



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

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](https://doi.org/10.1038/s41586-018-0300-2)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Nature

General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.



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 change¹. However, the atmospheric CO₂ stock grew by 'only' 180
23 PgC over that period², 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 forests¹, but likely between a quarter and
27 a third was due to the enhanced growth of trees in tropical forests^{3,4,5}.
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^{1,6,7,8,9}, and reverse to a source in hotter years¹⁰, 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 budget¹. 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^{5,11,12,13,14,15} or coarse resolution^{6,7,10}. 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 cycle¹; 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^{1,16}, 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^{1,3,7,17,18}. This decline is caused by a combination of the
49 decrease in the area of intact forest^{19,20}, and increasing temperatures and drought
50 reducing trees' ability to respond to higher CO₂ concentrations by growing
51 faster^{12,13}. 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^{21,22}.

54 **The carbon balance of tropical forests**

55 Living tropical trees store 200-300 Pg of carbon^{5,23,24,25}, about a third as much as is
56 held in the atmosphere¹. 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 year²⁶, but also releasing a similar amount back to the
59 atmosphere through respiration of both the plants themselves and other
60 organisms^{17,27}. Given these large fluxes, a small proportional change in either the
61 uptake or release of CO₂ 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⁻¹, about
64 1 % per year^{5,28,29}. It is clearly though that this sink has very high inter-annual
65 variability, driven by temperature and rainfall fluctuations^{16,30,31}.

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⁻¹ (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^{4,5,7}(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^{1,10} (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 maps²⁰, with large scale
84 independent maps also available and broadly consistent^{19,39}. 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^{20,39}). 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 Africa³².

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^{7,32,35,37}, 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^{25,40}. 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⁻¹ (refs 32,35).

105 In contrast, it is much harder to estimate the area affected, and carbon losses
106 caused, by forest degradation^{41,42}. 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^{41,43}. 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^{4,6,7,10,14,15,36,44}, and thus far exceeding the <1 ha size
112 of most degradation events^{42,45}. 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^{46,47}, 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 LiDAR⁴⁸ or Synthetic Aperture Radar⁴⁵, 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^{7,45}. 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^{29,38,41,42}.

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 Congo⁴⁹ and
132 Amazon⁵⁰ basins has increased the known area of tropical peat by 50% to 577,000
133 km² (combining figures from refs^{49,51}). 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^{5,23,24,25}. 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^{52,53}), therefore contributing significantly to land use change
140 emissions by releasing 0.3-0.54 Pg C yr⁻¹ (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 CO₂ growth rates^{10,54}. 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 flux⁵⁵.

149 Even undisturbed peatlands are however likely losing carbon due to climate
150 change^{3,51,53}. 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^{49,53}.

155 Tracking losses is further complicated because of the range of mechanisms through
156 which peats can lose carbon: respiration in peats releases CH₄ as well as CO₂;
157 burning releases CO and C in addition to CO₂; and dissolved and particulate organic
158 carbon is washed away in rivers. There is some data on non-CO₂ emissions: both
159 satellite and modelling datasets suggest that all tropical peatlands are significant

160 methane sources⁵⁶, 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 1990-2008⁵². 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^{3,29,51,53}.

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 Pg C yr^{-1} (refs^{5,13,57,58}).
170 Though it has been suggested that artefacts in plot remeasurements could lead to
171 erroneous findings of increasing carbon storage with time⁵⁹, there is also
172 considerable evidence of a sink of around this magnitude from independent
173 methods, such as atmospheric inversion studies^{4,14,15}, satellite data^{7,36}, and models¹⁷,
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 Uganda⁶⁰, but over $10 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ throughout the first ten years in moist
180 sites in Latin America¹¹. 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 years¹¹ (though biodiversity
183 does not recover in these timescales^{11,42,60}). 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 Pg C yr^{-1}), with large
187 uncertainty^{3,4,5}.

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^{3,4,7,36} (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^{20,38}, whereas satellite-based data see an increase in the loss rate¹⁹ (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 trends⁶¹: while some tropical countries probably produce very good data, their
203 monitoring capacity is variable⁶². As an example, 14 African countries have reported
204 exactly the same annual change in forest area every year from 1990 - 2015³⁸, even
205 though other datasets see significant changes in their rates of loss through time³³.

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.¹⁹ 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 Brazil⁶³, and the recent rapid acceleration of loss in the Democratic
211 Republic of Congo⁶⁴; and matches well to detailed high resolution data in a study
212 comparing areas with different patterns of forest loss⁶⁵. 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^{32,63,64}. 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 deforestation⁵⁵. 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 increasing⁶⁶. 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 commodities⁶⁷.
227 The case of Brazil makes an interesting case study here: it greatly reduced its rate of
228 forest loss from 2005-2014¹⁹, due to reductions in global commodity prices and
229 policy interventions⁶³, 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^{63,68}.

