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## The tropical forest carbon cycle and climate change

Citation for published version: Mitchard, E 2018, 'The tropical forest carbon cycle and climate change', Nature. https://doi.org/10.1038/s41586-018-0300-2

#### **Digital Object Identifier (DOI):**

10.1038/s41586-018-0300-2

Link: Link to publication record in Edinburgh Research Explorer

**Document Version:** Peer reviewed version

**Published In:** Nature

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### 1 The tropical forest carbon cycle and climate change

Edward T A Mitchard

#### 3 **Preface:**

2

4 Tropical forest makes an approximately neutral contribution to the global carbon 5 cycle, with intact and recovering forests taking in as much carbon as is released 6 through deforestation and degradation. In the near future, tropical forests will likely 7 become a carbon source, due to continued forest loss and the impact of climate 8 change on the remaining forests' ability to capture excess atmospheric CO<sub>2</sub>. This will 9 make it much harder to keep global warming below 2° C. Encouragingly, recent international agreements commit to halting deforestation and degradation, but a 10 11 lack of fundamental data for monitoring and model design makes policy action 12 difficult.

13

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 and variable, such as the Land Use Change (LUC) flux<sup>1,16</sup>, making accurately 41 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 climate45 change scenarios and policy interventions.

46 Considering all sources of evidence, it appears likely that tropical forests are in the process of switching from being approximately neutral, to a net source, as the intact 47 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 faster<sup>12,13</sup>. With both forest loss and climate change likely to accelerate over this 51 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  $\sim$ 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  $CO_2$  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

and forest degradation (where some trees are removed but the area retains

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 independent maps also available and broadly consistent<sup>19,39</sup>. Deforestation affects 84 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  $0.6-0.8 \text{ Pg C yr}^{-1}$  (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 degradation<sup>46,47</sup>, however these give numbers on a per hectare basis that are hard to 116 117 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 is129 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>.

Even undisturbed peatlands are however likely losing carbon due to climate
change<sup>3,51,53</sup>. This is hard to monitor because satellites can only see the trees, but

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

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

methane sources<sup>56</sup>, and field data suggests that both intact and disturbed peats in SE
Asia have significant fluvial organic carbon transport, which has increased by >30%
from 1990-2008<sup>52</sup>. While more baseline data is needed, it seems likely that climate
change caused warming and droughts are resulting in peat forests being net sources
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  $\sim 0.5$  Mg C ha<sup>-1</sup> yr<sup>-1</sup> over the

169 past decades, adding up to a total sink of a little over 1 Pg C yr<sup>-1</sup> (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 Mg C ha<sup>-1</sup> yr<sup>-1</sup> 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 Mg C ha<sup>-1</sup> yr<sup>-1</sup> 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 does not recover in these timescales<sup>11,42,60</sup>). As we do not have good maps of past 183 184 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 Pg C yr<sup>-1</sup>), with large

187 uncertainty<sup>3,4,5</sup>.

#### 188 Trends in the sources and sinks

Despite the uncertainties related to individual components, we do have a reasonable
understanding of the carbon balance of the tropics in the recent past, with various
methods agreeing that the tropics make an approximately neutral contribution to
the global carbon budget<sup>3,4,7,36</sup> (Fig. 1). However, we are much less certain about
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  $2000^{20,38}$ , 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

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

Over the coming decades, as the global demand for agricultural, timber and mineral
commodities, and local population density, continue to grow, it seems likely that the
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.

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  $^{11,69}$ . 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  $CO_2$  fertilisation: as atmospheric  $CO_2$  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

reversal into a source<sup>10,73,74,75,76</sup>. There is evidence from networks of field plots that
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 evidence is from field plots<sup>12,13</sup> and satellites<sup>6,10</sup>, which show that the intact forest 292 293 sink is weakening, and becomes a source in unusually hot years, suggesting that it 294 will likely reverse under climate change.

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

301

#### 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  $CO_2$  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
- 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
- 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
- trees, be modeled<sup>71</sup>.
- 327 In order to standardise the inputs to modelling climate change under different
- 328 scenarios to 2100, for is 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
- are named after the radiative forcing in the year 2100 relative to pre-industrial

332 levels in W m<sup>-2</sup>: 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 ( $\sim$ 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.

The Paris Agreement of 2015, now ratified by 176 of the 197 countries of the
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 SGDs<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 deforestation rates<sup>32,63</sup>. 388

The New York Declaration on Forests further aims to restore 150 million hectares of
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 and storing it elsewhere<sup>29</sup>. As tropical trees are by far the most efficient carbon 405 406 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

The evidence suggests that unless the world makes a coordinated effort to change 420 421 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.

New satellite mission such as GEDI and OCO-3 (both planned for launch in 2018),
and BIOMASS (2021) will help by producing high resolution, globally consistent
maps of forest carbon stock changes for the first time. These will not only assist with
targeting and monitoring policies, but also allow us to discover the magnitude of the
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
- 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
- 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),
- supporting REDD+ and other policy efforts to reduce forest loss, and enabling the
- 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
- 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

Annual fluxes (in Pg C yr<sup>-1</sup>) into and out of tropical forests for different overlapping 481 482 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 forest degradation flux (including fire) is shown in red. Panels a-c shows there is 484 485 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  $\sim 5\%$  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 the520 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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527

#### 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>.

Atmospheric inversions: There is a sparse network of towers and marine
measurement sites across the tropics that permanently collect greenhouse gas
concentration and micro-meteorological data. These are supplemented by ship and
aircraft data, and combined with atmospheric transport models to estimate the net
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:

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

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

- sensing<sup>36</sup>, however the resolution (1-2 times coarser) makes it impossible to
  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  $\sim$ 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

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

change<sup>22</sup>.

577

#### 578 Acknowledgements

579

- 580 The author acknowledges partial support from NERC (grant NE/R000751/1) and
- the UK Space Agency (grant Forests 2020).

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### 588 Competing interests

- 590 The author declares no competing interests.
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### a) Forest inventory plots (2000-7)





c) Combination (1990-2007)

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





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



