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- 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, 2022) whose  
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 and 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) however, 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 (m<sup>3</sup>/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 pasture. 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 ( $\text{MgC ha}^{-1} \text{ yr}^{-1}$  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.



94 2.3.1. Adjustments to the bookkeeping model for wood harvest

95 Two adjustments, partially off-setting, were made for the original code used by Houghton and  
96 Nassikas (2017). The first resulted in a more accurate simulation of harvested wood products.  
97 We had overestimated harvest by failing to account for the fact that some harvested forest  
98 biomass becomes slash rather than wood product. This adjustment reduced the amount of wood  
99 harvested to match data from FAOSTAT and other data sources. The second adjustment  
100 increased the areas of secondary forests or plantations harvested because the intensity of harvest  
101 (MgC/ha removed) is generally lower in secondary forests than in primary forests. Thus a larger  
102 area of secondary forests was harvested in the improved version to obtain the same volume of  
103 wood. The larger area harvested led to a greater gross uptake of carbon by recovering forests  
104 and, thus, lower net emissions from wood harvest than estimated by Houghton and Nassikas  
105 (2017).

106 2.3.2. Incorporation of new data from the FAO

107 We used two data sources from the FAO to update the analyses to 2020. Every five years since  
108 1990 the FAO publishes a Forest Resources Assessment (FRA), the latest being FRA2020. The  
109 FRAs report the areas and biomass/carbon stocks of forests, country by country. Every year since  
110 1960 FAOSTAT reports the national areas of forests, croplands, pastures, and other lands. It also  
111 reports annual rates of harvest of industrial wood and fuelwood. We used data from the most  
112 recent FAOSTAT2020, thereby accounting not only for additional years but also for revisions to  
113 earlier estimates. Revised data from FRA2020 and FAOSTAT2021 often required that we revise  
114 pre-1990 estimates in order to avoid abrupt changes. We assumed that rates reported by the FAO  
115 for 2015-2019 continued in 2020.

116 For a few countries, we used sources of data other than from the FAO. For example, for China  
117 we used cropland areas from Liu and Tian (2010) from 1961 to 1995, after which we used data  
118 from FAO. For Russia, Ukraine, and Belarus we used arable land from Schierhorn et al. (2013)  
119 to simulate a much larger abandonment of cropland after 1990 than reported by FAOSTAT2020.  
120 Then, after 2007 croplands were again expanded as reported by Bartalev et al. (2016) and  
121 Prishchepov et al. (2012). For Kazakhstan we used arable land from Kraemer et al. (2015),  
122 increasing it after 2000 until it matched data reported in FAOSTAT2020. 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 1990

### 125 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 lands, 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 area. 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 of this  
148 apparent forest conversion to other land. In one case we assumed that the conversion represented  
149 degraded lands, 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 forests. 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 are

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 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 harvests 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  $277 \times 10^6$  ha  
188 in 1980, somewhat more than half of the (Fao/Unep, 1981) estimate of  $456 \times 10^6$  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 construction 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, trees are 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 

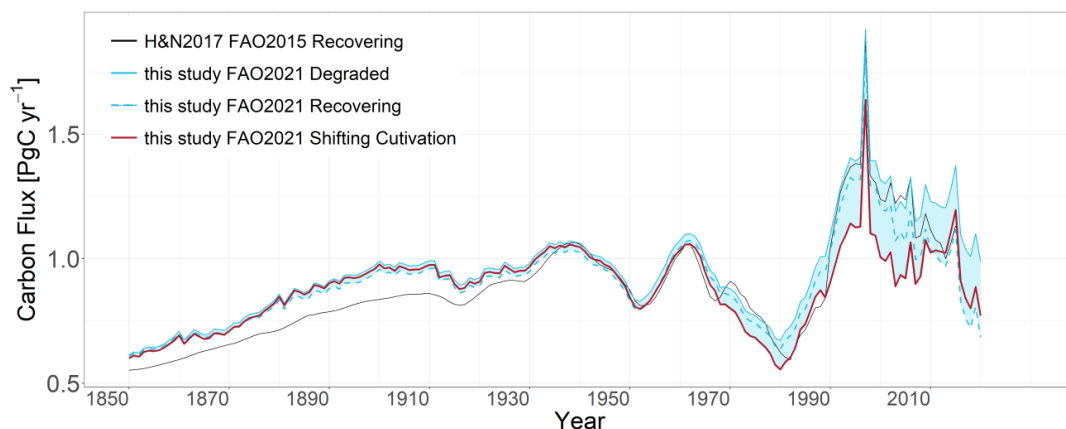
#### 215 2.3.4. The draining and burning of peatlands

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) 

### 223 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 LULUCF. 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)

region	time period	based on FAOSTAT2015		based on FAOSTAT2015		based on FAOSTAT2021			peat - 2020 SSEA + Northern Countries
		H&N2017 recovering		this study recovering		this study degraded	this study recovering	this study shifting cultivation	
		with SSEA peat	no peat	with SSEA peat	no peat	no peat			
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

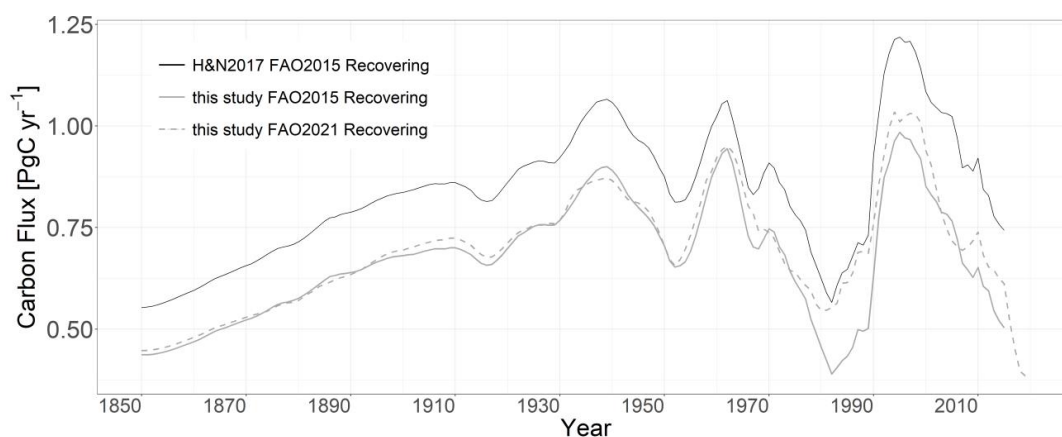
235

### 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).



245

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).

