

1 **Taking the pulse of Earth's tropical forests using networks of highly**
2 **distributed plots.**

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6 ForestPlots.net*

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11 *see Supplementary Table 1 for a complete list of contributing authors

12 **Abstract**

13 Tropical forests are the most diverse and productive ecosystems on Earth. While better
14 understanding of these forests is critical for our collective future, until very recently efforts to
15 measure and monitor them have been site-specific and disconnected. Networking is essential
16 to address fundamental questions across scales, national borders and beyond the horizon of
17 most funding agencies. Here, we show how the global ForestPlots.net research community has
18 responded to the challenge of understanding tropical forests via highly-distributed research
19 teams measuring forests tree-by-tree in long-term plots. We review the major scientific
20 discoveries of this work and show how this approach is changing the process of tropical forest
21 science. Our core approach has been to link long-term grassroots initiatives with standardized
22 protocols and data management to generate scaled-up results. By connecting and elevating the
23 role of tropical researchers themselves, this 'social research network' model also recognises
24 the key role of the data originator in this long-term ecological endeavour. Conceived in 1999
25 in South America with RAINFOR, our permanent plot networks have been adapted to Africa
26 (AfriTRON) and Southeast Asia (T-FORCES) and widely emulated worldwide, with many
27 such initiatives integrated via ForestPlots.net cyber-infrastructure supporting colleagues from
28 53 countries. The combined networks are transforming understanding of tropical forests and
29 their role in the biosphere. Most importantly, together we have discovered how, where, and
30 why forest carbon and biodiversity are responding to climate change, and how they feedback
31 on it. Three decades of pan-tropical collaboration has revealed a large long-term carbon sink
32 and its trends, as well as making clear which drivers are most important, which forest processes
33 are affected, where they are changing, what the lags are, and what the likely future responses
34 of tropical forests are as the climate continues to change. By leveraging a remarkably old
35 technology, forest plot networks have already sparked a revolution in tropical forest science.
36 In the future, science and humanity will benefit greatly by nurturing and sustaining the
37 grassroots communities now capable of generating unique, long-term understanding of Earth's
38 most precious forests.

39

40 **Introduction**

41 As the most diverse and productive ecosystems on Earth, tropical forests play essential roles in the
42 carbon and water cycles and maintenance of global biodiversity. Tropical forest lands are also home to
43 more than a billion people and a multiplicity of cultures and having first provided the environments and
44 germplasm that sustained foragers and farmers since the earliest days of humanity, they today underpin
45 a large fraction of our globalized diet and our intensifying demand for water, food and clean air. They
46 also affect our health in multiple, critical ways, providing rich pharmacopeias to traditional and modern
47 societies and harbour microbial diversity that is capable of changing the course of human history as
48 pandemic pathogens when forests and wildlife are exploited. Tropical forests are also central to
49 determining the degree and impact of anthropogenic climate change. Because of their extent, carbon
50 density and productivity, they may both slow climate change by absorbing carbon into their biomass
51 and soils, or accelerate it as deforestation and heating damage forests.

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53 Tropical carbon and biodiversity are therefore critical targets for environmental measurement and
54 monitoring. Although vital to our past, present and future, efforts to measure and monitor them have
55 until recently been localised and disconnected. Aspects of their ecology can be sensed remotely but

56 measurements on-the-ground and tree-by-tree are essential, not least to help interpret the plethora of
57 remotely acquired data (e.g., Chave et al. 2019, Duncanson et al. 2019, Phillips et al. 2019). And yet
58 the very features that enhance their ecological value, such as remoteness, exceptional diversity, and
59 high productivity and rainfall, make tropical fieldwork very challenging. Further, tropical forest science
60 and scientists from forest-rich countries are chronically under-resourced and often academically
61 marginalised, reflecting deeper structural biases in global society. Often colonized from afar and distant
62 from economic and political centres, tropical nature and many who explore it are often peripheral to
63 national and global academic and political priorities.

64
65 While these challenges persist, in recent years new opportunities have emerged which are helping to
66 mitigate some of these problems. Principally, the growth of the internet favours ways of working
67 together which are breaking down barriers of distance and old hierarchies. The focus of this paper is
68 specifically about the power of new collaborative networks to transform tropical forest science – both
69 *what* we do, and *how* we do it - to understand tropical forest functioning and dynamics over large
70 temporal and spatial scales. Our approach was conceived and funded in South America in 1999
71 (RAINFOR, e.g. Malhi et al. 2002) and since adapted to Africa (AfriTRON, Lewis et al. 2009) and
72 Southeast Asia (T-FORCES, Qie et al. 2017). It emphasizes the formation and linking of international
73 grassroots initiatives with standardized field methods and data management. With ForestPlots.net, we
74 now support multiple networks by developing and providing the new cyber-infrastructure (Lopez-
75 González et al. 2011, 2015) needed to enable many tropical scientists to do together what was previously
76 impossible alone. Critically, this includes tools that ensure tropical researchers can manage, share and
77 analyse their data themselves rather than simply handing it to others. ForestPlots.net is a global platform
78 where tropical researchers are in control and free to collaborate, support, or lead as much as they like.
79 Yet, while much has been done, the challenges run deep. Our aim, to support the best possible
80 collaborative science within a model of equitable access to data, tools and time, remains as much an
81 aspiration as a claim of achievements already made.

82
83 Here, we first review how the continental networks and ForestPlots.net have developed, in terms of
84 collaborators, institutions, people, and plots. Next, we focus on key scientific achievements of the
85 combined networks, including a comprehensive understanding of the variation in biomass carbon stock,
86 growth rates, and residence time among continents. Novel insights into large-scale changes over time
87 are then reviewed, to explore how the insights that are now emerging from hundreds of permanent plots
88 are transforming understanding of the role that tropical forests play in the biosphere. Finally, we return
89 to the challenges of building and sustaining long-term science networks in the tropics and outline key
90 priorities for the future.

91 92 **1. Network Development**

93 Tropical research plots that tag, measure, identify and follow forests tree-by-tree have existed for many
94 decades. While they long precede any continental or global network no plot survives since before 1939
95 and few predate 1970. The earliest efforts were closely connected to the imperial- and post-imperial
96 projects of European nations. As such, these were largely motivated by questions about forest-
97 production (timber), and only later floristic composition and diversity. The very first tropical forest
98 permanent sample plots we are aware of were installed in 1857 by the German forester Brandis, working
99 for the British in Burma (now Myanmar) and later other parts of India (Dawkins and Philip, 1998). In
100 India a few extant Forest Department plots date to 1939 (Pomeroy et al. 2003). Important early work in
101 Southeast Asia include plots installed by Don Nicholson and J.E.D. Fox in the 1950s though to 1970s,
102 as well as Peter Ashton since the 1960s and John Proctor since the 1970's. In Africa, early permanent

103 plots include those installed by William Eggeling in Uganda in the 1930s. Among those which survive
104 to this day are some established by Mike Swaine in Ghana and Hans Woell in Liberia in the 1970s, as
105 well as later work by Jan Reistma and Lee White (Gabon), Bonaventure Sonké (Cameroon), Kofi Affum
106 Baffoe (Ghana), and Henri-Félix Maître and colleagues (Gabon, Congo, Central African Republic).
107 Australian plot sampling began in north Queensland in the 1950s, 1960s, and 1970s, with some plots
108 still maintained by CSIRO. In the Americas, T.A.W. Davis and Paul Richards installed ecological plots
109 in Guyana in the 1930s (e.g., Davis and Richards 1933) but these do not survive, while Frank
110 Wadsworth established long-term plots in Puerto Rico's subtropical forests starting in 1943 (e.g. Drew
111 et al. 2009). In Suriname, Schulz and colleagues established silvicultural studies in the 1950s and 60s
112 that helped design the CELOS Management System (Werger 2011). Key neotropical ecological plots
113 which survive include many in Venezuela set up by Jean-Pierre Veillon in the 1950s, 1960s, and 1970s
114 (e.g., Vilanova et al. 2018) and Rafael Herrera and Ernesto Medina and colleagues in the 1970s, as well
115 as early plots in the Brazilian Amazon by João Murça Pires, H. Dobzhansky and G. A. Black and later
116 Ghilleen Prance, and in Costa Rica starting in 1969 by Diana and Milton Lieberman. Alwyn Gentry,
117 John Terborgh, Terry Erwin, David Neill and Rodolfo Vásquez set up the first permanent plots in the
118 western Amazonia in the late 1970s and 1980s (Gentry 1988a, Monteagudo et al. 2020), as did Ima
119 Vieira and Rafael Salomão in Pará (e.g. Salomão 1991, Pires and Salomão 2000), Tom Lovejoy, Niro
120 Higuchi and colleagues near Manaus, Henri-Félix Maître and colleagues in French Guiana, and later
121 Tim Killeen and Luzmila Arroyo in Bolivia and Beatriz Marimon in Mato Grosso. Meanwhile, the first
122 long-term tropical large plot (Hubbell 1979) in Costa Rica was an innovation that permitted plot-level
123 analysis of multi-species demography and the subsequent development by the Smithsonian Institution
124 of the CTFS/ForestGeo network (Davies et al., this volume).

125
126 The first international tropical forest network encompassing hundreds of long-term plots, RAINFOR,
127 was at root inspired by Alwyn Gentry, a virtuoso tropical botanist who established the first globally
128 standardized floristic inventories. Gentry developed a 0.1-ha sampling design to rapidly inventory
129 diversity in species-rich tropical forests, capturing each stem down to 2.5 cm diameter, and with
130 colleagues replicated it throughout the tropical Americas as well as parts of Africa, India, Southeast
131 Asia, Australasia, and even into Laurasian and Gondwanan temperate forests. By the time of his
132 untimely death in 1993, aged just 48, Gentry had completed 226 of these samples, inventorying
133 thousands of tree and liana species including many new to science. His legacy lives on in multiple ways.
134 After studying with Walter Lewis and recruited by Peter Raven in the early 1970's, Gentry was a key
135 figure in Missouri Botanical Garden's golden age of tropical botany. He made nearly 90,000 plant
136 collections including more lianas than anyone in history and his pioneering approach to identifying
137 plants in the world's most biodiverse forests (Gentry and Vásquez 1993) has inspired new generations
138 of botanists throughout Latin America. It was Gentry who embodied the ambition of combining
139 efficient ecological sampling with high-quality botanical identifications and replicating these to create
140 highly distributed measurements of the world's forests (e.g. Gentry 1988b, Clinebell et al. 1995, Phillips
141 and Miller 2002, Phillips and Raven 1997). He also established many permanent plots (Gentry 1988a)
142 that feature in the first continental and pan-tropical analyses of forest carbon and dynamics (Phillips
143 and Gentry 1994, Phillips et al. 1994, Phillips et al. 1998) and led to the creation of RAINFOR (Malhi
144 et al. 2002, López-Gonzalez and Phillips 2012) and standardized protocols (Phillips et al. 2002).
145 Originating in 1999 from a small nuclei of researchers and plots and EU funding to Brazil's LBA
146 initiative, RAINFOR grew to tackle the huge challenge of analysing Amazonian forests and climate
147 responses tree-by-tree from the ground-up. By bringing different groups together it was possible to
148 create long-term international collaborations to measure and understand not only forest dynamics and
149 diversity but also biogeochemistry and carbon fluxes.

