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Guidelines for including bamboos in tropical ecosystem monitoring

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Abstract

Bamboos are a diverse and ecologically important group of plants that have the potential to modulate the structure, composition, and function of forests. With the aim of increasing the visibility and representation of bamboo in forest surveys, and to standardize techniques across ecosystems, we present a protocol for bamboo monitoring in permanent research plots. A bamboo protocol is necessary because

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measurements and sampling schemes that are well-suited to trees are inadequate for monitoring most bamboo species and populations. Our protocol suggests counting all bamboo culms (stems) in the study plot and determining bamboo dimensions based on two different approaches: (a) measuring a random subset of 60 culms and calculating the average dimensions or (b) measuring all culms. With data from 1-ha plots in the Peruvian Andes, we show that both approaches provide very similar estimates of bamboo basal area. We suggest including all mature culms rooted inside change the to each plot from all woody bamboo species with maximum diameters ≥1 cm. We also present recommendations on how to collect vouchers of bamboo species for identification. Data collected according to our proposed protocols will increase our understanding of regional and global patterns in bamboo diversity and the role of bamboo in forest dynamics.

Abstract in Spanish is available with online material.

1 | INTRODUCTION

To fully understand the ecology of tropical forests, and their role in global climate dynamics, we must embrace their complexity. Forests include a diversity of taxa with different life forms—not just trees—all of which have unique natural histories, physiologies, and interactions. While short- and long-term forest monitoring efforts have traditionally focused on tree demographic data (Bastin et al., 2018; Phillips et al., 2009), in the last few decades, research on palms, lianas, epiphytes, and understory plants has revealed the important influence of these non-tree life forms on forest communities (Farris-Lopez, Denslow, Moser, & Passmore, 2014; Phillips et al., 2002; Ter Steege et al., 2013). For example, during most of the 20th century, lianas (woody vines) were excluded from forest censuses and their effects on forest dynamics were largely ignored (Schnitzer & Bongers, 2002; Schnitzer & Carson, 2000). After three decades of extensive research (Putz, 1984; Schnitzer, Putz, Bongers, & Kroening, 2015), we now know that lianas are fierce competitors that reduce tree growth, increase tree mortality, and limit tree regeneration (Gerwing & Lopes Farias, 2000; Ingwell, Wright, Becklund, Hubbell, & Schnitzer, 2010; Schnitzer & Carson, 2010), and in turn alter ecosystem processes such as forest transpiration and carbon sequestration (Schnitzer & Bongers, 2002). We also know that liana abundances are increasing in many forests due to global climate change, including increased frequency of disturbances (Schnitzer & Bongers, 2011).

Like lianas, bamboos (family Poaceae, subfamily Bambusoideae) include many ecologically important taxa that are ignored or avoided in most studies of forest dynamics, diversity, and ecophysiology, presumably because bamboos are assumed to have minimal influence on large-scale forest dynamics (*but see section on Impacts of bamboo on Neotropical forest dynamics*). With the aim of increasing the visibility of this important but understudied subfamily, we present a consensus view among a group of tropical bamboo experts and forest ecologists on the current state of bamboo ecology. To that end, we present a protocol for bamboo monitoring that should serve as a guide to standardize aboveground bamboo measurements across a wide diversity of ecosystems. Finally, to inform our guidelines and demonstrate the utility of the protocol, we include a section on *Protocol justification* using data collected in the Peruvian Andes.

1.1 | Bamboo life history, diversity, and distribution

Bamboos are the largest grasses on Earth and exhibit some of the fastest growth rates of all plants (Pearson, Pearson, & Gomez, 1994). For example, *Guadua weberbaueri* (tropical South America) can grow 3 m/month in height during the rainy season (Silveira, 2001) and *Bambusa bambos* (South-East Asia) can grow up to 30 cm/day (Shanmughavel & Francis, 1996). Bamboos have great plasticity in their physiological traits and can present combinations of traits typical of both early successional (high photosynthesis capacity, fast growth rate) and late-successional species (shade-tolerance, long leaf life span) (Lei & Koike, 1998; Montti, Villagra, Campanello, Gatti, & Goldstein, 2014); as such, many bamboos are adapted to live in open environments as well as the forest understory (Judziewicz, Clark, Londoño, & Stern, 1999).

Belowground, bamboos produce extensive rhizome networks that allow for clonal growth and a rapid resprouting response after disturbances (Griscom & Ashton, 2006; Smith & Nelson, 2011; Stapleton, 1998). There are three main rhizome morphologies that lead to different patterns of culm spacing, from tightly aggregated (i.e., clumping) to distantly spaced (i.e., running). Pachymorph rhizomes have short, thick segments with a sympodial branching pattern that usually lead to tightly clumped culms. Leptomorph rhizomes

have long, slender segments with monopodial branching pattern (running), or in some cases, with tillering culms (clumped). However, some pachymorph taxa have elongated necks, producing more or less diffuse clumps or distantly spaced culms, the latter mimicking the pattern produced by leptomorph rhizomes. Amphimorph rhizomes are a combination of both pachy- and lepto- morphologies and show amphipodial branching (see figure 2 in Judziewicz et al., 1999; McClure, 1966). The fibrous roots produced by bamboo rhizomes enhance and facilitate water uptake (Cochard, Ewers, & Tyree, 1994; Saha, Holbrook, Montti, Goldstein, & Cardinot, 2009; Yang, Zhang, Sun, Goldstein, & Cao, 2017). Rhizomes of some bamboo species are hypothesized to transport water and nutrients horizontally among ramets; however, rhizome connectivity between culms, and its implications for bamboo survival, community dynamics, and ecosystem functioning has not been studied in depth (Yuen, Fung, & Ziegler, 2017).

While most bamboos are clonal, they also can reproduce sexually. Many "woody" bamboo species (i.e., those with highly lignified stems; see section 2.3.1) have a gregarious monocarpic life cycle in which an entire population flowers, produces seeds, and then subsequently dies (Franklin, 2004; Janzen, 1976). Life cycle length is highly variable among species, for example, 28 years for *G. weberbaueri* (de Carvalho et al., 2013) and 120 years for *Phyllostachys bambusoides* (Kawamura, 1927), and is highly conserved within species (Guerreiro, 2014; Veller, Nowak, & Davis, 2015). Other bamboo species (mainly herbaceous species that lack hard, lignified stems) produce seeds annually (*Lithachne* spp, *Pariana* spp, *Cryptochloa* spp, *Olyra latifolia*) or irregularly (*Bambusa linata*) (Franklin, 2004; Judziewicz et al., 1999; McClure, 1966).

At least 1,680 species of bamboo have been described. Bamboos are native to all continents except Europe and Antarctica and occur in temperate as well as tropical regions. They grow in a diversity of habitats from sea level to 4,300 m a.s.l, from old-growth forests (e.g., *Guadua sarcocarpa*) to old-growth savannas (e.g., *Actinocladum verticillatum*) and human-modified environments such as abandoned slash and burn agricultural land (e.g., *Guadua paniculata*) (Clark, Londoño, & Ruiz-Sanchez, 2015; Clark & Oliveira, 2018; Judziewicz et al., 1999).