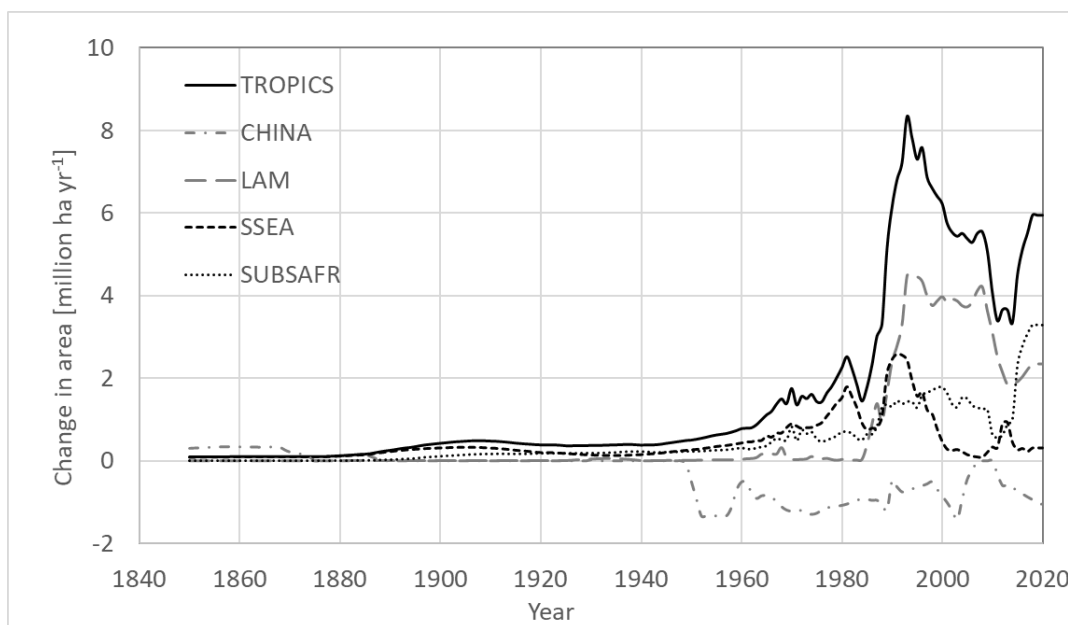
### 255 3.3. Alternative interpretations of the conversion of forest to other land

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).

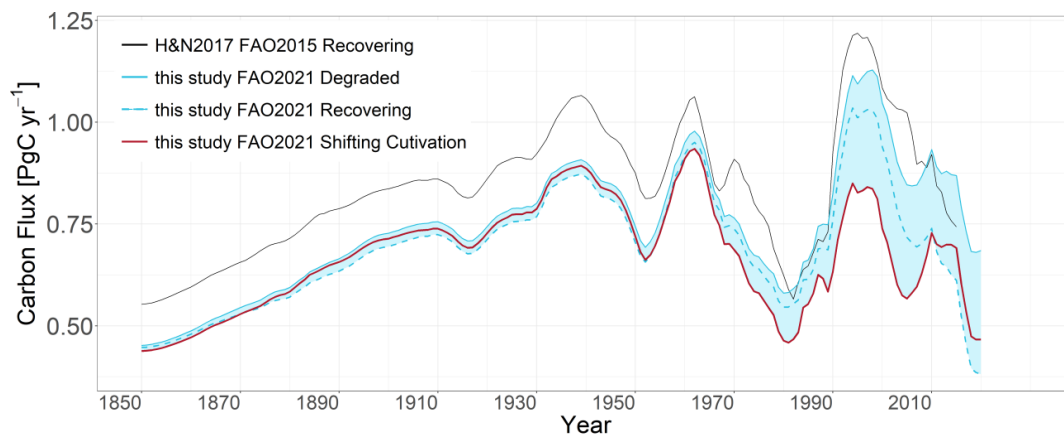


265  
266 Figure 3. Rates at which forests appeared to be converted to other lands (FCO). Negative values  
267 indicate the conversion of other lands to forests.

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, 115.4 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<sup>-1</sup> 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




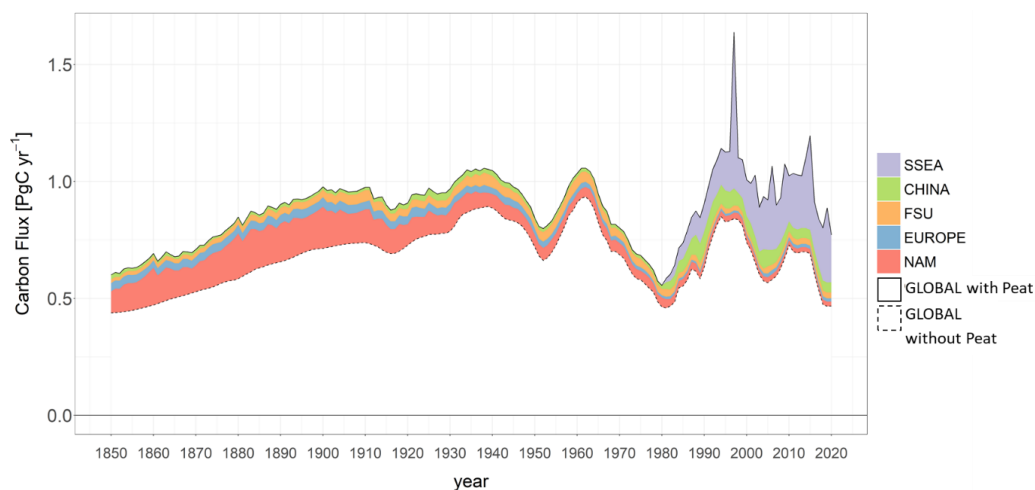
286 Table 2. Average annual net emissions from LULUCF for the globe and major regions for the  
 287 period 2011 to 2020 (or to 2015 for comparison with H&N2017). 

[PgC yr <sup>-1</sup> ]		based on FAOSTAT2021			peat - 2020	
		this study degraded	this study recovering	this study shifting cultivation		
region	time period	with Peat			SSEA + Northern 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).



