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EDITORIAL

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Plants, people and long-term ecological monitoring in the tropics

1 | INTRODUCTION

Long-term ecological monitoring of tropical moist forests has greatly expanded over recent decades and has been extremely successful in achieving its primary aim of improving our knowledge of tropical rain forest ecology (Davies et al., 2021; ForestPlots.net, 2021; Malhi et al., 2021). At the same time, as these monitoring efforts have developed, land use change in the tropics has accelerated (IPBES, 2019), removing vegetation entirely for intensive agriculture, or degrading it, for example via timber extraction. In the face of this environmental crisis, our tropical monitoring effort currently faces two interlinked challenges: how to use these ecological data to achieve the long-promised outcome of better management that can benefit local and global communities and how to expand these techniques beyond intact, moist forests into other biomes that are home to much of the global, tropical human population. This special issue addresses these challenges through a suite of papers on emerging uses of monitoring plot data. These include using information from plots for ecosystem management within two countries in South America, and the development of monitoring methods for dry biomes, degraded forests and the distribution of large trees.

2 | PEOPLE, POLICY AND LONG-TERM ECOLOGICAL MONITORING

A principal goal for this special issue was to go beyond the science of permanent ecological monitoring and to discuss how it can play a real role in improving lives and livelihoods in tropical countries. Beyond the contribution of permanent monitoring plots to understanding regulating ecosystem services (e.g., carbon sequestration), such societal value has been poorly appreciated, and contributions to this issue (**Ahrends et al.**; **Baker et al.**; **Norden et al.**; **The SEOSAW partnership**) suggest that the uses of plots can be diversified. We see four broad areas where plots can contribute to society:

2.1 | Linking understanding of regulating ecosystem services to policy

This is perhaps the area where plot-based ecological science is having its broadest societal impact, and **Norden et al.** (this issue) provide a case study of the *Red de Investigación y Monitoreo del Bosque Seco Tropical (BST) en Colombia* (Red BST-Col; a network for research and monitoring of tropical dry forests in Colombia) that aims to provide scientific information about the composition and diversity of tropical dry forests in Colombia to support management.

Permanent plot data have been especially important within policy for the measurement of carbon stocks (**Baker et al.**, this issue). At an international level, such data have been used to provide default estimates of the carbon stocks and fluxes of tropical forests for use by countries in their submissions of carbon emissions to the United Nations Framework Convention on Climate Change (Requena Suarez et al., 2019). For example, at national level, **Baker et al.** (this issue) outline how conservation and forest policy has been influenced by using plots to estimate the carbon stock of upland forests and tropical peatlands and to quantify the carbon sink provided by intact forests in protected areas (Vicuña Miñano et al., 2018).

2.2 | Managing provisioning ecosystem services—Timber, non-timber forest products

Forests provide provisioning ecosystem services such as food and products that can be an important income source. The most obvious of these income sources is timber, and in fact, the first permanent tropical forest plots were established to collect data to predict timber yield and define harvesting limits (Hall, 1977; Jones, 1955; see **Baker et al.**, **Harris et al.**, this issue for discussion). Accurate taxonomic identification of permanently marked trees in plots (Baker et al., 2017), coupled with detailed, species-by-species growth and recruitment information offers important information for timber management. Baker et al. give the example of the timber "species" called "cumala" in Peru, which in fact represents more than 40 species spread across three genera in the Myristicaceae (nutmeg) family, in which monitoring plot data show different maximum sizes and growth rates, implying a need for species-specific management strategies. There are numerous other such examples, including "angelim," which covers more than 50 Brazilian species of trees spread across five genera in two legume subfamilies.

Permanent monitoring plots can also be used in the management of non-timber forest products (NTFPs), which are diverse; for example, López-Camacho et al., (2019) documented the uses of 362 tropical dry forest species in Colombia. An elegant example of the use of plot data in management is the Amazonian palm *Euterpe precatoria* that provides the widely consumed "palm heart" from its apical shoot (**Baker et al.**, this issue). Because harvesting kills the plant, data from permanent plots can indicate rates of recruitment and therefore suggest harvesting rates that are within ecologically sustainable limits. In other cases, harvest of most NTFPs (e.g., fruit, medicines) do not cause mortality of individual trees. In these cases, permanent plots in intact forest can provide baseline information that can be used to set harvesting limits in conjunction with new monitoring plots established in forest areas where NTFPs are being extracted (e.g., see Wadt et al., 2008 for Brazil nut). The importance of plots in such "disturbed" forest is a priority, which we discuss in more detail below.