150

151 While RAINFOR has grown steadily, other plot networks soon emerged with complementary foci in
152 South America. Some are daughter initiatives to RAINFOR, while other were formed independently,
153 but most share a similar ethos and strongly overlapping protocols. To the extent that they can be
154 combined together they represent an impressive 'Observatory for Neotropical Forests'. Among these
155 (with dates when fieldwork explicitly used these network labels) are Tropical Ecology Assessment and
156 Monitoring (TEAM, 2002), Programa de Pesquisa em Biodiversidade (PPBio, 2004, Brazil), Amazon
157 Tree Diversity Network (ATDN, 2006), Rede Amazônia Sustentável (RAS, 2009, Brazil), Global
158 Ecosystems Monitoring (GEM, 2010; Malhi et al. this volume), Programa Ecológico de Longa Duração
159 (CNPq/PELD-TRAN, 2010), Latin American Seasonally Dry Tropical Forest Network (DryFlor,
160 2012), Red Colombiana de Monitoreo de los Bosques (ColTree, 2012), Fire Associated Transient
161 Emissions (FATE, 2014, Brazil), Secondary Forest Network (2ndFOR, 2015), Peru Monitoring
162 Network (MonANPerú, 2017), sANDES (Tree Diversity, Composition and Carbon in Andean Montane
163 Forests, 2019), Red de Bosques Andinos (RBA, 2020), Red Subtropical de Parcelas Permanentes
164 (RedSPP, 2020), as well as global networks and meta-networks such as ForestGEO (Anderson-Teixeira
165 et al. 2015), sPlot (Bruelheide et al. 2019), and TmFO on logged tropical forests (Sist et al. 2015). These
166 have notable achievements of their own; at the time of writing this in 2020 all but TEAM have active
167 research programmes.

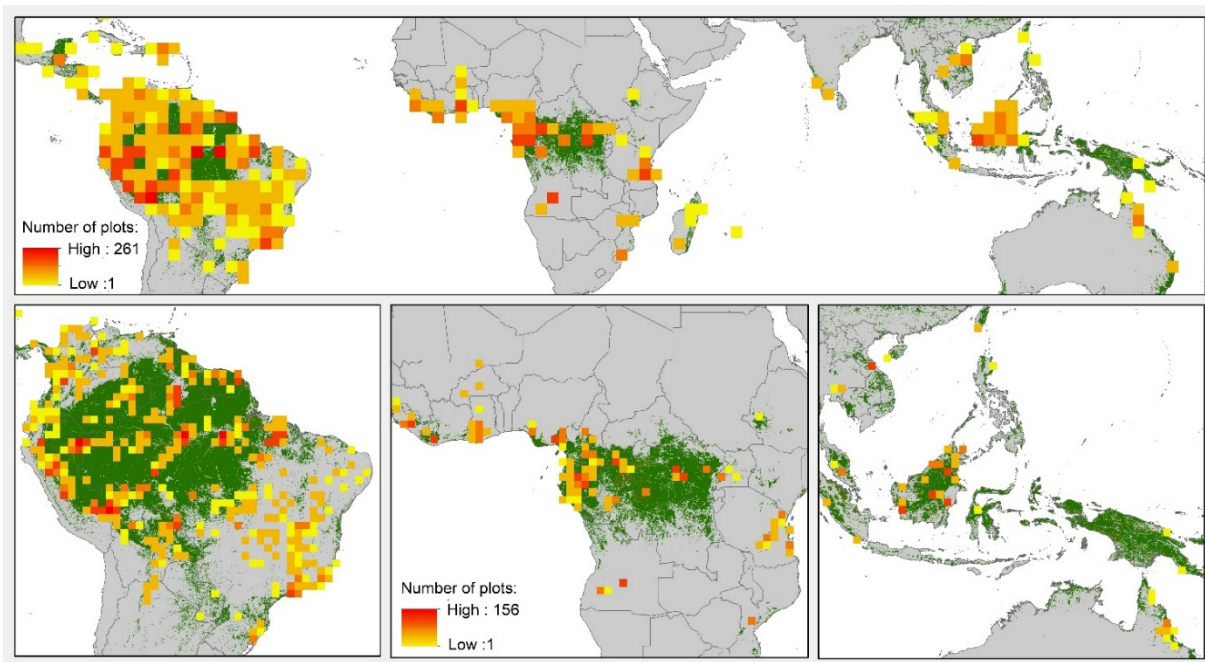
168
169 In Africa, our early networking focussed on assessing whether there were similar patterns of changes
170 in carbon stocks as observed in South American forests and the causes of such changes. Efforts began
171 in 2001 to recensus many of the earlier plots installed in post-independence Africa (UK funding to
172 Phillips, Malhi and Lewis), later formalised as the African Tropical Rainforest Observation Network
173 (AfriTRON; Lewis et al. 2009). These plots currently span 12 African countries supporting moist
174 forests, from Sierra Leone in the west to Tanzania in the east. Like RAINFOR in Amazonia, AfriTRON
175 pools expertise and data to tackle long-term, continental-scale questions relating to the ecology and
176 biogeochemistry of tropical forests. Networks sharing a similar ethos to AfriTRON now have
177 programmes in Africa, including TEAM (TEAM, 2002), DynAffFor (Gourlet-Fleury et al. 2013), TmFO
178 and ForestGEO [Davies et al. 2020?]. The recent establishment of the SEOSAW network
179 (<https://seosaw.github.io>) extends these observations into the woodlands and savannas that form the
180 largest land-cover on the continent, while AfriMont aims to monitor Africa's tropical montane forests
181 (Cuni-Sanchez et al. in prep).

182
183 Our work in Southeast Asia began in 2001 to assess forest carbon balance but only developed into a
184 network once Lan Qie undertook considerable fieldwork and networking. European Research Council
185 investment (T-FORCES 2012 grant to Phillips, Malhi and Lewis) enabled intensive campaigns to
186 develop long-term plot networking in Borneo (Qie et al. 2017), as well as supporting African
187 censuses. As in Amazonia and Africa, the Asian network builds on plots installed by a number of key
188 foresters and botanists as long as 60 years ago. Critically, RAINFOR, AfriTRON, T-FORCES and
189 TmFO use the same field and analytical protocols.

190
191 How can we combine the different strengths of these and other initiatives to maximise their impact on
192 science and society? To achieve this requires shared data management tools, and horizontal
193 organisational structures that foster leadership by tropical scientists. Our plot data management was
194 originally conceived in 2000 as a desktop database to support RAINFOR analyses of spatial variation
195 in wood density, biomass, productivity, and changes in biomass over time (Baker et al. 2004a, b; Malhi
196 et al. 2004). This was expanded to draw together inventory data from more than 100 sites in Amazonia,
197 and subsequently African forest plots too, to include some of the longest running monitoring sites
198 worldwide (Peacock et al. 2007). Since 2009 we have developed a global, on-line Structured Query

199 Language resource with sophisticated programming that supports multiple applications (Lopez-
 200 Gonzalez et al. 2011). Now, ForestPlots.net provides ecological informatics to colleagues in numerous
 201 scientist-led networks worldwide (Fig. 1). Key advances include the ability to manage complex time-
 202 series data, to track species linked to high-quality botanical records, and to analyse records with
 203 common BiomasaFP R protocols (López-Gonzalez et al. 2015). While focussed on identity, tree growth,
 204 mortality and carbon dynamics, ForestPlots.net encompasses many related forest attributes including
 205 lianas, soils, and plant traits. At their heart long-term plots are an intensely human enterprise, and so we
 206 document too the personal contributions: tracking who did what and when ensures we honour the inter-
 207 generational aspect of plots that allows contemporary analysts to stand on the shoulders of giants. Data
 208 contributors retain control, able to manage, share and analyse their long-term data with the tools
 209 provided, and if new collaborative projects requesting to use their data are proposed they agree, or not,
 210 as they wish; contributors also of course propose their own projects. ForestPlots.net can provide DOIs
 211 to datasets, further ensuring contributors are properly acknowledged. The result of developing all this
 212 functionality has been an increase in projects initiated from the tropics as opposed to the traditional
 213 model in which researchers from the Global North lead. Thus, as a platform to enable the level of
 214 collaboration that individual researchers wish for while underpinning network and multi-network
 215 integration, ForestPlots.net is empowering data owners and networks alike.

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220 **Figure 1. Current extent of ForestPlots.net**

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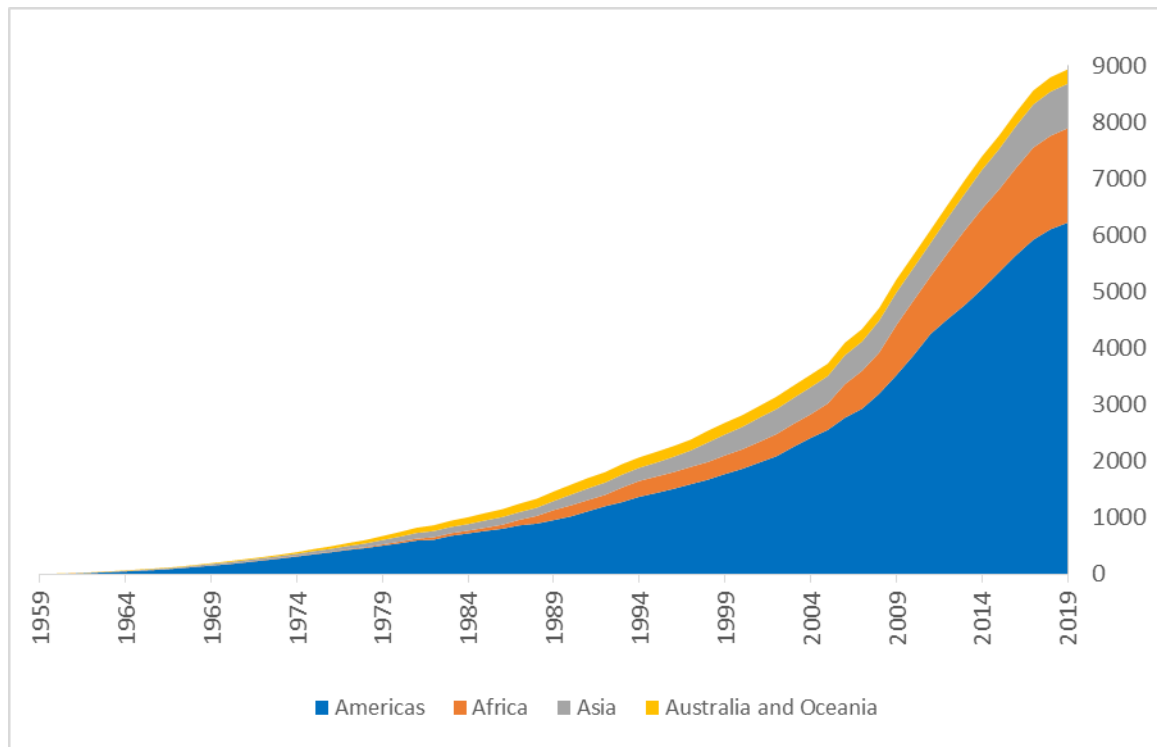
222 **Top:** Pantropical plot sampling density per 2.5 degree square with the 3,653 multiple- and single-inventory plots
 223 hosted at ForestPlots.net. These contribute to many networks including RAINFOR, AfriTRON, T-FORCES,
 224 ATDN, BIOTA, ColTree, FATE, GEM, Nordeste, PELD, PPBio, RAS, RBA and SEOSAW. Forest cover based
 225 on the Global Land Cover 2000 database (JRC, 2003) with tree cover categories: broadleaved, evergreen; mixed
 226 leaf type; regularly flooded.