Bamboo diversity is grouped into three tribes: Arundinarieae (temperate woody bamboos), Bambuseae (tropical woody bamboos), and Olyreae (herbaceous bamboos) (Clark et al., 2015). Detailed phylogenetic studies and population-level genetic studies are both hindered by the low molecular variation in bamboo plastomes and the complex ploidy levels (diploid, tetraploid, and hexaploid) characteristic of bamboos. Molecular evolution in the bamboo plastome is especially slow, likely as a consequence of the long flowering cycles in woody bamboos, and reflects only the maternal evolutionary history (Triplett & Clark, 2010). Thus, plastid-based phylogenies do not always provide reliable results (Fisher, Clark, & Kelchner, 2014). Similarly, DNA barcoding has only been successful for the identification of bamboo to the level of genus (Sosa, Mejía-Saules, Cuéllar, & Vovides, 2013). Nevertheless, AFLPs (amplified fragment length polymorphisms) (Ma et al., 2013; Suyama, Obayashi, & Hayashi,

2000) and microsatellites (Abreu et al., 2011) such as SSRs and ISSRs (Ely, Rada, Fermin, & Clark, 2019; Kitamura & Kawahara, 2009; Yang, An, Gu, & Tian, 2012) have been used successfully to identify clones within bamboo populations. New techniques such as RAD-seq have shown promising results to separate species and individuals (Wang, Zhao, Eaton, Li, & Guo, 2013) and to establish phylogenetic relationships between genera (Wang et al., 2017). Because of these limitations to the use of molecular tools for identifying bamboos and delineating individuals and populations, in the *Bamboo Protocol* (below) we describe the sampling of culms, rather than genetic individuals.

Although bamboo research has historically focused on the Asia-Pacific region, where most bamboo species occur (~1,140 spp.) and where 6.3 million km^2 of forest is covered by bamboo (Bystriakova, Kapos, & Lysenko, 2003), there are also at least 422 woody and 123 herbaceous bamboo species in the Americas (distributed mostly in the tropics) (Clark & Oliveira, 2018) and 43 in Africa and Madagascar (Bystriakova, Kapos, & Lysenko, 2004; Vorontsova, Clark, Dransfield, Govaerts, & Baker, 2016). Bamboos occupy vast areas, form distinctive ecosystems (Table 1) and play important roles in forest structure and dynamics (Saroinsong, Sakamoto, Miki, & Yoshikawa, 2006; Stokes, Lucas, & Jouneau, 2007), yet little is known about their ecology, particularly in the Neotropics. While we draw attention to Neotropical bamboos, the protocol guidelines we propose are applicable to all woody bamboo species regardless of where they occur. We encourage researchers worldwide to join our efforts to standardize and promote bamboo research.

1.2 | Bamboo in Neotropical forests monitoring

Studies from tropical and temperate South American forests show that bamboos are important modulators of forest dynamics. For example, many bamboos are effective at colonizing tree-fall gaps and altering regeneration (Campanello, Gatti, Ares, Montti, & Goldstein, 2007; Holz & Veblen, 2006; Montti et al., 2014; Rother, Rodrigues, & Pizo, 2016; Veblen, 1982, 1985), reducing tree density and growth (Griscom & Ashton, 2003, 2006; Lima, Rother, Muler, Lepsch, & Rodrigues, 2012; Medeiros, Castro, Salimon, Silva, & Silveira, 2013; Silman, Ancaya, & Brinson, 2003; Silveira, 1999), and modifying tree species composition by filtering species based on their life-history strategy (Griscom, Daly, & Ashton, 2007; Silman et al., 2003; Silveira, 1999; Tabarelli & Mantovani, 2000; Veblen, Ashton, Schlegel, & Veblen, 1977). Further negative interactions between bamboos and trees may arise through allelopathic effects (Jose et al., 2016) and changes to fire regimes (Gagnon, 2009; Veldman & Putz, 2011). Although their conservation values are often overlooked, bamboos are an important carbon sink (Veblen, Schlegel, & Escobar, 1980; Arango & Camargo, 2010) and provide critical habitat for specialized ants (Davidson, Castro-Delgado, Arias, & Mann, 1998; Silveira et al., 2013), birds (Rother, Alves, & Pizo, 2013) and mammals (Dunnum & Salazar-Bravo, 2004). Despite the mounting evidence of their ecological importance (Zhou, Fu, Xie, Yang, & Li, 2005), there are no

TABLE 1 Examples of Neotropical ecosystems with communities dominated by woody bamboo species

Ecosystem(s)	Country(s)	Bamboo species	References
Amazonian forest (*Guaduales or Tabocais*)	Bolivia Brazil Peru	*Guadua sarcocarpa* *Guadua weberbaueri*	Griscom and Ashton (2006), de Carvalho et al. (2013)
Chiquitano Dry Forest and Cerradão (*Guapasales*)	Bolivia Brazil	*Guadua paniculata*	Killeen (1990), Veldman (2008)
Atlantic forest (*Tacuarales*)	Argentina Brazil	*Chusquea ramosissima* *Merostachys* spp. *Guadua tagoara* *Merostachys riedeliana*	Campanello et al. (2007), Montti et al. (2011), Lima et al. (2012), Jose et al. (2016)
Andean cloud forest (*Guaduales*)	Colombia Ecuador	*Guadua angustifolia*	Young and Judd (1992), Kleinn and Morales-Hidalgo (2006)
Andean cloud forest (*Chusqueales, Chuscales*)	Argentina Bolivia Chile Colombia Ecuador Peru Venezuela	*Chusquea culeou* *Chusquea montana* *Chusquea* spp. (many)	Veblen (1982), Young (1991), Pearson et al. (1994), Judziewicz et al. (1999), González et al. (2002), Holz and Veblen (2006), Raffaele, Kitzberger, and Veblen (2007), Clark and Ely (2011)
Puna, paramo and subparamo (*Bamboo Paramo*)	Brazil Colombia Costa Rica Ecuador Peru Venezuela	*Chusquea subg. Platonia* *Chusquea subg. Swallenochloa* *Chusquea subtessellata*	Cleef (1981), Clark (1989), Stein and Weberling (1992), Judziewicz et al. (1999)
Central America montane forest Oak forests	Costa Rica Panama	*Chusquea talamancensis* *Chusquea foliosa* *Chusquea tomentosa* *Chusquea subtilis*	Widmer and Clark (1991), Widmer (1998)
Deciduous forest and xerophytic shrublands (*Otatales*)	Mexico	*Otatea acuminata* *Otatea ramirezii*	Ruiz-Sanchez, Sosa, Mejía-Saules, Londoño, and Clark (2011), Ruiz-Sanchez (2012)
Central America Rain forest	Mexico	*Olmeca recta* *Olmeca reflexa*	Soderstrom (1981)
Caribbean montane forest	Jamaica Puerto Rico	*Chusquea abietifolia*	Seifriz (1920), Seifriz (1950), Shreve (1914)

long-term forest monitoring projects in the Neotropics that employ measurement protocols suited to the typical sizes and growth habits of bamboos (Table 2).