2.3 | Understanding disturbance and trajectories to recovery

Permanent forest monitoring plots have tended to be placed in intact vegetation because the primary goal is to understand "natural" ecological processes. However, large areas of tropical forest are degraded through human impacts such as timber extraction and slash and burn agriculture, which can lead to exotic species invasion and fire (Sloan & Sayer, 2015). Understanding how widespread such degraded vegetation is, the species diversity it can maintain and how its composition and ecological functions will change over time, represents pressing science for the 21st century. Understanding the trajectory of disturbed tropical dry forest to recovery is an important goal of Red BST-Col (**Norden et al.**, this issue). In the same context, the 2nd FOR network (Secondary Forests Research Network; e.g., Poorter et al., 2016) of permanent monitoring plots across 75 sites in Latin America, plus other recent projects setting up permanent plots across disturbance gradients in tropical forests (http://sites.exeter.ac.uk/bioresilience/research/forest-ecology/) are very welcome developments.

Whilst permanent plots are helpful to understand the impact of degradation, they may not be so effective for understanding the extent and patterns of degradation because of the massive effort needed to place them over large areas at sufficient density (**Ahrends et al.**, this issue). Remote sensing methods are very effective at measuring deforestation, but degradation is more difficult to determine from space, especially where there is limited reduction in canopy cover and/or biomass (Ryan et al., 2012), or in dry tropical vegetation such as savanna that is naturally open. This leaves an important role for ground-based science in mapping and understanding degradation. Ahrends et al. present a transect-based protocol for rapid quantifications of forest condition, giving an example of its implementation in the Eastern Arc Mountains and coastal forests of Tanzania. They show that even in protected areas, 10% of trees have been cut, a change that would not be detected using optical remote-sensing maps of tree cover loss. Radar-based remote sensing was much more effective with good agreement with the ground data, but the field surveys are able to give more insights, especially on degradation processes such as harvest of NTFPs and spread of exotic species that do not necessarily involve a change in biomass, which is what the radar-based methods detect. Importantly, the Ahrends et al. field monitoring protocol can be implemented by non-specialists, opening the door to including local people in measuring impacts on their own forests.

2.4 | Underpinning restoration

The global environmental crisis caused by the loss of native vegetation and climate change has led to habitat restoration becoming a global priority for sustainable development (IPBES, 2019; Menz et al., 2013). The next decade (2021–2030) is The United Nations Decade on Ecosystem Restoration, and several international agreements including The Bonn Challenge, New York Declaration on Forests and the Paris Agreement have pledged to restore 350 million ha of degraded land by 2030, which has potential to promote biodiversity conservation, climate mitigation and improved quality of life (Chazdon et al., 2017). As **Norden et al.** (this issue) state, permanent plots can help to set our restoration targets by documenting ecological baselines in characterizing undisturbed forests in terms of species composition, biomass and structure. As explained above, plots have much to offer efforts in "passive" restoration in documenting the effects of habitat disturbance on species composition and ecosystem functioning and understanding trajectories of ecosystem recovery. We suggest that they also have key roles in active restoration efforts, as sources of seed and for understanding which species may thrive under future climates, thereby contributing to making ecosystem restoration climate-smart.