227 **Bottom:** The same plot sampling but displayed at higher-resolution (1 degree grid cells) for each focal continent,
 228 South America, Africa, and Southeast Asia and Australia.

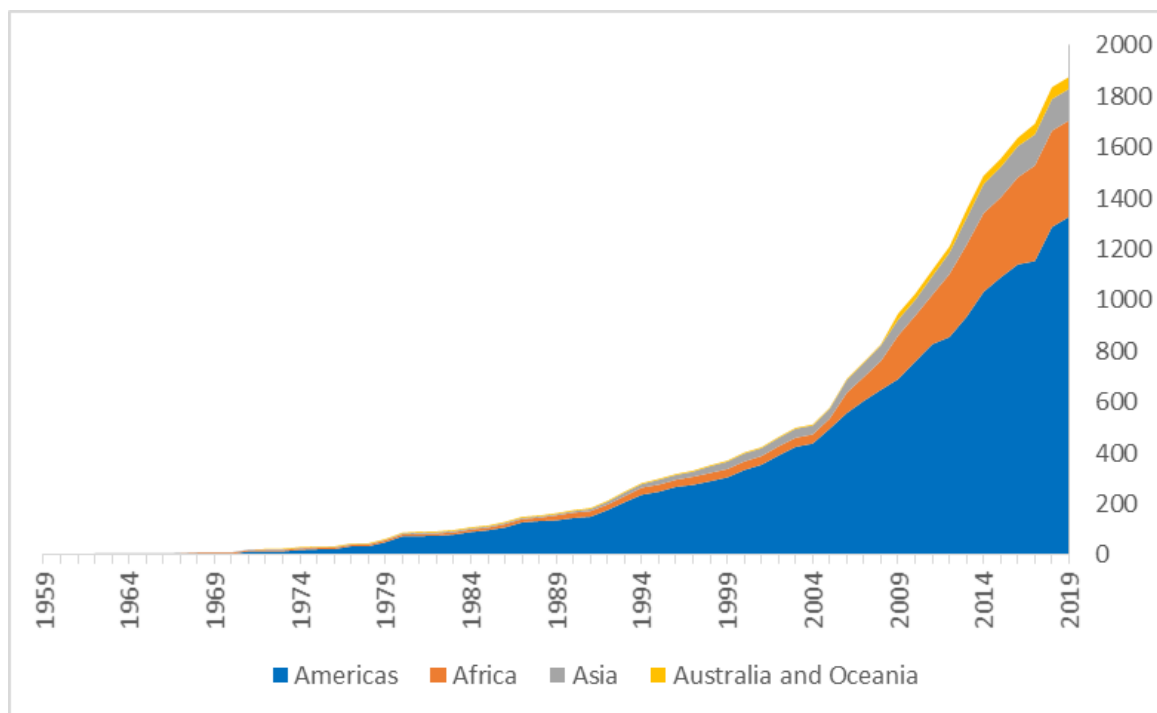
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231 The number of contributors, plots and outputs from ForestPlots.net and contributing networks have
232 increased substantially over their two decades existence. While our networks and ForestPlots share a
233 20-year history, the history of plot monitoring is of course much longer. Even in the tropics, the first
234 recorded census in ForestPlots.net dates from 1939. Forty years later by 1979, 676 censuses had been
235 completed from 90 plots. Since then, fieldwork accelerated greatly with 9,000 censuses completed from
236 3,500 plots by 2019 (Fig. 2a), reflecting the growing community of contributing ecologists (Fig 2b).
237 ForestPlots itself has grown steadily (Fig. 3), both in terms of censuses being uploaded and in terms of
238 output. The neotropics dominate much of this inventory and monitoring effort in general as well as the
239 growth of ForestPlots.net in particular, but contributions from Africa and other continents are increasing
240 too (Figs. 2, 3). The scientific outputs emerging from this collective effort span local to global scales
241 but have an increasingly pan-tropical theme (Fig. 3b).
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245 **Figure 2. Growth of pan-tropical forest monitoring since the mid-twentieth-century.**

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247 *Top:* Plot-censuses curated at ForestPlots.net by date of census;

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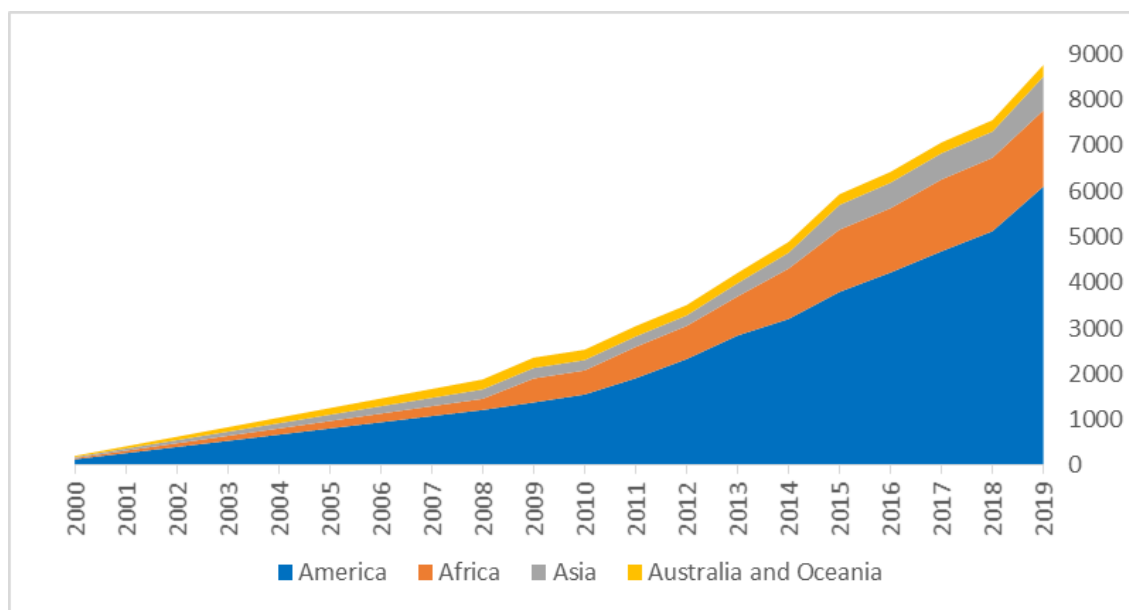
248 *Bottom:* Cumulative contributors to ForestPlots.net by date of first recorded fieldwork. Growth was slow following the first census in 1939, only reaching 100 censuses by 1969. For early censuses, records of field team personnel and leaders is often sparse or absent.

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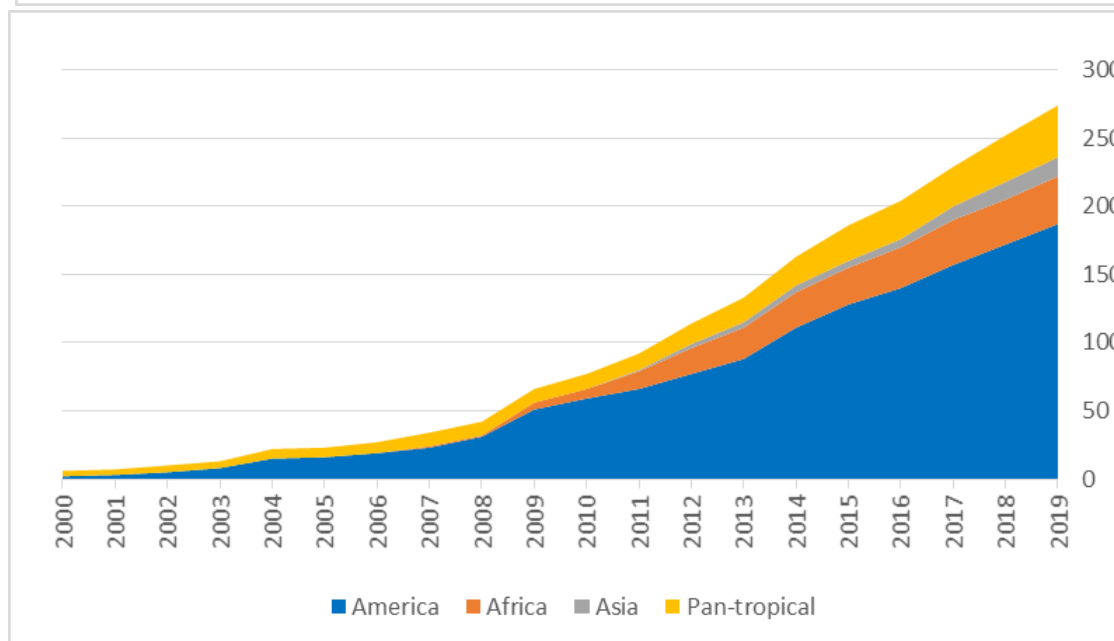
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256 **Figure 3. Growth of ForestPlots.net and contributing networks since 2000.**

257

258 *Top:* Cumulative upload of unique plot censuses to ForestPlots.net by date of upload, with pre-2009 uploads to
 259 pre-internet versions allocated evenly back to network beginnings;

260 *Bottom:* Cumulative peer-reviewed scientific articles based on network plots.