There are three main reasons for the limited long-term information about bamboos in Neotropical forests. First, few permanent plots have been established specifically to monitor bamboo-dominated areas. Second, long-term tree monitoring plots are often located in areas considered representative of a particular forest type (e.g., *terra firme* forests, alluvial forests) with no obvious signs of disturbance and therefore often implicitly avoid dense stands of bamboo. Third, most forest census protocols do not specify how to measure bamboos; for example, bamboo may be included only if its diameter exceeds the tree cutoff (typically ≥10 cm diameter—a girth that bamboos usually do not reach) or alternatively, may be excluded entirely (Table 2). Because of the distinctive growth form of bamboos (absence of secondary growth, variability of habit, and extensive clonal reproduction) (Fei, Gao, Wang, & Liu, 2016), they cannot be efficiently measured following the same guidelines as trees. Indeed,

the fact that the intrinsic biology of bamboo does not conform to that of trees (Clark et al., 2015) may be the underlying reason for the generalized exclusion of bamboo from forest monitoring efforts.

In the few studies focused specifically on bamboo, different methods are often employed to monitor their density and size. These approaches range from using the point-intercept method at 2 m aboveground to monitor bamboo density in transects (Montti, Campanello, & Goldstein, 2011) to measuring diameter at breast height of culms found in plots (Griscom & Ashton, 2006). These studies, while valuable to understand local processes, lack the standardization required for large-scale comparisons or long-term analysis. To our knowledge, the only efforts to standardize bamboo monitoring come from studies to improve management and quantification of productivity in commercial forestry (Camargo & Arango, 2012; Camargo, Garcia, & Morales, 2008).

The scarcity of long-term standardized information about bamboos limits our ability to understand their ecology, physiology, and diversity, but more broadly, limits understanding of the multi-faceted

TABLE 2 Examples of bamboo treatment in Neotropical forest monitoring networks

Plot network	General census	Bamboo inclusion and guidelines	Reference and url
RAINFOR-GEM	Stems dbh >10 cm Including trees, lianas (>10 cm diameter at any point within 2.5 m of the ground), palms, cycads, tree ferns, aloes, large herbs, and stranglers Small tree subplots dbh > 2cm	Include if dbh >10 cm In tight clumps, one culm is measured, and the rest are counted	Marthews et al. (2014) www.gem.tropicalforests.ox.ac.uk
The Madidi Project	Woody stems dbh >2.5 cm Including trees, lianas, palms, tree ferns and woody hemiepiphytes	Include if dbh >2.5 cm and woody	Arellano et al. (2016) www.missouribotanicalgarden.org
Forest Global Earth Observatory (ForestGEO)	Woody stems dbh >1 cm Including trees, palms, and tree ferns	Exclude (but case by case decision depending on project goals)	Condit (1998) www.forestgeo.si.edu
Tropical Ecology Assessment and Monitoring Network (TEAM)	Stems dbh >10 cm Including trees, lianas, palms and tree ferns	Not mentioned	TEAM Network (2010) www.teamnetwork.org
RAINFOR	Stems dbh >10 cm Including trees, lianas (>10 cm diameter at any point within 2.5 m of the ground) and palms	Not mentioned	Phillips et al. (2018) (first prepared 2001) www.rainfor.org

roles of bamboo in forest dynamics, including the association of bamboo with animal communities (e.g., Areta, Bodrati, & Cockle, 2009; Leite, Pinheiro, Marcelino, Figueira, & Delabie, 2013). Recent advancements in forest ecology are partly a consequence of the standardized methods that allow data to be combined across space and time (Brienen et al., 2015; Esquivel-Muelbert et al., 2018). This standardization now needs to be extended to include bamboo.

2 | THE BAMBOO PROTOCOL

Our proposed protocol was designed to encourage and facilitate bamboo data collection in existing vegetation plots and to promote the establishment of new plots that include bamboo monitoring. To make field measurements intuitive and feasible, we have tried to be as consistent as possible with established tree (Condit, 1998; Marthews et al., 2014; Phillips, Baker, Brienen, & Feldpausch, 2018) and liana protocols (Gerwing et al., 2006; Schnitzer, Rutishauser, & Aguilar, 2008). Like most forest monitoring protocols, our protocol focuses only on the aboveground component of bamboo, with full recognition that the extensive rhizome systems of bamboos, like roots systems of trees, can exert strong effects belowground.

Given the clonal nature of many bamboos, it is often difficult to be sure whether two stems belong to the same individual without excavation of their rhizome network or conducting genetic analyses. For this reason, we use the term culm (bamboo stem), rather than individual, and do not distinguish between ramets (clonal stems belonging to the same individual) and genets (stems from genetically distinct individuals).

Because censuses may have different objectives, we present a series of decisions to be made before bamboo sampling, associated

issues to be considered, and suggested guidelines for field measurements. The general indications for effective bamboo monitoring are as follows: (a) choose a sampling scheme based on the study goals, (b) apply the suggested guidelines regarding what to measure and how to take the measurements, and (c) collect specimens for identification.

2.1 | Sampling scheme to measure bamboo density and dimensions

Depending on the research goals of projects, the required level of detail for bamboo data collection can vary widely. While data on individual culms are most valuable, it can be overwhelming or impractical to measure every culm in places with high bamboo densities (e.g., 16,000 culms/ha in some Andean forests; see *Protocol justification*). To simplify and standardize the process of initiating a bamboo census, we provide guidelines that address two key questions: (a) How many bamboo culms do I need to count? (b) How many bamboo culms do I need to measure?

2.1.1 | Quantifying culm density

We encourage a complete census, in which all culms in the plot are counted and abundance per species and subplot is determined. Such detailed sampling can be necessary due to spatial aggregation of culms. Indeed, many bamboo populations have heterogeneous distributions that reflect spatial patterns of past disturbances or a species' characteristic rhizome growth (e.g., clumped vs. runner). If only partial sampling of the survey area is possible, we recommend using

subplots that are systematically positioned throughout the larger plot. In the case of large plots, if a complete sample is not possible, we recommend preliminary sampling and analyses to determine the minimum sample area (number of subplots). In the *Protocol justification*, we estimated that including ~75% of subplots (20 × 20 m) in a 1-ha plot provided a representative estimated of culm density.

To facilitate rapid counting of culms in dense bamboo stands, we suggest using a multi-unit tally counter, with each unit representing a unique species. Only bamboo culms whose rooting point is within the limits of the study plot (or subplot) should be included, regardless of the position of culm apex (see section 2.3).

