCO were higher (127.0, 118.0, 115.1 Pg C, respectively).

277

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

280   If the current rates of deforestation for new other land were to continue until the emissions

281   reached a steady state, the three interpretations (counting no other uses of land) would yield

282   emissions of 0.789, 0.126, 0.537 PgC yr^{-1} for degraded lands, recovering forests, and shifting

283   cultivation, respectively. Thus, not only are the emissions from this conversion large, but the

284   uncertainty is large as well.

285

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

[PgC yr⁻¹]		based on FAOSTAT2021			peat - 2020
		this study degraded	**this study** recovering	**this study** shifting cultivation	
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		-0.073		0.020
EUROPE	2011-2020		-0.094		0.014
CHINA	2011-2020	-0.021	-0.010	-0.025	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

288

289 3.4. The draining and burning of peatlands

290 Over the 170-year period 1850-2020 the emissions from use of peatlands added 7.6 Pg to

291 emissions from countries in Southeast Asia and 28.5 PgC to countries in the northern mid-

292 latitudes (Qiu et al., 2021 Table 1) (Fig. 5). The emissions from northern peatlands were not

293 included in Houghton and Nassikas (2017), and including them here largely offset the lowered

294 emissions that resulted from improvements in the model's simulation of wood harvest (Fig. 2)

295 (Table 1).

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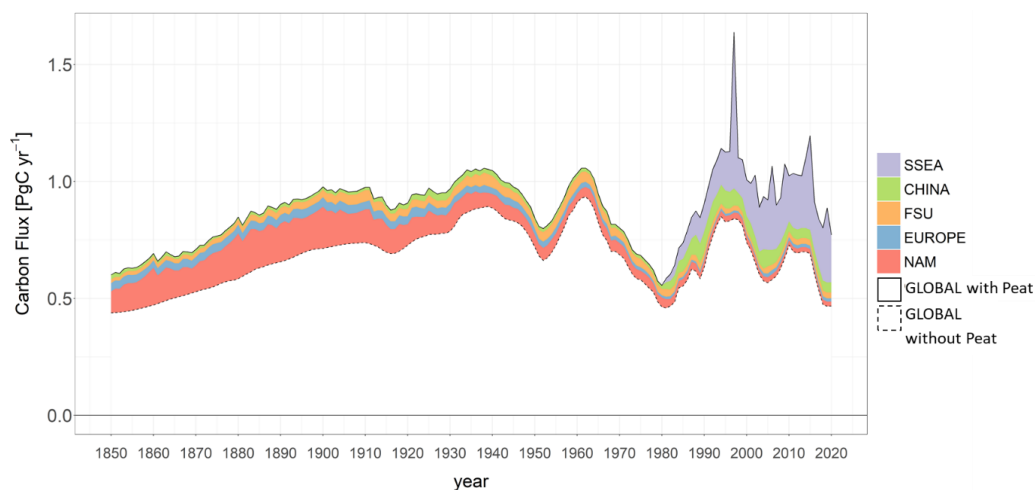
Figure 5. Annual emissions of carbon from use of peatlands, shown here above the annual net
emissions from the shifting cultivation alternative.

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.

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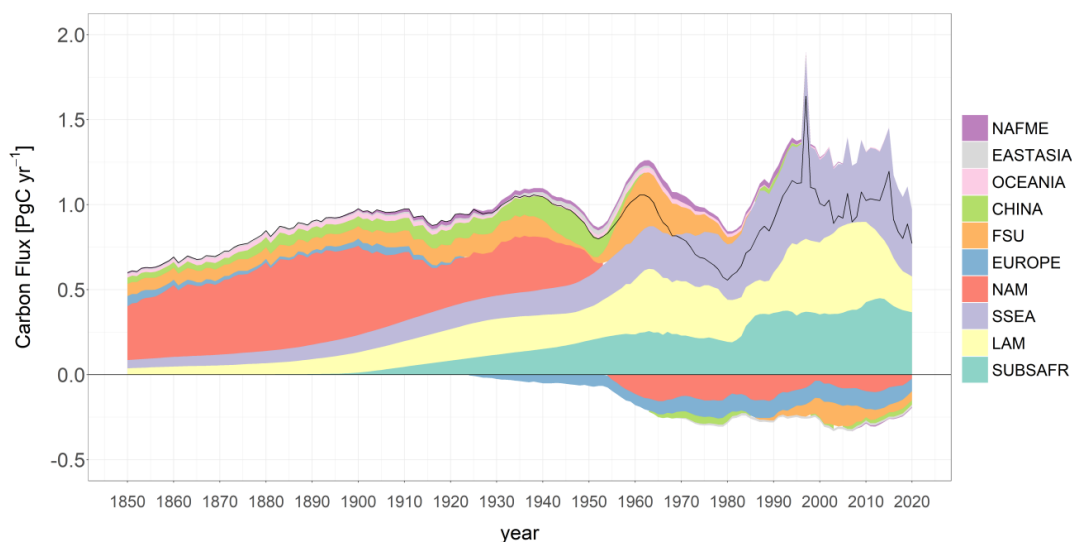


Figure 6. Net annual emissions of carbon from regions. The black line represents the global net
annual emissions.