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^{7,44,45,46}. Normally
235 degradation appears to be closely associated with deforestation⁴⁴, 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 up⁴³. 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^{41,42}. Degradation due to fire may also
244 increase with time due to climate change, as well as increasing fragmentation⁴².
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 time³. 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 CO₂ fertilization^{17,70}. 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 CO₂ scenario found only one of four models predicted an increased sink,
257 with the others showing no increased sink⁷⁰. 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 models⁷¹. 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 deforested⁷². 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 pressures⁵ (Figure
267 3). Theory and modelling studies generally agree that the most likely cause of the
268 sink is CO₂ fertilisation: as atmospheric CO₂ concentrations have risen from ~280
269 ppm in 1850 to over 400 ppm today fixing carbon through photosynthesis is easier,
270 with CO₂ concentrations in leaves increasing for a given level of stomatal opening
271 (itself limited by water availability)¹⁷. This effect should continue as CO₂ levels
272 increase^{8,17}, 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^{10,73,74,75,76}. There is evidence from networks of field plots that
278 this is already happening, with the sink magnitude decreasing through time^{12,13}.

279 However, models do not generally predict a reduction in the land sink, with many
280 predicting the CO₂ fertilisation will offset the negative influence of climate change
281 on ecosystem respiration and tree mortality^{8,17,70,77}. For example, six coupled
282 climate models run under the same CO₂ 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-CO₂ forcings (for example reduction in
287 aerosol concentrations or other greenhouse gases), which do not come with the
288 positive CO₂ fertilization effect⁸. The variability in model prediction of the current
289 size of the intact forest carbon sink^{8,71,78,79}, and model's lack of critical factors such
290 as mortality of large trees caused by droughts⁷⁶, 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^{12,13} and satellites^{6,10}, 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^{49,52,53,55}. 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^{32,63,64}, whereas the current sinks
307 (from intact and regrowing forest) will likely reduce, and could reverse and become
308 sources^{10,73,74,75,76}. Therefore it is very likely that tropical forests will become a net
309 source of CO₂ to the atmosphere in the near future, if they have not already³.

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 forest⁷¹. 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)²⁹. 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 CO₂
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 modeled⁷¹.

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)²⁹. 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 rapidly⁸⁰. 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^{8,81}. Much of the uncertainty in tropical land surface prediction (~80%) is
342 caused not by scenario uncertainty but differences in model structure⁷¹, specifically
343 for the tropics dominated by differences in predictions of the effect of specific
344 climate parameters and CO₂ concentration on NPP and vegetation turnover
345 (including structural shifts, wild fires and mortality)⁸². 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 agriculture⁸¹, 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 CO₂ concentrations would involve decarbonising the global economy at
357 a likely unfeasible rate^{21,22}, 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'⁸³. 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')⁸³. 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^{32,84,85}. Most tropical countries have thanks to 'REDD Readiness'
371 funding increased their capacity to monitor changes in their own forests⁶², 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 2014⁸⁶, 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 achievable³². More
382 ambitious still, the UN Sustainable Development Goals⁸⁷, 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 SDGs⁶⁶. 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^{32,63}.

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 carbon⁸⁸, or that agriculture will be displaced by restored forest, leading to
394 more deforestation elsewhere⁸⁹. 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^{21,89}.

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 sinks²².
404 This will require a large program of capturing carbon directly from the atmosphere
405 and storing it elsewhere²⁹. 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 CO₂ produced belowground²². 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)^{22,29}. 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^{32,63}.

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 CO₂ levels making it easier for intact forests to
424 photosynthesise and absorb carbon^{8,17}. 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^{21,22}. Keeping and
429 restoring these forests would have further immense benefits to human wellbeing,
430 through maintaining their biodiversity and ecosystem services⁶⁶. 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 degradation⁶², 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 (< 1km²) 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 countries⁶². 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 CO₂ 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 CO₂ concentration of large tropical forest plots. Such experiments are expensive to
467 run, and take many years to produce useful results⁷⁶, and therefore inevitably they
468 are almost nonexistant in the tropics⁹⁰. 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 ESMs⁷⁹.

471

472

473

474

475

476

477

478 **Figure legends**

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

481 Annual fluxes (in Pg C yr⁻¹) 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 CO₂ 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)¹⁹,
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 2015³⁸, 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.

526

527

528

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 mass⁹¹. Revisiting networks of
532 such plots every ~5 years gives precise estimates of how forest carbon stocks are
533 changing^{12,13,57}, 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 efficiency⁹², and rare experimental manipulations that test the response of trees
537 to conditions that do not naturally exist^{76,93}.

