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## The tropical forest carbon cycle and climate change

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15

16 Tropical forests have played a critical role in the changing atmospheric carbon  
17 concentrations of the industrial age, acting both as a very significant emissions  
18 source as they have been logged or burned, but also as a carbon sink, as the  
19 remaining forests have taken in much of the extra carbon added to the atmosphere.  
20 To illustrate this, from 1960 to 2015 anthropogenic emissions of carbon totalled  
21 408 PgC, 80% from burning fossil fuel and making cement, and 20% from (largely  
22 tropical) land use change<sup>1</sup>. However, the atmospheric CO<sub>2</sub> stock grew by ‘only’ 180  
23 PgC over that period<sup>2</sup>, meaning that 55% of these emissions were taken in by the  
24 Earth system, reducing the climate change caused. There are uncertainties around  
25 the relative contributions of the three main locations of this sink, namely the oceans,  
26 northern hemisphere forests, and tropical forests<sup>1</sup>, but likely between a quarter and  
27 a third was due to the enhanced growth of trees in tropical forests<sup>3,4,5</sup>.  
28 Understanding the size and causes of this sink is crucial for predicting its evolution  
29 over the coming century: the tropical land sink is known to be very variable year-to-  
30 year<sup>1,6,7,8,9</sup>, and reverse to a source in hotter years<sup>10</sup>, suggesting there is a real risk  
31 that over the coming decades under climate change it will become a major source  
32 every year.

33 The tropical land sink is the least certain major component of the global carbon  
34 budget<sup>1</sup>. There are various possible ways of estimating its size (Box 1), but none  
35 estimates the sink directly, and all have high uncertainty due to either sparse  
36 sampling<sup>5,11,12,13,14,15</sup> or coarse resolution<sup>6,7,10</sup>. As a result, the main way the land sink  
37 has been estimated is as the residual of the sum of all other components of the  
38 global carbon cycle<sup>1</sup>; however with this method it is not possible to estimate the  
39 relative contribution of the northern hemisphere and tropical forests to the sink.  
40 Further, some other components of the global carbon cycle are also very uncertain  
41 and variable, such as the Land Use Change (LUC) flux<sup>1,16</sup>, making accurately  
42 estimating trends in the sink very difficult. This uncertainty greatly limits the  
43 development and testing of theories and models, and thus means there is a wide

44 divergence of predictions as to how the sink will change under different climate  
45 change scenarios and policy interventions.

46 Considering all sources of evidence, it appears likely that tropical forests are in the  
47 process of switching from being approximately neutral, to a net source, as the intact  
48 forest sink declines in size<sup>1,3,7,17,18</sup>. This decline is caused by a combination of the  
49 decrease in the area of intact forest<sup>19,20</sup>, and increasing temperatures and drought  
50 reducing trees' ability to respond to higher CO<sub>2</sub> concentrations by growing  
51 faster<sup>12,13</sup>. With both forest loss and climate change likely to accelerate over this  
52 century, tropical forests are likely to release ever more carbon, making keeping  
53 global warming to less than 2° C above pre-industrial levels very difficult<sup>21,22</sup>.

## 54 **The carbon balance of tropical forests**

55 Living tropical trees store 200-300 Pg of carbon<sup>5,23,24,25</sup>, about a third as much as is  
56 held in the atmosphere<sup>1</sup>. This stock is very dynamic: tropical trees perform about  
57 60% of the the world's photosynthesis, capturing ~72 Pg of carbon from the  
58 atmosphere every year<sup>26</sup>, but also releasing a similar amount back to the  
59 atmosphere through respiration of both the plants themselves and other  
60 organisms<sup>17,27</sup>. Given these large fluxes, a small proportional change in either the  
61 uptake or release of CO<sub>2</sub> can result in a large net source or sink. There are multiple  
62 lines of evidence that over at least the past 50 years these two processes have been  
63 out of balance, with tropical vegetation increasing in biomass by >2 Pg C yr<sup>-1</sup>, about  
64 1 % per year<sup>5,28,29</sup>. It is clearly though that this sink has very high inter-annual  
65 variability, driven by temperature and rainfall fluctuations<sup>16,30,31</sup>.

66 The tropics are also the main nexus of global land use change, with deforestation  
67 and forest degradation (where some trees are removed but the area retains  
68 sufficient trees to be classed as a forest) releasing somewhere between 0.5 and 3.5  
69 Pg C yr<sup>-1</sup> (refs 7,20,32,33,34,35,36,37). The wide range of estimates is partly due to  
70 differences in time period, but mostly caused by differing definitions and included  
71 processes, different methods (Box 1), and wide uncertainty bounds.

72 Comparing different methods, there is consensus that the overall carbon balance of  
73 the tropics was approximately neutral over the past decades, with sinks in intact  
74 and regrowing forests equal in magnitude to sources from deforestation and forest  
75 degradation<sup>4,5,7</sup>(Fig. 1). However, it is also clear that in abnormally hot years, such  
76 as during strong El Niño events, the tropics becomes a major net source<sup>1,10</sup> (Fig. 1d).

77 The following section examines the current magnitude of the major sources and  
78 sinks. Then the evidence for trends in these over recent decades is considered, along  
79 with their likely future pathways, and whether international policy can change these  
80 trends.

