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Old-growth forest loss and secondary forest recovery across Amazonian countries

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1 Title
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27 Abstract

28 There is growing recognition of the potential of large-scale forest restoration in the Amazon as a “nature-based
29 solution” to climate change. However, our knowledge of forest loss and recovery beyond Brazil is limited, and carbon
30 emissions and accumulation have not been estimated for the whole biome. Combining a 33-year land cover dataset
31 with estimates of above-ground biomass and carbon sequestration rates, we evaluate forest loss and recovery across
32 nine Amazonian countries and at a local scale. We also estimate the role of secondary forests in offsetting old-growth
33 deforestation emissions and explore the temporal trends in forest loss and recovery. We find secondary forests across
34 the biome to have offset just 9.7% of carbon emissions from old-growth deforestation, despite occupying 27.6% of
35 deforested land. However, these numbers varied between countries ranging from 9.0% in Brazil to 23.8% in Guyana for
36 carbon offsetting, and 24.8% in Brazil to 56.9% in Ecuador for forest area recovery. We reveal a strong, negative spatial
37 relationship between old-growth forest loss and recovery by secondary forests, showing that regions with the greatest
38 potential for large-scale restoration are also those that currently have the lowest recovery (e.g. Brazil dominates
39 deforestation and emissions but has the lowest recovery). In addition, a temporal analysis of the regions that were
40 >80% deforested in 1997 shows a continued decline in overall forest cover. Our findings identify three important
41 challenges: (1) incentivising large-scale restoration in highly deforested regions, (2) protecting secondary forests
42 without disadvantaging landowners who depend on farm-fallow systems, and (3) preventing further deforestation.

43 Combatting all these successfully is essential to ensuring that the Amazon biome achieves its potential in mitigating
44 anthropogenic climate change.

45 Introduction

46 Deforestation is a major and ongoing threat, with an estimated 4.2 million km² of global forests cleared since
47 1990 (FAO and UNEP 2020). Across the world tropical deforestation represents around 8% of all anthropogenic
48 emissions (Seymour and Busch 2016), while deforestation and land-use change combined contribute the majority
49 of carbon emissions in most tropical forest countries. However, tropical forests are fundamental to the world's
50 climate crisis not only as a source of emissions, but also as a means for capturing atmospheric carbon. Secondary
51 forests growing on previously deforested land are rapidly sequestering carbon and providing refuge for many
52 forest dependant species. While old-growth forests are undeniably more valuable than secondary forests, both in
53 terms of biodiversity and carbon storage (Gibson *et al* 2011, Berenguer *et al* 2014), there is growing recognition of
54 the potential of large-scale tropical forest restoration as a "nature-based solution" to climate change mitigation
55 (UN 2019) and of its importance for meeting the ambitious emissions targets of the Paris agreement (Grassi *et al*
56 2021).

57

58 The Amazon biome has been recognised by researchers and policymakers alike for its key role in future climate
59 policy for two main reasons. First, the Amazon biome stores an estimated 86 Pg of carbon (Saatchi *et al* 2007),
60 making it one of the world's largest carbon strongholds (Saatchi *et al* 2011). Unchecked, deforestation could
61 convert much of this carbon stock into emissions (Gatti *et al* 2021), significantly accelerating climate change. The
62 Brazilian Amazon has witnessed amongst the highest absolute rates of deforestation in the tropics, with a notable
63 increase in recent years (PRODES 2020), placing Brazil in the top 10 emitters in the world (World Resources
64 Institute 2021). Second, compared with other tropical regions, the Amazon could be ideal for forest restoration as
65 it has low population densities (Cunningham and Beazley 2018), extensive areas of unproductive or unprofitable
66 agricultural systems (Garrett *et al* 2017, 2021), and moderate to high carbon sequestration rates (Requena Suarez
67 *et al* 2019). However, patterns of forest loss and recovery, and their impact on the carbon balance have not been
68 estimated for the whole biome. Our understanding has previously focused on Brazil (e.g. Smith *et al* 2020), which
69 only makes up 60% of the Amazon biome. The contribution of the other seven countries (Bolivia, Colombia,
70 Ecuador, Guyana, Peru, Suriname, Venezuela) and the French overseas territory (French Guiana; henceforth
71 included in the collective 'countries') is much less well understood. With recent studies showing increasing
72 occurrences of deforestation hotspots outside Brazil (Kalamandeen *et al* 2018), the need to expand our
73 knowledge beyond Brazil grows more critical. Furthermore, forest recovery also varies greatly over space and
74 time (Smith *et al* 2020, Chazdon *et al* 2020), making it crucial to understand where forests are already recovering
75 and how this recovery differs both across political units and on finer spatial scales, so that active restoration
76 efforts and novel policy incentives can be targeted effectively. Despite restoration offering a growing opportunity
77 to mitigate anthropogenic emissions (Chazdon *et al* 2016, Matos *et al* 2020), to date, we are not aware of any

78 analysis examining patterns of forest loss and recovery across Amazonia at both national and subnational level,
79 which are the relevant scales for policy interventions promoting restoration..

80

81 Here, we combine a 33-year land-use dataset (i.e. MapBiomas Amazonia 2; 1985-2018) with estimates of above-
82 ground biomass (AGB) (Avitabile *et al* 2016) and forest regrowth potential (Requena Suarez *et al* 2019) to
83 evaluate the distribution of forest loss and recovery across the nine countries and nine Brazilian states that
84 intersect the Amazon biome. We ask three questions. (1) What is the current (2017) extent of old-growth
85 deforestation and forest recovery, and their associated impact on the Amazonian carbon balance? We estimate
86 carbon emissions from forest loss and carbon accumulation from secondary forest growth (i.e. forest growing on
87 previously deforested land) across the Amazon biome and its major political units. (2) What is the geographic
88 relationship between old-growth deforestation and secondary forest recovery? We examine this at the country-
89 and state-level, and then at a finer resolution using a ~60 km² grid. (3) How have the rates of old-growth
90 deforestation and secondary forest recovery varied over the last two decades? We discuss our results in light of
91 the challenges of avoiding further deforestation and achieving large-scale forest restoration across Amazonia.

92 Results

93 Old-growth deforestation extent and carbon emissions

94 By 2017, we found that 813,944 km² of old-growth forest (OG) in the Amazon biome had been cleared (Table 1).
95 Brazil has seen the greatest loss in OG area both in absolute terms (689,451 km²; **Figure 1a**) and proportional to
96 its Amazonian extent (17.6%; **Figure 1b**). Two-thirds of Brazil's nine Amazonian states have an absolute area of
97 deforestation exceeding that of any of the other countries (**Figure 1a**); the deforested area in Pará state alone is
98 more than double that of all other countries combined (Pará: 262,869 km²; other countries: 124,493 km²; **Figure**
99 **1a**). By 2017, OG deforestation across the Amazon biome had resulted in the loss of 6.33 Pg C from AGB, emitting
100 the equivalent of 23.22 Pg CO₂ (Table 1). Brazil contributed 79.9% of all OG deforestation emissions (5.06 Pg C;
101 **Figure S1**). Ecuador had the greatest percentage loss of carbon relative to its original OG above-ground carbon
102 stock (12.3%), but this represents just 2.2% of total emissions. The Brazilian states of Pará, Mato Grosso and
103 Rondônia exceed the emissions of any other individual Amazonian country (Table 1).

104

105 Secondary forest extent, age, residence time and carbon accumulation

106 In 2017, secondary forests (SF) covered 234,795 km² of land in the Amazon biome, accounting for approximately
107 4.1% of the total forest cover (Table 1). 76.8% of Amazonian SF was in Brazil (180,215 km²; **Figure 1c**), with 10.9%
108 in Peru (25,579 km²; **Figure 1c**), and 4.7% in Colombia (11,055 km²; **Figure 1c**). Making up 5.3%, 3.7% and 2.5% of
109 each country's total forest cover respectively (Table 1). The majority (78.2%) of all SF was less than 20-years old
110 and the median age was 8 years. Very young SF (≤5 years old) accounted for 35.9% of all cover. This skewed age
111 distribution was apparent in the majority of countries (**Figure S3**). Guyana and Suriname were the only countries
112 with significantly different age distributions with large spikes in 18 to 24-year-old SF (Dunn's post-hoc test:

113 P<0.05; Figure S5), although this could be an artifact of poor temporal data availability in these countries (SI). As
114 our time series began in 1985, the maximum detectable age of SF is 32 years. However, the skewed distribution of
115 forest ages suggests that very little forest would have exceeded this maximum detectable age (Figure S2). Across
116 the Amazon biome, during the period 1997-2017, the majority (70.0%) of SF cleared was 5-years old or less and
117 the median residence time (from the start of SF regrowth to clearance) was just 2 years. There were no significant
118 differences in the distribution of residence times across countries or states (SI). SF present in 2017 had
119 accumulated 0.62 ± 0.11 Pg C, equivalent to 2.26 ± 0.41 Pg CO₂. SF deforestation has resulted in the loss of 38.9%
120 (391.65 ± 94.62 Tg C) of all carbon accumulated by SF between 1985 and 2017.

121

122 **Spatial relationships between deforestation and recovery**

123 In 2017, carbon accumulated in SF had offset less than 30% of OG deforestation emissions in every Amazonian
124 country or Brazilian state we assessed (Table 1). Across the Amazon biome as a whole just $9.7 \pm 1.8\%$ of carbon
125 emissions had been offset, despite 28.8% of deforested land being occupied by SF. Forest area recovery (defined
126 here as the percentage of deforested land occupied by SF) varied across countries and Brazilian states. Brazil had
127 the lowest forest area recovery (24.8%) of any Amazon country, while Ecuador and Amapá state had the greatest
128 forest area recovery, with SF occupying 56.9% and 69.1% of deforested land, respectively (**Figure 2a**). Carbon
129 recovery (defined here as the percentage of emissions from OG deforestation offset by carbon accumulation in
130 SF) also varied greatly between countries, with the lowest in Brazil (7.7%) and the highest in Guyana (23.8%;
131 **Figure 2c**).

132

133 Across countries and states, there were significant negative relationships between deforestation and recovery,
134 which followed linear or L shaped trends (**Figure 2a,c**; Table S3; see Methods). As such, countries or states with a
135 high percentage loss of OG typically have a low forest area recovery, while those which have lost less OG have a
136 higher forest area recovery (**Figure 2a**). For example, Ecuador, which was 12.7 % deforested in 2017, had the
137 greatest forest area recovery (56.9%), while Brazil, which was 17.6% deforested, had the lowest forest area
138 recovery (24.8%; **Figure 2a**). The extremes are more accentuated across Brazilian states: Tocantins had 82.9% OG
139 deforestation and just 18.5% forest area recovery, while Amapá had 4.0% OG deforestation and 69.1% forest area
140 recovery (**Figure 2a**). These spatial patterns of loss and recovery were even more pronounced for losses and gains
141 of above-ground carbon stocks (**Figure 2c**).