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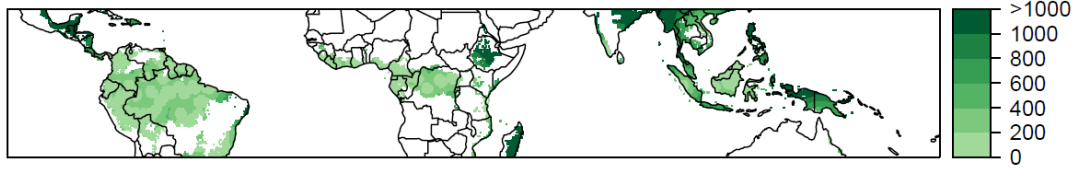
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263 **2. Environmental Representation**

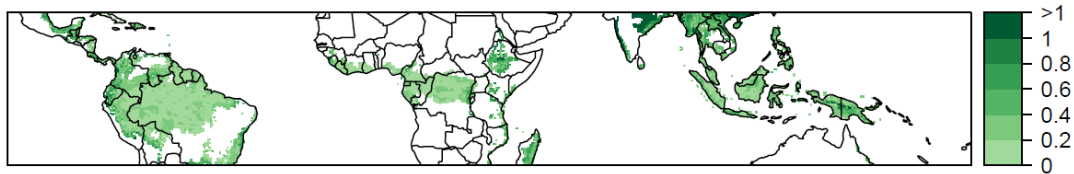
264 While it is not possible to intensively sample the whole tropical forest extent, in practice RAINFOR,
 265 AfriTRON and T-FORCES have managed to cover almost the entire climatic and geographic space
 266 across the humid tropics with permanent plots (Fig. 4a) as well as sample the biome space of the
 267 terrestrial tropics except for semi-arid biomes (Fig. 4b). Within each continent coverage focused on the
 268 moist tropical lowlands with sampling extending into montane and drier forest systems most effectively
 269 in South America (Fig 4c). Plots also cover the complex edaphic variation which is present in Amazonia
 270 (Quesada et al. 2012) and are representative of landscape-level variability within intact forests

271 (Anderson et al. 2009, 2010). This effective representation of intact moist forests provides good support
272 for large-scale inferences from what is, inevitably, still a limited sample of the domain. Yet even here
273 significant work remains to be done to increase representativeness, better understand impacts of
274 geological and edaphic variation, and expand sampling in remote areas especially in Central and
275 Western Amazonia, the central Congo Basin, and New Guinea (c.f. Brearley et al. 2019). Fuller
276 environmental coverage will help networks address long-term challenges such as monitoring of
277 protected area effectiveness (Baker et al. 2020) and consistent calibration-validation of space agency
278 investments in remote-sensing (Chave et al. 2019, Duncanson et al. 2019). Beyond the lowland humid
279 tropics, special effort is needed for long-term, ground-based monitoring in particular environments: (i)
280 tropical montane forests, which represent exceptional concentrations of endemism, great risk of
281 biodiversity loss due to deforestation and climate change, and therefore urgent conservation
282 opportunities (e.g. Malizia et al. 2020); (ii) forests affected by disturbance events such as logging,
283 fragmentation and edge effects, and wildfires (e.g. Elias et al. 2020); (iii) Asian dry forests, and (iv) the
284 wider extent of dry tropical forest and savanna biomes, home to distinctive biodiversity and larger
285 carbon stocks of their own (DRYFLOR 2016, Pennington et al. 2018). ForestPlots.net partner groups
286 are developing research and monitoring in such critical areas beyond the intact lowland forests which
287 have been the main focus of RAINFOR and AfriTRON.
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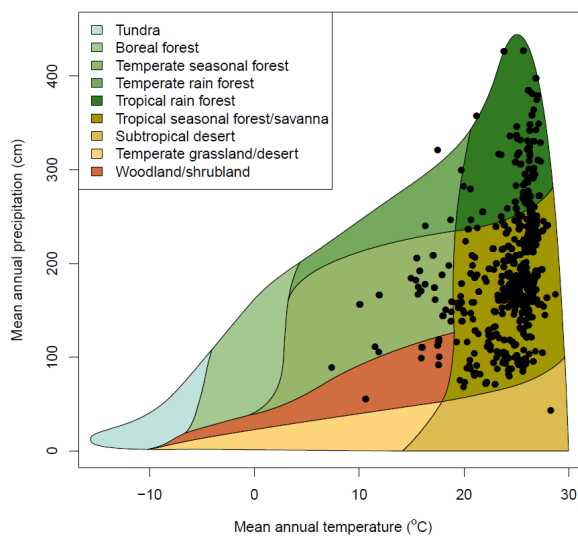
Geographic distance (km)



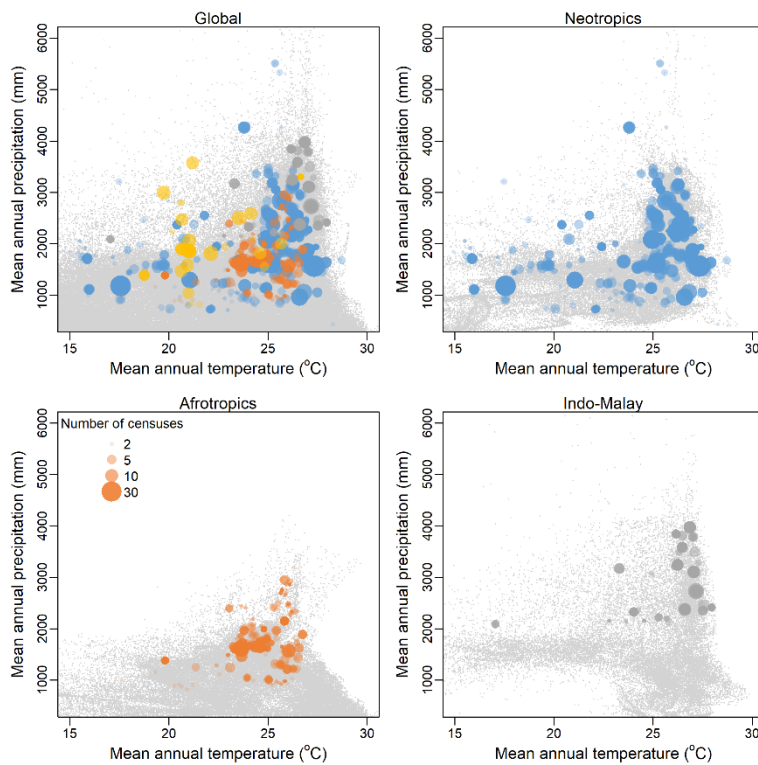
Environmental distance (Euclidean distance [SD])



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293

294 **[Previous Page] Figure 4.** Network coverage of geographical and climate space for >1,500 ForestPlots.net
295 permanent plots from 15 networks (RAINFOR, AfriTrON, T-FORCES, Andes, ColTree, ECOFOR, FATE, GEM,
296 I-For, Nordeste, PELD, PPBio, RAS, RBA and TROBIT). **(a) Top panels:** Geographic distance between multi-
297 census plots and Minimum climate dissimilarity (measured as Euclidean distance on variables scaled by their
298 standard deviation, accounting for mean annual temperature, temperature seasonality, mean annual precipitation
299 and precipitation seasonality) between 10 minute grid-cells across the humid tropical forest biome. For each cell
300 the environmental distance represents how dissimilar a location is to the most climatically similar plot in the
301 network. Note that more poorly sampled areas are often mostly deforested, such as the Brazilian Atlantic, Central
302 America, Madagascar, and much of tropical South Asia, and Southeast Asia; map baseline is the WWF terrestrial
303 ecoregions map (Olson et al. 2001); **(b) Middle panel:** Tropical plots displayed in global biome space (Whittaker
304 diagram), showing the main concentration from lowland wet through to moist forests and savanna, and sampling
305 into cooler montane climates; **(c) Lower panels:** Plots displayed within tropical humid and sub-humid climate
306 space (represented by light grey pixels), with plots displayed colour-coded by continent and with size of symbol
307 corresponding to total census effort; note the important differences in baseline climatic conditions between
308 continents.

309

310 **3. Discovery: Forest Ecology across the Tropical Continents**

311 The plots of RAINFOR, AfriTRON and T-FORCES have generated key ecological and biogeographical
312 insights only achievable via large-scale collaboration among ecologists and botanists. RAINFOR
313 revealed that Amazonian forests differ substantially from one another, even those that share essentially
314 identical climates. For example, basal-area weighted wood density of northeastern forests is 50%
315 greater at the stand level than that of southern and western forests. This reflects floristic differences
316 (Baker et al. 2004, ter Steege et al. 2006, Honorio et al. 2009, Patiño et al. 2009), and in turn is associated
317 with large differences in forest dynamics, with stem turnover twice as fast in the west as the east
318 (Phillips et al. 2004) due to soils with poorer structure (Quesada et al. 2012), and in spite of only modest
319 productivity differences (Malhi et al. 2004, 2014). In turn, biomass in northeastern Amazonia is much
320 higher than elsewhere due to the reduced mortality risk (Baker et al. 2004, Malhi et al. 2006, Marimon
321 et al. 2014, Pallqui et al. 2014, Johnson et al. 2016, Alvarez et al. 2018, Phillips et al. 2019).

322 In Africa, AfriTRON plots have also been used to show that species-driven differences in wood density
323 prevail at large scales. In mature moist forests soil-related compositional differences cause significant
324 variation in basal-area weighted wood density, with forests on younger and relatively fertile acrisols
325 and cambisols having 10% and 20% lower values than those on arenosols and histosols respectively
326 (Lewis et al. 2013). Similarly to Amazonia, African forests growing on developmentally older soils that
327 are less fertile have higher standing biomass (Lewis et al. 2013). While local and regional differences
328 in soils and resultant forest attributes are very important in both continents the key difference is that
329 only in Amazonia are there clear continent-scale gradients, due to the powerful influence of Andean
330 orogeny in the west (leading to much younger, geologically-more dynamic landscapes, more fertile and
331 less developed soils, and influencing speciation, immigration and extinction) contrasting with the
332 ancient, stable Brazilian and Guyanan Shields of the east. Here, the influence of climatic differences is
333 only of second-order importance.