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 CO₂ into or out of the atmosphere at a broad, regional scale^{4,14,15}.

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 onwards¹⁹. 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^{23,24}, albeit with large
554 uncertainties⁴⁰. These maps enable estimates of emissions when combined
555 with forest area change data³⁵, or when produced annually⁷. It is also
556 possible to estimate carbon stock changes using passive microwave remote

557 sensing³⁶, 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 CO₂. 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^{6,10}. 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 CO₂ concentrations and climate changes, dynamic vegetation models are used
570 directly to predict their responses^{8,17}. 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 power⁷¹. 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 change²².

577

578 **Acknowledgements**

579

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

582 **Author Information**

583 **Affiliation**

584 School of GeoSciences, University of Edinburgh, Crew Building, Alexander Crum
585 Brown Road, The King's Buildings, Edinburgh, EH9 3FF, UK.

586 **Corresponding author**

587 Correspondence to edward.mitchard@ed.ac.uk

588 **Competing interests**

589

590 The author declares no competing interests.

591

592

593

594 **References**

595 1 Le Quéré C, Andrew RM, Canadell JG, Sitch S, Korsbakken JI, Peters GP *et al.* Global
596 Carbon Budget 2016. *Earth System Science Data* 2016; **8**: 605–649. **An annually**
597 **produced analysis of the best evidence for the size and trends of the**
598 **components of the global carbon cycle.**

599 2 *Trends in atmospheric carbon dioxide, National Oceanic & Atmospheric*
600 *Administration, Earth System Research Laboratory (NOAA/ESRL).*
601 www.esrl.noaa.gov/gmd/ccgg/trends.

602 3 Grace J, Mitchard ETA, Gloor E. Perturbations in the carbon budget of the tropics.
603 *Global Change Biology* 2014; **20**: 3238–3255.

604 4 Schimel D, Stephens BB, Fisher JB. Effect of increasing CO₂ on the terrestrial
605 carbon cycle. *Proceedings of the National Academy of Sciences* 2014; **112**: 436–441.
606 **This study reconciles atmospheric inversions with models, and so confirms**
607 **there is a strong tropical carbon sink, driven by rising atmospheric CO₂.**

608 5 Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA *et al.* A large and
609 persistent carbon sink in the world's forests. *Science* 2011; **333**: 988–93. **This**
610 **paper combines evidence from thousands of global forest plots and other data**
611 **to estimate the size and location of forest sinks and sources.**

612 6 Patra PK, Crisp D, Kaiser JW, Wunch D, Saeki T, Ichii K *et al.* The Orbiting Carbon
613 Observatory (OCO-2) tracks 2-3 peta-gram increase in carbon release to the
614 atmosphere during the 2014-2016 El Niño. *Sci Rep* 2017; **7**: 13567.

615 7 Baccini A, Walker W, Carvalho L, Farina M, Sulla-Menashe D, Houghton RA.
616 Tropical forests are a net carbon source based on aboveground measurements of
617 gain and loss. *Science* 2017; **358**: 230–234.

618 8 Cox PM, Pearson D, Booth BB, Friedlingstein P, Huntingford C, Jones CD *et al.*
619 Sensitivity of tropical carbon to climate change constrained by carbon dioxide
620 variability. *Nature* 2013; **494**: 341–4.

621 9 Ma X, Huete A, Cleverly J, Eamus D, Chevallier F, Joiner J *et al.* Drought rapidly
622 diminishes the large net CO₂ uptake in 2011 over semi-arid Australia. *Scientific*
623 *Reports* 2016; **6**. doi:10.1038/srep37747.

624 10 Liu J, Bowman KW, Schimel DS, Parazoo NC, Jiang Z, Lee M *et al.* Contrasting
625 carbon cycle responses of the tropical continents to the 2015-2016 El Niño. *Science*
626 2017; **358**: eaam5690. **This study uses a satellite sensitive to atmospheric**
627 **greenhouse gas concentrations to show that all tropical forest areas released**
628 **CO₂ in response to the 2015-16 El Niño, but for different reasons.**

629 11 Poorter L, Bongers F, Aide TM, Zambrano AMA, Balvanera P, Becknell JM *et al.*
630 Biomass resilience of Neotropical secondary forests. *Nature* 2016; **530**: 211–214.

631 12 Brienen RJW, Phillips OL, Feldpausch TR, Gloor E, Baker TR, Lloyd J *et al.* Long-
632 term decline of the Amazon carbon sink. *Nature* 2015; **519**: 344–348. **Long-term**
633 **analysis of Amazon plot data shows that the intact forest sink is reducing in**
634 **size.**

635 13 Qie L, Lewis SL, Sullivan MJP, Lopez-Gonzalez G, Pickavance GC, Sunderland T *et*
636 *al.* Long-term carbon sink in Borneo's forests halted by drought and vulnerable to
637 edge effects. *Nature Communications* 2017; **8**. doi:10.1038/s41467-017-01997-0.