142

143 These relationships between OG deforestation and SF recovery (and their resulting carbon balance) were also
144 spatially linked at a local scale. A gridded analysis revealed strong negative, non-linear relationships that were
145 well described by broken-stick regression with two segments (**Figure 2b,d**; Table S4). Of the cells that had
146 experienced some OG deforestation (>0.01% forest loss), the majority (62.8%) were characterised by low
147 deforestation (<50% forest loss) with high forest area recovery (>50% of deforested area), and just 1.1% of cells
148 exhibit both high deforestation (>50%) and high forest area recovery (>50%; **Figure 2b**; **Figure 4c-d**). Moreover,

149 cells with very high deforestation in 1997 ($\geq 80\%$; $n=1919$) typically did not show increased recovery over time
150 (1997-2017; Figure 3) with a median change in total forest cover of -1.0% . Over half (56.2%) of these cells saw
151 further decline in total forest cover, while those that did increase ($n=843$) only did so by an average of 4.6%
152 (median). Finally, any small increases in secondary forest cover were more than offset by the continues loss of old
153 growth forest. These trends were even more pronounced for carbon, with high carbon recovery only occurring in
154 cellss with the smallest losses from OG deforestation (Figure 2d; Figure 4g-h). Mapping these data revealed clear
155 patterns in the distribution of the percentage of both OG loss and SF recovery (Figure 4). As expected, the highest
156 levels of OG deforestation were concentrated in the south and east, forming the well-characterised 'arc of
157 deforestation' (Figure 4). This contrasted with the spatial patterns for SF, where recovery of extent and carbon
158 stocks was highest in areas of low deforestation or low carbon losses (Figure 4e-f).

159

160 **Temporal trends in deforestation and recovery**

161 The annual trend in OG deforestation between 1997 and 2017 was best described by a broken-stick regression
162 with three segments (Table S1); the most recent of which (2009-2017) showed an increase in the annual rate of
163 deforestation from a low of $9,918 \text{ km}^2$ in 2013 to $11,899 \text{ km}^2$ in 2017 (Figure 5a). This reversed the previous trend
164 in which annual OG loss declined by more than half from $29,806 \text{ km}^2$ in 2002.

165

166 We found no temporal trend in the area of new SF from 1997 to 2017, which was on average $22,882 \pm 2,247 \text{ km}^2$
167 per year (mean \pm SD; Figure 5c). In contrast, the extent of SF deforestation has increased over time, from $15,775$
168 km^2 in 1997 to $17,750 \text{ km}^2$ in 2017, and is well described by a linear trend (Figure 5c; Table S1). However, there
169 was no temporal trend in net change in SF area (Table S1), which fluctuated between plus $10,263 \text{ km}^2$ and minus
170 $1,961 \text{ km}^2$ with a mean of plus 5490 km^2 .

171

172 OG deforestation emissions decreased from 0.82 Pg CO_2 in 2004, to a low of 0.40 Pg CO_2 in 2010, before
173 increasing to 0.56 Pg CO_2 in 2017 (Figure 5b), best described by a broken-stick model with two segments (Table
174 S2). Annual carbon accumulation from the expansion and growth of SF increased from 1997 to 2017 and is well
175 described by a linear trend (Table S2). It was typically 2.42 ± 0.3 times (mean \pm sd) the carbon emitted by SF
176 deforestation each year (Figure 5d), which was best described by a broken stick model with two segments. SF net
177 annual carbon accumulation increased linearly from 65.91 Tg CO_2 in 1997 to 103.91 Tg CO_2 in 2017 (Figure 5d,
178 Table S2). The trend in annual OG deforestation emissions offset by net annual secondary forest carbon
179 accumulation (i.e. carbon recovery) was described by a broken stick regression with three segments (Table S2). It
180 remained below 15% until 2007, then peaked at 26.1% in 2013 before declining again.

181 Discussion

182

183 We conduct the first comparison of forest loss and recovery across national and sub-national political boundaries
184 in Amazonia, analysing its impact on the carbon balance and exploring recent temporal trends. We found that,

185 across the biome, SF offset just 9.7% of carbon emissions from OG deforestation despite occupying 28.9% of
186 deforested land. We also reveal a strong, negative spatial relationship between OG deforestation extent and
187 recovery by SF, with high recovery unlikely where a greater percentage of OG has been cleared, even decades
188 after deforestation. These findings show there are clear barriers to recovery in landscapes that have been highly
189 deforested, likely reflecting both biophysical limitations and socio-economic drivers (Crouzeilles *et al* 2020, Curtis
190 *et al* 2018). Interestingly, the lack of increase in forest cover in highly deforested landscapes suggests Amazonian
191 forest-agriculture dynamics are very different from those in the Brazilian Atlantic forest, where distance to closest
192 forest was an important predictor of natural regeneration from 1995-2016 (Crouzeilles *et al.* 2020). Building upon
193 recent work in the Brazilian Amazon (Smith *et al* 2020, Nunes *et al* 2020, Silva Junior *et al* 2020), we use the newly
194 expanded MapBiomas land cover dataset to look beyond changes in Brazil and examine trends across the entire
195 Amazon biome.

196

197 By providing measures of OG deforestation and SF recovery specific to each Amazonian country, our study reveals
198 high variation across political boundaries. Some countries, such as Ecuador, demonstrate much greater levels of
199 recovery than the Amazon biome as a whole, while in other countries and Brazilian states recovery is much lower.
200 As expected, we find that Brazil is dominating Amazonian deforestation and emissions (85.4%; 79.9%), but its
201 dominance also goes beyond that expected by the portion of the Amazon biome it contains. For example, Pará
202 state alone has contributed more deforestation than that of all other Amazonian countries combined.
203 Furthermore, Brazil has the lowest forest area recovery, with just 24.8% of deforested land occupied by SF,
204 compared to 28.8% for the Amazon biome as a whole and a range of 28.8–56.9% amongst the other countries.
205 These trends were even more marked when we analysed the percentage of carbon emissions resulting from OG
206 deforestation that have been offset by SF carbon accumulation. Despite growing awareness of deforestation in
207 other Amazonian countries (Kalamandeen *et al* 2018), these findings make it clear that combating land-use
208 change in Brazil remains fundamental to efforts to mitigate global climate change. However, the Brazilian
209 Amazon's high deforestation rates – including the recent uptick in deforestation that was not covered by the time
210 series we analysed (PRODES 2020) – and its low percentage of restoration also suggest that there are major
211 institutional and social barriers to overcome (Arima *et al* 2014). These are exacerbated by issues of governance,
212 with the current Brazilian administration being accused of encouraging deforestation by weakening policies,
213 undermining forest monitoring, cutting resources for environmental law enforcement (Barlow *et al* 2020, Vale *et*
214 *al* 2021) and censoring scientific publications (Escobar 2021).

215

216 Our findings show that OG deforestation emissions are outstripping SF carbon accumulation across the Amazon
217 biome, with less than a third of emissions offset in every country or state we assess and less than 10% for the
218 biome as a whole. These findings confirm the need to prioritise halting deforestation and to preserve remaining
219 OG. However, it is widely accepted that in order to mitigate climate change reducing emissions is not enough,
220 and we must also recapture carbon from the atmosphere (Griscom *et al* 2017, Houghton *et al* 2015, Edenhofer *et*

221 *al* 2014), with SF growth suggested as an efficient and cost-effective method to do so (Rogelj *et al* 2018, Lubowski
222 and Rose 2020). Our analysis provides some important insights into the challenges of large-scale forest
223 restoration.

224

225 First, the negative relationship between OG deforestation and forest area recovery demonstrates the difficulty of
226 increasing SF cover in low-OG cover landscapes, despite them having the greatest potential for large-scale
227 recovery of forest cover. The scale of the challenge is clear from our assessment of landscapes with >80%
228 deforestation in 1997; which show no evidence of forest recovery over time. Many of these highly-deforested
229 landscapes were in Brazil (see S.I. map), showing that the National Vegetation Protection Law (and the previous
230 Forest Code) has not helped enhance forest cover in these regions. These findings highlight the importance of
231 new incentives and targeted policy interventions for increasing SF in low-OG cover landscapes. Policies must be
232 targeted locally and regionally as well as nationally, and could build on some of the ambitious state-level plans for
233 achieving carbon neutrality, such as Pará's State Plan for the Amazon Now (Plano Estadual Amazônia Agora,
234 Decree nº 941, 03/08/2020). Although SF growth rates may be lower in these highly deforested regions than
235 those proposed by Requena Suarez *et al.* (2019) (e.g. Elias *et al.*, 2019; Heinrich *et al.*, 2021), restoration in these
236 regions could also deliver important co-benefits, such as regulating local temperatures and stream flows as well
237 as providing habitat for a number of species (Lennox *et al* 2018) including some of the most threatened in the
238 Amazon such as the Critically Endangered Belém curassow (*Crax [fasciolata] pinima*), black-winged trumpeter
239 (*Psophia obscura*), and the Kaapori capuchin (*Cebus kaapori*). Furthermore, assisted natural regeneration could
240 help encourage forest recovery where natural regeneration is limited by a lack of seed dispersal from adjacent
241 forests or the intensity of previous land uses (Shono *et al* 2020, Chazdon *et al* 2020, Jakovac *et al* 2021).

242

243 Second, the young SF age and low carbon offsets found across the biome highlight the importance of addressing
244 the high turnover rates and low residence times of SF (Jakovac *et al* 2017, Schwartz *et al* 2020), which result in the
245 loss of huge quantities of carbon annually (Wang *et al* 2020, Smith *et al* 2020, Tyukavina *et al* 2017).
246 Implementing and enforcing policies to protect SF from deforestation could substantially increase their
247 effectiveness as long-term carbon stores (Chazdon and Guariguata 2016). For example, following the
248 accumulation rates reported by Requena Suarez *et al.* (2019), preserving the 2017 extent of SF (234,795 km²)
249 would result in the accumulation of 3.3±0.5 Pg C by 2050. However, any such policy needs to be carefully
250 implemented as the use of forests as fallows is crucial for the livelihoods of many Amazonian smallholders and
251 traditional peoples (Porro *et al* 2015) and some SF clearance may buffer against further OG loss (Wang *et al*
252 2020). Furthermore, the temporal consistency of the net increase in SF indicates that it is less sensitive to socio-
253 economic events than OG deforestation, suggesting that instigating change may be difficult.