## 81 **Carbon sources**

82 Deforestation is easy to map using optical satellite data, with free Landsat satellite  
83 data meaning most countries produce their own maps<sup>20</sup>, with large scale  
84 independent maps also available and broadly consistent<sup>19,39</sup>. Deforestation affects  
85 very large areas: about 100 Mha were deforested in the tropics from 2000-2012,  
86 about 50% in Latin America, 30% in SE Asia, and 20% in Africa (ref 19 using a forest  
87 definition of >25% canopy cover; similar values are found in studies<sup>20,39</sup>). The main  
88 drivers of this deforestation differ by location, with large-scale commercial  
89 agriculture/pasture and mining dominating in much of Latin America, palm oil and  
90 pulp/paper plantations in SE Asia, and smallholder agriculture and only more  
91 recently mining and commercial agriculture/plantations driving deforestation in  
92 Africa<sup>32</sup>.

93 Estimating the carbon released from deforestation is more difficult than assessing  
94 its spatial extent. Often estimates are produced by simply multiplying the area  
95 deforested by a single carbon density per unit area value, with the result therefore  
96 very sensitive to that single value: normally this is the mean carbon density from a  
97 number of local forest inventory plots, but to be accurate they must be numerous  
98 and representative of the type of forest deforested. At a pantropical scale recent  
99 studies have improved on this by overlaying the deforestation data on continuous  
100 maps of carbon density<sup>7,32,35,37</sup>, though such methods have errors caused by their

101 carbon data having a coarser resolution than their deforestation data, and the  
102 carbon maps having potential large regional biases<sup>25,40</sup>. Overcoming these issues,  
103 there has been some consensus in recent years that the flux from gross tropical  
104 deforestation in the 2000s was 0.6-0.8 Pg C yr<sup>-1</sup> (refs 32,35).

105 In contrast, it is much harder to estimate the area affected, and carbon losses  
106 caused, by forest degradation<sup>41,42</sup>. Partly this is because degradation is caused by a  
107 wide variety of processes with different impacts, including commercial logging,  
108 fuelwood extraction, sub-canopy cultivation, grazing, fire, and edge effects caused by  
109 nearby deforestation<sup>41,43</sup>. But further it is because the only remote sensing methods  
110 that are sensitive to degradation are coarse resolution, with each pixel containing  
111 twenty to thousands of hectares<sup>4,6,7,10,14,15,36,44</sup>, and thus far exceeding the <1 ha size  
112 of most degradation events<sup>42,45</sup>. This means that estimates inevitably mix the fluxes  
113 from deforestation, forest degradation, regrowth of previously disturbed forest, as  
114 well as changes in intact forest, into a single combined change per pixel.

115 There are studies that have used inventory plots to estimate fluxes from  
116 degradation<sup>46,47</sup>, however these give numbers on a per hectare basis that are hard to  
117 scale, as we do not have maps of degradation. High resolution remote sensing from  
118 LiDAR<sup>48</sup> or Synthetic Aperture Radar<sup>45</sup>, combined with local field biomass plots, can  
119 directly map the carbon stock changes from deforestation, degradation and  
120 regrowth at a suitable resolution, but so far such studies are rare and have only  
121 been used for small areas, so cannot help much with pantropical estimates. They can  
122 however show the broad ratio between carbon losses from deforestation and  
123 degradation; though this varies widely in space and time, there is a suggestion that  
124 at a large scale degradation is responsible for perhaps twice the carbon release of  
125 deforestation, with great regional variation<sup>7,45</sup>. Further, there is agreement that  
126 degradation is more significant as a proportion of total emissions in Africa than in  
127 South America or SE Asia<sup>29,38,41,42</sup>.

128 Tropical peat forests are independently a major potential source of carbon. Peat is  
129 carbon-rich partially decayed organic matter, associated with waterlogged and

130 acidic conditions, which exists in layers up to 20 m thick under tropical swamp  
131 forests. Recent large discoveries under the forests of the Congo<sup>49</sup> and  
132 Amazon<sup>50</sup> basins has increased the known area of tropical peat by 50% to 577,000  
133 km<sup>2</sup> (combining figures from refs<sup>49,51</sup>). These peat forests have very high carbon  
134 densities, meaning they have the potential to make an outsized contribution to the  
135 global carbon cycle: about 5% of tropical forests overlay peat, but they store 70-130  
136 Pg C (ref 49), significant compared to 200-300 Pg C in all tropical trees<sup>5,23,24,25</sup>. The  
137 majority of tropical peat is in SE Asia, which has been extensively cleared and  
138 drained in recent decades (over half the area present in 1990 had been deforested  
139 or degraded by 2008<sup>52,53</sup>), therefore contributing significantly to land use change  
140 emissions by releasing 0.3-0.54 Pg C yr<sup>-1</sup> (refs 3,16). This large flux is included in the  
141 land use change numbers in Figure 1, but excluded from normal values giving the  
142 deforestation flux (e.g. refs 7,32,35,37), as such methods exclude below-ground  
143 carbon. Further, intact, degraded and drained peatlands in SE Asia have been  
144 subject to fires in El Niño years that have released much larger quantities of carbon:  
145 up to 2.5 Pg C in a single year, sufficient to cause noticeable anomalies in the  
146 atmospheric CO<sub>2</sub> growth rates<sup>10,54</sup>. In contrast, the peatlands of the Congo and  
147 Amazon basins were until recently largely undisturbed, so are not currently thought  
148 to contribute significantly to the land use change flux<sup>55</sup>.

149 Even undisturbed peatlands are however likely losing carbon due to climate  
150 change<sup>3,51,53</sup>. This is hard to monitor because satellites can only see the trees, but  
151 the vast majority of the carbon in peat forest ecosystems is instead stored in  
152 belowground as peat. Gruelling fieldwork to ascertain peat depths and extract cores  
153 for chemical analysis is a necessity to ascertain carbon stocks, but these point  
154 estimates are hard to scale to large areas due to great spatial variability<sup>49,53</sup>.