334

335 Large-scale analysis thus reveals how soils and species control the amount of carbon that tropical forests
336 store, which has implications for monitoring their carbon stocks over large areas using remotely-sensed
337 data. In tropical forests neither soil nor tree composition is easily perceived from space. For example,
338 we showed that the invisible large-scale floristic gradients can compromise LiDAR-derived biomass
339 estimates of Amazonia (Mitchard et al. 2014), but by accounting for these by relating plot-derived

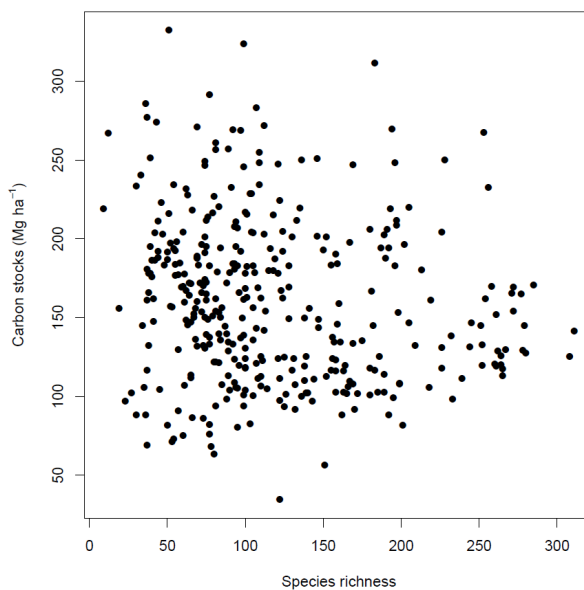
340 woody density and allometry to LiDAR sampling plots greatly improve biomass maps (Mitchard et al.
341 2014, Avitabile et al. 2016). The role of soils and species composition in determining aboveground
342 biomass carbon stocks is a key reason why ground data are essential for mapping forests (Chave et al.
343 2019). Meanwhile, Earth Observation has great benefits in terms of coverage and ability to update
344 frequently. In principle therefore the synergy is bidirectional: both approaches can gain greatly from
345 one-another.

346
347 When networks using the same protocols are combined it becomes possible to discover and explore
348 variation between continents too. Common protocols have shown major pan-tropical variation in
349 vertical structure, including tree height and height-diameter allometry (Feldpausch et al 2011) which
350 have important implications for estimating biomass (Feldpausch et al 2012; Sullivan et al 2018).
351 Comparison of AfriTRON and RAINFOR plots shows that African forests average one-third higher
352 biomass per unit area than Amazon forests (Lewis et al. 2013), yet have many fewer stems >10 cm
353 diameter per unit area. This appears to be driven by lower tree mortality and longer carbon residence
354 times in Africa (Hubau et al. 2020). Similarly, comparing climatically and edaphically similar forests
355 in parts of Borneo with northwest Amazonia reveals that Bornean forests produce much more wood,
356 with trees growing up to half as fast again, suggesting that differences in phylogenetic composition of
357 the communities, especially the dominance of the dipterocarp family of trees in tropical Asia (Corlett
358 and Primack 2011), determine the efficiency with which atmospheric carbon becomes tree carbon
359 (Banin et al. 2014).

360
361 Which tree species, and how dominant they are, strongly control forest function within continent too.
362 For example, a recent RAINFOR study discovered that Amazon woody productivity is enhanced in
363 more phylogenetic diverse forests (Coelho de Sousa et al. 2019). Research led by the ATDN network
364 has shown that remarkably few species dominate Amazon forests in terms of stems (ter Steege et al.
365 2013), while RAINFOR plots showed that a different set of species dominate biomass stocks and woody
366 productivity (Fauset et al. 2015). A number of such 'hyperdominants' may have been long-favoured by
367 indigenous people (Levis et al. 2017, Oliveira et al. 2020). These and many other studies show just how
368 much identity matters: whether storing carbon, converting solar energy into wood, or sustaining whole
369 cultures, it is those species which dominate and their evolutionary history which largely control the
370 ecology and value of forests.

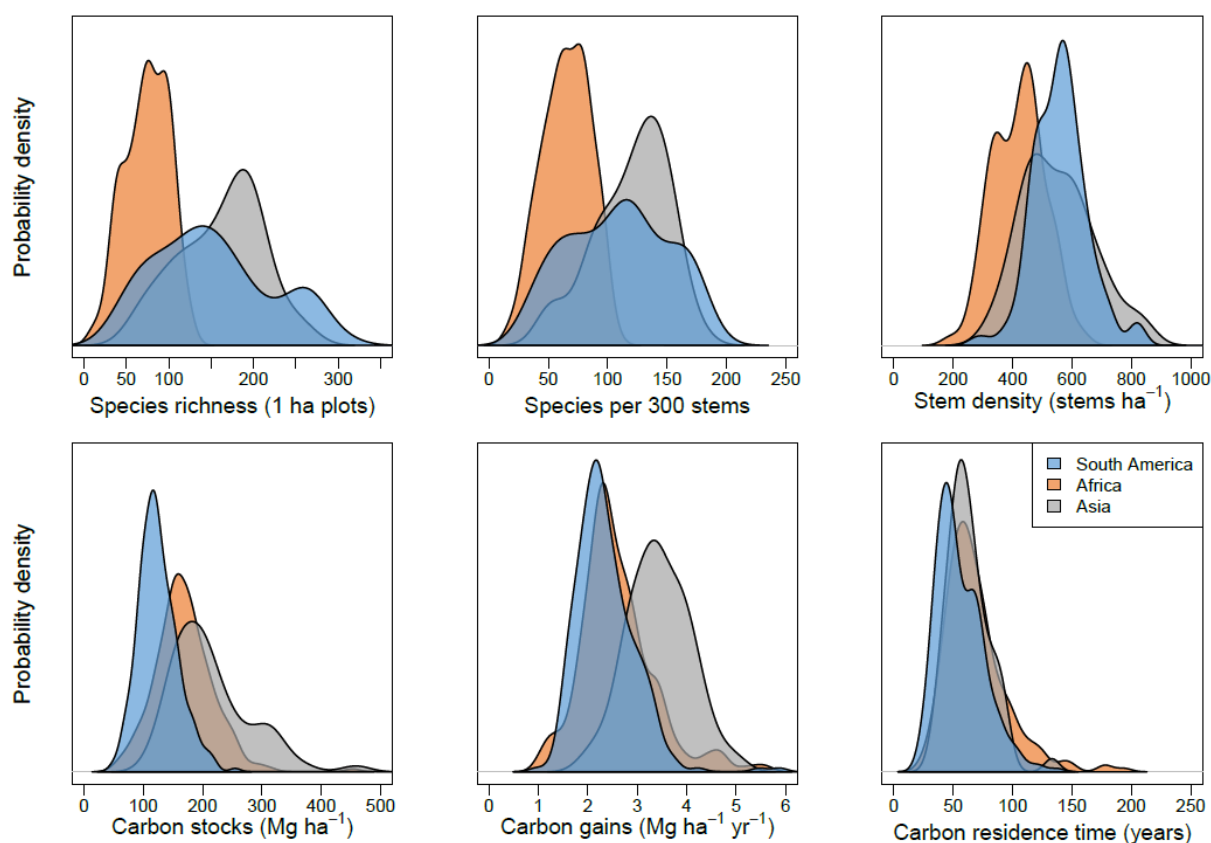
371
372 These insights show that two of the defining challenges of the twenty-first century, climate change and
373 biodiversity loss, are potentially linked. Hence, how do we best devise the conservation strategies to
374 achieve the twin targets of tropical biodiversity protection and climate mitigation? Can we rely for
375 example on carbon conservation via global schemes like REDD+ to protect tropical diversity too? While
376 the answers to these questions depend on the relationship between diversity and carbon storage
377 assessing this has been challenging due to the scarcity of inventories with carbon stocks and species
378 identifications both robustly quantified. Combining RAINFOR, AfriTRON and T-FORCES plots
379 (Sullivan et al. 2017) we found that for tropical trees at least diversity-carbon storage relationships are
380 virtually non-existent (Fig. 5). For example, South America, the continent with the richest forests,
381 actually stores the least carbon per hectare, while within continents there is no association. Independent
382 data from the RAS network data supports this, showing that strong carbon-biodiversity relationships
383 are only found in disturbed and secondary forests but not in old growth forests (Ferreira et al. 2018). As
384 intact forests can have any combination of tree diversity and carbon stocks both require explicit
385 consideration to protect the climate and biodiversity. We cannot simply focus on carbon and achieve
386 our biodiversity goal, and vice versa.

387



388
 389 **Figure 5. Pantropical forest carbon storage and species richness.**
 390 There is no relationship between carbon stocks per unit area and tree species richness per hectare in intact tropical
 391 forests. Figure adapted from Sullivan et al. 2017.

392
 393



394
 395
 396 **Figure 6. Tropical continental macroecology**
 397 The figure shows that major differences among tropical forests emerge when networks are combined. Graphics
 398 depict probability densities such that the whole area always sums to 1. The y-axis scale for each variable thus
 399 varies depending on the range of the x-axis area: for continents with larger variation in x, the probability density
 400 at any point in the y axis is correspondingly smaller. Analysis adapted from Sullivan et al. 2017 and 2020.

401
402 When network data are combined surprisingly large and coherent continental-level differences emerge
403 (Fig. 6). African forests are remarkably species-poor at the 1-ha scale. In contrast, South American and
404 Asian forests are more than twice as rich on average, but are also much more variable in terms of
405 species-richness and diversity. The very richest forests in the world are located in parts of Western
406 Amazonia, vindicating Gentry's assertion more than three decades ago (Gentry 1988a, b). African
407 forests have many fewer stems than their Asian and South American counterparts, but South American
408 forests have considerably less biomass. In terms of woody productivity it is the Sundaland forests of
409 Southeast Asia which are outliers, being often twice as productive as in South America and Africa. And
410 yet, in spite of this, it is in South America where woody carbon turns over fastest; fully half the carbon
411 in neotropical trees has been replaced since 1970. Overall these comparisons reveal remarkable
412 continental differences in tropical forests that are apparently not driven by rainfall or temperature or
413 even soil (Sullivan et al. 2020). The clear implication is that other factors related to the evolutionary
414 and historical happenstance of each continent must matter. Global-scale ecological modelling ignores
415 biological composition at its peril. And, each continent needs its own strong research and monitoring
416 programme, and, maybe, each region might be expected to respond to climate change in its own,
417 idiosyncratic way.

418

419

420 **4. Discovery: Tropical Forest Change**

421 The single most significant scientific impact of multiple permanent plot networks has been to transform
422 our understanding of the role of tropical forests in the functioning of the Earth system.