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.

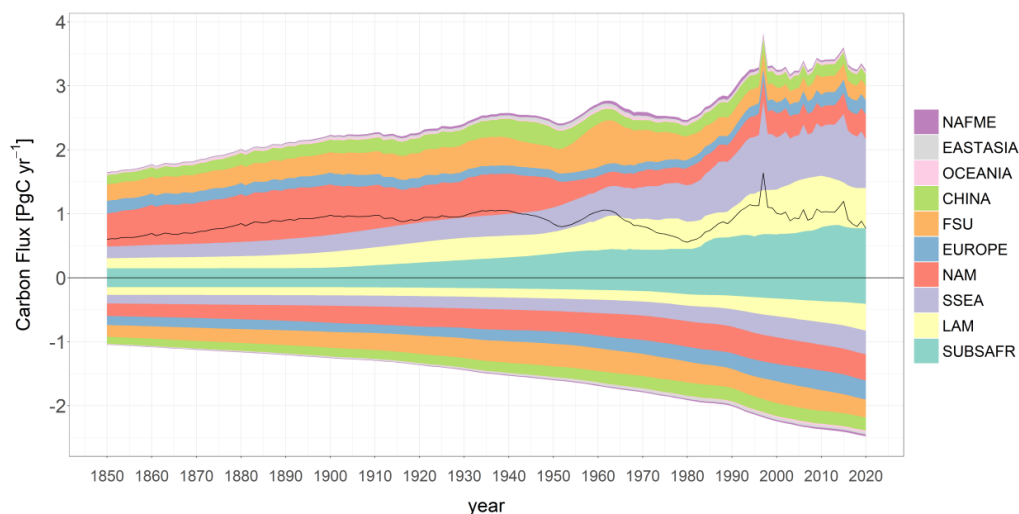
The offset is not simultaneous, however, and has implications for mitigation. Because most
emissions happen rapidly, while most removals occur over a longer time, a reduction in shifting
cultivation or wood harvest would result in a rapid reduction in (gross) emissions, while the
(gross) removals (in 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

331 discussed above, actual gross emissions and removals are larger than estimated here because

332 rates of land-use change are based on *net* changes in area as reported by FAOSTAT.

333 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
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
Non Tropics 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

334

335

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

337 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.

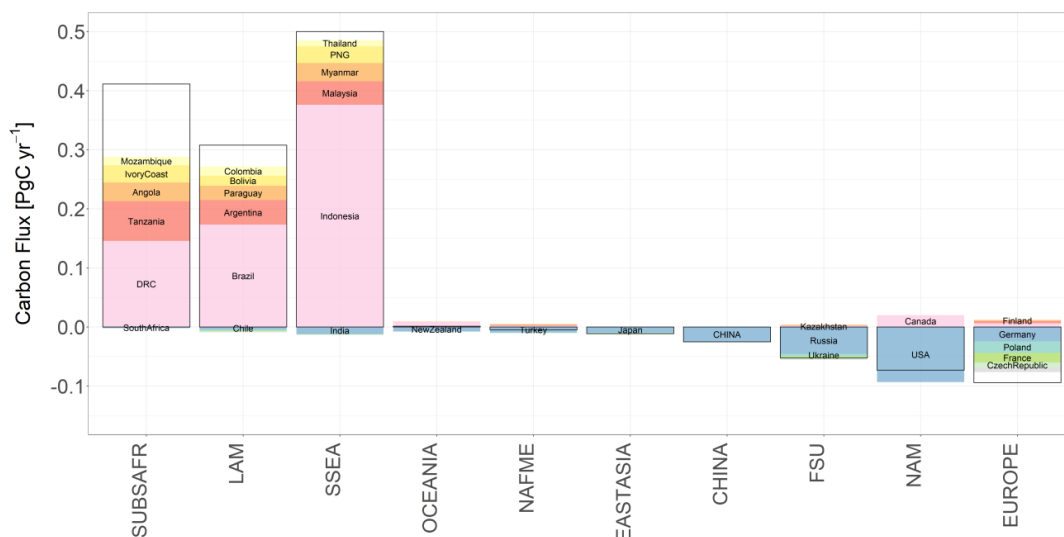



Figure 8. Regions and countries with the largest net annual emissions and removals, including emissions from use of peatlands (average for 2011-2020). The white portions of the columns represent the contribution of all other countries in the corresponding regions.