155 Tracking losses is further complicated because of the range of mechanisms through  
156 which peats can lose carbon: respiration in peats releases CH<sub>4</sub> as well as CO<sub>2</sub>;  
157 burning releases CO and C in addition to CO<sub>2</sub>; and dissolved and particulate organic  
158 carbon is washed away in rivers. There is some data on non-CO<sub>2</sub> emissions: both  
159 satellite and modelling datasets suggest that all tropical peatlands are significant

160 methane sources<sup>56</sup>, and field data suggests that both intact and disturbed peats in SE  
161 Asia have significant fluvial organic carbon transport, which has increased by >30%  
162 from 1990-2008<sup>52</sup>. While more baseline data is needed, it seems likely that climate  
163 change caused warming and droughts are resulting in peat forests being net sources  
164 of carbon<sup>3,29,51,53</sup>.

## 165 **Carbon sinks**

166 The remeasurements of millions of trees in networks of forest inventory plots  
167 across the undisturbed forests of Latin America, Africa and SE Asia suggest these  
168 forests have all been gaining carbon at a similar rate of  $\sim 0.5 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$  over the  
169 past decades, adding up to a total sink of a little over  $1 \text{ Pg C yr}^{-1}$  (refs<sup>5,13,57,58</sup>).  
170 Though it has been suggested that artefacts in plot remeasurements could lead to  
171 erroneous findings of increasing carbon storage with time<sup>59</sup>, there is also  
172 considerable evidence of a sink of around this magnitude from independent  
173 methods, such as atmospheric inversion studies<sup>4,14,15</sup>, satellite data<sup>7,36</sup>, and models<sup>17</sup>,  
174 so there is little doubt that it exists.

175 Regrowing and disturbed forest are also clearly taking in carbon from the  
176 atmosphere, but as with forest degradation, there is little reliable data on the  
177 magnitude of this sink. Studies tracking individual field plots show great variation:  
178 following total clearance there was no increase in biomass at all after 20 years at a  
179 site in Uganda<sup>60</sup>, but over  $10 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$  throughout the first ten years in moist  
180 sites in Latin America<sup>11</sup>. A meta-analysis of 1468 plots in 45 sites found average  
181 recovery rates of  $3.05 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$  for the first 20 years, and that sites regained  
182 90% of old-growth biomass values after a median of 66 years<sup>11</sup> (though biodiversity  
183 does not recover in these timescales<sup>11,42,60</sup>). As we do not have good maps of past  
184 disturbance it is hard to turn plot values into tropical estimates, but these data are  
185 consistent with inversion studies and satellite observations of a current flux with a  
186 similar magnitude to the intact forest sink (i.e.  $1 \text{ Pg C yr}^{-1}$ ), with large  
187 uncertainty<sup>3,4,5</sup>.

188

## Trends in the sources and sinks

189 Despite the uncertainties related to individual components, we do have a reasonable  
190 understanding of the carbon balance of the tropics in the recent past, with various  
191 methods agreeing that the tropics make an approximately neutral contribution to  
192 the global carbon budget<sup>3,4,7,36</sup> (Fig. 1). However, we are much less certain about  
193 how the system is changing.

194 While there is general agreement that total forest area is shrinking across the  
195 tropics, there is considerable controversy as to whether the rate of loss is rising or  
196 falling. Official figures from the Food and Agriculture Organisation (FAO, collated  
197 from national statistics) show a decline in annual net forest loss rates since  
198 2000<sup>20,38</sup>, whereas satellite-based data see an increase in the loss rate<sup>19</sup> (Fig. 2).  
199 Some of this difference can be explained by differing definitions of forest and the  
200 precise area compared, but the difference in trend is too large to be explained by  
201 these alone. It has long been known that FAO statistics are not ideal for analysing  
202 trends<sup>61</sup>: while some tropical countries probably produce very good data, their  
203 monitoring capacity is variable<sup>62</sup>. As an example, 14 African countries have reported  
204 exactly the same annual change in forest area every year from 1990 - 2015<sup>38</sup>, even  
205 though other datasets see significant changes in their rates of loss through time<sup>33</sup>.

206 On balance, the evidence from the remote sensing data sources appears more  
207 reliable than the FAO data. This is because the data from Hansen et al.<sup>19</sup> is produced  
208 consistently across the tropics; detects country-level trends where we have good  
209 alternative sources of data, for example correctly seeing the rapid reduction in  
210 deforestation in Brazil<sup>63</sup>, and the recent rapid acceleration of loss in the Democratic  
211 Republic of Congo<sup>64</sup>; and matches well to detailed high resolution data in a study  
212 comparing areas with different patterns of forest loss<sup>65</sup>. It is therefore likely that the  
213 rate of deforestation in the tropics is increasing.

214 Over the coming decades, as the global demand for agricultural, timber and mineral  
215 commodities, and local population density, continue to grow, it seems likely that the  
216 rate of forest loss will continue to increase<sup>32,63,64</sup>. Current areas that are largely

217 undisturbed due to inaccessibility, such as the peat forests of the western Amazon  
218 and the Congo, will likely become accessible and suffer deforestation<sup>55</sup>. Eventually  
219 the rate of forest loss will stabilise and start to fall, partly because the area of  
220 remaining unprotected forest will have greatly decreased, but also because the that  
221 once countries reach a sufficient level of economic development and forest loss,  
222 policy and civil society drivers result in the remaining forest area stabilising or even  
223 increasing<sup>66</sup>. However this point may come only once most forest has been lost, and  
224 even once countries reach this point (such as Vietnam, China or much of the  
225 developed world), they themselves will export deforestation to less economically  
226 developed countries as their economies demand increasing levels of commodities<sup>67</sup>.  
227 The case of Brazil makes an interesting case study here: it greatly reduced its rate of  
228 forest loss from 2005-2014<sup>19</sup>, due to reductions in global commodity prices and  
229 policy interventions<sup>63</sup>, but the rate has since increased again and could climb faster  
230 as the global demand for agricultural and mineral commodities increases, and laws  
231 promote development not forest protection<sup>63,68</sup>.