254

255 This study used three up-to-date resources to quantify forest cover dynamics and their resulting effects on carbon
256 balance (Methods). Yet important uncertainties remain. First, while this study focuses on emissions from

257 deforestation, it is important to note that forest degradation, which affects up to 17% of forest cover (Bullock *et*
258 *al* 2020), is also resulting in huge losses of carbon from OG (Bullock and Woodcock 2021). As our biomass map
259 was from the early 2000s, the carbon emissions from OG deforestation reported in this study may be over-
260 estimated as some of the above-ground carbon will have already been lost to prior disturbance. Recent advances
261 in assessing forest disturbance (e.g. Matricardi *et al.*, 2020; Qin *et al.*, 2021) are restricted to the Brazilian
262 Amazon, but demonstrate the importance – and complexity (Silva *et al.* 2020) - of estimating it across decadal
263 time-scales. Second, we used above-ground biomass accumulation rates from Requena Suarez *et al.* (2019) to
264 estimate the SF carbon accumulation. However, this is likely to over-estimate recovery in the more deforested
265 and drier regions of the ‘arc of deforestation’ (e.g. Elias *et al.*, 2019; Heinrich *et al.*, 2021). As such, Brazil’s
266 contribution to carbon recovery may be over-estimated in our analysis, increasing its contribution to net carbon
267 emissions.

268

269 Although our analysis shows a pan-Amazonian uptick in deforestation in recent years, it also helps highlight
270 moments in space and time that can be used to guide more positive actions. For example, the huge reduction in
271 Brazilian OG deforestation from an all-time high in 2004 to an all-time low in 2012 is a demonstration of what can
272 be achieved with well-implemented policy (PRODES 2020, Boucher *et al* 2013, Saraiva *et al* 2020). Furthermore,
273 although instigating change in Brazil will be key to restoration efforts within the Amazon biome, an understanding
274 of what is enabling other countries to achieve greater levels of recovery could also help guide policy interventions
275 across the Amazon biome (Latawiec *et al* 2014). For example, the high levels of recovery in Ecuador and Amapá
276 demonstrates that there are contexts where recovery is occurring, and there may be valuable lessons to be
277 learned from previous and ongoing success. However, future research needs to go beyond mapping forest cover
278 change and examine the socio-economic conditions which are key to restoration success (Rudel *et al* 2016, Aide *et*
279 *al* 2013, Grau *et al* 2003). Quantifying the role of policy as driver of the relationships outlined in this study would
280 be a valuable next step and should be a priority for future research in this field. Finally, the strong negative
281 patterns of recovery found consistently across geographic scales show that the regions with the greatest potential
282 for large-scale restoration are also those that currently have the least amount of recovery. The new challenge
283 facing policy makers is how to incentivise large-scale restoration in these regions in order to break this trend.
284 Doing so successfully is essential to ensuring that the Amazon biome achieves its potential in mitigating
285 anthropogenic climate change.

286 **Methods**

287 **Old-growth and secondary forest extent**

288 We use the MapBiomas Amazonía 2 dataset to assess deforestation and SF extent for the Amazon Biome (SI). By
289 using the MapBiomas dataset we were able to exclude forestry plantations, which is important for evaluating
290 changes in SF extent. We reclassify the MapBiomas schema into: forest, pasture, cropland and other, then use a
291 change detection algorithm to produce annual maps of the extent of OG and SF cover across the Amazon biome

292 (SI). Any pixel (900 m²) classified as 'forest' in the first year of the time series (1985) was considered to be OG until
293 it transitioned to 'non-forest'. Pixels that transitioned from 'non-forest' to 'forest' were classified as SF. As the
294 MapBiomas time series begins in 1985, any SF that began growing before this date is included in our OG class (SI).
295 Our method is based on the approach previously described by Smith et al (2020). All code is available here: [GIT
296 HUB LINK].

297

298 **Secondary forest age and residence time.**

299 We measured SF age as the number of consecutive years a pixel was classified as SF in our annual maps of forest
300 cover. Due to incomplete data coverage in some regions this should be considered a "minimum" age estimate
301 rather than a precise measure (SI). We measured SF residence time as the age of SF at clearance. We conducted
302 Kruskal-Wallis tests to determine if SF age or residence time (for SF cleared 1997 to 2017) differs between
303 countries and Brazilian states. To avoid assigning significance to small effect sizes due to large samples, we used a
304 sample size of 100. We repeated this process 10,000 times and recorded the mean p-value. Brazil was excluded
305 from the analysis in favour of its component states to avoid pseudo-replication. Where the Kruskal-Wallis test was
306 significant, we conducted Dunn's post-hoc tests to identify which pairs of countries or states had different
307 distributions. We do not explore the dynamics of repeated clearances or "third-growth" forests in this study as
308 less than 0.04% of deforested pixels had been cleared multiple times during the study period.

309 **Calculating above-ground carbon**

310 *Old-growth forest:* We calculated AGB in OG using the Avitabile et al. (2016) 1-km resolution pan-tropical AGB
311 map, which we downscaled to match the 30-m resolution MapBiomas land cover data. For areas deforested
312 before 2010, prior to the most recent dataset used by Avitabile et al. (2016), we interpolate AGB using the
313 *KNNImputer* function from the Python package *sklearn*, which infills missing values with the mean of a pixel's
314 twenty nearest neighbours. We converted AGB to carbon stock using the Intergovernmental Panel on Climate
315 Change (IPCC) conversion factor of 0.47 g C (g biomass)⁻¹ (Eggleston *et al* 2006). For the purposes of this study, we
316 assume above-ground carbon to be static as, although OG are accumulating carbon, it is at a very slow rate (~1
317 Mg ha⁻¹ year⁻¹; Requena Suarez et al, 2019). Due to the complexity of mapping the intensity of disturbance in OG
318 over large spatial scales, accounting for the impact of degradation on carbon stocks was beyond the scope of this
319 study. Therefore, we may be over-estimating carbon emissions from deforestation. Below-ground carbon is
320 estimated to contribute an additional 25% to tropical forest carbon stocks (Luysaert *et al* 2007), but its
321 assessment was also beyond the scope of this study.

322

323 *Secondary forest:* We estimate SF AGB using our maps of SF age in conjunction with the Requena Suarez et al.
324 (2019) biomass accumulation rates for old (>20 years) and young (<20 years) SF. We converted AGB values to
325 carbon stock as above (conversion factor: 0.47). Carbon accumulation rates can vary greatly in response to local
326 climatic, environmental and disturbance factors (Elias *et al* 2019, Poorter *et al* 2016), but to date analyses
327 calculating local scale accumulation rates have been limited to the Brazilian Amazon (Heinrich *et al* 2021). As our

328 study encompasses the entire Amazon biome, we opted to use the baseline carbon accumulation rates calculated
329 by (Requena Suarez *et al* 2019) for the FAO Ecozones (FAO 2012). Four ecozones intersect our study area: tropical
330 rainforest (~61.7%), tropical moist forest (~25.6%), tropical montane forest (~11.7%) and tropical dry forest
331 (~1.0%).

332

333 **Deforestation extent and emissions**

334 Using the change in forest cover captured by our analysis of MapBiomas, we calculated the annual extent of OG
335 and SF deforestation and the associated carbon emissions. For each forest type, we applied an exponential decay
336 of 0.49 (van Leeuwen *et al* 2014) to our estimate of the pixel's above-ground carbon in order to extend emissions
337 from a deforestation event over several years, as is seen in long-term assessments of AGB loss on deforested land
338 (e.g. Berenguer *et al.*, 2014). Above-ground carbon was converted to carbon dioxide equivalent using the
339 conversion factor 3.67. For pixels classified as cropland or pasture in the first year of our time series (1985), we
340 calculate emissions as if the pixels were cleared in 1984. While this means that some of the pixels are assumed to
341 have been cleared more recently than they actually were, the impact of this on our estimates of OG deforestation
342 emissions is negligible as, by the most recent year of our analysis (2017), more than 99.99% of the carbon they
343 contained is accounted for. We report variation in SF emissions using the 95% confidence interval of estimates of
344 Requena Suarez *et al.* (2019). While some deforested timber is harvested and utilized long-term –meaning not all
345 above-ground carbon is transferred to the atmosphere – we believe the impact of this on our estimate of carbon
346 emissions to be small as: (i) our map of old-growth above-ground carbon includes degraded forest, so much of the
347 carbon loss associated with timber removal is already accounted for; (ii) timber offtake rates are generally low
348 (e.g. Sist *et al* 2021), (iii) the efficiencies of turning natural timber to long-lifespan area also very low (Alice-Guier
349 *et al* 2020).

350

351 **Relationship between deforestation and recovery**

352 *Political scale:* We use the term *forest area recovery* to mean the percentage of the total area of OG deforestation
353 occupied by SF, and the term *carbon recovery* to mean the percentage of total OG deforestation emissions offset
354 by carbon accumulated in SF. We use Akaike information criterion (AIC) model selection to find best-fit models
355 (Mac Nally *et al* 2018) for the relationships between the percentage of OG deforestation (relative to original OG
356 extent; see above) and forest area recovery, and between the percentage of OG carbon emissions (relative to
357 original carbon stock; see above) and SF carbon recovery. We conducted this analysis across political units,
358 comparing the AIC score of five difference models: null, linear and broken-stick (up to three segments). This
359 analysis was conducted using the *stats* (R Core Team 2021) and *segmented* (Muggeo 2017) R-packages. The
360 assumptions of the models were checked by graphical analysis (Quinn and Keough 2002)

361

362 *Local scale:* We repeated the above analysis at a local scale by dividing the Amazon biome into a regular grid of
363 ~58.9 km² cells (65,536 pixels; pixel size: 0.0009 km²; size determined by computational efficiency). Cells with

364 >99% of pixels classified as 'other' (i.e. where less than 1% of the cell area is capable of being forest) were
365 excluded from the grid level analysis. Cells with $\leq 0.1\%$ deforestation were considered to have experienced no
366 deforestation and were excluded from the analysis. To understand how recovery in highly deforested landscapes
367 has changed over time, we selected cells that had lost more than 80% of their OG cover by 1997 (Figure S7) and
368 calculated the change in their percentage OG, SF and total forest cover from 1997 to 2017.

369

370 **Temporal trend analysis**

371 To explore how OG deforestation, SF extent and their associated carbon emissions have changed over time, we
372 used the AIC model selection method described above using AICc; a small-sample-size corrected version of AIC.
373 We conduct this analysis between 1997 and 2017 to avoid assigning significance to 'trends' that are an artifact of
374 SF older than 33-years being included in our OG class.