3.5.2. Emissions by land use

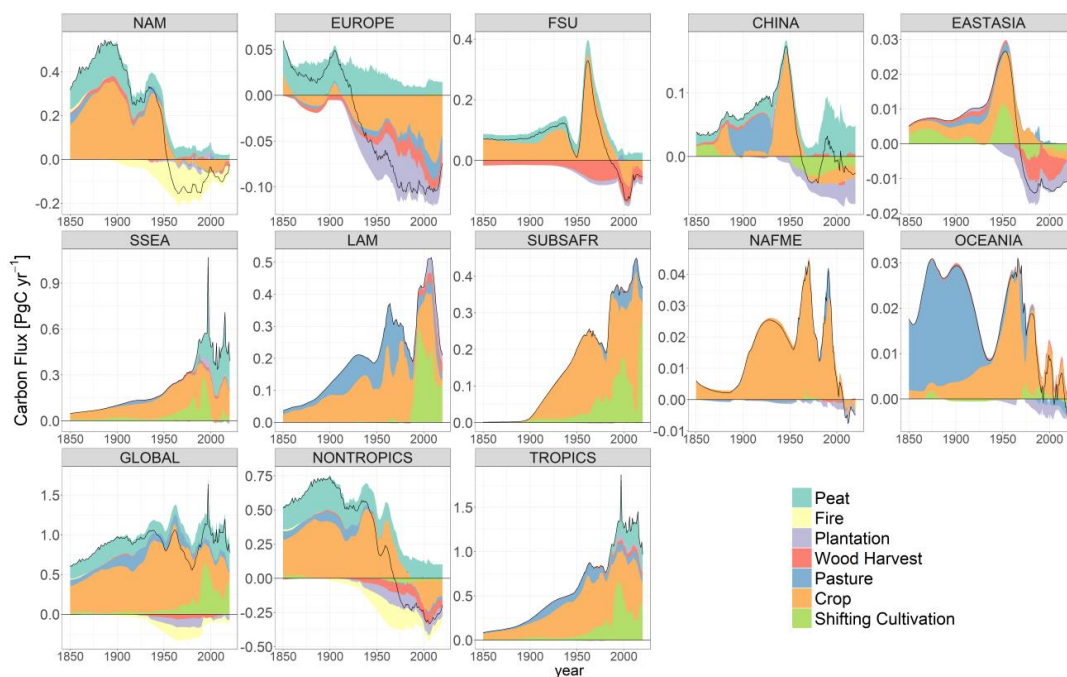
Land uses with the greatest emissions or removals of carbon varied among regions and over time (Fig. 9). The expansion of croplands generally accounted for the greatest emissions everywhere except in Oceania where pastures were the dominant source of carbon before 1950. Shifting cultivation was greatest in the three largely tropical regions. Emissions from the use of peatlands

356   were most noticeable, historically, in North America and Europe and, more recently, in South

357   and Southeast Asia and China. Removals of carbon resulting from agricultural abandonment,

358   establishment of tree plantations, and declining rates of harvest were dominant in Europe, FSU,

359   China, and North America (-0.108, -0.077, -0.068, -0.109 PgC yr^{-1} in the last 10 years) (Table 4).

360   The net US sink was -0.109 PgC yr^{-1} when the history of fire suppression was included.

361

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

363

364   Table 4. Annual net emissions by land use by region, averaged over the last decade (2011-
365   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

366   ### 3.5.3.   Emissions by carbon pool

367   The annual net flux of 0.960 PgC yr^{-1} to the atmosphere for the period 2011-2020 was composed

368   of gross emissions of 3.380 PgC yr^{-1} from burning of live vegetation, decay of dead vegetation,

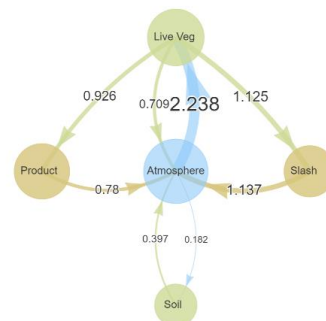
369   oxidation of wood products, and soil as a result of cultivation, including peatland emissions; and

370   gross removals of -2.420 PgC yr^{-1} by vegetation and soil recovering from wood harvest and

371   agricultural abandonment (Table 5).

372   Table 5. Annual emissions (+) and removals (-) of carbon by ecosystem component 2011-2020
373   (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

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

378   The annual transfers of carbon among pools for the period 2011-2020 are shown in (Fig. 10). By

379   far the largest flux was from the atmosphere to growing vegetation (2.238 PgC yr^{-1}). As

380   discussed above, this gross removal of carbon by growing forests will continue for many decades

381   even if emissions are reduced through management. Hence, the potential for mitigation is

382   significant as long as changes in climate do not affect rates of regrowth. Fluxes half that

383   magnitude were into and out of slash each year, and smaller still were the flows into and out of

384   wood products.

385   It is unclear whether the emissions of carbon from peatlands in northern regions were from

386   forests or not. Ignoring peatlands, global forests accounted for nearly all emissions (99%) for the

387   decade 2011-2020. Emissions from peatlands were 37% of the total global net flux, and some of

388   those emissions were probably from forested lands, as well.

389   **4. Discussion**

390   We limit the discussion, below, to three general topics. First, how can we reconcile reduced

391   emissions of carbon from LULUCF in the tropics with increased rates of deforestation widely

392   reported (Wiltshire et al., 2022; Van Marle et al., 2022; Feng et al., 2022; Prodes, 2021). Second,

393   what does "forest converted to other land" mean? And, third, how do these new estimates of

394   emissions compare with other recent studies?