638 14 Peylin P, Law RM, Gurney KR, Chevallier F, Jacobson AR, Maki T *et al.* Global
639 atmospheric carbon budget: results from an ensemble of atmospheric CO₂
640 inversions. *Biogeosciences* 2013; **10**: 6699–6720.

641 15 Stephens BB, Gurney KR, Tans PP, Sweeney C, Peters W, Bruhwiler L *et al.* Weak
642 Northern and Strong Tropical Land Carbon Uptake from Vertical Profiles of
643 Atmospheric CO₂. *Science* 2007; **316**: 1732–1735.

- 644 16 van der Werf GR, Morton DC, DeFries RS, Olivier JGJ, Kasibhatla PS, Jackson RB *et*
645 *al.* CO₂ emissions from forest loss. *Nature Geoscience* 2009; **2**: 737–738.
- 646 17 Sitch S, Friedlingstein P, Gruber N, Jones SD, Murray-Tortarolo G, Ahlström A *et*
647 *al.* Recent trends and drivers of regional sources and sinks of carbon dioxide.
648 *Biogeosciences* 2015; **12**: 653–679.
- 649 18 IPCC. *Climate Change 2013: The Physical Science Basis. Contribution of Working*
650 *Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
651 *Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY,
652 USA, 2013.
- 653 19 Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A *et al.*
654 High-resolution global maps of 21st-century forest cover change. *Science* 2013; **342**:
655 850–3. **A revolutionary dataset is presented and analysed: global deforestation**
656 **maps at 30 m resolution from 2000-2012.**
- 657 20 Keenan RJ, Reams GA, Achard F, Freitas JV de, Grainger A, Lindquist E. Dynamics
658 of global forest area: Results from the FAO Global Forest Resources Assessment
659 2015. *Forest Ecology and Management* 2015; **352**: 9–20.
- 660 21 Houghton RA, Byers B, Nassikas AA. A role for tropical forests in stabilizing
661 atmospheric CO₂. *Nature Climate Change* 2015; **5**: 1022–1023.
- 662 22 Schleussner C-F, Rogelj J, Schaeffer M, Lissner T, Licker R, Fischer EM *et al.*
663 Science and policy characteristics of the Paris Agreement temperature goal. *Nature*
664 *Climate Change* 2016; **6**: 827–835.
- 665 23 Saatchi SS, Harris NL, Brown S, Lefsky M, Mitchard ET, Salas W *et al.* Benchmark
666 map of forest carbon stocks in tropical regions across three continents. *Proc Natl*
667 *Acad Sci U S A* 2011; **108**: 9899–904.
- 668 24 Baccini A, Goetz SJ, Walker WS, Laporte NT, Sun M, Sulla-Menashe D *et al.*
669 Estimated carbon dioxide emissions from tropical deforestation improved by
670 carbon-density maps. *Nature Climate Change* 2012; **2**: 182–185.

671 25 Avitabile V, Herold M, Heuvelink GBM, Lewis SL, Phillips OL, Asner GP *et al.* An
672 integrated pan-tropical biomass map using multiple reference datasets. *Global*
673 *Change Biology* 2016; **22**: 1406–1420.

674 26 Beer C, Reichstein M, Tomelleri E, Ciais P, Jung M, Carvalhais N *et al.* Terrestrial
675 Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate.
676 *Science* 2010; **329**: 834–838.

677 27 Malhi Y. The productivity metabolism and carbon cycle of tropical forest
678 vegetation. *Journal of Ecology* 2011; **100**: 65–75. **This paper presents how**
679 **tropical forests cycle carbon, and the physiological basis of how this will**
680 **change with climate change.**

681 28 Malhi Y. The carbon balance of tropical forest regions 1990-2005. *Current*
682 *Opinion in Environmental Sustainability* 2010; **2**: 237–244.

683 29 IPCC. *Climate Change 2013: The Physical Science Basis. Contribution of Working*
684 *Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
685 *Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY,
686 USA, 2013.

687 30 Poulter B, Frank D, Ciais P, Myneni RB, Andela N, Bi J *et al.* Contribution of semi-
688 arid ecosystems to interannual variability of the global carbon cycle. *Nature* 2014;
689 **509**: 600–603.

690 31 Jung M, Reichstein M, Margolis HA, Cescatti A, Richardson AD, Arain MA *et al.*
691 Global patterns of land-atmosphere fluxes of carbon dioxide latent heat, and
692 sensible heat derived from eddy covariance, satellite, and meteorological
693 observations. *Journal of Geophysical Research* 2011; **116**.
694 doi:10.1029/2010jg001566.