375

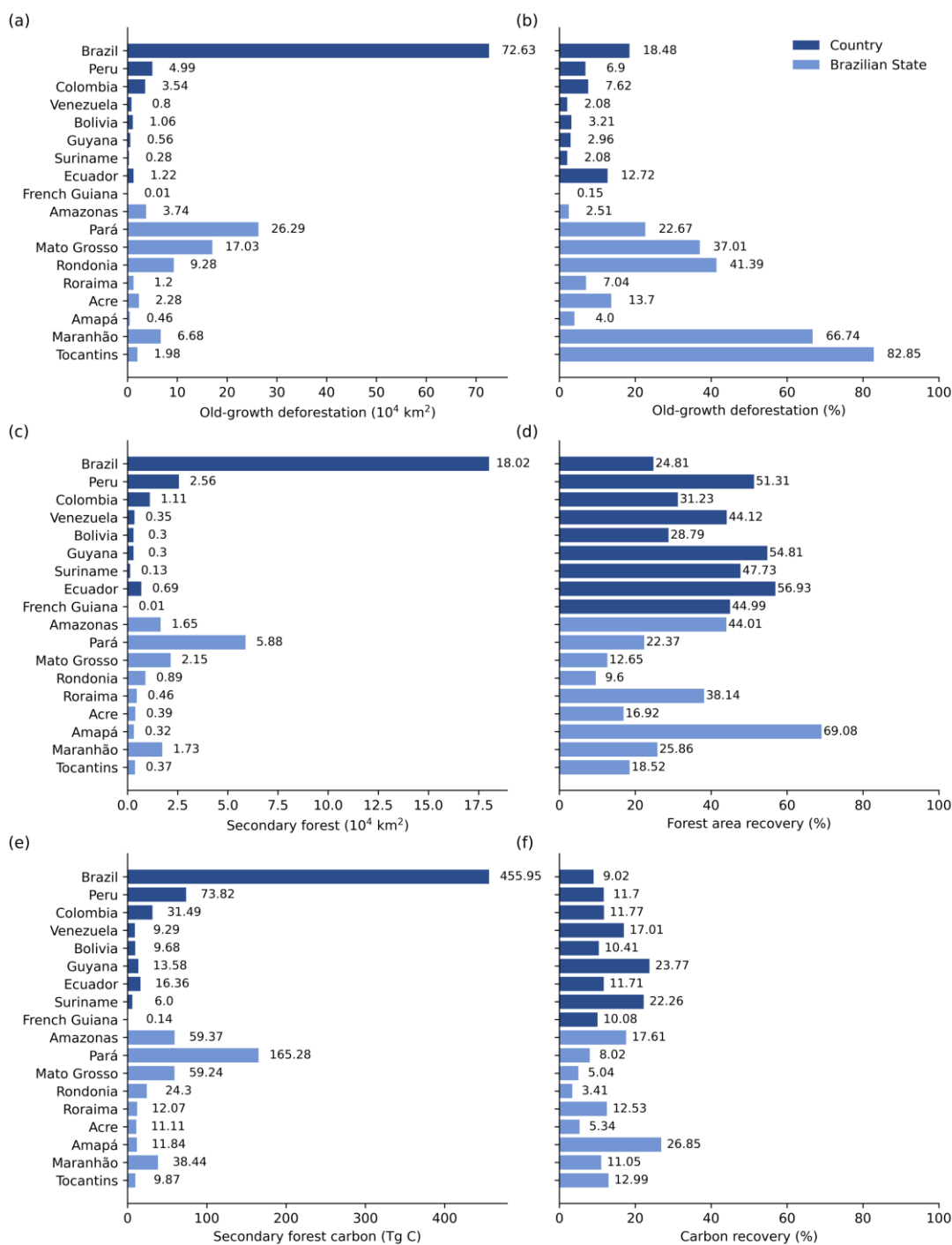


Figure 1: Old-growth deforestation, secondary forest extent and secondary forest carbon recovery in Amazonian countries and Brazilian states in 2017

The (a) area of old-growth deforestation, (c) area of secondary forests, and (e) secondary forest carbon stock for Amazonian countries (dark) and Brazilian states (light) in 2017. Proportional values (right) are measured as (b) the percentage of original old-growth forest extent (measured as the total area capable of supporting forest) that has been deforested, (d) the percentage of deforested land occupied by secondary forest, and (f) the percentage of old-growth deforestation emissions offset by carbon sequestration in secondary forests. Countries and states are ordered by the area of the Amazon they contain.

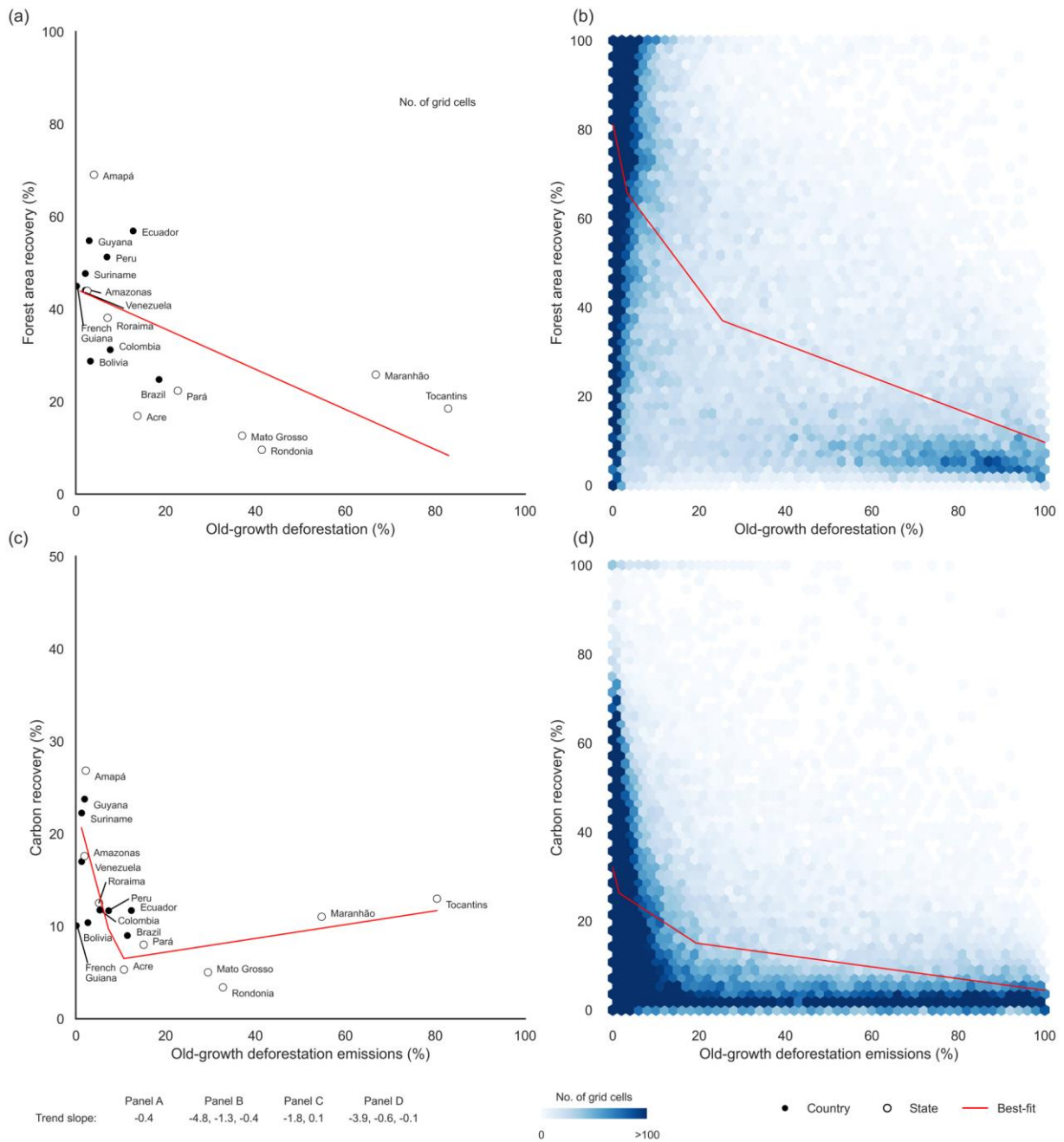


Figure 2: Proportional recovery of secondary forest in the Amazon biome in 2017.

The relationship between secondary forest recovery, measured as the percentage of cleared land occupied by secondary forest and deforestation as a percentage of total land within the Amazon basin (a, b). The relationship between emissions offset by secondary forest carbon accumulation and deforestation emissions as a percentage of original above-ground carbon (c, d). For (a, c) Amazonian countries (●) and Brazilian states (○); and (b, d) the Amazon basin gridded at ~59.8km². The best-fit models (where AICc ≥ 2) are shown in red: generalised linear model for panel a; and broken stick for panels b, c, d. Brazil was excluded from the calculation of the best-fit models for panels a and c in favour of its component states. Note the y-axis is different on panel C.

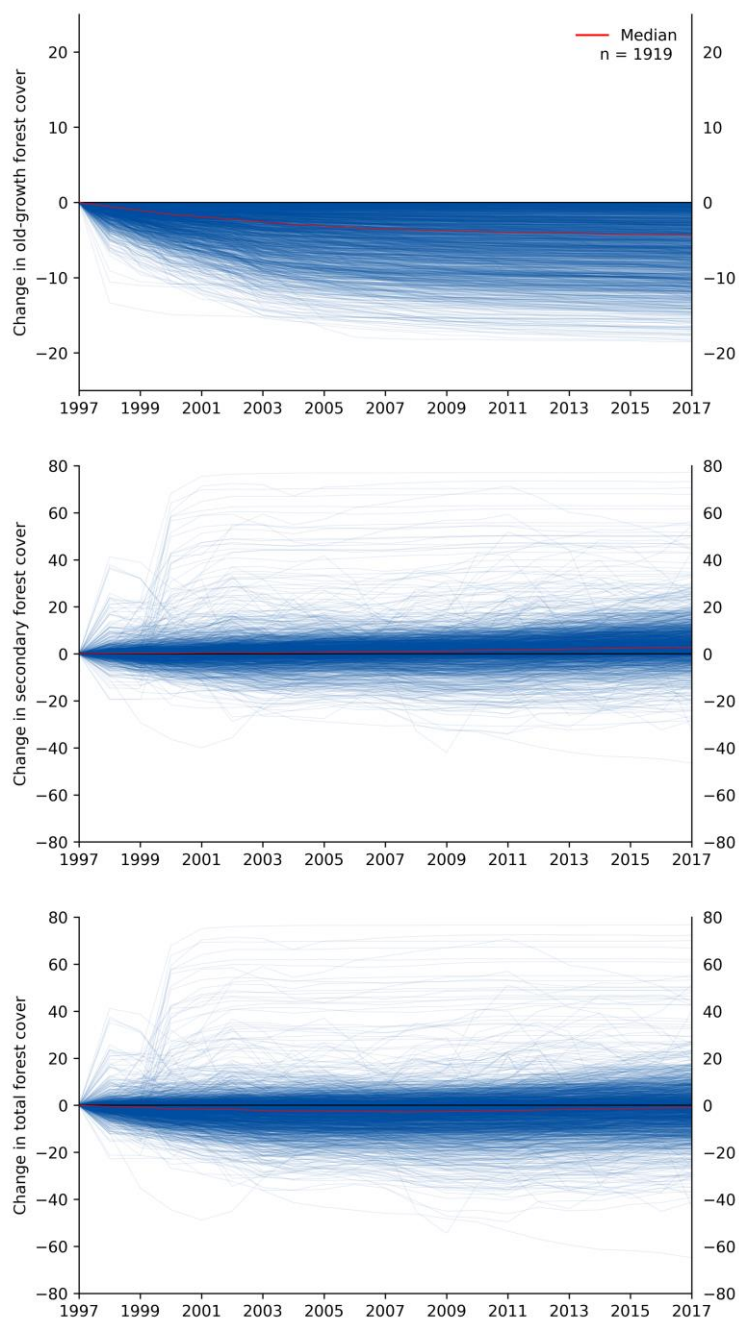


Figure 3 Temporal changes in forest cover in highly deforested Amazonian landscapes

The change in (a) old-growth forest, (b) secondary forest, and (c) total forest cover in highly deforested Amazonian landscapes from 1997 to 2017. The Amazon biome was gridded at $\sim 58.9 \text{ km}^2$, and each line represents a grid cell where old-growth deforestation was $\geq 80\%$ in 1997. Change in forest cover is measured as the difference in the percentage of a grid cell occupied by each forest type compared to its percentage cover in 1997. The median change across all the highly deforested cells is shown in red.