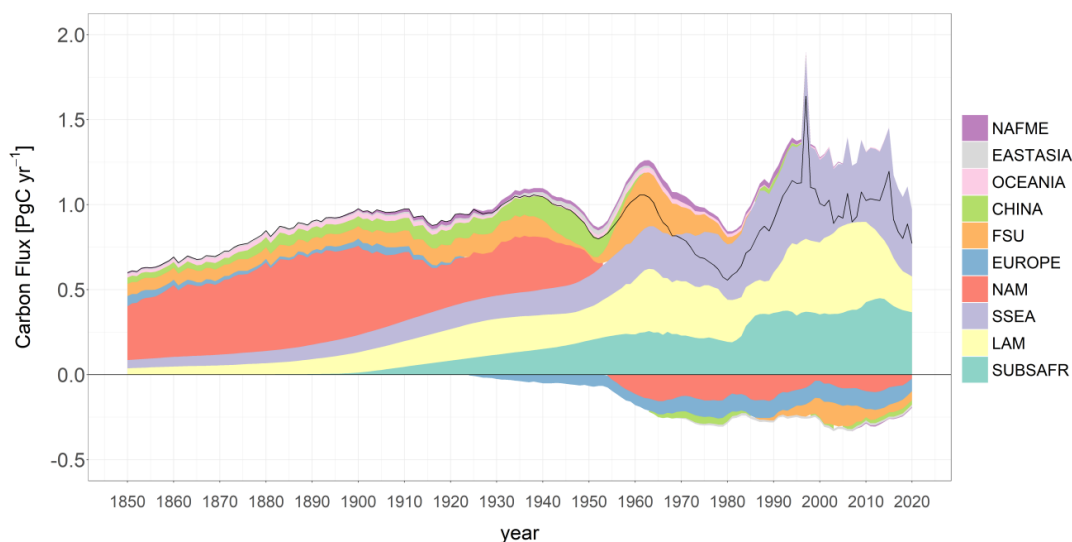
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297 Figure 5. Annual emissions of carbon from use of peatlands, shown here above the annual net  
298 emissions from the shifting cultivation alternative.

### 299 3.5.Overall

300 Unless otherwise specified, the estimates described below refer to the shifting cultivation  
301 interpretation of forests converted to other lands (FCO). Global net emissions of carbon from  
302 LULUCI increased from about 0.6 PgC yr<sup>-1</sup> in 1850 to about 1.0 PgC yr<sup>-1</sup> in the 1930s and never  
303 got much higher (except in 1997 as a result of unusually high emissions from peatland  
304 Southeast Asia) (Fig. 6). The emissions were far from constant after 1930, however. Rather,  
305 emissions peaked around 1960, in the 1990s, and around 2015, with declines during the 1940s,  
306 the 1970s and 1980s, and after 2015.

307 The largest net emissions in the last ten years (2011-2020) were from the three tropical regions (a  
308 mean of 0.500, 0.411, 0.308 PgC yr<sup>-1</sup> for South and Southeast Asia, SubSaharan Africa, and  
309 Latin America, respectively) (Table 2) while four regions (Europe, North America, Former  
310 Soviet Union (FSU), and China) showed net sinks of about -0.094, -0.073, -0.052, -0.025 PgC yr<sup>-1</sup>,  
311 respectively. The net negative emissions (carbon sinks) for individual regions first appeared in  
312 the 1920s (Fig. 6), reached about -0.3 PgC yr<sup>-1</sup> in the 1970s, and remained nearly constant  
313 thereafter, although the sink seems to have declined slightly since 2005.



314

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

317 In the period 2011-2020 global gross emissions ( $3.38 \text{ PgC yr}^{-1}$ ) were more than three times  
318 higher than net emissions ( $0.96 \text{ PgC yr}^{-1}$ ), while gross removals averaged  $2.42 \text{ PgC yr}^{-1}$  (Fig. 7)  
319 (Table 3).

320 Gross emissions were predominantly (69%) in the three tropical regions (Latin America, tropical  
321 Africa, and South and Southeast Asia), while the gross sink was distributed nearly equally  
322 between tropical (46%) and non-tropical (54%) regions. The difference is largely attributable to  
323 the higher rates of deforestation in the tropics. In contrast to deforestation, rotational uses of  
324 land, such as shifting cultivation and the harvest of wood, have much lower net emissions  
325 because gross emissions and removals (due to forest regrowth) are largely offsetting.

326 The offset is not simultaneous, however, and has implications for mitigation. Because most  
327 emissions happen rapidly, while most removals occur over a longer time, a reduction in shifting  
328 cultivation wood harvest would result in a rapid reduction in (gross) emissions, while the  
329 (gross) removals (in re-growing forests) would continue for decades. Hence, gross fluxes are  
330 more indicative of the potential for mitigation than net fluxes are (compare Fig. 6 and Fig. 7). As



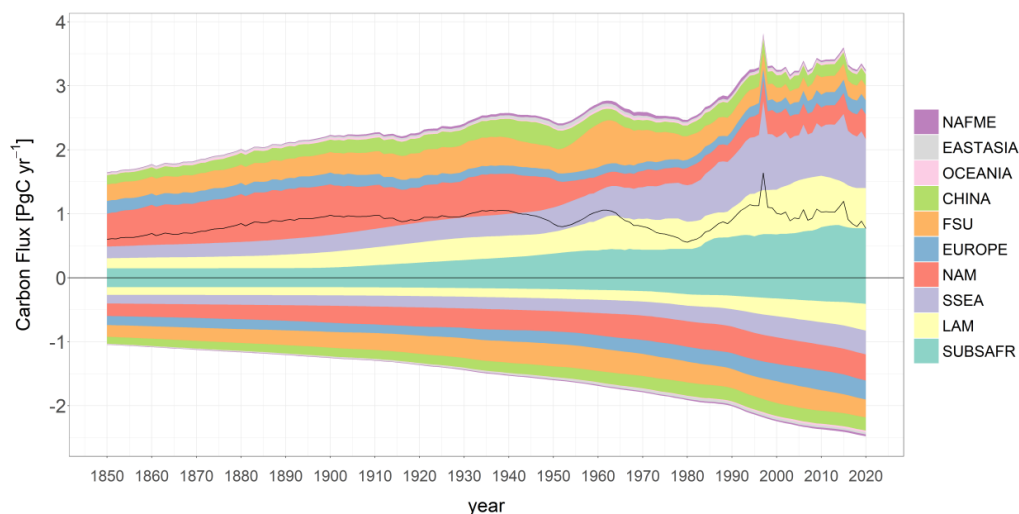


331 discussed above, actual gross emissions and removals are larger than estimated here because  
 332 rates of land-use change are based on *net* changes in area as reported by FAOSTAT.

