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BRIEF REPORT

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Expanding tropical forest monitoring into Dry Forests: The DRYFLOR protocol for permanent plots

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Societal Impact Statement

Understanding of tropical forests has been revolutionized by monitoring in permanent plots. Data from global plot networks have transformed our knowledge of forests' diversity, function, contribution to global biogeochemical cycles, and sensitivity to climate change. Monitoring has thus far been concentrated in rain forests. Despite increasing appreciation of their threatened status, biodiversity, and importance to the global carbon cycle, monitoring in tropical dry forests is still in its infancy. We provide a protocol for permanent monitoring plots in tropical dry forests. Expanding monitoring into dry biomes is critical for overcoming the linked challenges of climate change, land use change, and the biodiversity crisis.

KEYWORDS

floristics, long term plots, tropical dry forests, vegetation dynamics, vegetation structure

1 | THE VALUE OF FOREST MONITORING

Long-term forest plots are sites where all trees above a specified diameter are numbered, identified, and measured, and where repeated censuses record growth, mortality, and recruitment. Such plots have become widespread in tropical rain forests, exemplified by networks such as RAINFOR (Amazon Forest Inventory Network; Malhi et al., 2002), AfriTRON (African Tropical Rainforest Observation Network; Lewis et al., 2009), T-FORCES (Tropical Forests in the Changing Earth System; Qie et al., 2017), and CTFS-forestGEO (Center for Tropical Forest Science-Forest Global Earth Observatory; Anderson-Teixeira et al., 2014). The RAINFOR, AfriTRON, and T-FORCES networks collectively comprise > 1,000 1 ha plots across the tropics, where every tree with a stem diameter ≥ 10 cm is measured. CTFS-forestGEO employs much larger (often 50 ha) plots where every stem ≥ 1 cm in diameter is measured, and this more intensive survey means that there are fewer (<100) of such plots across the tropics.

These long-term tropical rain forest plots have been extremely successful in achieving their primary aim of improving our knowledge of tropical forest ecology, including, for example: the relationships of climate with biomass (Álvarez-Dávila et al., 2017) and forest structure (Feldpausch et al., 2012); the role of diversity in carbon storage and productivity (Coelho de Silva et al., 2019; Sullivan et al., 2017); and drivers of monodominance in Amazonia (ter Steege et al., 2019). In addition, they have helped increase understanding of community floristic diversity and composition (Baker et al., 2016; Guevara et al., 2016; Levis et al., 2017), continental scale floristic patterns (Esquivel-Muelbert et al., 2017; ter Steege et al., 2006; ter Steege, Pitman, Sabatier, Baraloto, & Salomão, 2013), biome delimitation, and mapping (Silva-de-Miranda et al., 2018), and even facilitated the discovery of species new to science (reviewed by Baker et al., 2017). Repeated censuses of these plots have provided insight into the role of tropical forests in global cycles of carbon, energy, and water (Pan et al., 2011; Phillips et al., 1998), long-term trends in forest dynamics (Brienen et al., 2015), and the impacts of extreme climatic events (Feldpausch et al., 2016; Phillips et al., 2009). As such, these international standardized networks are a helpful macroecological tool to study humanity's effect on the Earth system and the vital role that moist tropical forests play in carbon sequestration and therefore in mitigating the effects of increasing concentration of atmospheric CO_2. Conversely, they have also demonstrated how tropical forest destruction and degradation account for an estimated 1.3 Pg carbon emissions (Malhi, 2010) and that, following deforestation, the recovery of forest species composition can take centuries (Rozendaal et al., 2019). They may also have critical implications at national levels too - in Peru, for example, long-term permanent plots have been used to show that the country's intact rain forests have helped to remove 86% of the country's emissions from the combustion of fossil fuels (Vicuña-Minaño et al., 2018).

2 | DRY FORESTS: A GLOBAL RESOURCE

Long-term monitoring started in tropical rain forests and has been concentrated there since. This reflects the importance of such forests as the largest above-ground terrestrial carbon stock (Pan et al., 2011) and their unparalleled levels of local (alpha) diversity of plants and animals (e.g. Bass et al., 2010). However, half of the global tropics are too seasonally dry to support such forests and instead are home to tropical dry forests (Figure 1) and savannas (Pennington, Lehmann, & Rowland, 2018). An estimated one-third of the global population inhabits the seasonally dry tropics (GLP, 2005), and, as a consequence, these systems have been commonly and severely altered (e.g., Fajardo et al., 2005; Janzen, 1988; Linares-Palomino, Kvist, Aguirre-Mendoza, & Gonzales-Inca, 2010; Portillo-Quintero & Sánchez-Azofeifa, 2010). Because they can be erroneously viewed as semi-natural, and because of their smaller stature and lower local diversity than rain forests, tropical dry forests have been under-appreciated by science and conservation. However, new information suggests that their floristic diversity at continental scale (gamma diversity) may approach that of rain forests (Flora do Brasil, 2020; DRYFLOR, 2016), and that they play an essential role in controlling the interannual variability in the global carbon cycle (Poulter, Frank, Ciais, Myneni, & Andela, 2014). It is clear that science and society cannot continue to largely ignore these tropical dry biomes.

3 | PUTTING DRY FORESTS IN THE SPOTLIGHT

Even thirty years ago tropical dry forests were already considered the most threatened tropical biome on the planet (Janzen, 1988), and less than 10% of their original extent remains in many Latin American countries, which house the largest remaining areas of this vegetation (Miles et al., 2006; Pennington et al., 2018; Pennington, Prado, & Pentry, 2000). This high level of loss is not only due to recent conversion but also is a reflection of a long history of deforestation and use by early civilizations inhabiting dry forest areas, especially in Latin America (Murphy & Lugo, 1986).