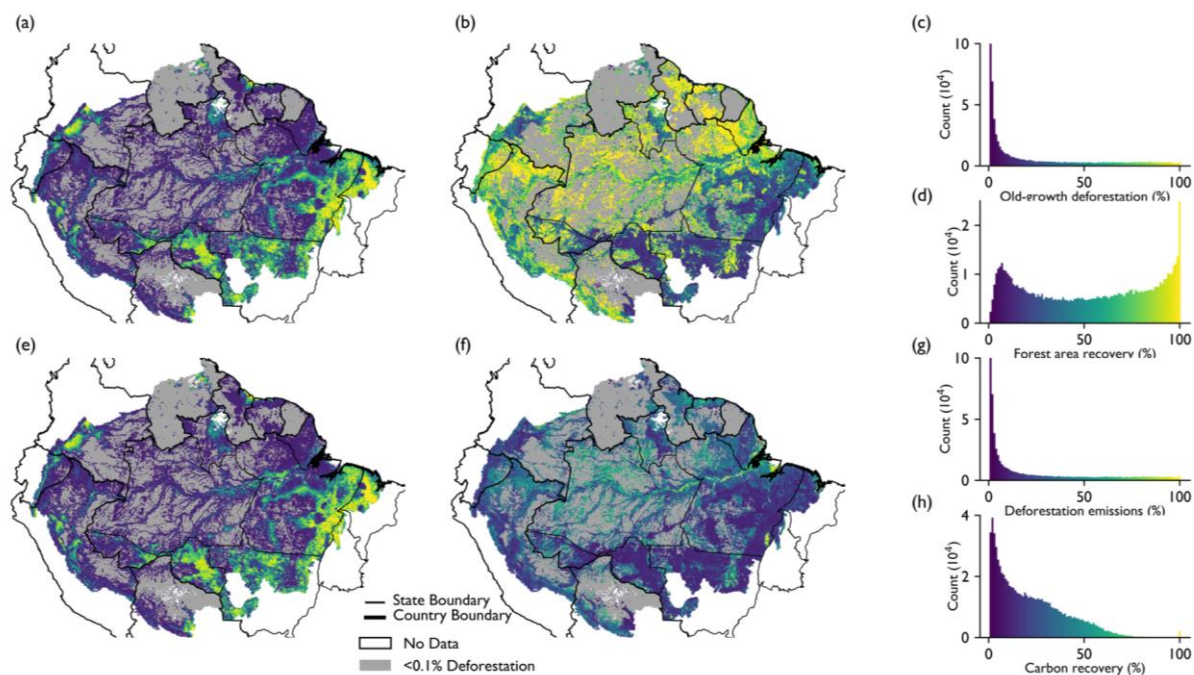


Figure 4: Old-growth deforestation, secondary forest recovery, carbon emissions and carbon accumulation in the Amazon biome in 2017.

The spatial distribution of (a) old-growth deforestation, (b) secondary forest recovery, (e) carbon emissions from old-growth deforestation and (f) carbon accumulation in secondary forest for the Amazon biome in 2017. Values were calculated over a regular grid of $\sim 59.8 \text{ km}^2$ cells. Old-growth deforestation is measured as the percentage of the cell area cleared of forest. Secondary forest recovery is measured as the percentage of deforested land occupied by secondary forest. Old-growth deforestation emissions are measured as the percentage of the original old-growth above-ground carbon lost to deforestation. Carbon recovery is measured as secondary forest carbon stock as a percentage of old-growth deforestation emissions. The distribution of cell values for each variable is shown in panels c, d, g, and h, respectively, which also define the colours used in panels a, b, e and f.

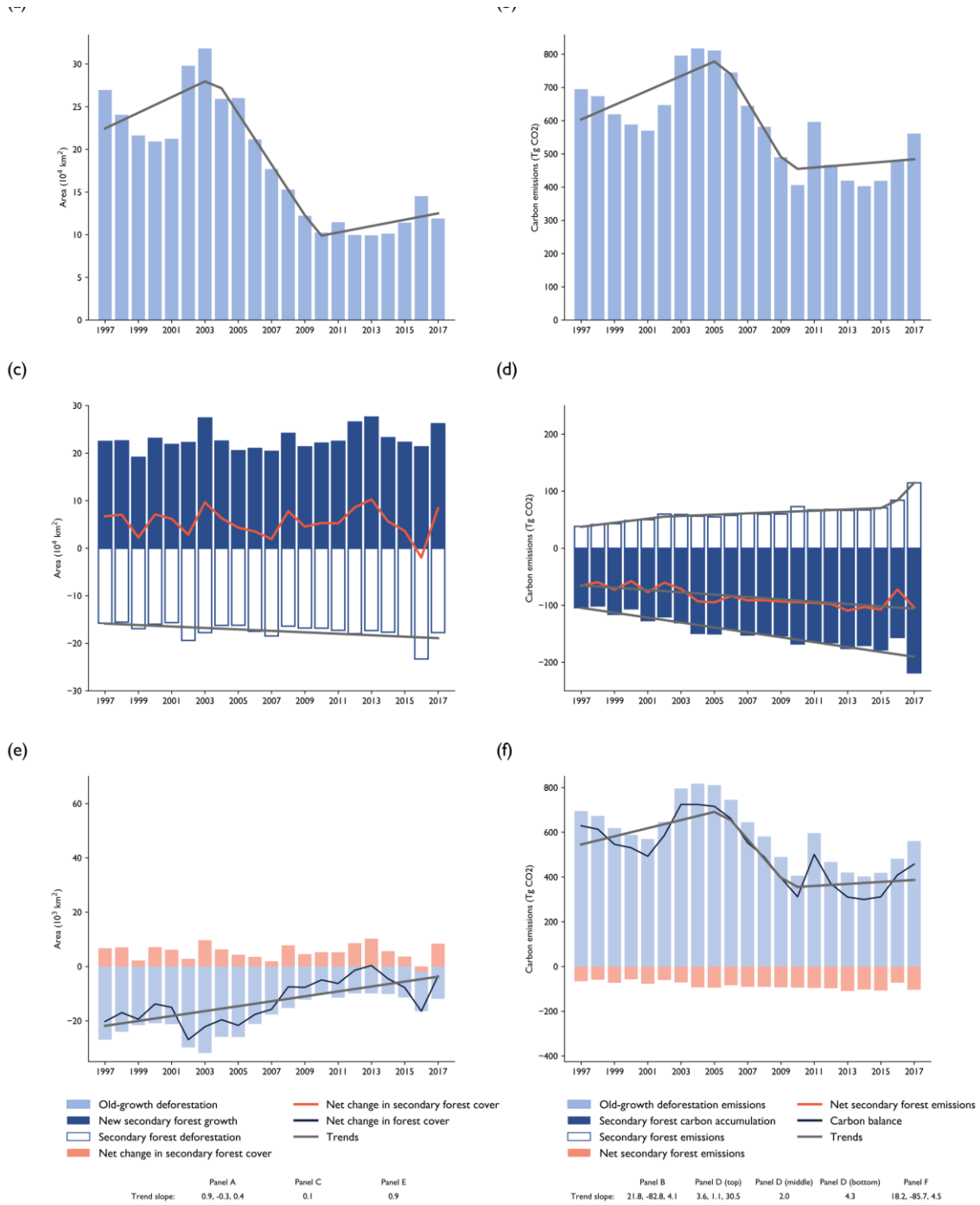


Figure 5: Annual change and temporal trends in forest cover and carbon emissions in the Amazon biome from 1997 to 2017

(a) The annual change in the extent of old-growth deforestation and (b) its associated carbon emissions. (c) The annual change in secondary forest extent comprising new secondary forest growth (dark), secondary forest clearance (white) and the net change in secondary forest extent (red line). (d) The annual carbon balance of secondary forests, comprising carbon accumulation from new and existing secondary forests (dark), carbon emissions from secondary forest clearance (white) and net change in secondary forest carbon (red). (e) The annual balance of forest extent with old growth deforestation (blue), net change in secondary forest extent (red) and the net change in total forest cover (dark blue line). (f) The annual balance in carbon emissions with old-growth deforestation emissions (blue), net change in secondary forest carbon (red) and the net carbon emissions from old-growth deforestation after offset by secondary forest carbon accumulation (dark blue line). The best-fit models (where $AIC_c \geq 2$) for temporal trends are shown in grey: broken stick for old-growth deforestation extent and emissions, secondary forest gross carbon emissions, and net emissions from forest cover change; and generalised linear model for secondary forest clearance, carbon accumulation and net carbon emissions, and the net change in total forest cover.