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

[PgC yr <sup>-1</sup> ]		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

334



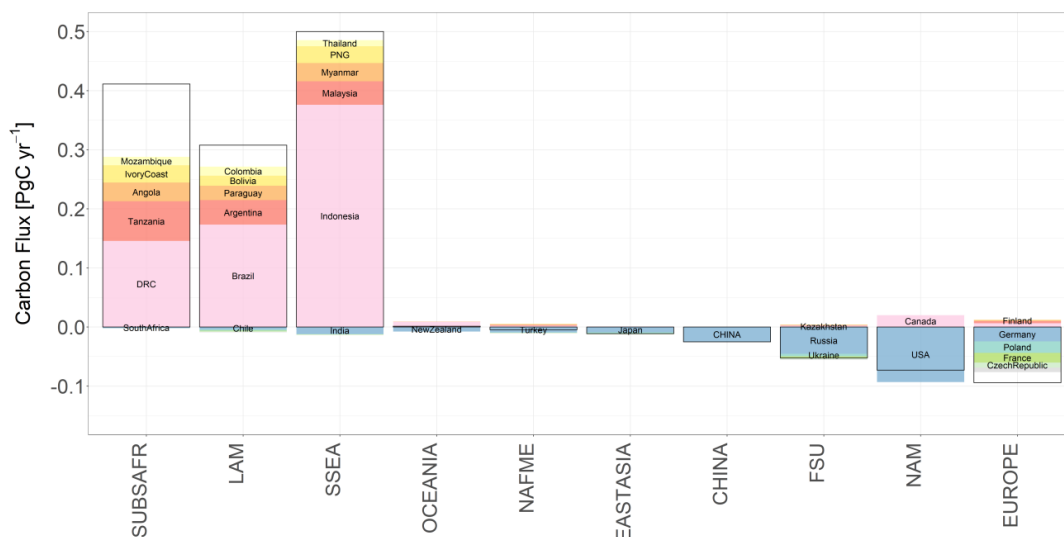
335

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



### 338 3.5.1. Emissions by country

339 Over the last decade (2011-2020), according to the analysis based on the shifting cultivation  
340 interpretation of FCO, three countries (Indonesia, Brazil and DRC) accounted for 54% of the  
341 global net emissions, and 20 countries accounted for 85.7% (Fig. 8). Seven countries offset  
342 18.1% of the total emissions, while about 80 countries with negative emissions offset 26.3% of  
343 total net emissions from LULUCF. The total net removal (sum of all net removal countries)  
344 ( $3.41 \text{ PgC yr}^{-1}$ ) was less than the emissions from Indonesia ( $3.76 \text{ PgC yr}^{-1}$ ). Indonesia alone  
345 accounted for 30% of all emission in this last 10 years, with 56% of those emissions from  
346 burning and draining of peatlands.



347

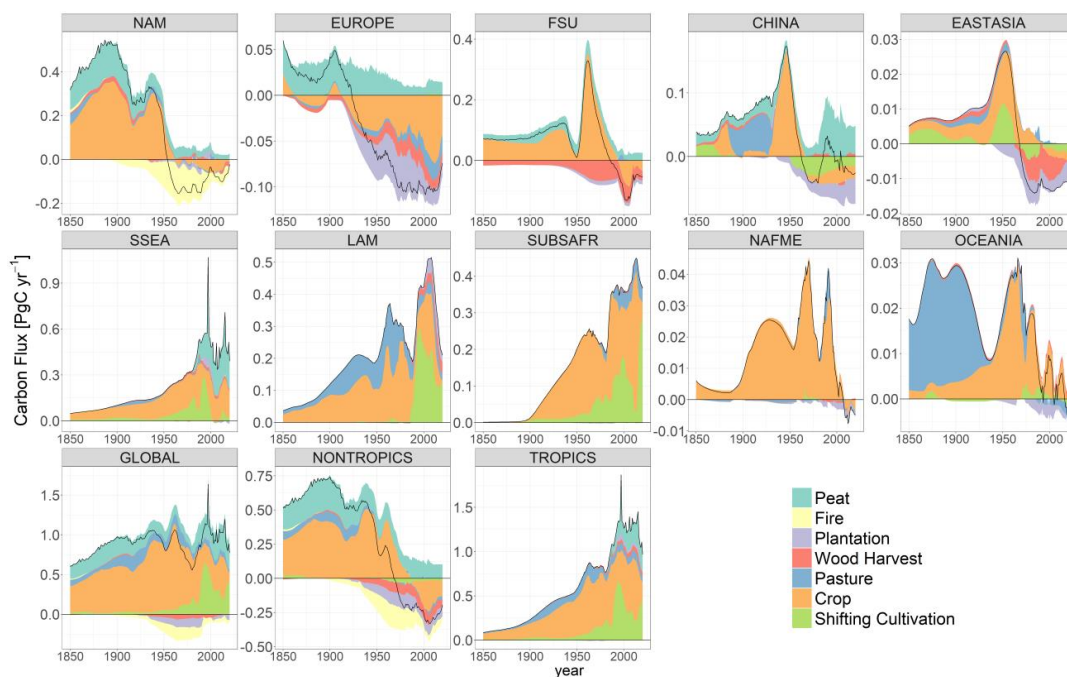
348 Figure 8. Regions and countries with the largest net annual emissions and removals, including  
349 emissions from use of peatlands (average for 2011-2020). The white portions of the columns  
350 represent the contribution of all other countries in the corresponding regions.

### 351 3.5.2. Emissions by land use

352 Land uses with the greatest emissions or removals of carbon varied among regions and over time  
353 (Fig. 9). The expansion of croplands generally accounted for the greatest emissions everywhere  
354 except in Oceania where pastures were the dominant source of carbon before 1950. Shifting  
355 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<sup>-1</sup> in the last 10 years) (Table 4).  
360 The net US sink was -0.109 PgC yr<sup>-1</sup> 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 <sup>-1</sup> ] (2011-2020)	Net Flux with peat	Net Flux without peat	Wood Harvest	Crop	Pasture	Shifting Cultivation	Plant	Peat	Fire
GLOBAL		<b>0.960</b>	<b>0.603</b>	-0.003	<b>0.344</b>	<b>0.060</b>	<b>0.298</b>	<b>-0.044</b>	<b>0.357</b>	<b>-0.051</b>
NONTROPICS		<b>-0.259</b>	<b>-0.361</b>	<b>-0.061</b>	<b>-0.133</b>	<b>-0.023</b>	<b>-0.016</b>	<b>-0.077</b>	<b>0.102</b>	<b>-0.051</b>
TROPICS		<b>1.219</b>	<b>0.964</b>	<b>0.058</b>	<b>0.476</b>	<b>0.083</b>	<b>0.314</b>	<b>0.033</b>	<b>0.255</b>	0.000
Tropics	LAM	<b>0.308</b>	<b>0.308</b>	<b>0.039</b>	<b>0.063</b>	<b>0.039</b>	<b>0.123</b>	<b>0.044</b>	0.000	0.000
	SUBSAFR	<b>0.411</b>	<b>0.411</b>	0.003	<b>0.212</b>	<b>0.044</b>	<b>0.153</b>	-0.001	0.000	0.000
	SSEA	<b>0.500</b>	<b>0.245</b>	<b>0.016</b>	<b>0.201</b>	0.000	<b>0.038</b>	-0.010	<b>0.255</b>	0.000
Non Tropics	NAM	<b>-0.073</b>	<b>-0.093</b>	<b>-0.017</b>	<b>-0.023</b>	-0.002	0.001	0.000	<b>0.020</b>	<b>-0.051</b>
	EUROPE	<b>-0.094</b>	<b>-0.108</b>	-0.011	<b>-0.063</b>	<b>-0.018</b>	0.001	<b>-0.018</b>	0.014	0.000
	CHINA	<b>-0.025</b>	<b>-0.068</b>	0.005	<b>-0.020</b>	0.000	<b>-0.015</b>	<b>-0.038</b>	<b>0.043</b>	0.000
	FSU	<b>-0.052</b>	<b>-0.077</b>	<b>-0.037</b>	<b>-0.026</b>	0.000	0.000	-0.014	<b>0.025</b>	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