232 Forest degradation is hard to map and monitor: as discussed previously there is  
233 little hard evidence about its overall current magnitude, let alone trends, though we  
234 suspect it involves a much larger area than deforestation each year<sup>7,44,45,46</sup>. Normally  
235 degradation appears to be closely associated with deforestation<sup>44</sup>, and it is  
236 reasonable to assume in the future as the area of forest that is accessible increases,  
237 due to fragmentation caused by deforestation and road building, the area of forest  
238 degraded each year will also increase. About 20% of all tropical forest is now within  
239 100 m of an edge, with 84% of these edges anthropogenic, and this proportion will  
240 continue to increase as more anthropogenic edges are created each year than closed  
241 up<sup>43</sup>. Commercial logging, a major direct cause of degradation but also a driver of  
242 increase fragmentation and access roads, also seems likely to increase in impact as  
243 ever more logging concessions are granted<sup>41,42</sup>. Degradation due to fire may also  
244 increase with time due to climate change, as well as increasing fragmentation<sup>42</sup>.  
245 Overall it is hard to believe that the area of forest degraded each year is not  
246 increasing, nor that it will stop increasing in the near future.

247

248 As the area of degraded forest increases, so does the area of forest with the potential  
249 for regrowth; thus the proportion of the forest sink that comes from previously  
250 disturbed forest is likely to increase with time<sup>3</sup>. Disturbed forest normally takes up  
251 carbon much faster per hectare than undisturbed forest, though with high  
252 variability<sup>11,69</sup>. Under climate change the rate of growth that could be achieved by  
253 disturbed forest could increase further, due to CO<sub>2</sub> fertilization<sup>17,70</sup>. However, other  
254 factors (increased temperature, changing precipitation) could negate this effect: a  
255 specific modelling test as to whether land use change increased the land sink under  
256 an extreme CO<sub>2</sub> scenario found only one of four models predicted an increased sink,  
257 with the others showing no increased sink<sup>70</sup>. Fundamentally the size of the sink  
258 from regrowing forest is very hard to model using current knowledge, with a high  
259 level of divergence between models<sup>71</sup>. Separately, there is evidence that in the long  
260 term, once deforested, land is ultimately normally permanently converted to  
261 agriculture, pasture or settlements; and most degraded land is itself ultimately  
262 deforested<sup>72</sup>. This pattern is unlikely to change as the global economy and  
263 population continue to grow, so ultimately carbon captured in the regrowing sink  
264 may not remain captured long.

265 It is also difficult to predict how the intact forest sink will change with climate  
266 change because we know that climate change will have opposing pressures<sup>5</sup> (Figure  
267 3). Theory and modelling studies generally agree that the most likely cause of the  
268 sink is CO<sub>2</sub> fertilisation: as atmospheric CO<sub>2</sub> concentrations have risen from ~280  
269 ppm in 1850 to over 400 ppm today fixing carbon through photosynthesis is easier,  
270 with CO<sub>2</sub> concentrations in leaves increasing for a given level of stomatal opening  
271 (itself limited by water availability)<sup>17</sup>. This effect should continue as CO<sub>2</sub> levels  
272 increase<sup>8,17</sup>, but climate change will also raise temperatures, increasing soil and  
273 plant respiration rates, and droughts and fires will also increase, directly killing  
274 trees (Fig. 3). Further, deforestation and degradation will continue to reduce the  
275 area of intact forest that can act as a sink. Many studies therefore suggest that  
276 climate change could lead to a reduction in the sink strength, and ultimately its

277 reversal into a source<sup>10,73,74,75,76</sup>. There is evidence from networks of field plots that  
278 this is already happening, with the sink magnitude decreasing through time<sup>12,13</sup>.

279 However, models do not generally predict a reduction in the land sink, with many  
280 predicting the CO<sub>2</sub> fertilisation will offset the negative influence of climate change  
281 on ecosystem respiration and tree mortality<sup>8,17,70,77</sup>. For example, six coupled  
282 climate models run under the same CO<sub>2</sub> growth scenario found changes in tropical  
283 land carbon storage between 1960-2099 ranging from -11 Pg C to +319 Pg C, with a  
284 mean of +172 Pg C (Ref 8). The differences between these models is mostly caused  
285 by differences in the sensitivity of tropical vegetation to temperature, and the extent  
286 to which temperature rises due to non-CO<sub>2</sub> forcings (for example reduction in  
287 aerosol concentrations or other greenhouse gases), which do not come with the  
288 positive CO<sub>2</sub> fertilization effect<sup>8</sup>. The variability in model prediction of the current  
289 size of the intact forest carbon sink<sup>8,71,78,79</sup>, and model's lack of critical factors such  
290 as mortality of large trees caused by droughts<sup>76</sup>, makes it difficult to use model-  
291 based predictions for predicting trends in the forest sink. Therefore the best  
292 evidence is from field plots<sup>12,13</sup> and satellites<sup>6,10</sup>, which show that the intact forest  
293 sink is weakening, and becomes a source in unusually hot years, suggesting that it  
294 will likely reverse under climate change.