2.1.2 | Estimating bamboo dimensions

Because they lack secondary growth, culm diameter does not change during the life of a mature culm and is constrained within specific limits (e.g., *Chusquea ramosissima*: 1–1.5 cm, *Guadua chacoensis*: 8–15 cm, *Dendrocalamus giganteus*: 10–37 cm) (Judziewicz et al., 1999; Montti, 2010; Ramanayake & Yakandawala, 1998). The relatively low variability in culm diameter within bamboo species, compared to trees, permits a simplified protocol. Depending on research goals, we propose two approaches: determination of average diameter, height, and length by measuring a subset of culms (Approach 1), or measurement of these dimensions in all culms in the plot (Approach 2). Approach 1 is appropriate for studies of forest structure, composition, and diversity, to quantify the impact of bamboo abundance on tree growth and regeneration, or for estimating bamboo contribution to biomass (see steps in Table 3). Approach 2 requires more time and is appropriate for studies of bamboo population dynamics or demography. Basal area estimates made with both approaches are highly correlated (see *Protocol justification*, below).

Approach 1—Average culm dimensions
For each species at a study site, a random subset of 60 mature culms should be measured to establish the mean culm diameter, height, and length (see *Protocol justification*). This process should be repeated at each study site if environmental conditions are sufficiently heterogeneous to influence bamboo morphology (e.g., differences in elevation, sun exposure). If any species has <60 culms at a site, all culms should be measured. For tall bamboo culms, cutting 60 randomly selected culms in the vicinity of the plot, when permitted, can facilitate length measurements. Material harvested from these cut culms can be used to develop allometric relationships for biomass estimation (Chan, Takeda, Suzuki, & Yamamoto, 2013; Nath, Das, & Das, 2009).

Approach 2—Complete bamboo dimensions
Every culm in the sample area is visually assigned to a 1-cm-diameter class (e.g., 1–2 cm, 2–3 cm) and counted (only culms that are near the class cutoff need to be measured). In this case, each tally counter unit represents a diameter range for each species. Height and length may be measured for each culm, on at least 20 culms per diameter class and species to obtain mean values per class and species.

2.2 | Bamboo size and cover

2.2.1 | How to measure diameter

Culm diameter should be measured on the midpoint of the internode that occurs at 1.3 m along the length of the culm (as opposed to 1.3 m above the ground) (Kleinn & Morales-Hidalgo, 2006). In species with mature culm lengths shorter than 1.3 m, we recommend measuring basal diameter on the middle of the first fully aboveground internode. Bamboo species architecture follows many different habits: erect, erect and arching at the apices (semi-erect), arching, decumbent, sprawling, scandent, and twining (Figure 1; Judziewicz et al., 1999). We recommend noting habit in the species comments and including culms from all habits in the census.

Some bamboos form dense clumps that prohibit proper measurement of each culm diameter. Sampling Approach 1 (described above) largely surmounts this problem but requires some access points where it is possible to view and count culms (as suggested by Marthews et al., 2014). Of secondary importance, if the clump has a well-defined area with discrete boundaries, we also suggest estimating clump area. This is achieved by making two perpendicular measurements of clump width, including the longest axis, and then calculating clump area as an ellipse. Total clump area per subplot can be reported together with bamboo cover data. Documenting clump area can be particularly important in forests with patchy bamboo distributions, because plot-scale estimates of culm densities may obscure the degree of local-scale bamboo dominance.

Unless specifically required for the goal of the project, marking or tagging culms at the measuring point is unnecessary since woody bamboo culms increase in length but maintain a constant diameter throughout their development. However, repeated bamboo censuses are necessary given that culm density and diameters may vary throughout the life cycle of the population. In addition, frequent monitoring ensures the opportunity to detect mortality events and document life cycles, which remain unknown for many species.

2.2.2 | How to measure height and length

Unless a bamboo culm is perfectly erect (see Figure 1), its mature height will be shorter than its length. Whereas culm height determines which forest strata and processes are affected by bamboo (e.g., by shading or mass-loading; Griscom & Ashton, 2006), culm length may be a more important measurement, for example, for estimating bamboo biomass (Veblen et al., 1980). We suggest measuring both height and length on the same 60 culms used for determining the average culm diameter of each species (Approach 1) or measuring at least 20 culms per diameter class and species (Approach 2). Culm height should be measured as the straight-line vertical distance between the highest point of the culm (including culm branches) and the ground. Culm length is the distance between the rooting point and the tip of the culm (or furthest bamboo branch) measured along the culm. We suggest measuring height with a telescopic measuring

TABLE 3 Steps to follow when using approach 1 of the protocol, tasks to complete, and relevant sections of the paper

Step	Task	Protocol information
1—Determine the number of bamboo species in the plot	Decide which species will be included in the monitoring	2.3.1—Woody versus Herbaceous 2.3.3—Diameter cutoff
	Learn to distinguish the different species looking at diagnostic characters	2.4—Bamboo collection for identification
2—Collect species data	Record diameter, height and length of 60 random mature culms	2.1.2—Estimate bamboo dimensions 2.2.1—How to measure diameter 2.2.2—How to measure height and length 2.3.2—Maturity stages 2.5—Recording and reporting information (Form 2)
	Collect specimens for identification	2.4—Bamboo collection for identification
3—Collect plot/subplot data	Record density of stems per subplot	2.1.1—Quantify culm density 2.3.2—Maturity stages 2.5—recording and reporting information (Form 1)
	Record cover	2.2.3—How to measure cover 2.5—recording and reporting information (Form 1)

FIGURE 1 Bamboo growth habits and point of diameter measurement (Drawings adapted from Figure 6, Judziewicz et al. (1999) and the Bamboo Biodiversity website)
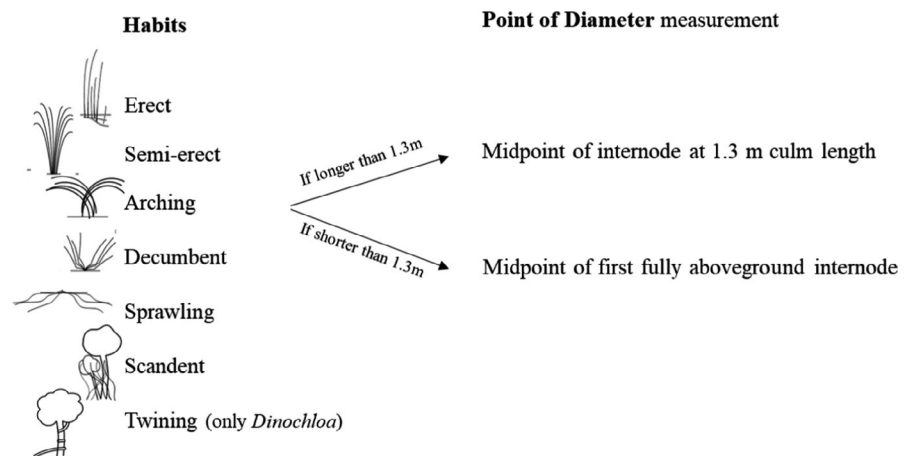
pole or a clinometer. We also recommend having a trained researcher visually estimate length based on the height measurement when direct measurement is not logistically feasible (i.e., when a culm is too tall). Another option for measuring length, suggested in Approach 1, is to select 60 culms outside the monitoring plot to be cut, extended on the ground and measured from root to tip. It is also possible to estimate length based on diameter using species-specific allometric models (Camargo & Kleinn, 2010).