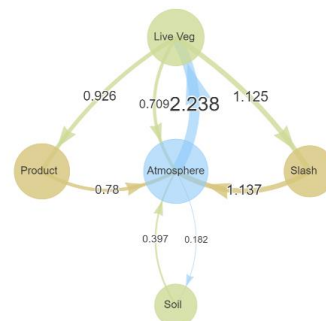
366 3.5.3. Emissions by carbon pool

367 The annual net flux of 0.960 PgC yr<sup>-1</sup> to the atmosphere for the period 2011-2020 was composed  
 368 of gross emissions of 3.380 PgC yr<sup>-1</sup> 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<sup>-1</sup> 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<sup>-1</sup>).

[PgC yr <sup>-1</sup> ] (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<sup>-1</sup>) 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<sup>-1</sup> 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 ( $2.238 \text{ PgC yr}^{-1}$ ). 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.

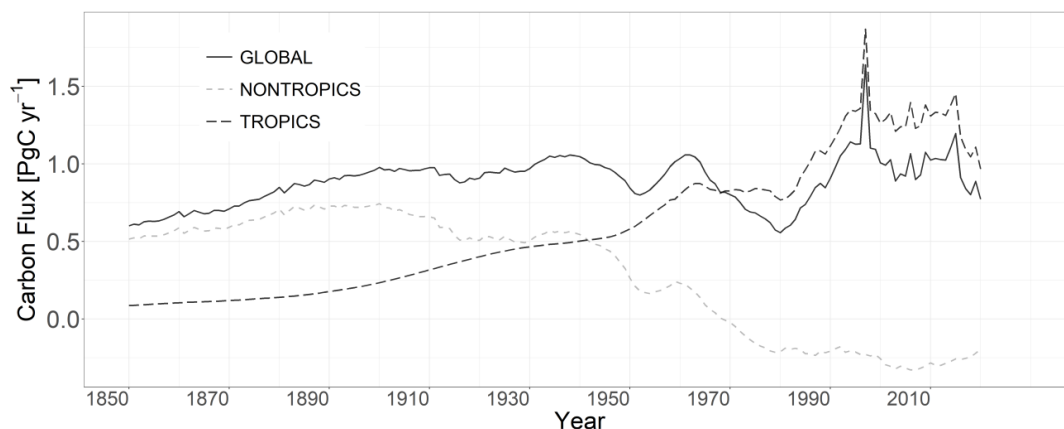
385 It is unclear whether the emissions of carbon from peatlands in northern regions were from  
386 forests or not. Ignoring peatlands, global forests accounted for nearly all emissions (99%) for the  
387 decade 2011-2020. Emissions from peatlands were 37% of the total global net flux, and some of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

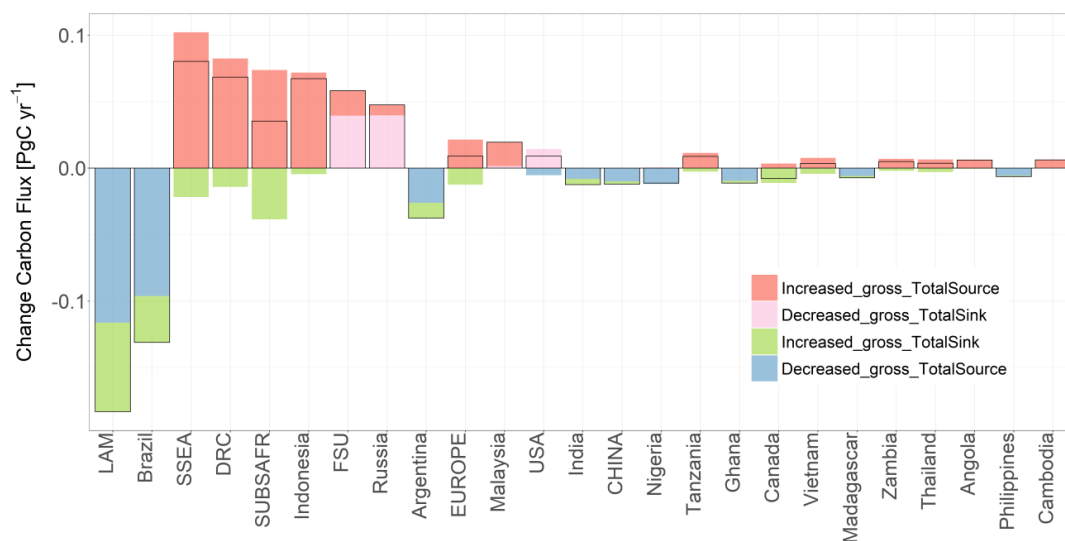
404 The decline in emissions reported here over the last decade is consistent with other bookkeeping  
405 models used by the Global Carbon Project (Carbonbrief, 2021), but more precipitous. The  
406 decline in tropical emissions was new in the 2020 GCP budget (Friedlingstein et al., 2022) and  
407 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  $0.97 \text{ PgC yr}^{-1}$ ) and 2015-2019  
417 ( $1.99 \text{ PgC yr}^{-1}$ ), 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  $1.8 \text{ PgC yr}^{-1}$  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<sup>-1</sup> for both intervals.

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 FAOSTAT2021.  
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 21<sup>st</sup> 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. In 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 disturbances?

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 forests. 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  $450 \times 10^6$  ha in 2020. More  
506 importantly, the annual re-clearing of these lands was  $25.7 \times 10^6$  ha in 2020. This rate is large in  
507 comparison to tropical deforestation rates of  $10 \times 10^6$  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; Heinemann 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 Samdong et  
537 al. (2018) found shifting cultivation to have been the main cause of deforestation in the  
538 Democratic Republic 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  $0.260 \text{ PgC yr}^{-1}$  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 emissions.



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  $277 \times 10^6$  ha in 1980 and  $450 \times 10^6$  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 Heinemann et al. (2017), based in part on  
563 satellite data for the period 2000-2014, estimated an area of  $260 \times 10^6$  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; Heinemann 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<sup>-1</sup> in comparison to total gross  
574 emissions and removals were  $3.379$  and  $-2.420$  PgC yr<sup>-1</sup>, 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?