391 *Table 1 : Old-growth deforestation, secondary forest growth and their associated carbon emissions in the Amazon biome in 2017*

Region	Percent of the Amazon biome (%)	Area of old-growth deforestation (km ²)	Old-growth forest loss (%)	Old-growth carbon loss (Tg C)	Old-growth carbon loss (%)	Area of secondary forest (km ²)	Percentage of total forest area (%)	Forest area recovery (%)	Secondary forest carbon (Tg)	Secondary forest carbon 95% CI (Tg)	Carbon recovery (%)	Carbon recovery 95% CI (%)
Brazil	61.9%	689,451	17.6%	5,057.7	15.8%	180,215	5.3%	24.8%	391.5	65.7	7.7%	1.3%
<i>Amazonas</i>	23.6%	37,403	2.5%	337.1	1.9%	16,462	1.1%	44.0%	59.4	9.3	17.6%	2.7%
<i>Pará</i>	18.4%	262,869	22.7%	2,060.4	15.1%	58,800	6.2%	22.4%	165.3	27.3	8.0%	1.3%
<i>Mato Grosso</i>	7.3%	170,288	37.0%	1,175.3	29.3%	21,541	6.9%	12.6%	59.2	10.1	5.0%	0.9%
<i>Rondonia</i>	3.6%	92,835	41.4%	712.5	32.7%	8,909	6.4%	9.6%	24.3	4.0	3.4%	0.6%
<i>Roraima</i>	2.7%	12,029	7.0%	96.3	5.2%	4,588	2.8%	38.1%	12.1	2.4	12.5%	2.5%
<i>Acre</i>	2.6%	22,756	13.7%	207.9	10.7%	3,851	2.6%	16.9%	11.1	1.8	5.3%	0.9%
<i>Amapá</i>	1.8%	4,606	4.0%	44.1	2.2%	3,182	2.8%	69.1%	11.8	1.8	26.9%	4.0%
<i>Maranhão</i>	1.6%	66,832	66.7%	348.0	54.7%	17,280	34.2%	25.9%	38.4	7.2	11.1%	2.1%
<i>Tocantins</i>	0.4%	19,833	82.9%	76.0	80.4%	3,674	47.2%	18.5%	9.9	1.8	13.0%	2.4%
Peru	11.5%	49,852	6.9%	630.7	7.3%	25,579	3.7%	51.3%	73.8	15.4	11.7%	2.4%
Colombia	7.4%	35,393	7.6%	267.5	5.3%	11,055	2.5%	31.2%	31.5	5.5	11.8%	2.1%
Venezuela	6.1%	7,996	2.1%	54.6	1.3%	3,528	0.9%	44.1%	9.3	1.9	17.0%	3.5%
Bolivia	5.2%	10,592	3.2%	93.1	2.7%	3,049	1.0%	28.8%	9.7	2.4	10.4%	2.5%
Guyana	3.0%	5,558	3.0%	57.2	1.9%	3,046	1.6%	54.8%	13.6	2.5	23.8%	4.4%
Suriname	2.1%	2,816	2.1%	27.0	1.3%	1,344	1.0%	47.7%	6.0	1.2	22.3%	4.5%
Ecuador	1.5%	12,160	12.7%	139.7	12.3%	6,922	7.7%	56.9%	16.4	3.7	11.7%	2.6%
French Guiana	1.3%	126	0.2%	1.3	0.1%	57	0.1%	45.0%	0.1	0.0	10.1%	1.5%
Amazon	100.0%	813,944	13.4%	6,328.8	8.6%	234,795	4.1%	28.8%	616.3	111.3	9.7%	1.8%

393

394

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References

401

402 Aide T M, Clark M L, Grau H R, López-Carr D, Levy M A, Redo D, Bonilla-Moheno M, Riner G, Andrade-Núñez M J
403 and Muñiz M 2013 Deforestation and Reforestation of Latin America and the Caribbean (2001-2010)

404

Biotropica **45** 262–71 Online: <http://doi.wiley.com/10.1111/j.1744-7429.2012.00908.x>

405

Alice-Guier F E, Mohren F and Zuidema P A 2020 The life cycle carbon balance of selective logging in tropical

406

forests of Costa Rica *Journal of Industrial Ecology* **24** 534–47 Online:

407

<https://onlinelibrary.wiley.com/doi/10.1111/jiec.12958>

408

Arima E Y, Barreto P, Araújo E and Soares-Filho B 2014 Public policies can reduce tropical deforestation: Lessons
409 and challenges from Brazil *Land Use Policy* **41** 465–73 Online:

410

https://www.sciencedirect.com/science/article/pii/S026483771400146X?casa_token=J7GGVAaVwcUAAAAA:BRuE1BI_nSw8BtlbkDFocApiM5BwEqAAqn0n7C-UZiPzt7YoDG4VZFbrDTed33ZVmWXco8uX

411

412 Avitabile V, Herold M, Heuvelink G B M, Lewis S L, Phillips O L, Asner G P, Armston J, Ashton P S, Banin L, Bayol N,
413 Berry N J, Boeckx P, de Jong B H J, DeVries B, Girardin C A J, Kearsley E, Lindsell J A, Lopez-Gonzalez G, Lucas
414 R, Malhi Y, Morel A, Mitchard E T A, Nagy L, Qie L, Quinones M J, Ryan C M, Ferry S J W, Sunderland T, Laurin
415 G V, Gatti R C, Valentini R, Verbeeck H, Wijaya A and Willcock S 2016 An integrated pan-tropical biomass
416 map using multiple reference datasets *Global Change Biology* **22** 1406–20 Online:

417

<http://doi.wiley.com/10.1111/gcb.13139>

418

Barlow J, Berenguer E, Carmenta R and França F 2020 Clarifying Amazonia's burning crisis *Global Change Biology*

419

26 319–21 Online: <https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.14872>

420

421 Berenguer E, Ferreira J, Gardner T A, Aragão L E O C, de Camargo P B, Cerri C E, Durigan M, Oliveira R C de, Vieira I
422 C G and Barlow J 2014 A large-scale field assessment of carbon stocks in human-modified tropical forests
Global Change Biology **20** 3713–26 Online: <http://doi.wiley.com/10.1111/gcb.12627>

423

424 Boucher D, Roquemore S and Fitzhugh E 2013 Brazil's success in reducing deforestation *Tropical Conservation
Science* **6** 426–45

425

426 Bullock E L and Woodcock C E 2021 Carbon loss and removal due to forest disturbance and regeneration in the
Amazon *Science of The Total Environment* **764** 142839 Online:

427

[https://www.sciencedirect.com/science/article/pii/S0048969720363695?casa_token=pw4-](https://www.sciencedirect.com/science/article/pii/S0048969720363695?casa_token=pw4-kb6AcRkAAAAA:uHJLX9E1heb-TRU3SXWrAYvB6-p-kUoBAxcTfYb6Utcz7TXOhSjp1kKtb_8aCTEU1zpV9TAYbtY)

428

[kb6AcRkAAAAA:uHJLX9E1heb-TRU3SXWrAYvB6-p-kUoBAxcTfYb6Utcz7TXOhSjp1kKtb_8aCTEU1zpV9TAYbtY](https://www.sciencedirect.com/science/article/pii/S0048969720363695?casa_token=pw4-kb6AcRkAAAAA:uHJLX9E1heb-TRU3SXWrAYvB6-p-kUoBAxcTfYb6Utcz7TXOhSjp1kKtb_8aCTEU1zpV9TAYbtY)

429

430 Bullock E L, Woodcock C E, Souza C and Olofsson P 2020 Satellite-based estimates reveal widespread forest
degradation in the Amazon *Global Change Biology* **26** 2956–69 Online:

431

<https://onlinelibrary.wiley.com/doi/10.1111/gcb.15029>

432

433 Chazdon R L, Broadbent E N, Rozendaal D M A, Bongers F, Zambrano A M A, Aide T M, Balvanera P, Becknell J M,
434 Boukili V, Brancalion P H S, Craven D, Almeida-Cortez J S, Cabral G A L, de Jong B, Denslow J S, Dent D H,
435 DeWalt S J, Dupuy J M, Durán S M, Espírito-Santo M M, Fandino M C, César R G, Hall J S, Hernández-
436 Stefanoni J L, Jakovac C C, Junqueira A B, Kennard D, Letcher S G, Lohbeck M, Martínez-Ramos M, Massoca
437 P, Meave J A, Mesquita R, Mora F, Muñoz R, Muscarella R, Nunes Y R F, Ochoa-Gaona S, Orihuela-Belmonte
438 E, Peña-Claros M, Pérez-García E A, Piotto D, Powers J S, Rodríguez-Velazquez J, Romero-Pérez I E, Ruiz J,
439 Saldarriaga J G, Sanchez-Azofeifa A, Schwartz N B, Steininger M K, Swenson N G, Uriarte M, van Breugel M,
440 van der Wal H, Veloso M D M, Vester H, Vieira I C G, Bentos T V, Williamson G B and Poorter L 2016 Carbon
441 sequestration potential of second-growth forest regeneration in the Latin American tropics *Science
Advances* **2**