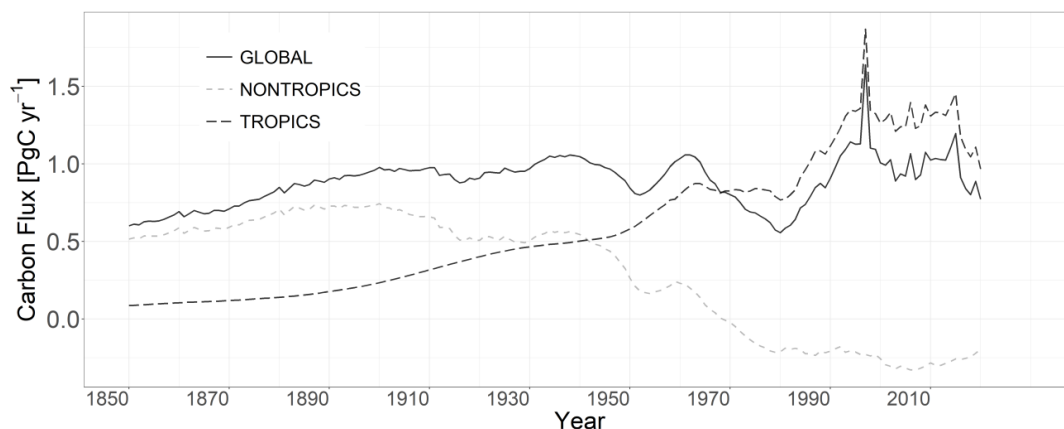
395   4.1. Are emissions from LULUCF in the tropics declining?

396   Perhaps the most surprising result of these revisions and updates was the apparent sharp decline

397   in LULUCF emissions since 2015 (Fig. 11). The decline was even greater for tropical countries

398   than the global decline because countries outside the tropics showed a small reduction in carbon

399   sink; although we note that a recent analysis of land use in China found a larger sink in recent

400   decades than reported here (Yu, in press)).

401
402   Figure 11. Net annual emissions of carbon from LULUCF for the globe, tropical regions, and
403   non-tropical regions.

404   The decline in emissions reported here over the last decade is consistent with other bookkeeping

405   models used by the Global Carbon Project (Carbonbrief, 2021), but more precipitous. The

406   decline in tropical emissions was new in the 2020 GCP budget (Friedlingstein et al., 2022) and

407   represented a notable revision to global emissions (Carbonbrief, 2021). The emissions from the

408   bookkeeping models BLUE (Hansis et al., 2015) and OSCAR (Gasser et al., 2020) were based

409   on land-use data from HYDE (History Database of the global Environment) (Klein Goldewijk et

410   al., 2017), which are semi-independent of the data reconstructed here. That is, all the land-use

411   data used in the three analyses were based on rates of land-use change from FAOSTAT, but the

412   data sets varied in their mapping of those changes. (See Kondo et al. (2022), for a more detailed

413   example of differences among data sets for Southeast Asia.).

414   In contrast to the declining emissions driven by FAO data, Feng et al. (2022), using high-

415   resolution satellite data to document changes in forest area in the tropics, reported a near

416   doubling of emissions between 2001-2005 (average emissions of 0.97 PgC yr^{-1}) and 2015-2019

417   (1.99 PgC yr^{-1}), respectively. Their estimates were based on committed emissions; that is,

418   assuming all the carbon lost from vegetation and soils was released to the atmosphere at the time

419   of deforestation. When we calculated emissions similarly (gross emissions from deforestation

420   alone), our estimates were 1.9 and 1.8 PgC yr^{-1} for the same intervals. Our estimates and those of

421   Feng et al. (2022) were similar for the period 2015-2019 and very different for the first period.

422   Did Feng et al. (2022) underestimate deforestation rates and emissions in the earlier period, or

423   did FAO overestimate deforestation then? Including shifting cultivation and emissions from peat

424   increased our estimated gross emissions from the tropics to about 2.4 PgC yr^{-1} for both interval

425   None of our simulations showed the increase in emissions that Feng et al. (2022) did.

426   Interestingly, although not evident from the 2015-2019 mean, Feng et al. (2022) show a

427   reduction in rates of forest loss after 2016, similar to the pattern reported by FAOSTAT202

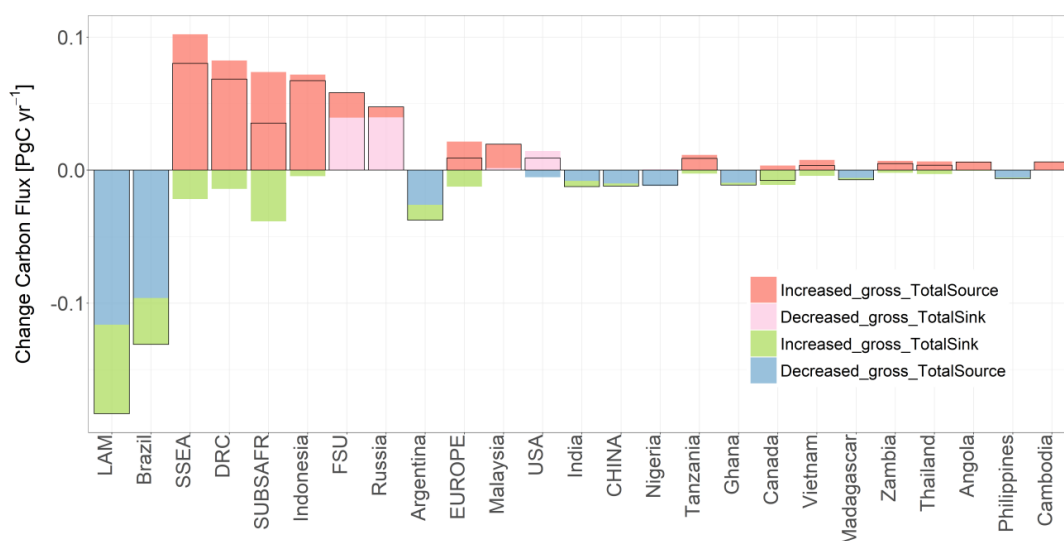
428   Furthermore, despite the absolute differences, our analysis and that of Feng et al. (2022) were