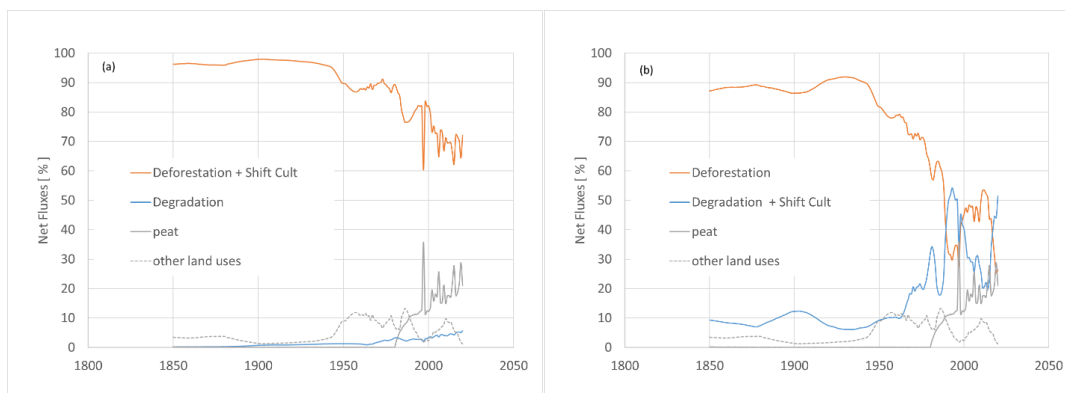
579 Estimates of the emissions from degradation vary widely, from nearly zero (Xu et al., 2021) to  
580 greater than the emissions from deforestation (Baccini et al., 2017). Xu et al. (2021) reported  
581 little degradation, perhaps to avoid double counting it in the other drivers considered: forest  
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

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

### 613 4.3. Comparisons with other studies

614 Houghton and Nassikas (2017) interpreted FCO to represent the replacement of old croplands  
615 with new ones (from forests), with an equivalent area of old croplands abandoned. These  
616 abandoned croplands began gaining carbon after 15 years (the same as the *recovered*  
617 interpretation). Thus, while Houghton and Nassikas (2017) did not include shifting cultivation  
618 explicitly, they did include the conversion of forest to other land. More importantly, Houghton  
619 and Nassikas (2017) considered this conversion of forest to other land only in the years  
620 following 1990, when the FAO began their consistent reporting of changes in forest area. In the  
621 analysis reported here, we extrapolated FCO into the past based on earlier FAO estimates (Fao,  
622 1980) and qualitative expert opinion reported in Heinimann et al. (2017).

623 As discussed above, the three bookkeeping models used by the Global Carbon Project (GCP)  
624 have all shown declining emissions from land-use and land-cover change over the last decade  
625 (Friedlingstein et al., 2022), although the net emissions estimated by Houghton and Nassikas  
626 (2017) were lower than the emissions calculated by BLUE (Hansis et al., 2015) and OSCAR  
627 (Gasser et al., 2020). The difference may be explained by lower values of biomass in the model  
628 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 be 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 environment, while we (and other bookkeeping models) have tried to estimate  
639 only the effects of management (i.e., land-use change). Because 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=09ee9f75-3b93-4755-8be6-9da7ac06dd60>, final DOI to be updated during publication process). The tabular data include  
656 <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 (rthoughton@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<sub>2</sub> 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.

### 682 **Acknowledgements**

683 We thank Chunjing Qiu for providing annual emissions from use of northern peatlands and  
684 Guido van der Werf for updated estimates of carbon emissions from fires in Southeast Asia





685 (GFED). The work was funded by Woodwell Climate Research Center, through its Fund for  
686 Climate Solutions. We are most appreciative of this support.

#### 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.

#### 691 **References**

- 692 Aragão, L. E. O. C., Anderson, L. O., Fonseca, M. G., Rosan, T. M., Vedovato, L. B., Wagner, F. H., Silva, C.  
693 V. J., Silva Junior, C. H. L., Arai, E., Aguiar, A. P., Barlow, J., Berenguer, E., Deeter, M. N., Domingues, L. G.,  
694 Gatti, L., Gloor, M., Malhi, Y., Marengo, J. A., Miller, J. B., Phillips, O. L., and Saatchi, S.: 21st Century  
695 drought-related fires counteract the decline of Amazon deforestation carbon emissions, *Nature*  
696 *communications*, 9, 536, 10.1038/s41467-017-02771-y, 2018.
- 697 Baccini, A., Walker, W., Carvalho, L., Farina, M., Sulla-Menashe, D., and Houghton, R. A.: Tropical forests  
698 are a net carbon source based on aboveground measurements of gain and loss, *Science*,  
699 10.1126/science.aam5962, 2017.
- 700 Bartalev, S. A., Plotnikov, D. E., and Loupian, E. A.: Mapping of arable land in Russia using multi-year time  
701 series of MODIS data and the LAGMA classification technique, *Remote Sensing Letters*, 7, 269-278, 2016.
- 702 Bastos, A., Hartung, K., Nützel, T. B., Nabel, J. E. M. S., Houghton, R. A., and Pongratz, J.: Comparison of  
703 uncertainties in land-use change fluxes from bookkeeping model parameterisation, *Earth Syst. Dynam.*,  
704 12, 745-762, 10.5194/esd-12-745-2021, 2021.
- 705 Betts, R. A., Cox, P. M., Collins, M., Harris, P. P., Huntingford, C., and Jones, C. D.: The role of ecosystem-  
706 atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global  
707 climate warming, *Theor Appl Climatol*, 78, 157-175, 10.1007/s00704-004-0050-y, 2004.
- 708 CarbonBrief: [https://www.carbonbrief.org/global-co2-emissions-have-been-flat-for-a-decade-new-data-](https://www.carbonbrief.org/global-co2-emissions-have-been-flat-for-a-decade-new-data-reveals)  
709 [reveals](https://www.carbonbrief.org/global-co2-emissions-have-been-flat-for-a-decade-new-data-reveals), 2021.
- 710 Ceccherini, G., Duveiller, G., Grassi, G., Lemoine, G., Avitabile, V., Pilli, R., and Cescatti, A.: Abrupt  
711 increase in harvested forest area over Europe after 2015, *Nature*, 583, 72-77, 10.1038/s41586-020-  
712 2438-y, 2020.
- 713 Ciais, P., Tan, J., Wang, X., Roedenbeck, C., Chevallier, F., Piao, S. L., Moriarty, R., Broquet, G., Le Quéré,  
714 C., Canadell, J. G., Peng, S., Poulter, B., Liu, Z., and Tans, P.: Five decades of northern land carbon uptake  
715 revealed by the interhemispheric CO<sub>2</sub> gradient, *Nature*, 568, 221-225, 10.1038/s41586-019-1078-6,  
716 2019.
- 717 Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A., and Hansen, M. C.: Classifying drivers of global forest  
718 loss, *Science*, 361, 1108-1111, 2018.
- 719 De Sy, V., Herold, M., Achard, F., Beuchle, R., Clevers, J., Lindquist, E., and Verchot, L.: Land use patterns  
720 and related carbon losses following deforestation in South America, *Environmental Research Letters*, 10,  
721 124004, 2015.
- 722 Fantini, A. C., Bauer, E., de Valois, C. M., and Siddique, I.: The demise of swidden-fallow agriculture in an  
723 Atlantic Rainforest region: Implications for farmers' livelihood and conservation, *Land Use Policy*, 69,  
724 417-426, 2017.
- 725 FAO: Food and Agriculture Organization of the United Nations, 1980.