695 32 Zarin DJ, Harris NL, Baccini A, Aksenov D, Hansen MC, Azevedo-Ramos C *et al.*
696 Can carbon emissions from tropical deforestation drop by 50% in 5 years? *Glob*
697 *Chang Biol* 2016; **22**: 1336–47.

698 33 Achard F, Beuchle R, Mayaux P, Stibig H-J, Bodart C, Brink A *et al.* Determination
699 of tropical deforestation rates and related carbon losses from 1990 to 2010. *Global*
700 *Change Biology* 2014; **20**: 2540–2554.

701 34 Houghton RA, House JI, Pongratz J, Werf GR van der, DeFries RS, Hansen MC *et al.*
702 Carbon emissions from land use and land-cover change. *Biogeosciences* 2012; **9**:
703 5125–5142.

704 35 Tyukavina A, Baccini A, Hansen MC, Potapov PV, Stehman SV, Houghton RA *et al.*
705 Aboveground carbon loss in natural and managed tropical forests from 2000 to
706 2012. *Environmental Research Letters* 2015; **10**: 074002.

707 36 Liu YY, Dijk AIJM van, Jeu RAM de, Canadell JG, McCabe MF, Evans JP *et al.* Recent
708 reversal in loss of global terrestrial biomass. *Nature Climate Change* 2015; **5**: 470–
709 474.

710 37 Harris NL, Brown S, Hagen SC, Saatchi SS, Petrova S, Salas W *et al.* Baseline Map
711 of Carbon Emissions from Deforestation in Tropical Regions. *Science* 2012; **336**:
712 1573–1576.

713 38 FAO. Global Forest Resources Assessment 2015. Rome, 2015.

714 39 Kim D-H, Sexton JO, Townshend JR. Accelerated deforestation in the humid
715 tropics from the 1990s to the 2000s. *Geophysical Research Letters* 2015; **42**: 3495–
716 3501.

717 40 Mitchard ETA, Feldpausch TR, Brienen RJ, Lopez-Gonzalez G, Monteagudo A,
718 Baker TR *et al.* Markedly divergent estimates of Amazon forest carbon density from
719 ground plots and satellites. *Glob Ecol Biogeogr* 2014; **23**: 935–946.

720 41 de Andrade RB, Balch JK, Parsons AL, Armenteras D, Roman-Cuesta RM, Bulkan J.
721 Scenarios in tropical forest degradation: carbon stock trajectories for REDD+.
722 *Carbon Balance and Management* 2017; **12**. doi:10.1186/s13021-017-0074-0.

723 42 Bustamante MMC, Roitman I, Aide TM, Alencar A, Anderson LO, Aragão L *et al.*
724 Toward an integrated monitoring framework to assess the effects of tropical forest

725 degradation and recovery on carbon stocks and biodiversity. *Global Change Biology*
726 2015; **22**: 92–109.

727 43 Brinck K, Fischer R, Groeneveld J, Lehmann S, Paula MDD, Pütz S *et al.* High
728 resolution analysis of tropical forest fragmentation and its impact on the global
729 carbon cycle. *Nature Communications* 2017; **8**: 14855.

730 44 Chaplin-Kramer R, Ramler I, Sharp R, Haddad NM, Gerber JS, West PC *et al.*
731 Degradation in carbon stocks near tropical forest edges. *Nature Communications*
732 2015; **6**: 10158.

733 45 Ryan CM, Berry NJ, Joshi N. Quantifying the causes of deforestation and
734 degradation and creating transparent REDD+ baselines: A method and case study
735 from central Mozambique. *Applied Geography* 2014; **53**: 45–54.

736 46 Berenguer E, Ferreira J, Gardner TA, Aragão LEOC, Camargo PBD, Cerri CE *et al.* A
737 large-scale field assessment of carbon stocks in human-modified tropical forests.
738 *Global Change Biology* 2014; **20**: 3713–3726.

739 47 Andrade RB de, Balch JK, Parsons AL, Armenteras D, Roman-Cuesta RM, Bulkan J.
740 Scenarios in tropical forest degradation: carbon stock trajectories for REDD+.
741 *Carbon Balance and Management* 2017; **12**. doi:10.1186/s13021-017-0074-0.

742 48 Meyer V, Saatchi SS, Chave J, Dalling JW, Bohlman S, Fricker GA *et al.* Detecting
743 tropical forest biomass dynamics from repeated airborne lidar measurements.
744 *Biogeosciences* 2013; **10**: 5421–5438.

745 49 Dargie GC, Lewis SL, Lawson IT, Mitchard ETA, Page SE, Bocko YE *et al.* Age
746 extent and carbon storage of the central Congo Basin peatland complex. *Nature*
747 2017; **542**: 86–90.