429   qualitatively similar in identifying the regions and countries with declining and increasing rates

430   of deforestation. In both studies, emissions were increasing in Africa and Southeast Asia and

431   declining in Latin America (Fig. 12). In our analysis, the recent decline in emissions was led by

432   Brazil and Argentina. An analysis comparing changes between 2001-2005 and 2015-2019 did

433   not change the results appreciably from those shown in Fig. 12.

434

435   Figure 12. Changes in the sources and sinks of carbon between the first and second decades of

436   the 21st century. Changes in the net source/sink are shown by black horizontal lines. Negative

437   values indicate reduced emissions in second decade.

438   *Why do tropical deforestation rates reported by FRA2020 (Fra, 2020) and* Feng et al. (2022)

439   *differ?* Many countries do not have the means to measure changes in forest area, and thus rates of

440   deforestation may be out of date. Even Brazil, which may be unique in its ability to monitor

441   deforestation, may underreport recent rates of deforestation. Amazonia rates of deforestation

442 declined greatly between 2004 and 2012 but seem to have been increasing since 2014 (Wiltshire

443 et al., 2022). In contrast, FAO estimates of deforestation for all Brazil show a pattern similar to

444 Legal Amazonia but with no increase after 2014 (Fra, 2015, 2020) .Thus, the FAO may lag

445 somewhat in reporting the uptick in deforestation for Amazonia and Brazil

446 The lag may result from the uncertain fate of deforested lands. In Amazonia, for example, forests

447 may be burned years before they show up on the books as cattle pasture or cropland. We note

448 that this time lag may explain the nearly constant rates of deforestation reported in recent years

449 by FAO. The lag could also explain an increase in "other land" in FAOSTAT, suggesting that

450 new agricultural lands may account for the emissions and not shifting cultivation, as assumed

451 here

452

453 Overall, deforestation rates in Brazil have not fallen as sharply as reported by FAOSTAT, and

454 perhaps they have increased in recent years. Thus, emissions may not have declined as sharply as

455 calculated in this study. However, the regions showing the greatest increases in emissions,

456 according to Feng et al. (2022), were Africa and Southeast Asia, not Latin America. Thus, Feng

457 et al. (2022) are most different from FAOSTAT2021 in Africa and Southeast Asia. If Feng et al.

458 (2022) are correct, the decline in tropical emissions reported by all bookkeeping models would

459 seem to be wrong. On the other hand, it may be that the analysis by Feng et al. (2022) is flawed

460 (Hansen, 2022). The disagreement is a major uncertainty.

461 However, the possibility exists that both studies are correct, and that the disagreement can be

462 explained by definitional and methodological issues.

463 *Are changes in land cover anthropogenic?* One possible explanation is to recognize that some

464 deforestation is not directly anthropogenic, not a part of LULUCF, but rather a consequence of

465 indirect effects (e.g., changes in climate, fires, storms) (Gatti et al., 2021). If Feng et al. (2022)

466 counted all deforestation, while FAOSTAT counted only anthropogenic deforestation, the

467 difference might represent environmental effects. For example, Aragão et al. (2018) found that

468 the emissions from deforestation in Brazilian Amazonia were declining while the emissions from

469 drought-related fires were increasing. The authors reported this finding despite the observation

470 that many fires in Amazonia are arguably the direct effect of human activities (deliberate burning

471   to clear forests) and, thus, part of LULUCF. Is the difference between Feng et al. (2022) and

472   FAOSTAT explained by an increase in environmentally-driven disturbance?

473   The broader issue is whether changes in land *cover* are anthropogenic or not. If they are not

474   directly anthropogenic, but rather driven by climate change, for example, then Land-Use and

475   *Land-Cover Change* (LULCC) is different from Land Use, Land-Use Change, and Forestry

476   (LULUCF). The terms are generally used interchangeably but perhaps ought not to be. LULCC

477   includes land-cover change; LULUCF does not. We previously attributed the calculated fluxes to

478   LULCC (Houghton et al., 2012; Houghton and Nassikas, 2017), but the more precise attribution

479   is LULUCF because we focus on direct anthropogenic effects exclusively (clearing, planting,

480   cultivating, harvesting) and do not assume that changes in land cover are necessarily

481   anthropogenic. Examples of non-anthropogenic changes in land cover include droughts,

482   wildfires, storms, natural disturbances. The issue is whether a change in land cover represents

483   direct anthropogenic activity or is, instead, attributable to indirect (environmental) effects (Grassi

484   et al., 2018). Globally, indirect effects are responsible for a land sink that is larger than the net

485   emissions from management. But Amazonia may be an example where indirect effects are

486   leading to additional emissions instead of, or as well as, sinks of carbon. The possibility would

487   help explain why the global land sink seems to have shifted from the tropics to boreal regions

488   after the 1980s (Ciais et al., 2019).

