PROTOCOL FOR INVENTORY OF MAPPED PLOTS IN TROPICAL FOREST

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Received November 2013

LEDO A. 2015. Protocol for inventory of mapped plots in tropical forest. Inventorying field mapped plots can be difficult in tropical forest because visibility and access are limited due to high density of woody plants. Additionally, steep slopes and frequent presence of fog further complicate field measurements in mountain areas. The objective of this study was to propose a detailed field census protocol. The method described allowed inventory of mapped 1-ha plots in a montane cloud forest with little cost and time. The inventory also included the recording of some environmental conditions, namely, light, soil coverage temperature and humidity. A detailed explanation dealing with species identification in the forest is also included. The method can be extended to different tropical as well as temperate forest ecosystems. Finally, a summary and comparison with different inventories focusing on mapped trees are given, along with a number of recommendations.

Keywords: Dasometric variables, ecological modelling, fieldwork, field measurements, field methods, spatial analysis, tree assessment

INTRODUCTION

Inventorying forest plots, including mapping of trees, is not an easy task. Mapping trees is necessary for developing spatial individual-based models, and it has been used to study the spatial patterns of tropical trees (Pelissier 1998, Condit et al. 2000, Plotkin et al. 2002), forest dynamics (Batista & Maguire 1998) and spatial dependence between trees and habitats (Harms et al. 2001, John et al. 2007, Ledo et al. 2013). It has also been used to study mechanisms that allow species coexistence (Dislich et al. 2010, Bagchi et al. 2011), aboveground biomass in the forest (Chave et al. 2003) and develop and propose efficient management strategies (Batista & Maguire 1998).

Anyone who has attempted to inventory and map tropical trees will have a number of difficulties, both in technical and economic terms. Tropical forest has a mix of hundreds of tree species and due to high density of woody plants (trees, shrubs and lianas), the forest can be an intricate tangle with limited visibility and scope for movement. In montane forest, the ever-present fog and steep slopes make the problem worse. Despite these difficulties, many important research projects which include mapping of plots are currently being undertaken. For example, the Centre for Tropical Forest Science has a global network of tropical forest research plots and has made substantial advances in the understanding of tropical forest (Comita et al. 2010). Nevertheless, the use of mapped plots is also important in smaller-scale research and in projects around the world such as India (Pelissier 1998), Central America (Clark et al. 1999), South America (Ledo 2012) and Africa (Lewis et al. 2009).

In some cases, when spatially-explicit models are not the aim of study, location of each tree is not required. In such cases, trees are measured but not mapped. An example of this is the RAINFOR network, which is a long-term international collaboration of forest inventories aimed at furthering the understanding of long-term dynamics of Amazon ecosystems (Phillips et al. 1998, Talbot et al. 2014). Projects which require mapping of trees are frequently hindered by the expense and high level of man-hours involved, particularly under the current scenario of a global economic crisis. This is the reason why an efficient (in terms of time and

The inventory data is available by contacting the author money) field census protocol is presented here. This protocol was used for inventory of three 1-ha plots in Bosque de Neblina de Cuyas montane cloud forest in northern Peru (Ledo 2012). Cloud forest has limited visibility due to the abundant fog, steep slopes and copious understorey plants (Hamilton 1995, Foster 2001). In tropical rainforest, the visibility is less affected by fog but is similarly limited by the quantity of lianas (Schnitzer et al. 2012). Apart from mapping all free standing trees in the three 1-ha plots, microenvironmental conditions (light, humidity, temperature and ground cover characteristics) and recruitment density were sampled in 42 randomly selected locations. Two people were able to complete the entire inventory in 4 months. Complete botanical identification was formerly carried out, both during and after the inventory. The proposed inventory method is applicable to all kinds of tropical forest as well as to temperate and boreal forests.

MATERIALS AND METHODS

Materials

In order to perform the tree inventory, we used compass, hypsometer vertex and transponder, tape measure, tree callipers, adhesive tapes, permanent markers, wooden stakes, paint, inventory sheets or notebook, camera and global positioning system (GPS). Data-logger receptors were used to estimate the temperature and humidity within the plots. To measure light, a camera attached with a fish-eye lens was used and the photographs were analysed using HemiView® 2.1 Canopy Analysis Software.

Establishment of 1-ha square plots

When performing an inventory in a forest, it is necessary to establish plots in the inner part of the forest in a well-developed stand, at least 200 m from the edge of the forest to avoid edge effects. Otherwise, the recorded values of forest variables may be biased due to forest boundary effects. Hence, the measured values will not represent forest conditions accurately. If the aim of a project is to establish long-term permanent plots (for a 20-year period for example), the use of metallic plates to mark each tree is recommended.