2.2.3 | How to measure cover

Non-erect species represent a challenge for characterizing forest structure. For example, a 1-cm-diameter sprawling culm can cover several square meters of ground; a 20 × 20 m subplot can be completely covered by arching bamboo culms but have an insignificant culm basal area. As bamboo likely plays an important role in forest regeneration (Campanello et al., 2007; Holz & Veblen, 2006), it is important to estimate bamboo cover at the ground level (<1 m). Bamboo ground cover provides an approximation of the percentage of ground that is shaded by sprawling and scandent bamboos.

Ground cover can be estimated visually in several small (1–10 m^2) divisions of the subplots. For taller strata, separating tree cover from bamboo cover can be challenging, and often unnecessary, if culm diameter, height and length adequately characterize bamboo abundance. Nevertheless, if bamboo cover is central to the goal of the study, we suggest using the same visual estimation of overstory bamboo canopy cover (height ≥1 m) at the height intervals where most of the bamboo canopy occurs (height intervals: 1–5, 5–10, 10–20, 20–30, >30 m). If a tree cover protocol exists for a specific forest monitoring plot (e.g., hemispheric photos at different heights), we recommend researchers follow the same protocol for bamboo.

2.3 | Bamboo culms to include in the census

2.3.1 | Woody versus Herbaceous

Bamboos can be woody or herbaceous. Woody bamboos belong to the tribe Bambuseae or to the tribe Arundinarieae and herbaceous bamboos belong to the tribe Olyreae (Clark et al., 2015; Kelchner & Bamboo Phylogeny Group, 2013). Woody bamboos do not have

FIGURE 2 Vegetative bamboo structures. (a) Culm leaf with the blade reflexed. (b) Intravaginal branching, with the branches more or less erect and pushing the culm leaf sheath away from the internode. (c) Extravaginal branching, with the emerging branches splitting the base of the culm leaf sheath. (d) Infravaginal branching, with the branches emerging through the girdle. (e) Culm segment with two nodes (each bearing one bud) and one internode. (f) Bud complement of one bud, showing a persistent girdle. (g) Bud complement of one larger central bud subtended by several smaller subsidiary buds of two sizes. (h) Leaf complement. (i) Branch complement of three subequal branches borne on a promontory. (j) Branch complement of one dominant branch with a few secondary branches developed from its base, all bearing thorns. Illustrations redrawn by Graham Hagan, figure 1a [e], f [h], h [c], i [b], 2d [a], 3a [f], e [i], and i [j] from Soderstrom and Young (1983, *Annals of the Missouri Botanical Garden* 70:130–132), figure 3f [d] from Clark (1985, *Annals of the Missouri Botanical Garden* 72:869) and figure 3d [g] from Clark (1993, *Novon* 3:234), with permission from the Missouri Botanical Garden Press. Figures a–c, e–f, and h–j originally drawn by Alice R. Tangerini, Dept. of Botany, Smithsonian Institution and d, g by Lynn G. Clark, Iowa State University

secondary xylem; rather, their woodiness comes from lignified culms and branches, which allows them to grow taller and thicker than herbaceous bamboos (Clark et al., 2015). Although some herbaceous bamboos can be several meters tall, most species are rarely thicker than 1 cm diameter. Herbaceous bamboos are distinguishable by having simple branching or no branches at all, only the inner foliage leaf ligule (the outer ligule is absent; see Figure 2 for morphological features), and unisexual flowers. In contrast, woody bamboos present complex branching, have inner and outer ligules on the foliage leaves (see figure 12 in Judziewicz et al., 1999), and have bisexual flowers (Judziewicz et al., 1999). Unless it is of specific interest for the study, we recommend focusing census efforts on woody bamboos because of the greater role that they play in forest dynamics (monocarpic cycles), biomass accumulation (lignified culms), and vegetation structure.

2.3.2 | Maturity stages

Bamboo culms have different life spans depending on the species, and bamboo populations are typically composed of culms at different stages of maturity. As a general rule, we recommend including all mature culms that are green (or yellow in many species) and have green leaves. However, if the goal of the study is to understand the dynamics of bamboo populations or ecosystem carbon storage, culms at different maturity stages, including standing dead culms, should be recorded, tagged, and classified as alive or dead. Deciduous bamboos rarely lose all their leaves and maintain a healthy culm condition (green or yellow). Dead bamboo culms are straw to brown in color and either leafless or with retained dead leaves. Young woody bamboo culms are typically shiny, sometimes covered by the culm leaves, and lack fully developed branches or foliage leaves.

2.3.3 | Diameter cutoff

For studies on the role of bamboo in forest structure, functioning or dynamics, we recommend including all woody species whose culms can reach diameters ≥1 cm. Note that many species with maximum diameters ≥1 cm can have a substantial proportion of culms <1 cm. Rather than selecting a diameter threshold that includes some culms of one species and excludes the rest, we

recommend a species-level approach that will include all culms of each species.

2.4 | Bamboo collection for identification

Identification of bamboo species is essential not only for studies of tropical forest diversity, but also for studies of ecosystem water dynamics, bamboo reproductive cycles, and carbon storage. Bamboo identification relies on very different characters than that of trees, and so bamboo herbarium specimens should be specially prepared to display as many as these characters as possible. Below we provide a brief summary on how to collect bamboos for subsequent identification (see Figure 2 for morphological terms). For more detailed information on bamboo collections and morphological descriptions, see Soderstrom and Young (1983), and Judziewicz et al. (1999).

When collecting bamboos, the specimen should include two nodes with the corresponding internode, at least two culm leaves (sheath and blade) pressed flat on the paper, one representative branch complement (group of branches from the same node) and a leafy twig showing both sides of the leaves. If a bamboo is flowering, collect the flowering branch, and if it has seeds, include them in the sample. To ensure correct identification, we recommend recording information about bamboo habit and growth form, and detailed descriptions of the culm, culm leaf, branches, branching pattern, foliage leaves, inflorescence (if present), and rhizome (Judziewicz et al., 1999; Soderstrom & Young, 1983).

2.5 | Recording and reporting bamboo census data

Recording the information in the field will require two separate forms per plot. To ensure long-term access and promote collaboration, we suggest including this information in an online repository (e.g., ForestPlots.net) linked to the rest of the plot data and metadata.