295 There is so little data on the carbon balance of intact peat forests that it is hard to  
296 speculate with confidence how they are changing. But it is likely that increasing  
297 temperature and variable precipitation has increased the rate of carbon loss,  
298 especially when combined with draining and other disturbance, and that such losses  
299 are likely to accelerate in future<sup>49,52,53,55</sup>. However there are high uncertainties, and  
300 an increase in basic observations of peat forests are urgently needed.

301

302

### 303 **Modelling the future of tropical carbon**

304 From recent trends, it appears likely that the current major sources of emissions  
305 (deforestation and degradation of forests, including peat forests) will at least stay  
306 stable or likely increase over the coming decades<sup>32,63,64</sup>, whereas the current sinks  
307 (from intact and regrowing forest) will likely reduce, and could reverse and become  
308 sources<sup>10,73,74,75,76</sup>. Therefore it is very likely that tropical forests will become a net  
309 source of CO<sub>2</sub> to the atmosphere in the near future, if they have not already<sup>3</sup>.

310 Estimating the size of this tropical source through time is very difficult though, even  
311 when considering a specific scenario of land use and climate change, due to complex  
312 feedbacks and interactions between different elements of the carbon cycle, climate  
313 change, people, policy and the global economy.

314 The climate modelling community has produced ever more complex models that  
315 include the complex feedbacks between land use change, climate change and intact  
316 forest<sup>71</sup>. A noticeable difference between the 4th and 5th Assessment Report of the  
317 International Panel on Climate Change (IPCC) is that the latter uses Earth System  
318 Models (ESMs) for much of its predictions, rather than Atmosphere-Ocean General  
319 Circulation Models (AOGCMs)<sup>29</sup>. ESMs include all the processes of AOGCMs, but add  
320 representations of biogeochemical cycles, including the full carbon cycle, and couple  
321 these cycles with other components allowing for feedbacks. For example,  
322 deforestation in a AOGCM simulation will increase the atmospheric CO<sub>2</sub>  
323 concentration, and change the physical properties of the ground surface, but only in  
324 an ESM will the smoke and dust released from deforestation, and their subsequent  
325 effect on atmospheric chemistry and the rate of photosynthesis of the remaining  
326 trees, be modeled<sup>71</sup>.

327 In order to standardise the inputs to modelling climate change under different  
328 scenarios to 2100, for its 5th Assessment Report the IPCC developed four  
329 Representative Concentration Pathways (RCPs)<sup>29</sup>. These are trajectories of  
330 atmospheric greenhouse gas concentration and consequent radiative forcing, and  
331 are named after the radiative forcing in the year 2100 relative to pre-industrial

332 levels in  $W m^{-2}$ : RCP2.6, RCP4.5, RCP6 and RCP8.5. They are based on underlying  
333 assumptions about social and technological development, and the extent to which  
334 climate mitigation activities take place, with RCP8.5 assuming annual fossil fuel  
335 emissions increase rapidly to about 2070 before eventually stabilising, whereas  
336 RCP2.6 assumes emissions peak by 2020 and then decrease rapidly<sup>80</sup>. Ideally it  
337 would be possible to provide confident predictions for the size of the forest sinks  
338 under these different scenarios, but unfortunately ESMS still have high variability in  
339 their predictions of the tropical carbon cycle, and cannot agree as to whether the  
340 tropical land surface will gain or lose carbon overall under the different  
341 scenarios<sup>8,81</sup>. Much of the uncertainty in tropical land surface prediction (~80%) is  
342 caused not by scenario uncertainty but differences in model structure<sup>71</sup>, specifically  
343 for the tropics dominated by differences in predictions of the effect of specific  
344 climate parameters and CO<sub>2</sub> concentration on NPP and vegetation turnover  
345 (including structural shifts, wild fires and mortality)<sup>82</sup>. It is thus urgent that we  
346 improve our knowledge of how the components of the tropical carbon cycle  
347 function, in order to better design and test such models.

## 348 **Policy impact on tropical forests**

349 The extreme RCPs (RCP2.6 and RCP8.5) assume similar levels of conversion of  
350 tropical forest to agriculture<sup>81</sup>, with the differences coming largely from the degree  
351 of fossil fuel burning. However, in reality big developments in national and  
352 international policy since the last IPCC report in 2013 have made reducing tropical  
353 deforestation and degradation, and restoring previously degraded and deforested  
354 tropical land, a key pillar of reducing climate change. This is sensible, as unless  
355 tropical deforestation and degradation is reversed the task of halting the rise in  
356 atmospheric CO<sub>2</sub> concentrations would involve decarbonising the global economy at  
357 a likely unfeasible rate<sup>21,22</sup>, and offers the possibility of a different path for the  
358 tropical carbon cycle than continuing current trends.

359 The Paris Agreement of 2015, now ratified by 176 of the 197 countries of the  
360 UNFCCC and having entered into force in 2016, aims to keep increases in global

361 average temperature to 'well below 2°C above pre-industrial levels'. It does not set  
362 specify how this should be reached, but includes a strong statement in Article 5 that  
363 countries '*should* take action to conserve and enhance ... forests'<sup>83</sup>. In order to assist  
364 developing countries with meeting Article 5, it 'encourages' all countries to engage  
365 in REDD+ ('reducing emissions from deforestation and forest degradation, and the  
366 role of conservation, sustainable management of forests and enhancement of forest  
367 carbon stocks in developing countries')<sup>83</sup>. The details of financing and monitoring  
368 have yet to be agreed, but there is significant optimism that REDD+ can succeed in  
369 increasing the area of forest, and the proportion of it that is undisturbed, compared  
370 to business as usual<sup>32,84,85</sup>. Most tropical countries have thanks to 'REDD Readiness'  
371 funding increased their capacity to monitor changes in their own forests<sup>62</sup>, and are  
372 submitting Forest Reference (Emission) Levels, official baselines against which  
373 future emissions can be compared, and plans for reducing emissions below these  
374 levels if funding is provided.