489   *Deforestation versus forest loss.* Another possible explanation for declining emissions despite

490   increasing deforestation is related to the definition of deforestation. FAOSTAT defines

491   deforestation as the conversion of forest to another land use, i.e., cropland, pasture, or other land.

492   The temporary loss of forests as a result of harvests, fire, or other disturbances, even if directly

493   anthropogenic, is not deforestation because the disturbed forest is expected to recover. The land

494   is still defined as forest even if it is temporarily without trees. Some estimates of deforestation,

495   particularly those from satellite data, may include temporary losses of forest resulting from

496   disturbance. Such estimates of deforestation would be higher than those reported by the

497   FAOSTAT and used here to calculate emissions.

498   *Re-clearing of fallows already in shifting cultivation.* A third possible explanation for declining

499   emissions despite increasing deforestation rates is that the re-clearing of fallows in shifting

500   cultivation may be attributed to deforestation. The term deforestation is appropriate the first time

501   a forest is converted to shifting cultivation, but subsequent re-clearing of fallow is not (unless the

502   recovery of forest in the fallows is identified as an increase in forest area). Even the cropped

503   areas of shifting cultivation have tree cover and may be mistakenly identified as forest. Older

504   fallows are even more forest-like, although perhaps recognizable as degraded forest.

505   According to our analysis, the area in shifting cultivation was 450 x 10^6 ha in 2020. More

506   importantly, the annual re-clearing of these lands was 25.7 x 10^6 ha in 2020. This rate is large in

507   comparison to tropical deforestation rates of 10 x 10^6 ha reported by the FAO (Fra, 2020;

508   Faostat, 2021). If only a small fraction of re-clearing is counted as deforestation, it would inflate

509   the rate reported.

510   If any of these three possible explanations is correct, the net effect is to overestimate

511   anthropogenic emissions and, thereby, overestimate the (non-anthropogenic) land sink as well (if

512   the land sink is determined from the global carbon budget). Such a mistaken attribution could

513   mask a declining land sink. Indeed, declining emissions, given a generally constant airborne

514   fraction, suggest that land and/or ocean sinks are declining (Van Marle et al., 2022).

515   Overall, one would expect satellite-based changes in land use to be more accurate than changes

516   reported to the FAO by individual countries using varied methods for determining change. Sadly,

517   however, if the distinctions described above account for the divergent trends between rates of

518   deforestation and reported emissions, then data from satellites may not provide an easy

519   resolution. Anthropogenic versus non-anthropogenic disturbances are difficult to distinguish with

520   any kind of measurement, and the fate (both land use and carbon density) of disturbed lands may

521   remain uncertain for years following a disturbance. The recent disagreement between satellite-

522   based and ground-based rates of wood harvest in Europe provides another recent example of the

523   limitations of satellite-based measures of land-use change (Palahí et al., 2021; Ceccherini et al.,

524   2020; Picard et al., 2021; Wernick et al., 2021).

525   ## 4.2. Forests converted to other lands

526   In the discussion below we compare our estimates of area under shifting cultivation with other

527   estimates. We also discuss the importance of shifting cultivation for gross emissions of carbon

528   and, finally, whether emissions of carbon from shifting cultivation should be attributed to forest

529   degradation or to deforestation

530   Trends in the area of shifting cultivation are uncertain (Van Vliet et al., 2012; Heinimann et al.,

531   2017). Van Vliet et al. (2012) found that the area of shifting cultivation was declining in 55% of

532   their case studies, while the other 45% showed either an increase or no change in area. Where the

533   areas of shifting cultivation were declining, they were most often being converted to permanent

534   croplands rather than being allowed to return to forest. Curtis et al. (2018) found that shifting

535   agriculture accounted for as much temporary loss of forest cover, globally, as fire and logging.

536   Regionally, it was sometimes a dominant cause of forest cover loss. For example Samndong et

537   al. (2018) found shifting cultivation to have been the main cause of deforestation in the

538   Democratic Repubic of Congo (DRC). In contrast, De Sy et al. (2015) found that shifting

539   cultivation was a minor contributor to deforestation in South America, and Fantini et al. (2017)

540   reported the end of swidden-fallow agriculture within the Brazilian Atlantic rainforest.

541   As an alternative approach to evaluating changes in shifting cultivation, we used changes in

542   "other land" reported by FAOSTAT. The rate at which forests were converted to other lands

543   (FAOSTAT, 2021) increased in Latin America and Africa but declined in tropical Asia (Fig. 3).