2.5.1 | Form 1—Subplot data

We suggest using Form 1 to record general plot information (name, code, coordinates, date, etc.), detailed subplot information
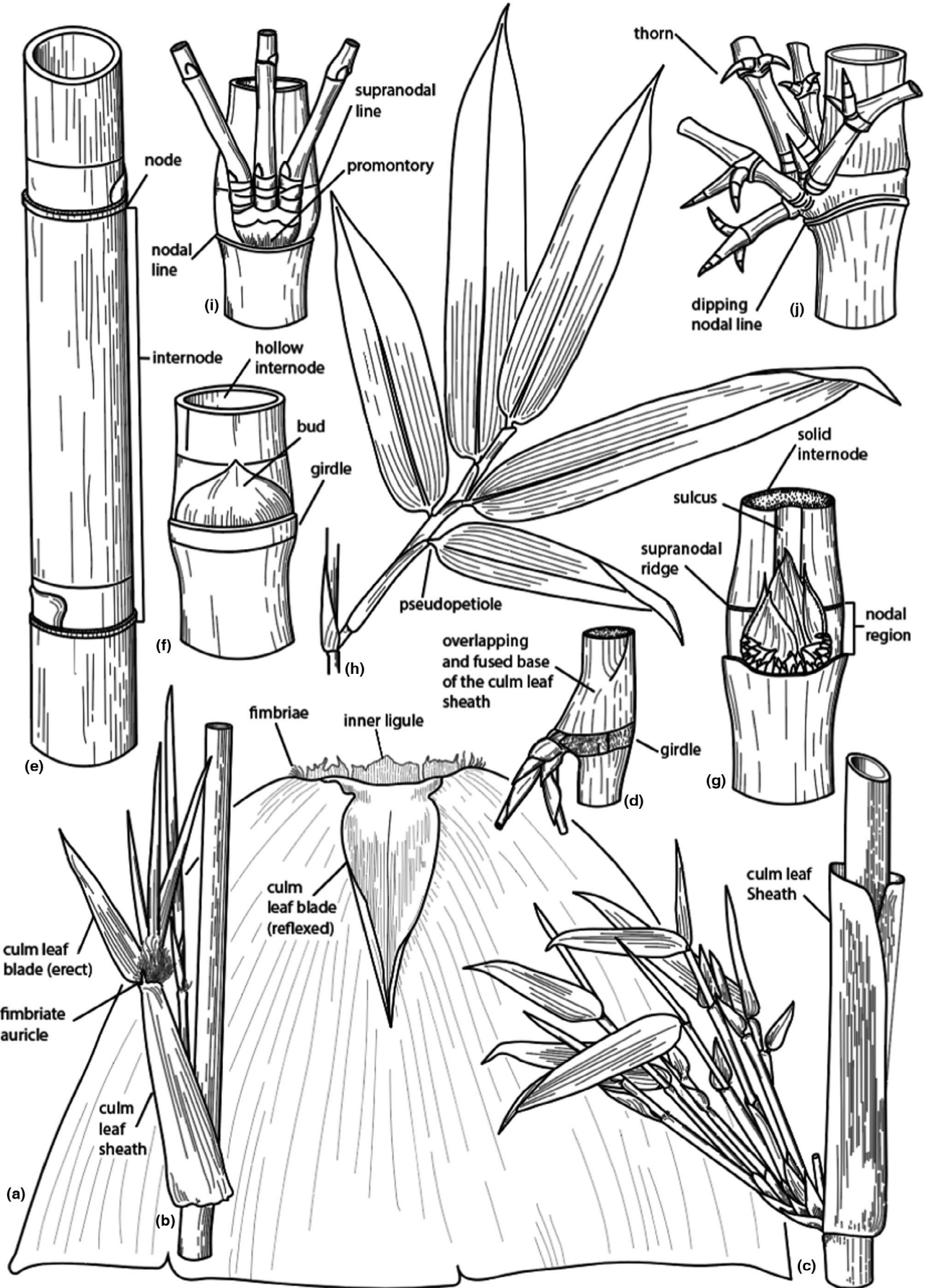
of bamboo count per species, individual culm dimensions if using Approach 2, bamboo ground and overstory cover, and clump area (if available). An example of Form 1 using Approach 1 is provided in Table S1.

2.5.2 | Form 2—Species data

We suggest using Form 2 to record culm measurements, growth habit, voucher number and species descriptors (see section 2.4) for each species separately. An example of Form 2 for Approach 1 can be found in Table S2.

3 | PROTOCOL JUSTIFICATION: BAMBOO CENSUS IN THE PERUVIAN ANDES

To determine the minimum sampling effort required to quantify bamboo density and basal area, we carried out bamboo censuses in eight 1-ha plots, maintained by the Andean Biodiversity Ecosystem Research Group (ABERG; http://www.andesconservation.org), located in and near Manu National Park, Peru, from 1,000 to 3,600 m a.s.l. (Table S3). Although Andean forests are a center for diversity and endemism of Neotropical bamboos (Fadrique, Pianissola, Feeley, & Clark, 2019; Judziewicz et al., 1999), the ABERG forest monitoring practices do not include bamboos. We initially divided each 1-ha plot into 25 subplots of 20-m × 20-m, such that each subplot represented 4% of the plot area. In six of eight plots, we sampled 10 to 13 subplots (i.e., 40%–52% of the plot area); in two plots (WAY and ESP; Table S3), we sampled all the subplots (i.e., 100% of the plot area).

In each of the selected subplots, we counted every mature bamboo culm belonging to a woody species able to reach at least 1 cm in diameter. During the counts, we identified each culm to species (or morphospecies) and assigned the culm to a 1-cm-diameter class (i.e., 0–1.0 cm, 1.01–2.0 cm; as in Approach 2). Species present in multiple plots were analyzed separately.

3.1 | Minimum sample area

To determine the minimum number of subplots necessary to estimate mean culm density, for each plot we: (a) Summed the number of culms in each subplot; (b) Randomly sampled an increasing number of subplots without replacement to calculate mean culm density (i.e., we created random groupings from two up to the total number of subplots measured, which ranged from 10 to 25); (c) Repeated the random sampling 10,000 times per subplot grouping (i.e., 10,000 means based on two subplot densities, …, 10,000 means based on 25 subplot densities); (d) Identified the subplot grouping where 90% of the 10,000 replicates provided a good representation of culm density (within 20% of the true plot mean). In partially sampled plots (six of eight), we treated the mean of all subplots as the best estimate for true culm density.

On average, the sample area necessary to estimate mean culm density was 75% of the subplots in a 1-ha plot (Figure 3). As indicated in the protocol guidelines, we nonetheless recommend counting the bamboo culms in the entire plot due to the high variability of bamboo density between subplots and the lack of a clear asymptote in the culm density estimation of some of the plots. The number of culms per plot estimated for each subplot combination is in Figure S1.