375 Though the Paris Agreement is ambitious in overall terms, its proposals on forests  
376 lack concrete detail, stating only that countries should 'take action'. However, there  
377 are other international agreements involving many or most of the same countries  
378 that are more specific. For example, the New York Declaration on Forests, signed by  
379 192 organisations including 40 governments in 2014<sup>86</sup>, aims to: "At least halve the  
380 rate of loss of natural forests globally by 2020 and strive to end natural forest loss  
381 by 2030". This was ambitious, but some believed it was achievable<sup>32</sup>. More  
382 ambitious still, the UN Sustainable Development Goals<sup>87</sup>, agreed in 2015, include as  
383 Target 15.2 an aim to "By 2020 ... halt deforestation". This was included not just  
384 because preventing climate change is a key aim of the SDGs, but because healthy  
385 tropical forests are important for the achievement of most of the 17 SDGs<sup>66</sup>. Few  
386 believe deforestation can really be stopped so fast, but these international  
387 agreements will spur at least some countries to enact policies to greatly reduce their  
388 deforestation rates<sup>32,63</sup>.

389 The New York Declaration on Forests further aims to restore 150 million hectares of  
390 currently deforested or degraded land by 2020, and 350 million hectares by 2030.

391 There are worries related to these ambitious targets: there is a risk that natural  
392 grasslands will be afforested, leading to a loss of biodiversity and potentially also  
393 soil carbon<sup>88</sup>, or that agriculture will be displaced by restored forest, leading to  
394 more deforestation elsewhere<sup>89</sup>. Also many countries have not committed to meet  
395 their goal solely through natural forest (e.g. through leaving degraded land to  
396 regenerate naturally, with the greatest ecological and long-term carbon benefits),  
397 but instead will plant monocultures of exotic tree species such as teak and rubber.  
398 Nonetheless, this overall enthusiasm for restoration of forests should be positive for  
399 tropical carbon storage (Fig. 3), and if the sites are chosen well and the restoration  
400 type carefully considered, it could be highly beneficial for people and the  
401 environment<sup>21,89</sup>.

402 Looking further into the future, the Paris Agreement mandates that by the second  
403 half of this century remaining anthropogenic emissions will be balanced by sinks<sup>22</sup>.  
404 This will require a large program of capturing carbon directly from the atmosphere  
405 and storing it elsewhere<sup>29</sup>. As tropical trees are by far the most efficient carbon  
406 capture method known, a proposal called Bioenergy with Carbon Capture and  
407 Storage (BECCS) is proposed, which will generate energy through the burning of  
408 tropical plantations and store the CO<sub>2</sub> produced belowground<sup>22</sup>. To meet the  
409 negative emissions targets needed to keep global warming below 2°C by 2100,  
410 models suggest it would need to be implemented on an enormous scale (400 - 800  
411 Mha, for comparison India covers 329 Mha)<sup>22,29</sup>. This would clearly make the tropics  
412 a major carbon sink, but with negative biodiversity and ecosystem services  
413 consequences.

414 Overall, these agreements are sufficient to dramatically change current trends, and  
415 if fully implemented would increase the forest carbon storage of the tropics  
416 markedly over the coming century. However, meeting the targets would involve  
417 drastic and coordinated action from people, policy makers and companies  
418 globally<sup>32,63</sup>.

## 419 **Safeguarding tropical forest carbon**

420 The evidence suggests that unless the world makes a coordinated effort to change  
421 from its current course, deforestation, degradation and climate change will combine  
422 to make the tropics a net source of carbon to the atmosphere over the coming  
423 decades. This is despite increasing CO<sub>2</sub> levels making it easier for intact forests to  
424 photosynthesise and absorb carbon<sup>8,17</sup>. However, if we were able to stop  
425 deforestation and forest degradation, leave currently degraded forests to recover,  
426 and reforest, as targeted in international agreements, then tropical forests would  
427 instead likely become a significant carbon sink, contributing to the Paris Agreement  
428 goal of keeping mean global temperatures rises to below 2°C<sup>21,22</sup>. Keeping and  
429 restoring these forests would have further immense benefits to human wellbeing,  
430 through maintaining their biodiversity and ecosystem services<sup>66</sup>. However, two  
431 interconnected problems limit the achievement of these goals. Our spatial  
432 information on how forests are changing is poor, and a lack of field experiments  
433 means ESMS cannot predict well how forests will respond to different climate and  
434 land use change scenarios.

435 While we monitor deforestation well, we do not have good data on changes within  
436 forests. We have techniques that can observe the integrated carbon flux over large  
437 regions, but have very little knowledge of the size of the individual processes  
438 involved (such as degradation, regrowth, or the impact of droughts and fire). This  
439 makes it hard to design and implement policy: for example no country has reliable  
440 baseline figures on their rate of forest degradation<sup>62</sup>, making it hard to set targets or  
441 create policies to reduce degradation under REDD+, nor receive payments even if  
442 such policies are successful. This also limits model development and testing.