If ambitious national and international restoration targets are to be met, huge volumes of seed will be required, whether restoration is done by direct seeding or first by growing plants in a nursery. Whilst there will be a role for ex situ seedbanks, especially local ones (León-Lobos et al., 2020), in many tropical countries such facilities do not exist, and when they do, their capacity would not be sufficient for ambitious broad-scale restoration efforts (Merritt & Dixon, 2011). In addition, there are technical difficulties in storing the seeds of tropical rain forest species because they have no dormancy (i.e., they are recalcitrant). Against this background, we suggest a new role for permanent plots as local seed sources for trees. Establishing a permanent plot involves tagging and identifying all trees, meaning that individual trees, authoritatively identified to species level, can be easily re-visited for collection of seed. This circumvents a considerable problem in seed collection in the species-rich floras of the tropics, which is correct taxonomic identification. If a research goal is to study long-term population dynamics in a plot, because seed collection will affect recruitment processes, it may be necessary to set up paired harvested and unharvested plots as suggested above for NTFPs. This would have the additional benefit of being able to understand in the long term what level of seed harvest is sustainable. An alternative, outlined by **Norden et al.** (this issue), is to collect seed from trees around plots—Red BST-Col have collected seeds of over 100 species in this way that are now in a Seed Bank collection located at the Humboldt Institute.

Use of distributed networks of plots as seed sources would address other restoration bottlenecks such as use of site-adapted seed sources (León-Lobos et al., 2020; Pedrini & Dixon, 2020). In the United States and Europe, for tree species, local genetic adaptation has been taken into account by use of maps of seed transfer zones (STZs), also called seed zones, which are geographic areas where seeds can be moved without loss of fitness (Fremout et al., 2021). In many tropical countries such STZs do not exist, even for species of commercial and ecological importance (León-Lobos et al., 2020). In the long term, STZs should be built on studies of genetic diversity and differentiation, with an excellent recent example for the tropical dry forests of Colombia provided by Fremout et al., (2021). Permanent plots form an ideal framework for sampling of individual plants for such genetic studies in the tropics (e.g., Coronado et al., 2014; 2019). In the absence of such a framework, it would seem prudent to use local seed for local restoration projects, but we note that developing seed markets, for example in Brazil, are selling seed across the country. Community seed networks that supply these markets can provide a valuable income source (e.g., http://www.sementesdoportal.com.br/) for local communities, but currently, they are distributing seed to areas very distant from the site of collection (e.g., seed collected in Amazonia may be used in southern Brazil). Distributed networks of permanent plots could serve as living, local, seed banks, maintained by local people and providing them with an income source whilst simultaneously contributing to global efforts in ecosystem monitoring.

We also need to ensure that any restoration efforts take into account future climate variability. Whilst this can be approached by species distribution modelling methods, data from permanent monitoring plots are already indicating which species are winning, and which are losing, in a race against rapidly changing climates. For example, Esquivel-Muelbert et al. (2019), based on 106 lowland Amazonian plots monitored for 30 years have shown that tree recruitment has increasingly favoured species in dry-affiliated, compared with wet-affiliated, genera. Similarly, in Ghanaian moist tropical forests, deciduous species with distributions located biased towards climatically drier forests have increased in abundance compared with species from wetter forests, during several decades of low rainfall (Aguirre-Gutierrez et al., 2019; Fauset et al., 2012). Both these examples suggest that using species from climatically drier forests for restoration projects may prove a sensible strategy to ensure regenerating lowland tropical forests are resistant to future climate change.

3 | EXPANDING LONG-TERM MONITORING PLOTS TO TROPICAL DRY BIOMES

Half of the tropics is too seasonally dry to support rain forest and is home to different biomes, principally tropical dry forests and savannas. Many tropical savannas and dry forests have suffered high rates of conversion, both historically (e.g., Latin American dry forests; DRYFLOR, 2016) and more recently (e.g., the savannas of the Brazilian cerrado), but despite this have suffered relative neglect by science and conservation. Indeed, in a parallel with the phenomenon of "plant awareness disparity" (Parsley, 2020; previously "plant blindness"), which has been the theme of a special issue of *Plants*, *People*, *Planet* (Sanders, 2019), tropical dry biomes are also apparently invisible to many audiences, or at least under-appreciated, especially compared with tropical rain forest. Such "biome awareness disparity" can be a source of threat to tropical dry biomes: for example, it has been pointed out that tropical savannas should not be a global priority for reforestation because this ignores their unique biodiversity and the fact that they are not, in fact, forests at all (Veldman et al., 2019).