442 Chazdon R L and Guariguata M R 2016 Natural regeneration as a tool for large-scale forest restoration in the
443 tropics: prospects and challenges *Biotropica* **48** 716–30 Online: <http://doi.wiley.com/10.1111/btp.12381>
444 Chazdon R L, Lindenmayer D, Guariguata M R, Crouzeilles R, Rey Benayas J M and Lazos Chavero E 2020 Fostering
445 natural forest regeneration on former agricultural land through economic and policy interventions
446 *Environmental Research Letters* **15** 043002 Online: [https://iopscience.iop.org/article/10.1088/1748-](https://iopscience.iop.org/article/10.1088/1748-9326/ab79e6)
447 [9326/ab79e6](https://iopscience.iop.org/article/10.1088/1748-9326/ab79e6)
448 Crouzeilles R, Beyer H L, Monteiro L M, Feltran-Barbieri R, Pessôa A C M, Barros F S M, Lindenmayer D B, Lino E D
449 S M, Grelle C E v., Chazdon R L, Matsumoto M, Rosa M, Latawiec A E and Strassburg B B N 2020 Achieving
450 cost-effective landscape-scale forest restoration through targeted natural regeneration *Conservation Letters*
451 **13** e12709 Online: <https://onlinelibrary.wiley.com/doi/10.1111/conl.12709>
452 Cunningham C and Beazley K F 2018 Changes in human population density and protected areas in terrestrial
453 global biodiversity hotspots, 1995–2015 *Land* **7** 136
454 Curtis P G, Slay C M, Harris N L, Tyukavina A and Hansen M C 2018 Classifying drivers of global forest loss. *Science*
455 *(New York, N.Y.)* **361** 1108–11 Online: <http://www.ncbi.nlm.nih.gov/pubmed/30213911>
456 Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S and
457 Eickemeier P 2014 Contribution of Working Group III to the Fifth Assessment Report of the
458 Intergovernmental Panel on Climate Change *Climate change* 1–11
459 Eggleston H S, Buendia L, Miwa K, Ngara T and Tanabe, K. 2006 *2006 IPCC Guidelines for National Greenhouse Gas*
460 *Inventories* (Japan: IGES)
461 Elias F, Ferreira J, Lennox G D, Berenguer E, Ferreira S, Schwartz G, Melo L de O, Reis Júnior D N, Nascimento R O
462 and Ferreira F N 2019 Assessing the growth and climate sensitivity of secondary forests in highly deforested
463 Amazonian landscapes *Ecology* e02954
464 Escobar H 2021 Researchers face attacks from Bolsonaro regime. *Science (New York, N.Y.)* **372** 225 Online:
465 <http://www.ncbi.nlm.nih.gov/pubmed/33859015>
466 FAO 2012 *Global ecological zones for FAO forest reporting: 2010 Update* (Rome, Italy) Online:
467 <http://www.fao.org/3/a-ap861e.pdf>
468 FAO and UNEP 2020 *The State of the World's Forests 2020*. (Rome) Online: <https://doi.org/10.4060/ca8642en>
469 Garrett R D, Gardner T A, Morello F, Marchand S, Barlow J, Ezzine De Blas D, Ferreira J, Lees A C and Parry L 2017
470 Explaining the persistence of low income and environmentally degrading land uses in the Brazilian Amazon
471 **22** Online: <https://doi.org/10.5751/ES-09364-220327>
472 Garrett R D, Levy S A, Gollnow F, Hodel L and Rueda X 2021 Have food supply chain policies improved forest
473 conservation and rural livelihoods? A systematic review *Environ. Res. Lett* **16** 33002 Online:
474 <https://doi.org/10.1088/1748-9326/abe0ed>
475 Gatti L v., Basso L S, Miller J B, Gloor M, Gatti Domingues L, Cassol H L G, Tejada G, Aragão L E O C, Nobre C, Peters
476 W, Marani L, Arai E, Sanches A H, Corrêa S M, Anderson L, von Randow C, Correia C S C, Crispim S P and
477 Neves R A L 2021 Amazonia as a carbon source linked to deforestation and climate change *Nature* **595** 388–
478 93 Online: <http://www.nature.com/articles/s41586-021-03629-6>
479 Gibson L, Lee T M, Koh L P, Brook B W, Gardner T A, Barlow J, Peres C A, Bradshaw C J A, Laurance W F, Lovejoy T
480 E and Sodhi N S 2011 Primary forests are irreplaceable for sustaining tropical biodiversity *Nature* **478** 378–
481 81 Online: <http://www.nature.com/articles/nature10425>
482 Grassi G, Stehfest E, Rogelj J, van Vuuren D, Cescatti A, House J, Nabuurs G-J, Rossi S, Alkama R, Viñas R A, Calvin
483 K, Ceccherini G, Federici S, Fujimori S, Gusti M, Hasegawa T, Havlik P, Humpenöder F, Korosuo A, Perugini L,
484 Tubiello F N and Popp A 2021 Critical adjustment of land mitigation pathways for assessing countries'
485 climate progress *Nature Climate Change* **11** 425–34 Online: [http://www.nature.com/articles/s41558-021-](http://www.nature.com/articles/s41558-021-01033-6)
486 [01033-6](http://www.nature.com/articles/s41558-021-01033-6)
487 Grau H R, Aide T M, Zimmerman J K, Thomlinson J R, Helmer E and Zou X 2003 The Ecological Consequences of
488 Socioeconomic and Land-Use Changes in Postagriculture Puerto Rico *BioScience*
489 Griscom B W, Adams J, Ellis P W, Houghton R A, Lomax G, Miteva D A, Schlesinger W H, Shoch D, Siikamäki J v,
490 Smith P, Woodbury P, Zganjar C, Blackman A, Campari J, Conant R T, Delgado C, Elias P, Gopalakrishna T,
491 Hamsik M R, Herrero M, Kiesecker J, Landis E, Laestadius L, Leavitt S M, Minnemeyer S, Polasky S, Potapov P,
492 Putz F E, Sanderman J, Silvius M, Wollenberg E and Fargione J 2017 Natural climate solutions. *Proceedings of*
493 *the National Academy of Sciences of the United States of America* **114** 11645–50 Online:
494 <http://www.ncbi.nlm.nih.gov/pubmed/29078344>

495 Heinrich V H A, Dalagnol R, Cassol H L G, Rosan T M, de Almeida C T, Silva Junior C H L, Campanharo W A, House J
496 I, Sitch S, Hales T C, Adami M, Anderson L O and Aragão L E O C 2021 Large carbon sink potential of
497 secondary forests in the Brazilian Amazon to mitigate climate change *Nature Communications* **12** 1785
498 Online: <http://www.nature.com/articles/s41467-021-22050-1>

499 Houghton R A, Byers B and Nassikas A A 2015 A role for tropical forests in stabilizing atmospheric CO₂ *Nature*
500 *Climate Change* **5** 1022–3 Online: <http://www.nature.com/articles/nclimate2869>

501 Jakovac C C, Dutrieux L P, Siti L, Peña-Claros M and Bongers F 2017 Spatial and temporal dynamics of shifting
502 cultivation in the middle-Amazonas river: Expansion and intensification ed R Zang *PLoS ONE* **12** e0181092
503 Online: <https://dx.plos.org/10.1371/journal.pone.0181092>

504 Jakovac C C, Junqueira A B, Crouzeilles R, Peña-Claros M, Mesquita R C G and Bongers F 2021 The role of land-use
505 history in driving successional pathways and its implications for the restoration of tropical forests *Biological*
506 *Reviews* **96** 1114–34 Online: <https://onlinelibrary.wiley.com/doi/10.1111/brv.12694>

507 Kalamandeen M, Gloor E, Mitchard E, Quincey D, Ziv G, Spracklen D, Spracklen B, Adami M, Aragão L E O C and
508 Galbraith D 2018 Pervasive Rise of Small-scale Deforestation in Amazonia *Scientific Reports* **8** 1600 Online:
509 <http://www.nature.com/articles/s41598-018-19358-2>

510 Latawiec A E, Strassburg B B N, Rodriguez A M, Matt E, Nijbroek R and Silos M 2014 Suriname: Reconciling
511 agricultural development and conservation of unique natural wealth *Land Use Policy* **38** 627–36 Online:
512 <https://www.sciencedirect.com/science/article/abs/pii/S0264837714000088>

513 van Leeuwen T T, van der Werf G R, Hoffmann A A, Detmers R G, Rucker G, French N H F, Archibald S, Carvalho J
514 A, Cook G D, de Groot W J, Hély C, Kasischke E S, Kloster S, Mccarty J L, Pettinari M L, Savadogo P, Alvarado E
515 C, Boschetti L, Manuri S, Meyer C P, Siegert F, Trollope L A and Trollope W S W 2014 Biomass burning fuel
516 consumption rates Biomass burning fuel consumption rates: a field measurement database Biomass burning
517 fuel consumption rates *Biogeosciences Discuss* **11** 8115–80 Online: [www.biogeosciences-](http://www.biogeosciences-discuss.net/11/8115/2014/)
518 [discuss.net/11/8115/2014/](http://www.biogeosciences-discuss.net/11/8115/2014/)

519 Lennox G D, Gardner T A, Thomson J R, Ferreira J, Berenguer E, Lees A C, mac Nally R, Aragão L E O C, Ferraz S F B,
520 Louzada J, Moura N G, Oliveira V H F, Pardini R, Solar R R C, Vaz-de Mello F Z, Vieira I C G and Barlow J 2018
521 Second rate or a second chance? Assessing biomass and biodiversity recovery in regenerating Amazonian
522 forests *Global Change Biology* **24** 5680–94 Online: <http://doi.wiley.com/10.1111/gcb.14443>

523 Lubowski R N and Rose S K 2020 The Potential for REDD+: Key Economic Modeling Insights and Issues
524 <https://doi.org/10.1093/reep/res024> Online:
525 <https://www.journals.uchicago.edu/doi/abs/10.1093/reep/res024?journalCode=reep>

526 Luyssaert S, Inglima I, Jung M, Richardson A D, REICHSTEIN M, Papale D, Piao S L, Schulze E-D-D D, Wingate L,
527 Matteucci G, ARAGAO L, Aubinet M, Beer C, Bernhofer C, Black K G, BONAL D, Bonnefond J-M-M M,
528 Chambers J, Ciais P, Cook B, J. K, JANSSENS I A, Luyssaert S, Inglima I, Jung M, Richardson A D, REICHSTEIN
529 M, Papale D, Piao S L, Schulze E-D-D D, Wingate L, Matteucci G, ARAGAO L, Aubinet M, Beer C, Bernhofer C,
530 Black K G, BONAL D, Bonnefond J-M-M M, Chambers J, Ciais P, Cook B, Davis K J, DOLMAN A j, GIELEN B,
531 Goulden M, GRACE J, Granier A, GRELE A, Griffis T, Grünwald T, GUIDOLOTTI G, HANSON P J, Harding R,
532 Hollinger D Y, Hutyrá L R, Kolari P, KRUIJT B, Kutsch W, LAGERGREN F, Laurila T, LAW B E, Le maire G,
533 Lindroth A, LOUSTAU D, Malhi Y, Mateus J, Migliavacca M, Misson L, MONTAGNANI L, MONCRIEFF J, Moors
534 E, MUNGER J W, Nikinmaa E, Ollinger S V, Pita G, REBMANN C, Roupsard O, Saigusa N, SANZ m j, Seufert G,
535 SIERRA C, Smith M-L, Tang J, Valentini R, Vesala T and JANSSENS I A 2007 CO₂ balance of boreal, temperate,
536 and tropical forests derived from a global database *Global Change Biology* **13** 2509–37

537 Matos F A R, Magnago L F S, Aquila Chan Miranda C, Menezes L F T, Gastauer M, Safar N V H, Schaefer C E G R,
538 Silva M P, Simonelli M, Edwards F A, Martins S v., Meira-Neto J A A and Edwards D P 2020 Secondary forest
539 fragments offer important carbon and biodiversity cobenefits *Global Change Biology* **26** 509–22 Online:
540 <https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.14824>

541 Matricardi E A T, Skole D L, Costa O B, Pedlowski M A, Samek J H and Miguel E P 2020 Long-term forest
542 degradation surpasses deforestation in the Brazilian Amazon. *Science (New York, N.Y.)* **369** 1378–82 Online:
543 <http://www.ncbi.nlm.nih.gov/pubmed/32913104>

544 Muggeo V M R 2017 Interval estimation for the breakpoint in segmented regression: a smoothed score-based
545 approach *Australian & New Zealand Journal of Statistics* **59** 311–22 Online:
546 <http://doi.wiley.com/10.1111/anzs.12200>

547 mac Nally R, Duncan R P, Thomson J R and Yen J D L 2018 Model selection using information criteria, but is the
548 "best" model any good? ed A Mori *Journal of Applied Ecology* **55** 1441–4 Online:
549 <http://doi.wiley.com/10.1111/1365-2664.13060>

550 Nunes S, Oliveira L, Siqueira J, Morton D C and Souza C M 2020 Unmasking secondary vegetation dynamics in the
551 Brazilian Amazon *Environmental Research Letters* Online: [http://iopscience.iop.org/10.1088/1748-](http://iopscience.iop.org/10.1088/1748-9326/ab76db)
552 [9326/ab76db](http://iopscience.iop.org/10.1088/1748-9326/ab76db)