748 50 Draper FC, Roucoux KH, Lawson IT, Mitchard ETA, Coronado ENH, Lähteenoja O
749 *et al.* The distribution and amount of carbon in the largest peatland complex in
750 Amazonia. *Environmental Research Letters* 2014; **9**: 124017.

751 51 Page S, Rieley Jo, Banks CJ. Global and regional importance of the tropical
752 peatland carbon pool. *Global Change Biology* 2011; **17**: 798–818.

753 52 Moore S, Evans CD, Page SE, Garnett MH, Jones TG, Freeman C *et al.* Deep
754 instability of deforested tropical peatlands revealed by fluvial organic carbon fluxes.
755 *Nature* 2013; **493**: 660–663.

756 53 Hooijer A, Page S, Canadell JG, Silvius M, Kwadijk J, Wösten H *et al.* Current and
757 future CO₂ emissions from drained peatlands in Southeast Asia. *Biogeosciences*
758 2010; **7**: 1505–1514.

759 54 Page SE, Siegert F, Rieley JO, Boehm H-DV, Jaya A, Limin S. The amount of carbon
760 released from peat and forest fires in Indonesia during 1997. *Nature* 2002; **420**: 61–
761 65. **This study presents evidence that the peat fires in Indonesia during the**
762 **1997 El Niño event resulted in a globally significant release of carbon.**

763 55 Roucoux KH, Lawson IT, Baker TR, Torres DDC, Draper FC, Lähteenoja O *et al.*
764 Threats to intact tropical peatlands and opportunities for their conservation.
765 *Conservation Biology* 2017; **31**: 1283–1292.

766 56 Bloom AA, Bowman KW, Lee M, Turner AJ, Schroeder R, Worden JR *et al.* A global
767 wetland methane emissions and uncertainty dataset for atmospheric chemical
768 transport models (WetCHARTs version 1.0). *Geoscientific Model Development* 2017;
769 **10**: 2141–2156.

770 57 Lewis SL, Lopez-Gonzalez G, Sonké B, Affum-Baffoe K, Baker TR, Ojo LO *et al.*
771 Increasing carbon storage in intact African tropical forests. *Nature* 2009; **457**:
772 1003–1006.

773 58 Phillips OL. Changes in the Carbon Balance of Tropical Forests: Evidence from
774 Long-Term Plots. *Science* 1998; **282**: 439–442.

775 59 Sheil D. A critique of permanent plot methods and analysis with examples from
776 Budongo Forest Uganda. *Forest Ecology and Management* 1995; **77**: 11–34.

777 60 Wheeler CE, Omeja PA, Chapman CA, Glipin M, Tumwesigye C, Lewis SL. Carbon
778 sequestration and biodiversity following 18 years of active tropical forest
779 restoration. *Forest Ecology and Management* 2016; **373**: 44–55.

780 61 Grainger A. Difficulties in tracking the long-term global trend in tropical forest
781 area. *Proceedings of the National Academy of Sciences* 2008; **105**: 818–823.

782 62 Romijn E, Lantican CB, Herold M, Lindquist E, Ochieng R, Wijaya A *et al.* Assessing
783 change in national forest monitoring capacities of 99 tropical countries. *Forest*
784 *Ecology and Management* 2015; **352**: 109–123.

785 63 Moutinho P, Guerra R, Azevedo-Ramos C. Achieving zero deforestation in the
786 Brazilian Amazon: What is missing?. *Elementa: Science of the Anthropocene* 2016; **4**:
787 000125.

788 64 Butsic V, Baumann M, Shortland A, Walker S, Kuemmerle T. Conservation and
789 conflict in the Democratic Republic of Congo: The impacts of warfare mining, and
790 protected areas on deforestation. *Biological Conservation* 2015; **191**: 266–273.

791 65 Milodowski DT, Mitchard ETA, Williams M. Forest loss maps from regional
792 satellite monitoring systematically underestimate deforestation in two rapidly
793 changing parts of the Amazon. *Environmental Research Letters* 2016; **12**: 094003.

794 66 Swamy L, Drazen E, Johnson WR, Bukoski JJ. The future of tropical forests under
795 the United Nations Sustainable Development Goals. *Journal of Sustainable Forestry*
796 2017; : 1–36.

797 67 Meyfroidt P, Lambin EF. Forest transition in Vietnam and displacement of
798 deforestation abroad. *Proceedings of the National Academy of Sciences* 2009; **106**:
799 16139–16144.

800 68 Sonter LJ, Herrera D, Barrett DJ, Galford GL, Moran CJ, Soares-Filho BS. Mining
801 drives extensive deforestation in the Brazilian Amazon. *Nature Communications*
802 2017; **8**. doi:10.1038/s41467-017-00557-w.