- 726 FAO/UNEP: Los Recursos Forestales de la America Tropical (United Nations 32/6.1301-78-  
727 04, Informe tecnico 1, FAO, Rome, 1981); Forest Resources of Tropical Asia (UN  
728 32.6.1301-78-04, Tech. Rep. 2, FAO, Rome, 1981); Form Resources of Tropical Africa,  
729 Parts I and 2 (UN 32/6.1301-78-04, Tech. Rep. 3, FAO, Rome, 1981). , 1981.  
730 FAOSTAT: Food and Agriculture Organization of the United Nations, 2021.  
731 Feng, Y., Zeng, Z., Searchinger, T. D., Ziegler, A. D., Wu, J., Wang, D., He, X., Elsen, P. R., Ciais, P., and Xu,  
732 R.: Doubling of annual forest carbon loss over the tropics during the early twenty-first century, *Nature*  
733 *Sustainability*, 5, 444-451, 2022.  
734 FRA: Food and Agriculture Organization of the United Nations, 1990.  
735 FRA: Food and Agriculture Organization of the United Nations, 2015.  
736 FRA: Food and Agriculture Organization of the United Nations, 2020.  
737 Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Bakker, D. C., Hauck, J., Le Quéré, C.,  
738 Peters, G. P., Peters, W., and Pongratz, J.: Global carbon budget 2021, *Earth System Science Data*, 14,  
739 1917-2005, 2022.  
740 Gasser, T., Crepin, L., Quilcaille, Y., Houghton, R. A., Ciais, P., and Obersteiner, M.: Historical CO<sub>2</sub>  
741 emissions from land use and land cover change and their uncertainty, *Biogeosciences*, 17, 4075-4101,  
742 2020.  
743 Gatti, L. V., Basso, L. S., Miller, J. B., Gloor, M., Gatti Domingues, L., Cassol, H. L. G., Tejada, G., Aragão, L.  
744 E. O. C., Nobre, C., Peters, W., Marani, L., Arai, E., Sanches, A. H., Corrêa, S. M., Anderson, L., Von  
745 Randow, C., Correia, C. S. C., Crispim, S. P., and Neves, R. A. L.: Amazonia as a carbon source linked to  
746 deforestation and climate change, *Nature*, 595, 388-393, 10.1038/s41586-021-03629-6, 2021.  
747 Grassi, G.: Reference to be completed later, in press.  
748 Grassi, G., House, J., Kurz, W. A., Cescatti, A., Houghton, R. A., Peters, G. P., Sanz, M. J., Viñas, R. A.,  
749 Alkama, R., and Arneth, A.: Reconciling global-model estimates and country reporting of anthropogenic  
750 forest CO<sub>2</sub> sinks, *Nature Climate Change*, 8, 914-920, 2018.  
751 Hansen, M.: Response to Feng et al., 2022, To be completed later, 2022.  
752 Hansis, E., Davis, S. J., and Pongratz, J.: Relevance of methodological choices for accounting of land use  
753 change carbon fluxes, *Global Biogeochemical Cycles*, 29, 1230-1246, 2015.  
754 Harris, D. R.: Swidden systems and settlement, in: *Man, Settlement and Urbanism*, edited by: P.J. Ucko,  
755 R. T., G.W. Dimbleby, Duckworth, London, 245-262, 1972.  
756 Harris, N. L., Gibbs, D. A., Baccini, A., Birdsey, R. A., De Bruin, S., Farina, M., Fatoyinbo, L., Hansen, M. C.,  
757 Herold, M., and Houghton, R. A.: Global maps of twenty-first century forest carbon fluxes, *Nature*  
758 *Climate Change*, 11, 234-240, 2021.  
759 Heinimann, A., Mertz, O., Froking, S., Egelund Christensen, A., Hurni, K., Sedano, F., Parsons Chini, L.,  
760 Sahajpal, R., Hansen, M., and Hurr, G.: A global view of shifting cultivation: Recent, current, and future  
761 extent, *PloS one*, 12, e0184479, 2017.  
762 Hooijer, A., Page, S., Canadell, J., Silvius, M., Kwadijk, J., Wösten, H., and Jauhiainen, J.: Current and  
763 future CO<sub>2</sub> emissions from drained peatlands in Southeast Asia, *Biogeosciences*, 7, 1505-1514, 2010.  
764 Houghton, R., Hobbie, J., Melillo, J. M., Moore, B., Peterson, B., Shaver, G., and Woodwell, G.: Changes  
765 in the Carbon Content of Terrestrial Biota and Soils between 1860 and 1980: A Net Release of CO<sub>2</sub> to  
766 the Atmosphere, *Ecological monographs*, 53, 235-262, 1983.  
767 Houghton, R. A. and Nassikas, A. A.: Global and regional fluxes of carbon from land use and land cover  
768 change 1850–2015, *Global Biogeochemical Cycles*, 31, 456-472,  
769 <https://doi.org/10.1002/2016GB005546>, 2017.  
770 Houghton, R. A. and Nassikas, A. A.: Negative emissions from stopping deforestation and forest  
771 degradation, globally, *Global change biology*, 24, 350-359, 2018.