443 New satellite mission such as GEDI and OCO-3 (both planned for launch in 2018),  
444 and BIOMASS (2021) will help by producing high resolution, globally consistent  
445 maps of forest carbon stock changes for the first time. These will not only assist with  
446 targeting and monitoring policies, but also allow us to discover the magnitude of the  
447 forest sink at an unprecedented resolution (< 1km<sup>2</sup>) and how local conditions and

448 climate fluctuations influence it. However these satellites require pantropical forest  
449 inventory and airborne LiDAR data for calibration and validation. REDD+ will assist  
450 directly here: already significant funding has been spent on designing and setting up  
451 monitoring systems and capacity in developing countries<sup>62</sup>. Unfortunately the data  
452 collected is rarely made available to the international scientific community, as  
453 publishing such data is against the natural instincts of countries, who wish to  
454 protect their sovereignty (there are some exceptions, for example field and LiDAR  
455 data from recent carbon stock map of DRC is available  
456 at <http://panda.maps.arcgis.com>). Funders and scientists must persuade countries  
457 to be more open, or they will not obtain the full benefits from new satellite missions.

458 Better maps of forest carbon stocks will make a big difference, removing the current  
459 wide spread of figures on the carbon fluxes from tropical forests (Figs 1&2),  
460 supporting REDD+ and other policy efforts to reduce forest loss, and enabling the  
461 testing of ESMs and theories as to how tropical forests respond to climate  
462 fluctuations and disturbance events. However, these data will not improve our  
463 understanding of how forests will respond to climate and CO<sub>2</sub> conditions that do not  
464 currently exist, understanding that is necessary for improving ESMs. For this we  
465 need field experiments, such as those that artificially drought, warm or increase the  
466 CO<sub>2</sub> concentration of large tropical forest plots. Such experiments are expensive to  
467 run, and take many years to produce useful results<sup>76</sup>, and therefore inevitably they  
468 are almost nonexistant in the tropics<sup>90</sup>. Their development should be supported by  
469 governments, as without them there will be no data to develop and test the critical  
470 next generation of ESMs<sup>79</sup>.

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## 478 **Figure legends**

### 479 **Figure 1: Tropical forest carbon fluxes assessed using different** 480 **methods**

481 Annual fluxes (in Pg C yr<sup>-1</sup>) into and out of tropical forests for different overlapping  
482 time periods (a-c) and for a recent El Niño year (d). The net intact forest flux is  
483 shown in blue, the net flux in regrowing forest is in pink, and the deforestation and  
484 forest degradation flux (including fire) is shown in red. Panels a-c shows there is  
485 broad agreement that the tropics have made an approximately neutral contribution  
486 to atmospheric carbon stocks in the recent past, but panel d shows that in hot and  
487 dry years intact forest can become a carbon source, leading to significant net  
488 emissions from the tropics. a) Ref 5: data from networks of forest inventory plots,  
489 combined with forest area data from country surveys or ref 38. b) Ref 7: data from  
490 annual 463 m resolution optical satellite data, calibrated using LiDAR data and field  
491 plots from the mid 2000s. Intact and regrowth fluxes are not separated in this  
492 method. The figures in the study have been grossed up from biomass to total carbon  
493 stock change (i.e. including dead wood, litter, soil) using the data in Ref 5 Table 2  
494 (adding 16%). c) Ref 4: data derived from looking for overlap between atmospheric  
495 inversion, modelling and field plot estimates. d) Ref 10: data from satellites sensitive  
496 to atmospheric CO<sub>2</sub> concentrations for the 2015 El Niño year, contrasting sharply  
497 with the other estimates shown. Land use change could not be divided into separate  
498 regrowth and loss fluxes in this method.

499

### 500 **FIGURE 2: Contradiction in major forest area change datasets**

501 Satellite datasets and nationally reported statistics are in agreement about the rate  
502 of net tropical forest loss in the early 2000s, but diverge increasingly with time.

503 Orange points and trendline (quadratic OLS): net annual forest loss from a

504 systematic global satellite analysis from the University of Maryland (UMD)<sup>19</sup>,  
505 Version 1.4. Forest gain is not assigned to a particular year in this dataset, so is here  
506 distributed equally across the time period to give net figures. A forest definition of  
507 10% canopy cover in 2000 was used. Green points and trendline (linear OLS): net  
508 annual forest area change across tropical countries from the FAO FRA 2015<sup>38</sup>, as  
509 summarised in ref 20. Forest area is reported at 5-year intervals, the change has  
510 been calculated between each interval and then divided by 5 to give annual data. A  
511 variety of forest definitions are used by countries when producing these figures,  
512 with canopy cover ranging from 10-30%. This means that the total area of forest  
513 considered for 2000 is higher in the UMD dataset, and would be expected to lead to  
514 consistently slightly higher deforestation for the UMD dataset than the FAO dataset.  
515 However this difference in forest definition cannot explain the differences in trend,  
516 as only ~5% of losses in the UMD dataset are in forest with canopy cover between  
517 10 and 30 %.

518

519 **Figure 3: The impacts of climate and land use change on the**  
520 **intact forest carbon sink.**

521 The potential contrasting impacts of climate change and different land use change  
522 trajectories on the size of the intact forest carbon sink. Arrows pointing up show  
523 how climate change and policy could increase the magnitude of the sink, whereas  
524 arrows pointing down show how it will be reduced. All processes will occur to some  
525 extent, so predicting how the sink size will change is very difficult.

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## 529 **Box 1: Methods used to assess the tropical forest carbon balance**

530 **Forest inventory plots:** marked areas of forest where tree diameters are measured  
531 and species recorded, enabling estimation of tree mass<sup>91</sup>. Revisiting networks of  
532 such plots every ~5 years gives precise estimates of how forest carbon stocks are  
533 changing<sup>12,13,57</sup>, though uncertainties are increased because plots are rare and  
534 unevenly distributed, with some forest types undersampled. There are also plots  
535 that are intensively monitored to give insight into the detail of carbon allocation and  
536 use efficiency<sup>92</sup>, and rare experimental manipulations that test the response of trees  
537 to conditions that do not naturally exist<sup>76,93</sup>.