544   In China the area in other lands actually declined. An alternative explanation for the apparent

545   conversion of forests to other lands (FCO) is that the fate of forest loss is unknown when it

546   occurs and temporarily assigned to other land. Only later is it assigned to cropland, pasture, or

547   forest. The subsequent revision of other land to one of these other land uses would reduce the

548   emissions we attribute to shifting cultivation, but our alternative interpretations regarding forest

549   conversion to other lands should include the range of possible emissions (Fig. 4). Nevertheless,

550   the uncertainty remains, affecting both rates of land-use change and emissions of carbon. For

551   example, in the last 10 years the "degradation" interpretation emitted about 0.260 PgC yr^{-1} more

552   than the "recovery "interpretation, a difference that was greater than the annual emissions from

553   any country except Indonesia. The unknown fate of FCO lands (degraded, recovering or shifting

554   cultivation) introduced an uncertainty of about 13% in global net emission from LULUCF. If the

555   emissions from peatlands are ignored, the uncertainty for FCO was about 20% of global net

556   emission

557   If we assume that the apparent conversion of forests to other lands (FCO) was driven entirely by

558   the expansion of shifting cultivation, and that fallows are counted as "other land", then we

559   calculate the total area in shifting cultivation to have been 277 x 10^6 ha in 1980 and 450 x 10^6 ha

560   in 2020. These estimates are probably high because we assumed in this calculation that all of the

561   increase in other lands was attributable to shifting cultivation rather than to degraded lands or

562   forests. By comparison, a recent analysis and review by Heinimann et al. (2017), based in part on

563   satellite data for the period 2000-2014, estimated an area of 260 x 10^6 ha in shifting cultivation.

564   As those authors acknowledge, however, the area is uncertain. Previous estimates have ranged

565   between 260 and 450 million ha (Silva et al., 2011; Van Vliet et al., 2012; Heinimann et al.,

566   2017; Fao/Unep, 1981; Lanly, 1982).

567   4.2.1.   Gross emissions and removals

568   The greatest difference between shifting cultivation and the two other interpretations of tropical

569   forest loss is the effect they have on gross fluxes of carbon. Aside from wood harvest and

570   agricultural abandonment, both of which include forest recovery, there are few other land uses

571   that generate gross fluxes of carbon. Shifting cultivation accounted for 30% of the global gross

572   emissions of carbon over the period 2011-2020 in our analysis. Gross emissions and removals

573   for shifting cultivation, alone, were 1.016 and -0.718 PgC yr^{-1} in comparison to total gross

574   emissions and removals were 3.379 and -2.420 PgC yr^{-1}, respectively (Table 3). And these gross

575   fluxes are probably conservative because, as mentioned above, the changes in land use reported

576   by FAOSTAT are *net* changes within a country. If data on gross changes in land use were

577   available, they would presumably yield higher gross fluxes.

578   4.2.2.   Is shifting cultivation deforestation or forest degradation?

579   Estimates of the emissions from degradation vary widely, from nearly zero (Xu et al., 2021) to

580   greater than the emissions from deforestation (Baccini et al., 2017). Xu et al. (2021) reported

581   little degradation, perhaps to avoid double counting it in the other drivers considered: forest

582   clearing, forest fire, and non-forest fire. Baccini et al. (2017) found that degradation accounted

583   for more carbon loss from the tropics than deforestation. Rappaport et al. (2018) reported

584   degradation in Amazonian forests due to fire and logging, but it is unclear whether shifting

585   cultivation was counted in either the fire or the logging data.

586 Aside from issues of measurement, the relative proportions of deforestation and degradation to
587 carbon emissions may depend on where the emissions from shifting cultivation are counted. If
588 the emissions of carbon from shifting cultivation are attributed to deforestation, the relative
589 contributions of deforestation and degradation to the net emissions from the tropics were 68.8%
590 and 4.8%, respectively, for the period 2011-2020 (Fig. 13). The fraction of emissions attributed
591 to neither deforestation nor degradation was largely from burning and draining of peatlands.
592 Most of the degradation, or lowering of biomass, resulted from harvest of wood. But if we
593 include shifting cultivation as forest degradation, arguing that fallows may be identified as
594 forests by some definitions, then the relative contributions were more nearly equal (41.7% and
595 31.9%, for deforestation and degradation respectively), and in some years the emissions from
596 degradation were more than 50% (Fig. 13).

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

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

608

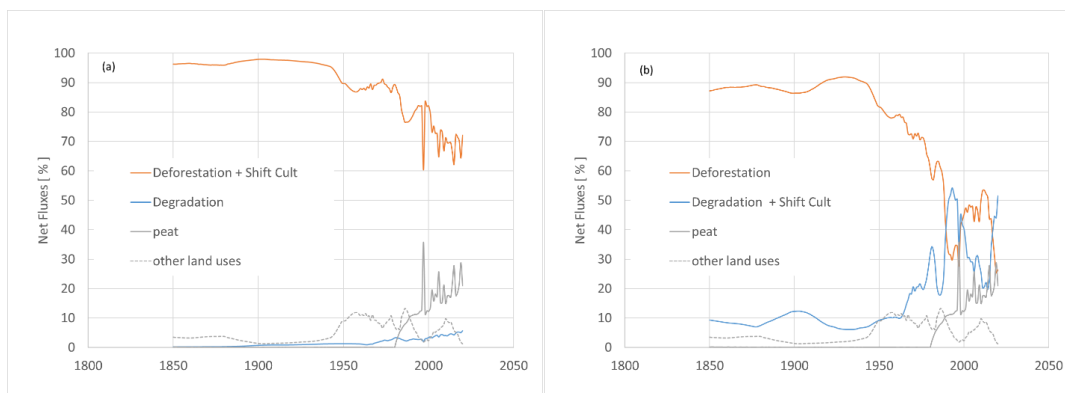



Figure 13. Emissions from deforestation and forest degradation if conversion of forests to
shifting cultivation is deforestation (a) and if conversion of forests to shifting cultivation is
degradation of forests (b). In the latter case, the emissions from degradation and deforestation are
comparable.