- 772 Houghton, R. A., House, J. I., Pongratz, J., van der Werf, G. R., DeFries, R. S., Hansen, M. C., Le Quéré, C.,  
773 and Ramankutty, N.: Carbon emissions from land use and land-cover change, *Biogeosciences*, 9, 5125-  
774 5142, 10.5194/bg-9-5125-2012, 2012.
- 775 Ickowitz, A.: Shifting cultivation and deforestation in tropical Africa: critical reflections, *Development*  
776 and Change, 37, 599-626, 2006.
- 777 Klein Goldewijk, K., Beusen, A., Doelman, J., and Stehfest, E.: Anthropogenic land use estimates for the  
778 Holocene–HYDE 3.2, *Earth System Science Data*, 9, 927-953, 2017.
- 779 Kondo, M., Sitch, S., Ciais, P., Achard, F., Kato, E., Pongratz, J., Houghton, R. A., Canadell, J. G., Patra, P.  
780 K., and Friedlingstein, P.: Are Land-Use Change Emissions in Southeast Asia Decreasing or Increasing?,  
781 *Global biogeochemical cycles*, 36, e2020GB006909, 2022.
- 782 Kraemer, R., Prishchepov, A. V., Müller, D., Kuemmerle, T., Radeloff, V. C., Dara, A., Terekhov, A., and  
783 Frühauf, M.: Long-term agricultural land-cover change and potential for cropland expansion in the  
784 former Virgin Lands area of Kazakhstan, *Environmental Research Letters*, 10, 054012, 2015.
- 785 Lanly, J. P.: *Tropical Forest Resources* FAO Forestry Pap. 30, FAO, Rome, 1982.
- 786 Liu, M. and Tian, H.: China's land cover and land use change from 1700 to 2005: Estimations from high-  
787 resolution satellite data and historical archives, *Global Biogeochemical Cycles*, 24, 2010.
- 788 Ogle, S. M., Domke, G., Kurz, W. A., Rocha, M. T., Huffman, T., Swan, A., Smith, J. E., Woodall, C., and  
789 Krug, T.: Delineating managed land for reporting national greenhouse gas emissions and removals to the  
790 United Nations framework convention on climate change, *Carbon balance and management*, 13, 1-13,  
791 2018.
- 792 Palahí, M., Valbuena, R., Senf, C., Acil, N., Pugh, T. A., Sadler, J., Seidl, R., Potapov, P., Gardiner, B., and  
793 Hetemäki, L.: Concerns about reported harvests in European forests, *Nature*, 592, E15-E17, 2021.
- 794 Picard, N., Leban, J.-M., Guehl, J.-M., Dreyer, E., Bouriaud, O., Bontemps, J.-D., Landmann, G., Colin, A.,  
795 Peyron, J.-L., and Marty, P.: Recent increase in European forest harvests as based on area estimates  
796 (Ceccherini et al. 2020a) not confirmed in the French case, *Annals of Forest Science*, 78, 1-5, 2021.
- 797 Pongratz, J., Reick, C. H., Houghton, R., and House, J.: Terminology as a key uncertainty in net land use  
798 and land cover change carbon flux estimates, *Earth System Dynamics*, 5, 177-195, 2014.
- 799 Prishchepov, A. V., Radeloff, V. C., Baumann, M., Kuemmerle, T., and Müller, D.: Effects of institutional  
800 changes on land use: agricultural land abandonment during the transition from state-command to  
801 market-driven economies in post-Soviet Eastern Europe, *Environmental Research Letters*, 7, 024021,  
802 2012.
- 803 PRODES: Instituto Nacional de Pesquisas Espaciais. Coordenacao geral de observacao da Terra, 2021.
- 804 Qiu, C., Ciais, P., Zhu, D., Guenet, B., Peng, S., Petrescu, A. M. R., Lauerwald, R., Makowski, D., Gallego-  
805 Sala, A. V., and Charman, D. J.: Large historical carbon emissions from cultivated northern peatlands,  
806 *Science advances*, 7, eabf1332, 2021.
- 807 Rappaport, D. I., Morton, D. C., Longo, M., Keller, M., Dubayah, R., and dos-Santos, M. N.: Quantifying  
808 long-term changes in carbon stocks and forest structure from Amazon forest degradation,  
809 *Environmental Research Letters*, 13, 065013, 2018.
- 810 Samndong, R. A., Bush, G., Vatn, A., and Chapman, M.: Institutional analysis of causes of deforestation in  
811 REDD+ pilot sites in the Equateur province: Implication for REDD+ in the Democratic Republic of Congo,  
812 *Land Use Policy*, 76, 664-674, 2018.
- 813 Schierhorn, F., Müller, D., Beringer, T., Prishchepov, A. V., Kuemmerle, T., and Balmann, A.: Post-Soviet  
814 cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus, *Global*  
815 *Biogeochemical Cycles*, 27, 1175-1185, 2013.
- 816 Silva, J., Carreiras, J., Rosa, I., and Pereira, J.: Greenhouse gas emissions from shifting cultivation in the  
817 tropics, including uncertainty and sensitivity analysis, *Journal of Geophysical Research: Atmospheres*,  
818 116, 2011.



- 819 Snedaker, S. C. and Gamble, J. F.: Compositional analysis of selected second-growth species from  
820 lowland Guatemala and Panama, *Bioscience*, 19, 536-538, 1969.
- 821 Tubiello, F. N., Conchedda, G., Wanner, N., Federici, S., Rossi, S., and Grassi, G.: Carbon emissions and  
822 removals from forests: new estimates, 1990–2020, *Earth System Science Data*, 13, 1681-1691, 2021.
- 823 Turner, B., Hanham, R. Q., and Portararo, A. V.: Population pressure and agricultural intensity, *Annals of*  
824 *the Association of American Geographers*, 67, 384-396, 1977.
- 825 van Marle, M. J., van Wees, D., Houghton, R. A., Field, R. D., Verbesselt, J., and van der Werf, G.: New  
826 land-use-change emissions indicate a declining CO<sub>2</sub> airborne fraction, *Nature*, 603, 450-454, 2022.
- 827 Van Vliet, N., Mertz, O., Heinemann, A., Langanke, T., Pascual, U., Schmook, B., Adams, C., Schmidt-Vogt,  
828 D., Messerli, P., and Leisz, S.: Trends, drivers and impacts of changes in swidden cultivation in tropical  
829 forest-agriculture frontiers: a global assessment, *Global environmental change*, 22, 418-429, 2012.
- 830 Wernick, I. K., Ciais, P., Fridman, J., Höglberg, P., Korhonen, K. T., Nordin, A., and Kauppi, P. E.:  
831 Quantifying forest change in the European Union, *Nature*, 592, E13-E14, 2021.
- 832 Wiltshire, A. J., von Randow, C., Rosan, T. M., Tejada, G., and Castro, A. A.: Understanding the role of  
833 land-use emissions in achieving the Brazilian Nationally Determined Contribution to mitigate climate  
834 change, *Climate Resilience and Sustainability*, 1, e31, 2022.
- 835 Xu, L., Saatchi, S. S., Yang, Y., Yu, Y., Pongratz, J., Bloom, A. A., Bowman, K., Worden, J., Liu, J., and Yin, Y.:  
836 Changes in global terrestrial live biomass over the 21st century, *Science Advances*, 7, eabe9829, 2021.
- 837 Yu, Z., P. Ciais, S. Piao, R. A. Houghton, C. Lu, H. Tian, E. Agathokleous, G. R. Kattel, S. Sitch, D. Goll, X.  
838 Yue, A. Walker, P. Friedlingstein, A. K. Jain, S. Liu, G. Zhou: Forest expansion dominates China's land  
839 carbon sink since 1980, *Nature communications*, in press.

840