Landscape modification in tropical dry forest areas has been exacerbated by their frequently fertile soils, and this also makes them a continuing focus for agricultural expansion. Although at local scales plant species richness in tropical dry forests does

FIGURE 1 Dry forest in El Coto de Caza El Angolo, Piura, Peru in the dry season showing Ceiba trichistandra (A. Gray) Bakh. Photograph taken by P.W. Moonlight

not match that of tropical rain forest, in the Neotropics, at least, high floristic turnover amongst areas means that at continental scale their species diversity rivals that of rain forest. For example, DRYFLOR (Latin American Seasonally Dry Tropical Forest Floristic Network; 2016) recorded 6,958 woody species from just 1,602 surveys, whereas a current estimate of the number of tree species in the moist forests of the Amazon Basin is 6,727 (Cardoso et al., 2017).

Despite this diversity, tropical dry forests are woefully under-protected. For example, only 1.2% of remaining Brazilian Caatinga dry forest and 1.4% of Colombian inter-Andean dry forest are protected (García, Corzo, Isaacs, & Etter, 2014; MMA, 2016), falling massively short of the 17% target set by Aichi biodiversity target 11 (CBD, 2011). An integral part of improving the conservation outlook for tropical dry forests, and of gaining vital information relevant to their restoration, will come from long-term ecological monitoring. Such monitoring will be essential to understand how their species grow, reproduce, and recruit, and the mechanisms behind their mortality, especially in times of climatic and environmental changes.

The rapid growth of long-term forest monitoring in tropical rain forests partly reflects internationally agreed, standard protocols for plot establishment. Conversely, the slow adoption of monitoring in dry biomes is a consequence, among other factors, of the lack of agreed protocols. Such lack of consensus in part reflects the wide physiognomic spectrum of tropical savannas and dry forests. For dry forests, the focus of this paper, this can vary from tall, closed forest with a 25–30 m canopy, to more open, low, thorny, and cactus scrub (Pennington et al., 2000). Protocols designed for 1 ha plots in the moist tropics (e.g. Phillips, 2018) fail to capture the majority of growth, mortality, or recruitment dynamics in these systems, primarily because mature individuals of many species do not reach a minimum diameter at breast height (DBH) of 10 cm. These smaller trees play an important role when describing structure and functioning of dry forest vegetation (Torello-Raventos et al., 2013). We urgently need a standard for systematizing the way with which the large number of researchers now working in dry forests can measure and monitor these ecosystems. Only with such a standard protocol in place can we lay the foundations for generating a rich legacy of scientific and practical advancement in ecology across the tropics.

In response to this urgent need we here present an approach in measuring and monitoring tropical ecosystems, specifically adapted to meet the challenges of long term monitoring in dry forests. Our protocol, the *DRYFLOR Field Manual for Plot Establishment and Remeasurement* ("*DRYFLOR Plot Protocol*"; please see the Supporting Information for English, Portuguese and Spanish versions of the protocol), is based on wide tropical experience and has received rigorous field testing in the dry forests, semi-deciduous forests, and related dry biomes of Peru, southeast, and northeast Brazil. The protocol design is modified and expanded from that used by RAINFOR (The Amazon Forest Inventory Network; Phillips, Baker, Feldpausch, & Brienen, 2018) across the Americas and beyond with a particular emphasis on the Amazon Basin. The new *DRYFLOR Plot Protocol* captures most dry forest structure and dynamics and is specifically designed to enable a full and detailed comparison with data captured by humid forest protocols (Phillips et al., 2018) and by savanna and dry forest protocols (e.g. by measuring stems ≥ 5 cm diameter and at 130 and 30 cm, rather than ≥10 cm diameter at only 130 cm; in its provisions for multi stemmed individuals). Physiognomic and dynamics data from the protocol are fully compatible with the ForestPlots database (Lopez-Gonzalez, Lewis, Burkitt, & Phillips, 2011) and floristic data with the DRYFLOR database (www.dryflor.info). We believe it reaches a reasonable compromise between practical field constraints in terms of time and data captured for the purpose of estimating species abundances and biomass data, but it also provides optional modules that can be implemented if a more complete picture of dry forest dynamics is desired.

4 | CONCLUSIONS AND CHALLENGES AHEAD

The *DRYFLOR Plot Protocol* is a product of a large, collaborative network of researchers working across Latin American dry forests and related dry biomes. It is intended to permit the rapid and efficient collection of inventory data in the dry tropics and facilitate studies on the structure and function of forests. The development of this protocol is indebted to both the RAINFOR and the DRYFLOR networks and three projects funded from 2011 to 2019 by the UK Research Councils and the Brazilian Research Foundations FAPESP and FAPERJ. The uptake of the protocol in new geographic areas and beyond these networks will be a continuing challenge, but provides the considerable benefit of standardised data capture. This will enable further collaborative research at wider spatial scales that is vital for addressing questions about the current and future ecology of tropical forests in a rapidly changing world. The societal relevance of this research will ultimately depend not simply on the application of a universal dry forest protocol, but also on the development of lasting, meaningful relationships with local and regional stakeholders and policymakers.

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AUTHOR CONTRIBUTIONS

T.P. conceived the idea and P.M. led the writing of the manuscript and plot protocol, with significant input from authors K.B.-R. to D.M.V. All authors contributed to the design and field testing of the protocol, and had input in the manuscript. Portuguese translation of the Supporting Information was done by A.T.B., D.M.V., D.R.M., I.C., M.N. T.C.d.S.O, and R.C.M.; Spanish translation was done by C.Q, K.B.-R., R.L.-P., and R.R.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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