423

424 As the most diverse and carbon-rich tropical biome, the fate of humid tropical forests will strongly
425 determine the future of life on Earth. Until quite recently it was axiomatic that intact tropical forests
426 are essentially at 'equilibrium' when considered over sufficiently large scales, and that any apparent
427 changes observed at smaller scales are driven by natural disturbance-recovery processes. However,
428 large-scale imbalances in the global carbon balance cast doubt on this assumption (e.g. Taylor and
429 Lloyd 1992), and over time analyses of multiple long-term plots have helped us to recast our
430 understanding of contemporary intact tropical forests as being non-stationary systems. The carbon,
431 biodiversity and ecosystem processes of tropical forests are now recognised as dynamic and continually
432 responding to a suite of anthropogenic drivers (e.g. Lewis et al. 2004b, Pan et al. 2011, Malhi et al.
433 2014, McDowell et al. 2018, Reis et al. 2018). The key discoveries at this intersection between global
434 change science and forest dynamics, carbon cycle, and biodiversity include:

435

436 (1) The first evidence for a widespread impact of global anthropogenic change on intact tropical forests
437 was manifest as a pantropical increase in tree demographic rates (Phillips and Gentry 1994). The finding
438 that these forests were changing was highly controversial at the time, let alone the inference that global
439 drivers were responsible, and contradicted established ecological orthodoxy. A productive debate
440 helped generate new questions and analyses (e.g. Sheil 1996, Sheil and May 1996, Phillips and Sheil
441 1997), and potential biases being identified and addressed (e.g. Sheil 1995, Condit 1997, Lewis et al.
442 2004a, Gloor et al. 2009, Espirito-Santo 2014). A quarter of a century on the central concept that all
443 tropical forests are being influenced by a suite of anthropogenic global change drivers is no longer
444 contested.

445

446 (2) In parallel with changes in stem dynamics, it quickly became clear as RAINFOR grew that biomass
447 dynamics have also accelerated in Amazonia. Moreover, increased gains in stems (recruitment) and

448 biomass (woody productivity) clearly precede the increases in stems and biomass losses (mortality)
449 (Lewis et al. 2004b, Phillips et al. 2004, 2008, Brien et al. 2015, Nogueira et al. 2018). The
450 mechanism underlying the acceleration of forest dynamics must therefore involve stimulated
451 productivity, via an increase in resources for plant growth, as opposed to direct stimulation of tree
452 mortality such as by drought.

453

454 (3) The Amazon carbon sink. In conjunction with faster growth, mortality, and turnover, the biomass
455 density of Amazon forests has increased (Phillips et al. 1998, Baker et al. 2004). Intact Amazon forests
456 have absorbed (net) atmospheric carbon for at least three decades now (Brien et al. 2015). This net
457 sink is a true “subsidy from nature”, with magnitude matching or exceeding net fluxes from neotropical
458 deforestation (Aragao et al. 2014, Gatti et al. 2014). Consequently, monitoring networks have shown
459 that most Amazon nations are on balance not net emitters of carbon (Espirito-Santo et al. 2014, Phillips
460 and Brien et al. 2017). The location, magnitude and stability of this intact forest sink has major implications
461 for guiding approaches to meeting nationally differentiated targets for controlling climate change
462 (Vicuña Miñano et al. 2018).

463

464 (4) The African carbon sink. The AfriTRON network discovered a long-term net biomass increase
465 similar in magnitude to that of the Amazon (Lewis et al. 2009). The consistency of these results on a
466 second continent supports the idea that global drivers of change were affecting even the most remote
467 intact tropical forests. The fact that biomass is increasing across the entire wood density spectrum of
468 tree species, implies that forests were responding to increasing CO₂ (Lewis et al. 2009). The long-term
469 increase in carbon stocks of African forests was recently confirmed and updated with over three times
470 as many plots (Hubau et al. 2020).

471

472 (5) The Southeast Asian carbon sink. Once the T-FORCES network allowed sufficient plot coverage
473 across remaining Bornean forest a similar increase in aboveground biomass over recent decades was
474 revealed (Qie et al. 2017). Thus the three continental networks discovered that intact tropical forests as
475 a whole have been a long-term sink. The ground measurements imply this totalled more than one billion
476 tonnes of carbon each year for decades, i.e. half the terrestrial global carbon sink (e.g. Pan et al. 2011)
477 which is sufficient to significantly slow climate change. Evidence that the main blocs of remaining
478 intact tropical forests are now *en masse* out-of-equilibrium and undergoing biomass increases of similar
479 magnitude, points to a common global driver of growth. Increasing atmospheric CO₂ is the most
480 parsimonious candidate, a conclusion strengthened by close parallels to model predictions from first
481 principles (e.g., Huntingford et al. 2013), inferences from CO₂ fertilization experiments (Terrer et al.
482 2019), the greening of forest areas in the absence of significant land-use change (Nemani et al. 2003),
483 and recent analysis of the RAINFOR and AfriTRON plot data showing a significant role of [CO₂]
484 (Hubau et al. 2020).

485

486 (6) The Amazon sink is waning. After 30 years of monitoring Amazonian forests, the RAINFOR plots
487 show that the rate of increase in forest growth is slowing. Tree mortality rates have increased over the
488 whole period leading to a long-term decline in the magnitude of the net accumulation of biomass
489 (Brien et al. 2015). This subsidy from nature provided by tropical forests may be strictly time-limited.

490

491 (7) In Amazonia recent droughts have had large impacts. Long-term plots also monitored immediately
492 before and after droughts reveal that these forests can switch rapidly from being a major sink to a source
493 of carbon. Both the 2005 and the 2010 Amazon droughts had a net impact on the order of 1 Pg of carbon,
494 driven primarily by drought-induced mortality (Phillips et al. 2009, Lewis et al. 2011; Doughty et al.

495 2015, Feldpausch et al. 2016). RAINFOR and GEM quantified the drought-sensitivity of the world's
496 biggest rainforest and identified the key process affected (mostly tree mortality rather than growth, and
497 not photosynthesis) (e.g. Doughty et al. 2015). The biomass carbon sink impact of the 2010 drought
498 and non-drought years match independent inferences from measurements of atmospheric [CO₂] using
499 aircraft (Gatti et al. 2014).

500

501 (8) The African and Amazon sinks have diverged. Thirty years of monitoring AfriTRON plots show
502 that African forests have continued to function as a carbon sink, although the most intensively
503 monitored plots suggest that the sink is declining since 2010 (Hubau et al. 2020). When analysed
504 together with RAINFOR data the within-plot changes over time reveal a common set of drivers which
505 indicate that the sinks are on a trajectory of decline, with African forests lagging behind Amazonian
506 forests by 15 to 20 years (Hubau et al. 2020). Changes across both continents are best explained by a
507 combination of the positive effects of increasing CO₂ enhancing productivity, and negative effects of
508 higher temperatures and droughts in suppressing growth and accelerating tree mortality, combined with
509 the intrinsic properties of forests themselves. African forests have longer carbon residence times and
510 because mortality catches-up fastest in faster turnover forests this explains the time-lag of the African
511 sink saturation. Amazonian forests are also harder hit because most are hotter, warming faster, and more
512 often exposed to drought (Hubau et al. 2020). Together, the pan-tropical plot networks have revealed
513 long-term trends in carbon storage and determined which drivers matter, which processes are affected,
514 where they are impacting, what the lags are, and what the likely future responses of forests are as
515 climates continue to change.

516

517 (9) The future of the tropical intact forest carbon sink. By coupling RAINFOR and AfriTRON current
518 plot climates with different scenarios going forward the forest carbon sink across the networks is likely
519 to decline going forward (Hubau et al. 2020). The projected decline is steeper in Amazonia, and is
520 driven by the balance of CO₂ fertilization, higher temperatures, and impacts of future droughts. This
521 sharp contraction of the carbon sink is not seen in climate-driven vegetation models (Huntingford et al.
522 2013). However, a major uncertainty is that these projections do not include changes in species
523 composition which may extend the forest carbon sink further into the future if species that are better
524 adapted to the new environmental conditions compensate for others' losses.

525

526 (10). Tropical forest biodiversity is also changing. RAINFOR data show that an entire group of plants,
527 lianas (woody vines), are increasing in dominance across Amazonia (Phillips et al. 2002) which
528 contributes to higher tree mortality (Phillips et al. 2005). Tree community composition is changing too.
529 Climate change is inducing large-scale change in tropical biodiversity as wet-adapted tree taxa in
530 Amazonia face greater drought-mortality risks (Esquivel Muelbert et al. 2017, 2019) while in part of
531 west Africa a shift towards drought-deciduous tree species coincides with long-term drought (Fauset et
532 al. 2012, Aguirre-Gutiérrez et al. 2019). In both continents these community responses to drought
533 coincided with biomass gains. Nonetheless, the long generation times of tropical trees ensure that
534 biodiversity change is not keeping pace with the drying of Amazonia (Esquivel-Muelbert et al. 2019),
535 so ecological lags mean that forest carbon storage is still at risk from climate change. In addition,
536 deforestation and disturbance of the remaining forests is driving biodiversity loss across much larger
537 areas (Barlow et al. 2016). Improved modelling of the timing and magnitude of tropical carbon
538 responses to global change drivers will be needed to account for natural and human-induced variation
539 in biodiversity, demographic processes and their lags.

540

541 In sum, highly-distributed, long-term monitoring of the world's richest forests has profoundly increased
542 our understanding of nature's sensitivity to climate change. Looking forward, many of the key

543 uncertainties that remain concern the responses of tropical biodiversity itself, including the extent to
544 which the great complexity of most tropical forests offers an effective and timely insurance policy in
545 the face of rapidly changing climates.

546

547

548 **5. Challenges and the Future of Tropical Forest Monitoring**

549 RAINFOR and other highly-distributed plot networks have made a series of key scientific discoveries
550 and advances. But the RAINFOR social research network model has also influenced how tropical
551 ecology is being done, in intact moist forests and increasingly in disturbed and drier tropical systems
552 which cover more than 20 M km². Since 2000, tropical ecology has undergone a remarkable shift from
553 a small cadre of researchers working in single or few sites to a globalised, more decentralised process
554 with increasing contributions and leadership from tropical scientists. This is made possible by
555 supporting highly-distributed researchers and field sites and embracing groups hitherto sometimes
556 marginalised in research. It has been enabled by shared data management and an equitable concept of
557 data ownership. It has been nurtured by many researchers placing trust in the sharing of hard-won data
558 to answer big questions, and supported by mutual recognition of the value of developing trusting
559 relationships over time. More collaborative, multi-polar structures also help to ensure breadth and
560 resilience, while nurturing the leaders of the future. Critically, to grow such interactive multi-site, multi-
561 cultural science has also required standardized field and analytical methods to be developed, agreed,
562 formalised and promoted. Overall, the transformative power of this approach has led to many tropical
563 and global plot-centred ecological networks emerging that together are reshaping our understanding of
564 tropical vegetation. These all however face a number of key challenges if they are to sustain these gains
565 and ensure they reach deeper into society.