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

629 cover that are not directly anthropogenic. That is, the HYDE data set uses LULCC rather than

630 LULUCF to drive deforestation. Other differences may to attributed to different definitions of

631 land use (Pongratz et al., 2014), different data sets (Gasser et al., 2020), as well as different

632 model parameters and assumptions (Bastos et al., 2021). We would add to this list the difference

633 between land use and land cover, discussed above.

634 Overall, the variation in estimates among bookkeeping models is small in comparison to other

635 recent estimates of terrestrial carbon emissions (Harris et al., 2021; Xu et al., 2021; Tubiello et

636 al., 2021) in large part because the latter were based on total changes in forest carbon and not just

637 those changes attributable to LULUCF. These estimates included the effects of both management

638 (LULUCF) *and* environmen while we (and other bookkeeping models) have tried to estimate

639 only the effects of management (i.e., land-use change ecause the total net flux of carbon from

640 terrestrial ecosystems has been a net sink greater than the net emissions from LULUCF,

641 including both processes generates a net sink, rather than a source, globally

642 Second, we considered all ecosystems, not only forests. These non-forests accounted for about

643 4% of net emissions in 2011 and (as a sink) for about 6% of the net emissions in 2020.

644 Third, neither slash, harvested wood products, nor soils were included in the emissions

645 determined by the other studies cited. Their results were based on changes in the biomass and

646 area of forests. Table 5 shows the additional emissions from slash, harvested wood products, and

647 soils. And fourth, the approach reported here considered the delay in emissions from wood

648 products, soil, and dead organic matter, and the delay in removals of carbon in forest growth. In

649 contrast, most recent studies have assumed that observed reductions in aboveground carbon

650 storage are emitted to the atmosphere instantaneously. The differences may be significant if rates

651 of land-use change are increasing or decreasing.

652 **Data availability**

653 Annual emissions of carbon from Land Use, Land-Use Change, and Forestry (LULUCF) as

654 reported in this analysis (Houghton and Castanho, XXXX) are available through Harvard

655 Dataverse ([https://dataverse.harvard.edu/privateurl.xhtml?token=09ee9f75-3b93-4755-8be6-](https://dataverse.harvard.edu/privateurl.xhtml?token=09ee9f75-3b93-4755-8be6-9da7ac06dd60)

656 [9da7ac06dd60](https://dataverse.harvard.edu/privateurl.xhtml?token=09ee9f75-3b93-4755-8be6-9da7ac06dd60), final DOI to be updated during publication process). The tabular data include

657 both net and gross annual fluxes of carbon globally and regionally from 1850 to 2020, as well as

658 a list of the countries included in each region. The emissions were calculated with a bookkeeping

659 model using the shifting cultivation interpretation of land-use change, inferred from data from

660 FAOSTAT2021. Estimates include the emissions from peatlands in both Southeast Asia and

661 northern regions. Further breakdown of the data may be obtained directly from the authors

662 (rhoughton@woodwellclimate.org, acastanho@woodwellclimate.org).

663 **Conclusions**

664 The estimated emissions of carbon from LULUCF calculated in this analysis approximate the

665 emissions resulting from direct anthropogenic activities; that is, management. They are not

666 equivalent to total net terrestrial emissions because the total includes sources and sinks resulting

667 from natural and indirect anthropogenic effects, such as climate change and rising CO_2 levels.

668 Separating terrestrial emissions of carbon into those directly anthropogenic (LULUCF) and those

669 either natural or indirectly anthropogenic (environmental) is important, both for predicting future

670 rates of climate change and for identifying land-based solutions for mitigation. But the separation

671 may not be necessary for policy and, further, it may be limiting. Carbon credits and debits are

672 now limited to anthropogenic emissions, defined by the emissions from managed lands (Ogle et

673 al., 2018; Grassi et al., 2018; Grassi, in press). It would be much simpler in practice, consistent

674 with observations, and would provide the appropriate incentives for mitigation if countries were

675 credited and debited for *all* emissions and removals of carbon on *all* lands. Penalties for

676 emissions from droughts, fires, and natural disturbances would seem unfair, but the same

677 unfairness applies equally to rewards for carbon removals (the land sink). At present, at a global

678 scale, the non-anthropogenic land sink is greater than the net emissions attributable to

679 anthropogenic activities (i.e., LULUCF). Policies that rewarded countries for maintaining and

680 enhancing that sink would provide a greater opportunity for slowing climate change than policies

681 rewarding only reductions in anthropogenic emissions.

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687 **Author contributions**

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

689 **Competing interests**

690 The authors declare that they have no conflict of interest.

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