We acknowledge that our minimum sample area recommendation is based on 1-ha plots only and that larger plots, for example, 25 or 50-ha, may reduce the percentage of sample area required. In these cases, we recommend carrying out a preliminary analysis such as this one to determine the minimum sample area.

3.2 | Minimum number of culms for diameter estimate

We determined the minimum number of culm measurements necessary to estimate mean culm diameter for the six species with the widest diameter range (*Aulonemia hirsuta*, *Chusquea sp21*, *Chusquea sp3*, *Chusquea sp32*, *Chusquea sp19*, *G. weberbaueri*). For each species, we: (a) Assigned to each culm the midpoint diameter of its diameter range (0–1: dbh 0.5 cm; 1.01–2: dbh 1.5 cm, etc.); (b) Randomly sampled an increasing number of culm diameters without replacement to calculate mean culm diameter (i.e., we created groupings from 2 to 200 culms); (c) Repeated the random sample 100 times per culm grouping (i.e., 100 means based on two diameter values, …, 100 means based on 200 diameter values); (d) Calculated the range of mean culm diameter estimates (out of the 100 replicates) for each of the culm groupings; and (e) Identified the number of culms necessary to measure in order to obtain a range less than 0.5 cm.

Based on this analysis, we estimated that on average, 63 culms were required to obtain an estimated mean culm diameter that was within 0.5 cm of actual mean (Figure 4). We therefore recommend measuring a minimum of 60 culms per species and site when performing a census using Approach 1.

3.2.1 | Approach comparison

We compared estimates of bamboo basal area per species and plot following the two different diameter sampling schemes described in the protocol. For Approach 1, we estimated basal area per species and plot based on the mean diameter of 60 randomly selected diameter values from our bamboo census data and corresponding culm counts per species and plot. For Approach 2, we determined basal area per species and plot by measuring all culms in all sampled subplots and summing their basal area. We calculated bamboo basal area as the area of a circle corresponding to the culm diameter, regardless of whether the species had a solid or a hollow culm. We compared the estimated basal area per species and plot between the two approaches with Spearman correlation. All analyses were performed in R 3.5.2.
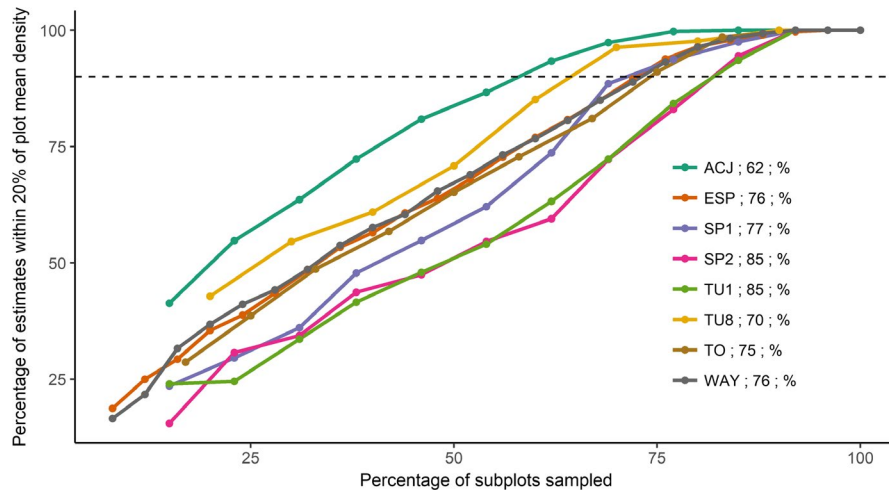
FIGURE 3 Percentage of culm density estimates (out of the 10,000 replicates) that fall within 20% of true mean plot culm density in each of the subplot groupings, in an increasing gradient of subplots sampled in each of the eight plots (colors). In partially sampled plots (six of eight), we treated the mean of all subplots as the best estimate for true culm density. The dashed line indicates that 90% of the estimates are within 20% of the actual overall mean (our requirement for minimum sampling area). The legend indicates the percentage of subplots per plot necessary to first reach the 90% cutoff (overall mean 75%). More information on the plots can be found in Table S3

FIGURE 4 Range of mean culm diameter (cm) estimates for the 100 replicates in each of the 10–200 culm groupings for six species of bamboo. The dashed line indicates when the range of estimates first achieves ≤0.5 cm. Legend shows number of culms in the grouping that first achieves ≤0.5 cm estimation range for each species shown in different colors
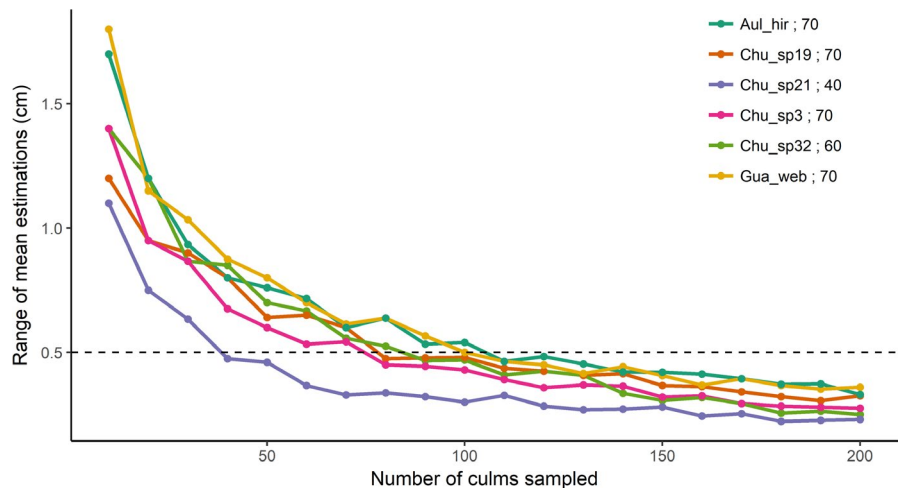
The two methods produced highly correlated estimates of bamboo basal area (Spearman correlation, $r = .98$, $p < .0001$; Figure 5); the mean percent difference for basal area estimates within species, using the two methods, was 10%. In summary, we found that measuring 60 culms (Approach 1) provides a good estimate of bamboo basal area compared to a full census (Approach 2). Thus, to minimize field effort, we only recommend Approach 2 when the aim of the study is related to bamboo demography.

Although these results come from one study region, we expect that the high variability of micro-environmental conditions, bamboo densities, basal area and species occupancy across the wide elevation range covered in this study (~2,600 m) will provide a good approximation of the minimum effort required for bamboo monitoring in most systems. We acknowledge however that other systems,

depending on their heterogeneity and structure, may require more or less sampling.