566

567 *1. How should we support leadership in the Global South?* No one project can reverse the impact of
568 centuries of global inequality, but neither is that a reason not to tackle some of the deep structural
569 impediments to creating a more equal world. Ecology and conservation science remain temperate-
570 biased, in terms of funding, researchers, and topical focus (e.g., Di Marco et al. 2017, Reboredo et al.
571 2020). Meanwhile tropical ecology is often detached from relevant policy-making processes and most
572 high-impact papers are still led from the North. Clearly, more leadership of forest inventory, monitoring,
573 and science from tropical countries can help address this and achieve more impact on forest
574 management (c.f. Baker et al. 2020). Supporting tropical students at different levels up to PhD is also
575 important. To help sustain this, ForestPlots.net has made shared tools widely available, and especially
576 data management and analytic tools to support data contributors as much as users. We also aim to ensure
577 that field contributions are fully recognised and that leadership in tropical researchers is fostered. To
578 assist this we have developed a Code of Conduct to emphasise contribution, encourage tropical national
579 scientists, and promote mentoring of junior scientists, and to oversee this we created a diverse steering
580 committee which is now supporting more than 30 projects each year
581 (<http://www.forestplots.net/en/join-forestplots/research-projects>). The proportion of ForestPlots.net
582 research projects and products being led by tropical nationals is increasing steadily, reaching 55% by
583 2019 from 35% in 2009. In spite of such gains there is much to be done as diversifying leadership is a
584 long-term process. At a wider level, sustained funding in tropical countries is still needed to ensure they
585 have strong training programmes to develop the core field and analytical skills, as well as opportunities
586 for further career development.

587

588 *2. How should we value and recognise collaboration and leadership?* Most of the obvious reward
589 structures in science - job security, income, grant success, peer reputation and public acclaim – can
590 favour a ‘me first’ approach. Credit accrues to individuals, while true collaboration involves guiding,

591 sharing and ceding credit to others. Psychologically, collaboration can be a joyful process but letting go
592 of our ego is challenging, especially if individuals feel that their contributions go unseen. A
593 developmental solution to this involves many people in the network having the opportunity to lead
594 analyses and get credit, with the expectation that these new leaders then support others with their
595 analyses after that. Another approach to ensuring those who have worked hard in a number of roles are
596 included is group authorship to share credit across all who contribute. This is the model for the current
597 paper as we are synthesising 20 years of shared successes and challenges, but by itself it cannot of
598 course resolve the wider challenge of developing tomorrows leaders.

599

600 *3. How do we value the long-term properly?* Project and thesis time-scales last from one to five years,
601 but the lifespans of even one generation of trees are measured in decades and centuries. What can seem
602 highly fashionable or vitally important in a hypothesis-driven research grant or a PhD may, in fact, have
603 little relevance to the longer natural rhythms of nature. And what if the dominant processes that govern
604 climate responses turn out to include long-term accumulated ecophysiological stress, tree demography
605 and species migration? Clearly long-term research is essential to decode these. Meanwhile, maintaining
606 permanent plots is as much an expression of hope in the future as a stake in an immediate scientific
607 outcome as rewards may accrue to others, far away in time and space. Indeed, we have all benefited
608 from researchers installing plots from the 1930s onwards who never thought that their careful tree
609 measurements and botanical identifications would help elucidate the impacts of climate change on
610 tropical forests. In sum, long-term ecological research is essential in order to discover environmental
611 change, to quantify it, identify the causes, and therefore ultimately to address it.

612

613 *4. Can we ensure fieldwork and human skills are valued for what they are?* As our society becomes
614 increasingly dependent on technology and proficient at using it there are many benefits, including for
615 tropical ecology. But there are significant risks too, particularly in a field where long-term
616 measurements can be perceived as 'old fashioned' (Ríos-Saldaña et al. 2018). One is simply that the
617 tail wags the dog: when technological advance becomes an end in itself there is no guarantee that true
618 scientific and human progress will actually follow. Another is that we naively believe the hype and
619 forget the unique skills needed to measure and identify tropical trees. It is notable that those measuring,
620 climbing, and collecting tropical trees in permanent plots are among the least well-paid of all actors in
621 the global science 'community'. And yet the skills of these true 'key workers' are irreplaceable. First,
622 in many locations, it is only human skill which can measure trees (Fig. 7), and in all other locations it
623 is *combinations* of people and new technology that provides the best results (next section). Second, in
624 tropical forests when tree floras usually run into the thousands of species (e.g., at least 4,700 tree species
625 in Peru, Vásquez et al. 2018) identification depends on trained botanists dedicated to making and
626 curating herbaria collections. The process involves collecting material from tree canopies, making
627 vouchers, identifying them in herbaria and storing them permanently. With vouchers we have the names
628 that minimise uncertainty in wood density and hence biomass. Without physical collections and the
629 skills required to produce them the identifications are untestable hypotheses whose quality cannot be
630 evaluated.

631

632 *5. How should we fund proven networks long-term?* This is perhaps the most pressing concern and it
633 intersects closely with all the above. Which organisations can or should fund measurement networks if
634 credit is shared diffusely and many benefits are long-term?

635

636 Specifically the following changes have transformational potential to unlocking these benefits: (1)
637 *Science agencies prioritising long-term efforts* that transcend individual countries and the short horizons
638 of hypothesis-driven research, whether or not they appeal to the fleeting zeitgeist of the time; (2) *Space*

639 *agencies who need tropical fieldwork to measure the things they can't*, seriously valuing the unique set
 640 of skills that tropical field scientists have and recognising the challenges they face; (3) *Development*
 641 *and conservation agencies who need to know about the long-term health of forests*, integrating on-the-
 642 ground tree-by-tree monitoring into their portfolios; (4) *National and International climate adaptation*
 643 *and mitigation funders focusing on monitoring forests for carbon with scientific-level accuracy to*
 644 *assess the carbon sink and determine land-based emissions*, as both impact on tropical countries'
 645 nationally determined contributions to reducing greenhouse gases. All these important user groups
 646 require networks of long-term, high-quality plots to accurately record biodiversity state and change and
 647 to assess stocks and flows of carbon in tropical forests.
 648
 649



650
 651

652 **Figure 7. Accurately measuring and identifying trees in remote tropical forests requires**
 653 **dedication, skill and courage.**

654 To measure the diameter of this giant *Ceiba* (Malvaceae) tree in Colombia's Chocó, three people need
 655 to climb more than 10 meters. Such approaches are often the most practical and accurate options for
 656 measuring large trees. Like most of our sites there is no electric power, and insecurity associated with
 657 conflict and narcotraffic means no plane or laser-scanner can be deployed. Images: Pauline Kindler.

658
 659

660 **Achievements, impact, and potential**

661 Despite such challenges tropical forest science has come a very long way. Until recently tropical
 662 ecology suffered from a massive data deficit. We had plenty of theory and conjecture, but few
 663 comparable observations over time and space to (deductively) put these ideas to the test, or (inductively)
 664 generate new ones. RAINFOR, AfriTRON and other networks have contributed much to resolving this.
 665 By leveraging a remarkably old technology forest plot networks have sparked a revolution in tropical
 666 forest science. Plot networks have provided the means with which we have quantified the past trajectory

667 of intact forest carbon balance, including its climate sensitivity, and provide a unique pan-tropical
668 Observatory for tracking these vital indicators of Earth's health going forward. Permanent plots are now
669 a key prism through which ecologists address an ever-expanding suite of significant questions, but
670 beyond this they have changed the way *others* see forests. Well-identified permanent plots have proved
671 fertile ground for, *inter alia*, botanists to discover species and even new genera (e.g. Reitsma et al. 1988,
672 Baker et al. 2017, Wurdack and Farfan Rios 2017, Vásquez et al. 2018, Gosline et al. 2019),
673 ethnoecologists to quantify forest people's values (Phillips and Gentry 1993, Lawrence et al. 2005),
674 atmospheric scientists to quantify organic volatiles production (Harley et al. 2004), ecophysiologicalists to
675 assess why trees die (Rowland et al. 2015, Mcdowell et al. 2018), foresters to predict and manage wood
676 production (Gourlet-Fleury et al. 2013), and so on. Plot networks' impacts on policy are also growing.
677 For example in Peru they are being used to validate national contributions to the Paris Climate Accord
678 (Vicuña et al 2018, Baker et al. 2020). To establish baseline forest reference level for Ghana's flagship
679 Cocoa Forest REDD+ Programme permanent plots were used to quantify historical and current forest
680 carbon stocks (FCPF, 2017). In Gabon the National Forest Inventory uses a stratified-random sampling
681 of permanent plots across the country with AfriTRON standard methods (Poulsen et al. in rev. Ecol.
682 Apps). And to assist countries to develop their own nationally determined contributions as part of the
683 UNFCCC process, RAINFOR, AfriTRON, T-FORCES and 2ndFor have just provided the new default
684 values on intact and secondary forest carbon sequestration to the IPCC (Requena Suarez et al. 2019).

685

686 What of the future? As new technologies emerge for probing trees and forests as never before, the
687 hundreds of globally standardised long-term plots and connected networks of multi-skilled tropical
688 researchers provide key infrastructure with which to enrich and validate the new insights that will arise.
689 The benefits of working within established permanent plots go beyond simply having confidence in
690 species and hence biomass. By leveraging them, the scientific value of new technology can be greatly
691 enhanced. For example being able to match individual trees from laser-scanning surveys to tagged,
692 censused individuals provides critical information on growth history as well as identity (Disney et al.
693 2018). Integrating the long-term botanical and ecological data of permanent plots with terrestrial and
694 airborne laser-scanning in designated 'super-sites' (Chave et al. 2019) will help overcome limitations
695 of different approaches, and so provide the highest quality and greatest certainty to the biomass
696 community. Thus the forest networks can help unlock the potential value of multiple missions to
697 monitor forests from space, in the past, present and future. Just like the constellation of Earth-observing
698 environmental satellites in space, the plot constellation represents critical global infrastructure and
699 potentially as great a public good. Last, but not least, as intact tropical ecosystems continue to shrink,
700 burn and fray at the edges, the intact forest permanent plots represent a priceless and irreplaceable
701 baseline for understanding biodiversity and ecosystem processes and thus for guiding our desperately
702 needed restoration efforts. So far the tropical ground effort has been enabled via the goodwill of
703 hundreds of colleagues, as well as over 50 one to five-year grants from more than a dozen sources (see
704 Acknowledgments). Yet such piecemeal and short-term support is too precarious to grow a global
705 public good (see Box 1). For the networks which have already contributed much and have so much
706 more to give, the question remains: Who will invest in this long-term collective success and ensure that
707 the overwhelming public benefits flow reliably?