Evidence is accumulating to demonstrate the unique and high species diversity of tropical dry forests and savannas. For example, 11,384 plant species have been recorded in the Brazilian "cerrado" savannas, which is 35 more than the 11,349 recorded in the Brazilian Amazon (Forzza et al., 2010), a statistic that may surprise many readers. 7,338 free-standing woody species (reaching 3 m) were recorded in just 1,610 sites of tropical dry forest (DRYFLOR, 2016), which is more than 6,727 tree species (>10 cm diameter) recorded in all of Amazonia (Cardoso et al., 2017). In addition to this outstanding species diversity, tropical dry biomes may hold the key to understanding inter-annual variability in the terrestrial global carbon sink (Ahlström et al., 2015; Poulter et al., 2014) and so are an increasing focus for land-surface modelling and monitoring using remote sensing within earth system science. Consistent, long-term ground-based monitoring in these tropical dry biomes is vital for calibrating and validating this work. Perhaps, because of the diversity of physical form of tropical dry forests (ranging from tall, closed canopy forests to more open scrubland; Pennington et al., 2000) and savannas (ranging from open grasslands to grasslands with abundant trees), methodologies for establishing long-term inventory plots in them have been variable, which has led to problems in data synthesis. This problem is addressed here by two contributions from the Latin American Seasonally Dry Tropical Forest Floristic Network (DRYFLOR) (**Moonlight et al.**, this issue) and SEOSAW networks (**The SEOSAW partnership**, this issue).

The DRYFLOR is a relatively new network that now numbers more than 100 scientists and conservationists working on the flora of dry forests across Latin America and the Caribbean from Mexico to Argentina. Although the primary goal of the network was documenting patterns of species richness and endemism (DRYFLOR, 2016), a new focus is to encourage the establishment of permanent monitoring plots in tropical dry forest as tools for ecosystem science, conservation and community engagement. In this issue, building on well-established protocols for rain forest plots (Phillips et al., 2018), **Moonlight et al.** present a new plot protocol for tropical dry forests. This protocol was extensively field tested during the recent UK-Brazilian "Nordeste" (Northeast) project when 33 plots were established across the largest expanse of dry forest in the caatinga region of north-eastern Brazil. It modified rain forest protocols by using a smaller diameter threshold (5 cm) and plot size (0.5 ha), reflecting the lesser size of the trees and lower local species diversity in tropical dry forests. A strength of the DRYFLOR plot protocol is a core approach onto which optional modules can be added, for example, measuring to a lower diameter threshold if there is a need for detailed studies of recruitment. Hence, the protocol is flexible, which will be essential given the broad physiognomic variability of tropical dry forests.

Such need for flexibility in plot protocols is emphasised by the Socio-Ecological Observatory for the Southern African Woodlands (**The SEOSAW partnership**; this issue). SEOSAW is also a relatively young network, with goals to guide land management in the woodlands of southern Africa and to answer fundamental scientific questions, such as their role in the global carbon cycle. The use of "woodland," a term not frequently used in describing vegetation in the New World (though see Fernandes et al., 2020), is illustrative of conceptual problems in comparing major biomes across continents (Dexter et al., 2015). Given that much of the vegetation that SEOSAW focuses on is grass-rich and burns, most workers would consider it part of the global savanna biome (Lehmann et al., 2014; Pennington et al., 2018). SEOSAW describes how such vegetation can vary, for example, in the size and density of trees and in species richness, and the implications of this variability for plot protocols. Where trees are small and species richness lower, 0.5-ha plot size may be sufficient, but in other cases, 1 ha is recommended. SEOSAW also make recommendations on how to sample the non-woody vegetation, which is especially important in savannas where much of the species diversity is found in the grasses and forbs. In terms of long-term observations, sampling herbs is much more challenging than for woody plants because permanent tagging is something that is difficult, even for perennial herbs. The SEOSAW solution is quantitative surveys in small areas embedded within the wider permanent sample plots established for woody plants, which could be adopted by workers in savannas elsewhere.