553 Poorter L, Bongers F, Aide T M, Almeyda Zambrano A M, Balvanera P, Becknell J M, Boukili V, Brancalion P H S,
554 Broadbent E N, Chazdon R L, Craven D, de Almeida-Cortez J S, Cabral G A L, de Jong B H J, Denslow J S, Dent
555 D H, DeWalt S J, Dupuy J M, Durán S M, Espírito-Santo M M, Fandino M C, César R G, Hall J S, Hernandez-
556 Stefanoni J L, Jakovac C C, Junqueira A B, Kennard D, Letcher S G, Licona J-C, Lohbeck M, Marín-Spiotta E,
557 Martínez-Ramos M, Massoca P, Meave J A, Mesquita R, Mora F, Muñoz R, Muscarella R, Nunes Y R F, Ochoa-
558 Gaona S, de Oliveira A A, Orihuela-Belmonte E, Peña-Claros M, Pérez-García E A, Piotta D, Powers J S,
559 Rodríguez-Velázquez J, Romero-Pérez I E, Ruíz J, Saldarriaga J G, Sanchez-Azofeifa A, Schwartz N B,
560 Steiner M K, Swenson N G, Toledo M, Uriarte M, van Breugel M, van der Wal H, Veloso M D M, Vester H F
561 M, Vicentini A, Vieira I C G, Bentos T V, Williamson G B and Rozendaal D M A 2016 Biomass resilience of
562 Neotropical secondary forests *Nature* **530** 211–4 Online: <http://www.nature.com/articles/nature16512>

563 Porro R, Lopez-Feldman A and Vela-Alvarado J W 2015 Forest use and agriculture in Ucayali, Peru: Livelihood
564 strategies, poverty and wealth in an Amazon frontier *Forest Policy and Economics* **51** 47–56 Online:
565 <https://www.sciencedirect.com/science/article/pii/S1389934114002299>

566 PRODES 2020 PRODES Online:
567 http://terrabrasilis.dpi.inpe.br/app/dashboard/deforestation/biomes/legal_amazon/rates

568 Qin Y, Xiao X, Wigner J-P, Ciais P, Brandt M, Fan L, Li X, Crowell S, Wu X, Doughty R, Zhang Y, Liu F, Sitch S and
569 Moore B 2021 Carbon loss from forest degradation exceeds that from deforestation in the Brazilian Amazon
570 *Nature Climate Change* **11** 442–8 Online: <http://www.nature.com/articles/s41558-021-01026-5>

571 Quinn G P and Keough M J 2002 *Experimental Design and Data Analysis for Biologists* (Cambridge University
572 Press) Online: <https://www.cambridge.org/core/product/identifier/9780511806384/type/book>

573 Requena Suarez D, Rozendaal D M A, de Sy V, Phillips O L, Alvarez-Dávila E, Anderson-Teixeira K, Araujo-Murakami
574 A, Arroyo L, Baker T R, Bongers F, Brienen R J W, Carter S, Cook-Patton S C, Feldpausch T R, Griscom B W,
575 Harris N, Hérault B, Honorio Coronado E N, Leavitt S M, Lewis S L, Marimon B S, Monteagudo Mendoza A,
576 Kassi N'dja J, N'Guessan A E, Poorter L, Qie L, Rutishauser E, Sist P, Sonké B, Sullivan M J P, Vilanova E, Wang
577 M M H, Martius C and Herold M 2019 Estimating aboveground net biomass change for tropical and
578 subtropical forests: Refinement of IPCC default rates using forest plot data *Global Change Biology* **gcb.14767**
579 Online: <https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.14767>

580 Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, Handa C, H. Kheshgi, Kobayashi S, Kriegler E, Mundaca L,
581 Séférian R and Vilariño M V 2018 Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable
582 Development. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C*
583 *above pre-industrial levels and related global greenhouse gas emission pathways, in the context of*
584 *strengthening the global response to the threat of climate change,*

585 Rudel T K, Sloan S, Chazdon R and Grau R 2016 The drivers of tree cover expansion: Global, temperate, and
586 tropical zone analyses *Land Use Policy* **58** 502–13 Online:
587 [https://www.sciencedirect.com/science/article/pii/S0264837715301678?casa_token=SdsilRrJ0c8AAAAA:BN](https://www.sciencedirect.com/science/article/pii/S0264837715301678?casa_token=SdsilRrJ0c8AAAAA:BNLYO730kkt_9GqXSf7Xuxt-w7a1ZxtxYb2bd2M0RxF0n51BUijQBI4pjPe82NWzRuLtsaT#sec0035)
588 [LYO730kkt_9GqXSf7Xuxt-w7a1ZxtxYb2bd2M0RxF0n51BUijQBI4pjPe82NWzRuLtsaT#sec0035](https://www.sciencedirect.com/science/article/pii/S0264837715301678?casa_token=SdsilRrJ0c8AAAAA:BNLYO730kkt_9GqXSf7Xuxt-w7a1ZxtxYb2bd2M0RxF0n51BUijQBI4pjPe82NWzRuLtsaT#sec0035)

589 Saatchi S S, Harris N L, Brown S, Lefsky M, Mitchard E T A, Salas W, Zutta B R, Buermann W, Lewis S L, Hagen S,
590 Petrova S, White L, Silman M and Morel A 2011 Benchmark map of forest carbon stocks in tropical regions
591 across three continents. *Proceedings of the National Academy of Sciences of the United States of America*
592 **108** 9899–904 Online: <http://www.ncbi.nlm.nih.gov/pubmed/21628575>

593 Saatchi S S, Houghton R A, dos SANTOS ALVALÁ R C, SOARES J v. and Yu Y 2007 Distribution of aboveground live
594 biomass in the Amazon basin *Global Change Biology* **13** 816–37 Online:
595 <http://doi.wiley.com/10.1111/j.1365-2486.2007.01323.x>

596 Saraiva M B, Ferreira M D P, da Cunha D A, Daniel L P, Homma A K O and Pires G F 2020 Forest regeneration in the
597 Brazilian Amazon: Public policies and economic conditions *Journal of Cleaner Production* **269** 122424 Online:
598 https://www.sciencedirect.com/science/article/pii/S0959652620324719?casa_token=ysWhJq2wwMIAAAA
599 [A:kDQy3Eo8belsawQZxtEXdcC_PQsr6dkg51WK3cto_eOTN9rhNvnY_-3WspYtq9infNvg2S6s](https://www.sciencedirect.com/science/article/pii/S0959652620324719?casa_token=ysWhJq2wwMIAAAA)

600 Schwartz N B, Aide T M, Graesser J, Grau H R and Uriarte M 2020 Reversals of Reforestation Across Latin America
601 Limit Climate Mitigation Potential of Tropical Forests *Frontiers in Forests and Global Change* **3** 85 Online:
602 <https://www.frontiersin.org/article/10.3389/ffgc.2020.00085/full>
603 Seymour F and Busch J 2016 *Why Forests? Why now? The Science, Economics, and Politics of Tropical Forests and*
604 *Climate Change*. (Washington DC) Online: [https://www.cgdev.org/sites/default/files/Seymour-Busch-why-](https://www.cgdev.org/sites/default/files/Seymour-Busch-why-forests-why-now-full-book.PDF)
605 [forests-why-now-full-book.PDF](https://www.cgdev.org/sites/default/files/Seymour-Busch-why-forests-why-now-full-book.PDF)
606 Shono K, Chazdon R, Bodin B, Wilson S J and Durst P 2020 Assisted natural regeneration: harnessing nature for
607 restoration. ed A Sarre *Unasylva* **252** 71–81
608 Silva Junior C H L, Heinrich V H A, Freire A T G, Broggio I S, Rosan T M, Doblaz J, Anderson L O, Rousseau G X,
609 Shimabukuro Y E, Silva C A, House J I and Aragão L E O C 2020 Benchmark maps of 33 years of secondary
610 forest age for Brazil *Scientific Data* **7** 269 Online: <http://www.nature.com/articles/s41597-020-00600-4>
611 Sist P, Pioniot C, Kanashiro M, Pena-Claros M, Putz F E, Schulze M, Verissimo A and Vidal E 2021 Sustainability of
612 Brazilian forest concessions *Forest Ecology and Management* **496** 119440 Online:
613 [https://www.sciencedirect.com/science/article/pii/S0378112721005296?casa_token=yeJIOWWJywoAAAAA:](https://www.sciencedirect.com/science/article/pii/S0378112721005296?casa_token=yeJIOWWJywoAAAAA:P72i4th-9B1A72cg6h6oISn0TSBrXJe39pQVvGZmqTT0Jh_oG2MFO3nCnjmIM_3DpD7bXcAu)
614 [P72i4th-9B1A72cg6h6oISn0TSBrXJe39pQVvGZmqTT0Jh_oG2MFO3nCnjmIM_3DpD7bXcAu](https://www.sciencedirect.com/science/article/pii/S0378112721005296?casa_token=yeJIOWWJywoAAAAA:P72i4th-9B1A72cg6h6oISn0TSBrXJe39pQVvGZmqTT0Jh_oG2MFO3nCnjmIM_3DpD7bXcAu)
615 Smith C C, Espírito-Santo F D B, Healey J R, Young P J, Lennox G D, Ferreira J and Barlow J 2020 Secondary forests
616 offset less than 10% of deforestation-mediated carbon emissions in the Brazilian Amazon *Global Change*
617 *Biology* **gcb.15352** Online: <https://onlinelibrary.wiley.com/doi/10.1111/gcb.15352>
618 Tyukavina A, Hansen M C, Potapov P v., Stehman S v., Smith-Rodriguez K, Okpa C and Aguilar R 2017 Types and
619 rates of forest disturbance in Brazilian Legal Amazon, 2000–2013 *Science Advances* **3**
620 UN 2019 UN Decade on Restoration Online: <https://www.decadeonrestoration.org/>
621 Vale M M, Berenguer E, Argollo de Menezes M, Viveiros de Castro E B, Pugliese de Siqueira L and Portela R de C Q
622 2021 The COVID-19 pandemic as an opportunity to weaken environmental protection in Brazil *Biological*
623 *Conservation* **255** 108994 Online: <https://www.sciencedirect.com/science/article/pii/S000632072100046X>
624 Wang Y, Ziv G, Adami M, Almeida C A de, Antunes J F G, Coutinho A C, Esquerdo J C D M, Gomes A R, Galbraith D,
625 Aparecido de Almeida udio, Gonamp F, Antunes alves, Camargo Coutinho A, Camp lio, Dalla Mora Esquerdo
626 sar, Rodrigues Gomes A and Galbraith D 2020 Upturn in secondary forest clearing buffers primary forest loss
627 in the Brazilian Amazon *Nature Sustainability* **3** 290–5 Online: <https://doi.org/10.1038/s41893-019-0470-4>
628 World Resources Institute 2021 *Climate Watch Historical GHG Emissions* (Washington, DC)
629