708

709 Two of the major crises of our century are climate change and biodiversity loss. Tropical forests are
710 situated at the intersection of both so what happens to them now is critical for how all of us will fare.
711 Our work has shown that key to understanding the role of tropical forests in a changing Earth system is
712 repeatable, reliable and geographically highly-distributed monitoring. It has shown the importance of
713 welcoming all contributors into this effort and of valuing the many skills and individuals who contribute
714 to understanding tropical biodiversity and their dynamic changes. More than ever, we need to sustain

715 and grow this global collaborative effort. Monitoring and understanding the complex and critical nature
716 of tropical forests will be best when the science is open, when field skills are properly valued, and when
717 the development of tropical scientists themselves is at its heart. Indeed we know of no other model
718 capable of achieving this.

719
720

721 [Insert Box]

722

723 **Box 1. What Does It Take?**

724

725 Clearly long-term ground-based monitoring of tropical forests requires a sustained global team effort,
726 but just how much does it take in practice to deliver tropical forest plot data? This requires skilled
727 people, and funds. So we address this question in terms of both *the human effort made so far* and in the
728 *financial investment needed to monitor across continents*.

729

730 **(a) The Human Contribution:** Network efforts include not only in-country field campaigns but much
731 besides: to deliver from conception to product high-quality data over a sustained period and multiple
732 countries requires multiple teams that are well-led, and consistent training, protocols, quality control,
733 and data management. In RAINFOR and AfriTRON this includes national or local field-team members
734 to establish and remeasure plots, others to collect and identify plants and collect and analyse soils,
735 colleagues to organize and manage the data, and other to sustain and lead the process nationally and
736 globally - and still more to support these processes with essential administration, herbarium assistance,
737 database development, analytical packages, IT support, technical training and so on. Naturally some
738 individuals contribute in more than one way, roles change over time as lives change, and local, national
739 and global efforts all critically dependent on funding.

740

741 In sum, the average effort *in the field, herbarium, and lab* required to install a typically remote and
742 diverse 1-ha plot and analyse its species and soil comes to 98 person-days, with an additional effort to
743 *support and sustain these teams and data management* of 38 person-days. Together, a total of *136*
744 *person-days can deliver high quality data from a new plot*.

745

746 To recensus a plot is somewhat less demanding (for example no soil collection, fewer plants to identify)
747 but still considerable: 45 person-days in the field and herbarium, and 31 person-days to support and
748 sustain. It therefore requires *76 person-days to deliver high quality data from a recensused plot*. These
749 represent long-term averages. Naturally, circumstances vary from site-to-site and country-to-country.

750

751 Thus far we have established 3653 plots in tropical forests of which 1626 are recensused, from as little
752 as once up to as much as 40 times each. Of the 3653 most are between 0.9 and 1.1 ha but there are
753 many smaller plots too (1728 are ≥ 0.9 ha, and 1925 are < 0.9 ha). Of the 1626 recensused, 70% are ≥ 0.9
754 ha (1088) with 538 < 0.9 ha. If we assume conservatively that all plots ≥ 0.9 ha (average size = 1.18 ha)
755 require 136 days to install and 76 to recensus, and those < 0.9 ha require half this effort (a simplifying
756 assumption, also likely to be conservative due to the fixed cost associated with all plots), then the total
757 effort to install these plots has been 176,044 person-days, while to recensus them it has been 341,204
758 person-days. In total this comes to 1,417 years.

759

760 Thus, as if one remarkably talented and tireless individual had been working continuously since AD
761 603.

762

763

764 **(b) Cost of Sustained Continental Monitoring:** *How much does it cost to monitor Earth's remaining*
765 *intact tropical forests with ground-networks?* This is a critical question given the exceptional ecological
766 value of these systems, the threats they are under, and the role they have and can play in modifying the
767 rate of global climate change.

768

769 At first sight this is difficult to answer, or even for scientists to agree on the terms of reference. We
770 would ask and argue: Monitoring what? For whom? With what precision, level of confidence, or spatial
771 and temporal resolution? Recognising such difficulties, we take a purely pragmatic approach and
772 reframe the question. Thus, instead, *How much will it cost to monitor tropical forests using all the*
773 *permanent plots which we have already remeasured?*

774

775 This question is tractable *practically* (these plots represent a known quantity: we know exactly *where*
776 they are, *what* most of the species are, and to a large extent we know *who* can actually do the work –
777 *each of which is critical*), it makes sense *scientifically* (these already have a baseline monitoring period
778 against which we can assess any change, *which is essential*), and it is justifiable *numerically* (with
779 somewhat smaller datasets than this we have already detected long-term changes in carbon balance,
780 productivity and mortality in each continent, reported short-term changes in response to drought driven
781 by El Niño and other climate anomalies, and attributed changes in carbon and biodiversity to climate
782 drivers, *which all establish proof of concept*).

783

784 There are 915 remeasured plots in tropical forest South America (290<0.9ha + 640>0.9ha), 462 in
785 tropical forest Africa (119 + 353), 192 in tropical forest Asia (106 + 86) and 32 in tropical forest
786 Australasia (22+ 10). If all 1626 are to be monitored on a four-year cycle this requires revisiting 406
787 plots annually, of which 272 are ≥ 0.9 ha.

788

789 Costs can vary site-to-site. Botanical identification is especially challenging in most of S. America due
790 to the extraordinary tree diversity, while some African forests are exceptionally remote; employment
791 and health costs vary but are rising almost everywhere. On average, considering all *the direct and*
792 *indirect human effort required* (above) and *additional direct costs* (consumables, equipment, travel,
793 subsistence, insurance, visas, permits, shipping, training, IT etc.), the current cost to deliver a high-
794 quality remote tropical recensus is $\approx 17,500$ USD for plots ≥ 0.9 ha, and at least half that for those <0.9
795 ha.

796

797 Thus, the annual delivery cost for a pantropical and practical ground-based census programme capable
798 of tracking and attributing forest change to published standards is in the order of:

799

800 $(272*17,500 + 134*8,750) \approx 5.93$ million US dollars.

801

802 This is sufficient to ensure that ground-measurements track the biome-wide and continent-specific
803 biomass carbon balance of the remaining intact tropical moist forests, and their climate sensitivity. And
804 to discover whether the tropical sink is now disappearing as predicted, and where and why, and what
805 the biodiversity consequences are, and to determine how much the intact carbon balance can contribute
806 to countries' nationally determined contributions (NDCs) to climate mitigation. While this sum is
807 significant it is instructive to compare this to that required for other global science initiatives. It is for

808 example a fraction of the Space Agency costs to develop each satellite mission designed to estimate
809 biomass wall-to-wall (from \$100 million to 500 million Euros or more for a single mission). Yet, ground
810 networks ultimately not only transcend the short-term time windows of most such missions but will
811 also be able to add huge value to them.

812

813 Given their great scientific and environmental benefit, the ongoing cost of monitoring Earth's intact
814 tropical forests on the ground is remarkably small. Now that the capacity to do this is established this
815 collective effort should continue.

816

817

818

819 **Acknowledgments**

820

821 This paper is a product of the RAINFOR, AfriTRON and T-FORCES networks and all other partners
822 and partner networks in ForestPlots.net which together support long-term forest science and monitoring
823 across tropical countries. These initiatives have been supported by numerous people and grants since
824 their inception. We are particularly indebted to more than 1,400 field assistants for their help in
825 establishing and maintaining the plots, as well hundreds of rural communities and institutions. For
826 additional assistance we thank Jon Lloyd, Michel Baisie, Wemo Betian, Vincent Bezar, Mireille
827 Breuer-Ndoundou Hockemba, Ezequiel Chavez, Douglas Daly, Armandu Daniels, Eduardo Hase,
828 Muhammad Idhamsyah, Phillipe Jeanmart, Cisquet Keibou Opepa, Jeanette Kemp, Mpanya Lukasu,
829 Sam Moore, Antonio Lima, Klaus Scipal and Rodrigo Sierra. We thank Mark Burkitt for help
830 developing the ForestPlots.net database.

831

832 The networks have been supported by multiple grants, most notably the European Research Council
833 (ERC Advanced Grant 291585 – 'T-FORCES'), the Gordon and Betty Moore Foundation (#1656
834 'RAINFOR', and # xxxx MonANPe), the David and Lucile Packard Foundation, the European Union's
835 Fifth, Sixth, and Seventh Framework Programme (EVK2-CT-1999-00023 – 'CARBONSINK-LBA',
836 283080 – 'GEOCARBON', 282664 – 'AMAZALERT'), the Natural Environment Research Council
837 (NERC grants NE/D005590/1 – 'TROBIT', NE/F005806/1 – 'AMAZONICA', 'PPFOR'
838 E/M0022021/1, NERC Urgency Grants and NERC New Investigators Grants, the NERC/ State of São
839 Paulo Research Foundation (FAPESP) consortium grants 'BIO-RED' (NE/N012542/1, 2012/51872-5),
840 'ECOFOR' (NE/K016431/1, 2012/51509-8), 'ARBOLES' (NE/S011811/1), the Royal Society
841 (University Research Fellowships and Global Challenges Awards ('FORAMA', ICA/R1/180100), the
842 National Geographic Society, the Centre for International Forestry (CIFOR), Gabon's National Parks
843 Agency (ANPN), and Colombia's Colciencias. We thank the National Council for Science and
844 Technology Development of Brazil (CNPq) for support to the Cerrado/Amazonia Transition Long-
845 Term Ecology Project (PELD/403725/2012-7), the PPBio Phytogeography of Amazonia/Cerrado
846 Transition project (CNPq/PPBio/457602/2012-0), PVE grants, and Productivity Grants to several
847 colleagues. Funding for plots in the Udzungwa Mountains (Tanzania) was obtained from the
848 Leverhulme Trust under the Valuing the Arc project. We acknowledge grant CEBA (ref. ANR-10-
849 LABX-25-01) and the support of the Forestry Development Authority of Liberia. We acknowledge the
850 support of the European Space Agency.

851

852 Data from RAINFOR, AfriTRON and T-FORCES are stored and curated at ForestPlots.net, a cyber-
853 infrastructure initiative developed at the University of Leeds that unites permanent plot records and
854 their contributing scientists from the world's tropical forests. The development of ForestPlots.net and
855 curation of data analysed has been funded by several grants including NERC NE/B503384/1,

856 NE/N012542/1 BIO-RED, ERC AdG 291585 T-FORCES', NE/F005806/1 'AMAZONICA', NERC
 857 New Investigators Awards, NERC NE/N004655/1, 'TREMOR ', and Gordon and Betty Moore
 858 Foundation #1656, ('RAINFOR', 'MonANPe'), EU Framework 6, and a Leverhulme Trust Research
 859 Fellowship.

860

861 We thank our late colleagues for their contributions that helped make possible all that the networks and
 862 ForestPlots.net have achieved together: Samuel Almeida, Elisban Armas, Sandra Brown, Gloria
 863 Galeano, Alwyn Gentry, Max Gunther, Sandra Patiño, John Proctor, David Smith and Jean-Pierre
 864 Veillon.

865

866

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