803 69 Bonner MTL, Schmidt S, Shoo LP. A meta-analytical global comparison of
804 aboveground biomass accumulation between tropical secondary forests and
805 monoculture plantations. *Forest Ecology and Management* 2013; **291**: 73–86.

806 70 Boysen LR, Brovkin V, Arora VK, Cadule P, Noblet-Ducoudré N de, Kato E *et al.*
807 Global and regional effects of land-use change on climate in 21st century
808 simulations with interactive carbon cycle. *Earth System Dynamics* 2014; **5**: 309–319.

809 71 Bonan GB, Doney SC. Climate ecosystems, and planetary futures: The challenge to
810 predict life in Earth system models. *Science* 2018; **359**: eaam8328. **An introduction**
811 **to ESMs, and how they can be improved.**

812 72 Gibbs HK, Ruesch AS, Achard F, Clayton MK, Holmgren P, Ramankutty N *et al.*
813 Tropical forests were the primary sources of new agricultural land in the 1980s and
814 1990s. *Proceedings of the National Academy of Sciences* 2010; **107**: 16732–16737.

815 73 Phillips OL, Aragao LEOC, Lewis SL, Fisher JB, Lloyd J, Lopez-Gonzalez G *et al.*
816 Drought Sensitivity of the Amazon Rainforest. *Science* 2009; **323**: 1344–1347.

817 74 Brando PM, Balch JK, Nepstad DC, Morton DC, Putz FE, Coe MT *et al.* Abrupt
818 increases in Amazonian tree mortality due to drought-fire interactions. *Proceedings*
819 *of the National Academy of Sciences* 2014; **111**: 6347–6352.

820 75 Ma X, Huete A, Cleverly J, Eamus D, Chevallier F, Joiner J *et al.* Drought rapidly
821 diminishes the large net CO₂ uptake in 2011 over semi-arid Australia. *Scientific*
822 *Reports* 2016; **6**. doi:10.1038/srep37747.

823 76 Rowland L, Costa ACL da, Galbraith DR, Oliveira RS, Binks OJ, Oliveira AAR *et al.*
824 Death from drought in tropical forests is triggered by hydraulics not carbon
825 starvation. *Nature* 2015. doi:10.1038/nature15539.

826 77 Betts RA, Golding N, Gonzalez P, Gornall J, Kahana R, Kay G *et al.* Climate and land
827 use change impacts on global terrestrial ecosystems and river flows in the
828 HadGEM2-ES Earth system model using the representative concentration pathways.
829 *Biogeosciences* 2015; **12**: 1317–1338.

830 78 Ahlström A, Schurgers G, Arneth A, Smith B. Robustness and uncertainty in
831 terrestrial ecosystem carbon response to CMIP5 climate change projections.
832 *Environmental Research Letters* 2012; **7**: 044008.

833 79 Stouffer RJ, Eyring V, Meehl GA, Bony S, Senior C, Stevens B *et al.* CMIP5 Scientific
834 Gaps and Recommendations for CMIP6. *Bulletin of the American Meteorological*
835 *Society* 2017; **98**: 95–105.

836 80 Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, Vuuren DP van *et al.*
837 The next generation of scenarios for climate change research and assessment.
838 *Nature* 2010; **463**: 747–756.

839 81 Ahlström A, Schurgers G, Arneth A, Smith B. Robustness and uncertainty in
840 terrestrial ecosystem carbon response to CMIP5 climate change projections.
841 *Environmental Research Letters* 2012; **7**: 044008.

842 82 Ahlström A, Xia J, Arneth A, Luo Y, Smith B. Importance of vegetation dynamics
843 for future terrestrial carbon cycling. *Environmental Research Letters* 2015; **10**:
844 054019.

845 83 UNFCCC. Article 5, Paris Agreement. 2015.

846 84 Turnhout E, Gupta A, Weatherley-Singh J, Vijge MJ, Koning J de, Visseren-
847 Hamakers IJ *et al.* Envisioning REDD+ in a post-Paris era: between evolving
848 expectations and current practice. *Wiley Interdisciplinary Reviews: Climate Change*
849 2016; **8**: e425.

850 85 Rossi V, Claeys F, Bastin D, Gourlet-Fleury S, Guizol P, Eba'a-Atyi R *et al.* Could
851 REDD+ mechanisms induce logging companies to reduce forest degradation in
852 Central Africa? *Journal of Forest Economics* 2017; **29**: 107–117.