SEOSAW and DRYFLOR developed their protocols largely independently (there is currently just one scientist who belongs to both networks), reflecting how few ecologists work across continents. However, it is reassuring to see that there is a good deal of commonality, partly derived from adaptation of the similar protocols as for moist forests, for example, in a recommended minimum plot size of 0.5 ha, which partly reflects a minimum size to link to remote sensed data, and especially radar sensors that are important for estimating biomass (**The SEOSAW partnership**, this issue). We, therefore, hope that these flexible protocols will become widely adopted by workers across the seasonally dry tropics, facilitating future data syntheses, which have been challenging to conduct thus far due to methodological heterogeneity. Such synthesis should include dialogue between the largely separate research communities working on rain forests and tropical dry biomes, which will be critical for understanding future climate-derived transitions between biomes.

4 | LONG-TERM ECOLOGICAL MONITORING AND "MEGAFLORA"—THE CHALLENGE OF HUGE TREES

There has been increasing recent interest in the disproportionate importance of "megabiota"—the largest plants and animals—for ecosystem function (e.g., Enquist et al., 2020; Schweiger & Svenning, 2020). In the tropics, the largest trees are found in tropical rain forests, and the fact that the largest ever trees have been discovered in the past few years in Asian and Amazonian rain forests using remote sensing (Shenkin et al., 2019) indicates that despite the proliferation of permanent monitoring plots in this biome, plots have not been effective in understanding the distribution of the largest trees.

Harris et al. (this issue) discuss how to survey the largest trees in a Central African rain forest. On comparing surveys based on scattered, typical 1-ha plots with rapid surveys seeking only the largest trees, they recommend measuring trees >70 cm dbh using large 10-ha plots. They recommend 10 of these plots (100 ha in total) spread across the landscape and demonstrate that double the number of large species attaining >80 cm dbh can be recorded using their new method (92 species vs. 48). They make the case that even the 50-ha plots of the ForestGeo network will miss the full diversity of big trees.

Pinpointing, taxonomically identifying and conserving these large trees in the last undisturbed tracts of tropical rain forest is critical. The taxonomic diversity of species found by **Harris et al.** underline the importance of ground-based surveys for this work; whilst remote sensing can pinpoint large individuals, it cannot in most cases identify them to species (Phillips et al., 2019). As **Harris et al.** point out, in addition to their disproportionate contribution to carbon storage, large trees are important food sources for the megafauna (forest elephants) in this forest. They are also important to local people in their provision food and income. The most common large tree recorded by Harris et al., *Entandrophragma cylindricum* ("Sapele"; 177 out of 1,221 large trees recorded) is an important timber species that contributes substantially to the formal economies of the Central African Republic, Cameroon and the Republic of Congo.

5 | CONCLUSIONS

Long-term ecological monitoring plots offer an opportunity for collaborations between scientists, land use managers and policy makers and therefore can play a key role in improving lives and livelihoods in tropical countries. Well-established networks of monitoring plots in tropical rain forests have led the way, but given that one third of the global population inhabits the seasonally dry tropics (Pennington et al., 2018), we must avoid “biome awareness disparity” and expansion of monitoring into tropical savannas and dry forests is essential (**Moonlight et al.**, **The SEOSAW partnership**, this issue).

In terms of making links to actions that influence policy and actually implementing conservation, restoration and sustainable use, the contributions to this issue also highlight the bottlenecks. Even within Latin America, the policy and legal frameworks outlined within Peru (**Baker et al.**) and Colombia (**Norden et al.**) are very different. The solutions that these papers present operate at a national scale, which is a trade-off that maximises the scale over which impact can be achieved whilst maintaining sufficient homogeneity in regulation and adequate depth of engagement by the collaborating organisations. Such divergences in socio-political contexts across countries suggest that a current fashion to try to solve “global challenges” at global scales will be extremely difficult for conserving and restoring tropical biomes across multiple countries because there is no “one size fits all” solution. The contributions to this issue, including national (e.g., Red BST-Col) and regional (e.g., SEOSAW, DRYFLOR) networks, which draw authors from diverse nationalities, across academia, NGOs and government agencies, suggest that much can be achieved from smaller scale projects built by collaborations between scientists, conservationists and land use practitioners. What all these inspiring projects have in common is that ground-based science focusing on long-term monitoring plots is required to solve issues surrounding the restoration, conservation and sustainable use of tropical vegetation.

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KEYWORDS

Conservation, ecological monitoring, ecosystem restoration, permanent inventory plots, policy, tropical dry forest, tropical rain forest, tropical savannah

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