538 **Atmospheric inversions:** There is a sparse network of towers and marine  
539 measurement sites across the tropics that permanently collect greenhouse gas  
540 concentration and micro-meteorological data. These are supplemented by ship and  
541 aircraft data, and combined with atmospheric transport models to estimate the net  
542 flows of CO<sub>2</sub> into or out of the atmosphere at a broad, regional scale<sup>4,14,15</sup>.

543 **Satellites** can be used to estimate:

544 - **Forest area** Landsat satellites have been used to produce consistent  
545 estimates of forest cover change since the early 1970s. Many countries  
546 produce their own maps, and global 30m resolution forest change data are  
547 available from 2000 onwards<sup>19</sup>. However loss data are much more reliable  
548 than gain, and relating the area-based data to carbon stock changes is  
549 difficult.

550 - **Carbon stocks** A unique LiDAR satellite operating in the mid-2000s  
551 collected distributed estimates of tree height in 70 m footprints, which were  
552 combined with field plots and other satellite data to make medium resolution  
553 (500 m – 1 km pixels) carbon stock maps<sup>23,24</sup>, albeit with large  
554 uncertainties<sup>40</sup>. These maps enable estimates of emissions when combined  
555 with forest area change data<sup>35</sup>, or when produced annually<sup>7</sup>. It is also  
556 possible to estimate carbon stock changes using passive microwave remote

557 sensing<sup>36</sup>, however the resolution (1-2 times coarser) makes it impossible to  
558 separate gain and loss fluxes.

559

560 - **GHG concentration** Satellites can measure the greenhouse gas  
561 concentrations of narrow columns of the atmosphere with a precision of  
562 ~1ppm CO<sub>2</sub>. These measurements have been used to directly observe the  
563 carbon entering and leaving tropical forests, giving information about the  
564 size of the tropical forest sink and its reaction to droughts at a continental  
565 scale<sup>6,10</sup>. However cloud cover means the observations are sparse in time and  
566 space, and the coarse resolution once again means forest loss and gain fluxes  
567 cannot be distinguished.

568 **Modelling:** Given the difficulty with directly observing forest responses to rising  
569 CO<sub>2</sub> concentrations and climate changes, dynamic vegetation models are used  
570 directly to predict their responses<sup>8,17</sup>. The latest generation of models, Earth System  
571 Models (ESMs), include many more processes and feedbacks than traditional  
572 Atmosphere-Ocean General Circulation Models (AOGCMs), increasing their  
573 predictive power<sup>71</sup>. Models provide information on processes or time periods where  
574 we have no other data, and enable us to synthesise our current knowledge about the  
575 Earth system to predict the future under specific scenarios of climate and land use  
576 change<sup>22</sup>.

577

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588 **Competing interests**

589

590 The author declares no competing interests.

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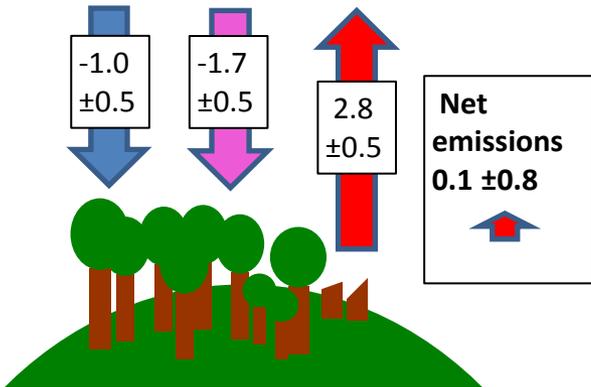
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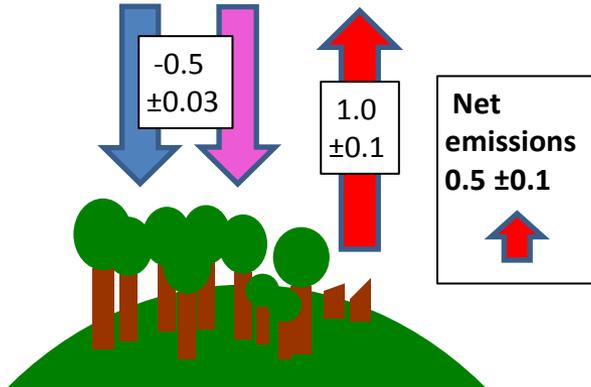
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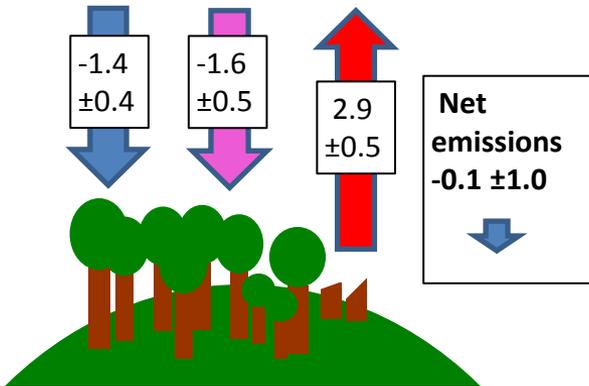
a) Forest inventory plots (2000-7)



b) RS: LiDAR + Optical (2003-14)



c) Combination (1990-2007)



d) El Niño – RS: [CO<sub>2</sub>] (2015)