853 86 UN. FORESTS: Action Statements and Action Plan.
854 [https://www.un.org/climatechange/summit/wp-](https://www.un.org/climatechange/summit/wp-content/uploads/sites/2/2014/07/New-York-Declaration-on-Forests_19May2014.pdf)
855 [content/uploads/sites/2/2014/07/New-York-Declaration-on-](https://www.un.org/climatechange/summit/wp-content/uploads/sites/2/2014/07/New-York-Declaration-on-Forests_19May2014.pdf)
856 [Forests_19May2014.pdf.](https://www.un.org/climatechange/summit/wp-content/uploads/sites/2/2014/07/New-York-Declaration-on-Forests_19May2014.pdf)

857 87 UN Resolution A/RES/70/1. Transforming our world: the 2030 Agenda for
858 Sustainable Development . 2015.
859 [http://www.un.org/en/development/desa/population/migration/generalassembly](http://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf)
860 [/docs/globalcompact/A_RES_70_1_E.pdf](http://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf)

861 88 Veldman JW, Silveira FAO, Fleischman FD, Ascarrunz NL, Durigan G. Grassy
862 biomes: An inconvenient reality for large-scale forest restoration? A comment on
863 the essay by Chazdon and Laestadius. *American Journal of Botany* 2017; **104**: 649–
864 651.

865 89 Latawiec AE, Strassburg BBN, Brancalion PHS, Rodrigues RR, Gardner T. Creating
866 space for large-scale restoration in tropical agricultural landscapes. *Frontiers in*
867 *Ecology and the Environment* 2015; **13**: 211–218.

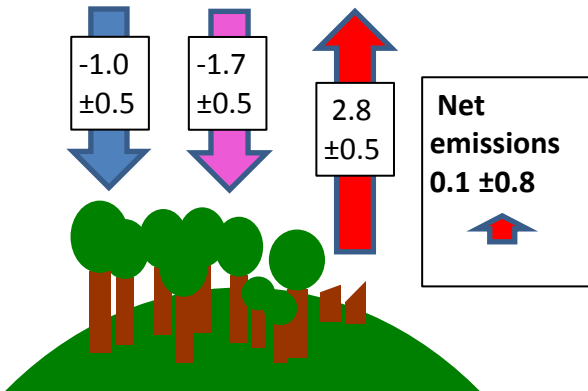
868 90 Cavaleri MA, Reed SC, Smith WK, Wood TE. Urgent need for warming
869 experiments in tropical forests. *Global Change Biology* 2015; **21**: 2111–2121.

870 91 Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan MS, Delitti WB *et al.*
871 Improved allometric models to estimate the aboveground biomass of tropical trees.
872 *Glob Chang Biol* 2014; **20**: 3177–90.

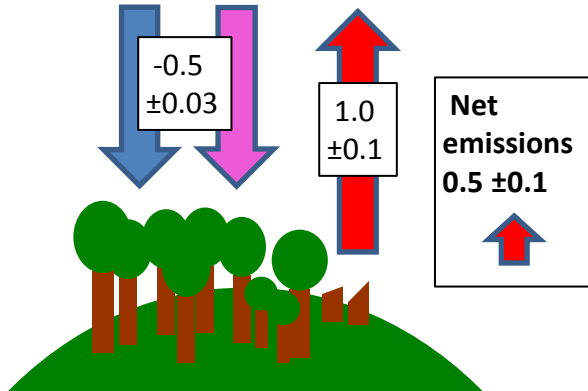
873 92 Doughty CE, Goldsmith GR, Raab N, Girardin CAJ, Farfan-Amezquita F, Huaraca-
874 Huasco W *et al.* What controls variation in carbon use efficiency among Amazonian
875 tropical forests?. *Biotropica* 2017; **50**: 16–25.

876 93 Nepstad DC, Tohver IM, Ray D, Moutinho P, Cardinot G. Mortality of large trees
877 and lianas following experimental drought in an amazon forest. *Ecology* 2007; **88**:
878 2259–2269.

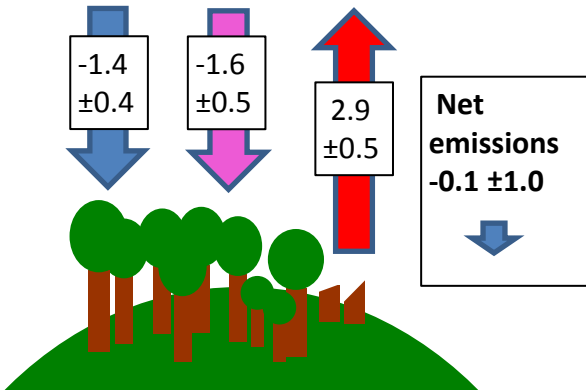
a) Forest inventory plots (2000-7)



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



c) Combination (1990-2007)



d) El Niño – RS: [CO₂] (2015)