3.3 | Bamboo contribution to the plot basal area

To assess the contribution of bamboo to the plot basal area, we gathered existing data on tree basal area from the plots (Farfan-Rios, 2011; Malhi et al., 2016). We used the calculated bamboo basal area from Approach 2 to calculate the contribution of bamboo to total plot basal area.

We recorded data from 14 woody bamboo species of four genera across the eight plots (*Arthrostylidium*, *Aulonemia*, *Chusquea*, and *Guadua*). Mean bamboo density per plot was 5,100 culms/ha,
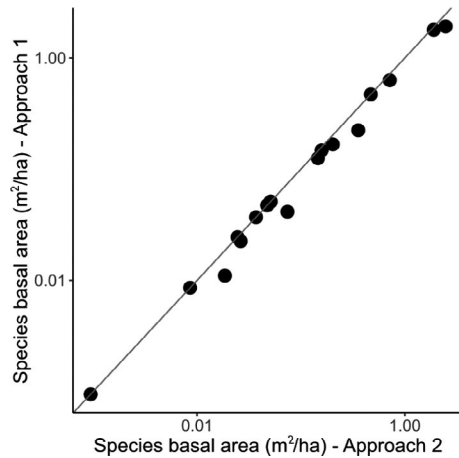
FIGURE 5 Bamboo basal area per species and plot. Correlation between basal area per species and plot estimated based on Approach 1 (60 culms) and Approach 2 (all culms). Both axes are shown in log10 scale. The line represents the 1:1 relationship
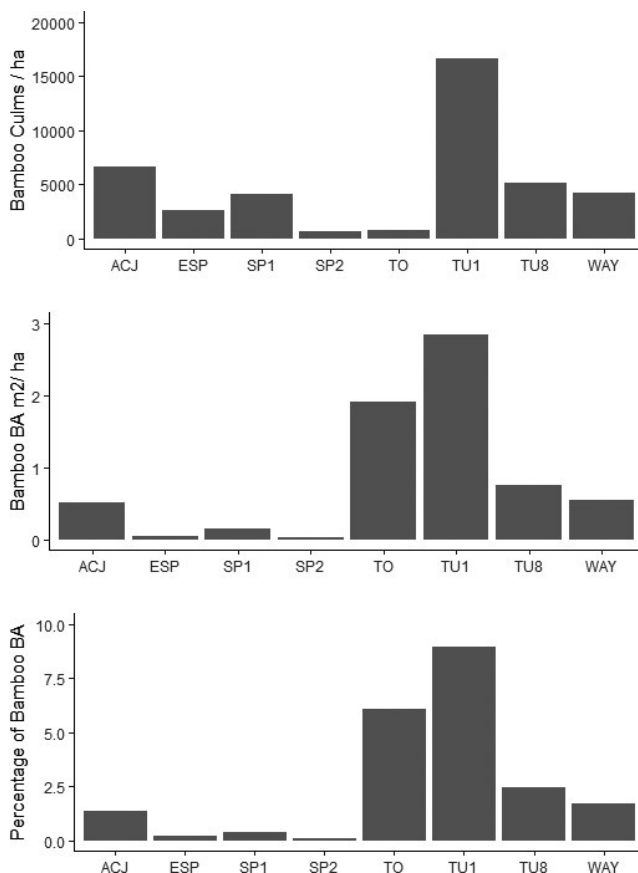

FIGURE 6 (a) Bamboo density (number of culms per ha) (b) basal area (m^2/ha) and (c) contribution to total basal area of the plot (bamboo basal area/[bamboo basal area + tree basal area]) for each of the plots in the *field example* calculated with Approach 2 (all culms)

reaching 16,000 culms/ha in the densest plot. Mean bamboo basal area was 0.85 m^2/ha representing 2.7% of the total basal area per plot; in the plot with highest bamboo density, basal area was 2.8 m^2/

ha, which represented 9% of the plot basal area (Figure 6). The high abundance of bamboo culms and its corresponding contribution to plot basal area highlight the need to include bamboos in forest monitoring programs.

4 | DISCUSSION

Data collected according to our proposed bamboo protocol will facilitate multi-site meta-analyses to advance our understanding of global patterns in bamboo diversity and their role in forest dynamics (Yuen et al., 2017). The standardized inclusion of bamboos is especially important given the strong interaction between human-driven (deforestation, etc.) and climate change related (fire, drought, etc.) disturbance (Wright, 2010)—conditions under which many bamboo species thrive (Montti et al., 2014; Mulkey, 1986; Saha et al., 2009). In addition, bamboo is an increasingly valued commodity and bamboo plantations are expanding in tropical regions (FAO, 2010; Stokes et al., 2007). A better understanding of the role of bamboo in forest dynamics, achieved by long-term monitoring of bamboo density, is crucial to develop efficient forest management and conservation strategies (Bystriakova et al., 2003; Campanello, Montti, MacDonagh, & Goldstein, 2009; Rockwell, Kainer, d'Oliveira, Staudhammer, & Baraloto, 2014; Yuen et al., 2017).

In our *Protocol justification* analysis, we show that measuring bamboo abundance over at least 75% of the plot area is key to obtaining accurate estimates of bamboo basal area in 1-ha forest plots. Bamboo diameters, which are consistent throughout the culm life with limited variation within species, can be estimated based on a subset of the population (60 culms). One of the main reasons for the omission of bamboo from monitoring efforts was the lack of a standardized and streamlined method to tackle the sometimes overwhelming density of bamboo culms (Table 2). We expect that this simplified protocol will promote the inclusion of bamboo in forest monitoring efforts worldwide.

We provide evidence that bamboo density and basal area represent a substantial fraction of the total basal area per plot in Andean forests (mean 0.85 m^2/ha, maximum 2.9 m^2/ha). Bamboo basal area in our example data from the Peruvian Andes is comparable to the basal area represented by lianas, for example, 1.00 m^2/ha in the lowland tropical forest of La Selva, Costa Rica (Yorke, Schnitzer, Mascaro, Letcher, & Carson, 2013), 0.78 m^2/ha in a subtropical montane forest in Argentina (Ceballos & Malizia, 2017), 0.74 m^2/ha in a seasonally moist lowland tropical forest in Barro Colorado Island, Panama (Schnitzer et al., 2012) and 1.9 m^2/ha in a seasonal lowland forest in Bolivia (Pérez-Salicrup, Sork, & Putz, 2001). We hope that these results, together with the literature reporting the effect of bamboo on forest structure, composition and function (e.g., Caccia, Kitzberger, & Chaneton, 2015; Campanello et al., 2007; González, Veblen, Donoso, & Valeria, 2002; Griscom et al., 2007; Muñoz, González, Celedón, & Veblen, 2012; Rother et al., 2013; Tabarelli & Mantovani, 2000), will motivate others to monitor bamboo in their forests following our proposed bamboo protocol.

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AUTHOR CONTRIBUTION

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DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.m0cfxpnz8 (Fadrique, Veldman, et al., 2019).

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SUPPORTING INFORMATION

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