Square 1-ha plots (100 m × 100 m, measured on a horizontal plane rather than on the ground, Figure 1a) were established for the study. This is one of the most common plot size used in the tropics and appears to be good enough to estimate forest variables in tropical areas (Condit 2008). Square plots are recommended for analysing spatial distribution of trees using Ripley's K function (Ripley 1977) since maximum distance for this analysis is half the length of the plot. All the distances mentioned in this document refer to projected distances rather than on the ground. Hence, the 1 ha is the total area in a projected horizontal map, whereas on the terrain the total area was larger (Figure 1a). To consider distances in a projected layer, the deviation values due to the slope were corrected in the field. The hypsometer gave the projected and real distances instantly. This device did not require doing any calculation in the field.

The start point to set out the plot was to mark the upper left vertex (Figure 1b). An upper vertex was chosen as start point because the visibility looking down slope was greater than up. To mark the vertex, a large tree was marked with red–white adhesive tape placed around the trunk at a height of around 1.5 m (eye-level). In this way, the vertex can be located easily and quickly. The left vertex was chosen because the path to reach the plot was on the left of the plot (Figure 1b). Walking within the plot may produce some minor disturbances, which should be avoided if possible. To obtain actual tree position values, universal transverse mercator coordinates and elevation of the first point were measured using GPS. From the start point, plot area was delimited before measuring the trees. This was useful to get an idea of plot dimensions and types of forests (i.e. with or without gaps). The north–south aspect was determined using compass and measured around 120 m in this direction to establish the second vertex. The third vertex was then established about 120 m from the east–west direction and so on to complete the square plot. There were three reasons why it was desirable to use a plot covering a larger area than the targeted area, i.e. (1) an approximate plot could be established more quickly than an exact plot, (2) it ensured that the whole hectare was included and (3) some edge effect could be corrected by having other trees around the edges of the plot. For replicates,

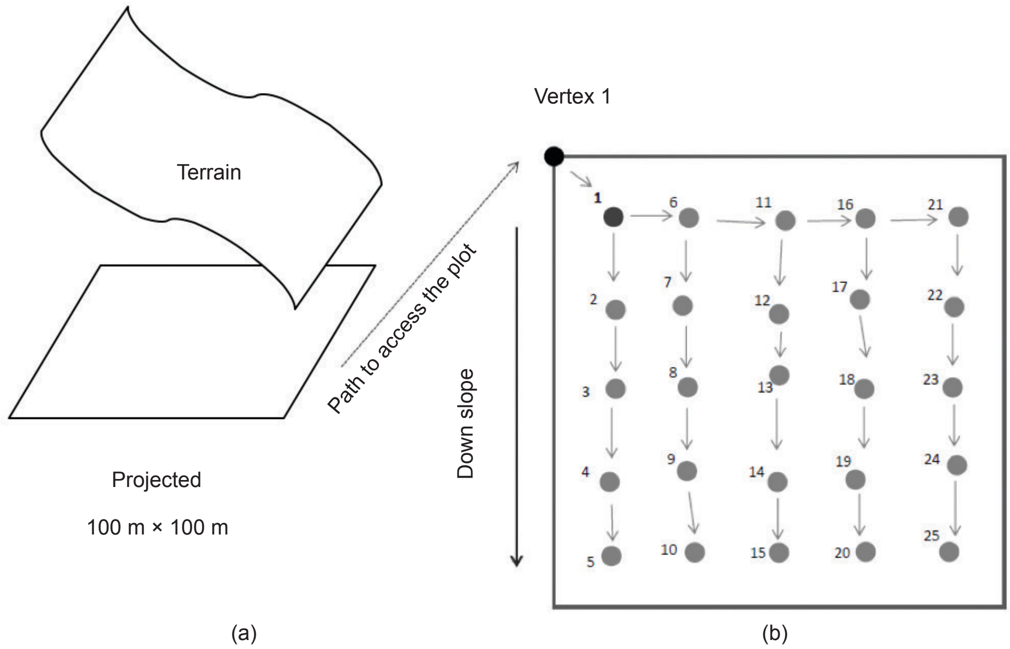

Figure 1 (a) 1 ha on the terrain and plot projected, 100 m × 100 m and (b) diagram indicating how to move within the plot to take measurements; points represent station points and arrows, the direction from the first station point (no. 1)

sites with fairly homogeneous environmental conditions and physiography were identified within the forest (with similar slopes, soil, humidity, temperature, tree density, basal area and canopy openness). Three replicated plots were established in this site.

Mapping trees within the 1-ha plot

To map the trees, different sampling points were established within the plot (Figure 1b). The first sampling point was situated using vertex 1 as a reference, at a distance of approximately 10 m. A vertex hypsometer was used to ascertain distance and slope, and a compass to determine the angle. This first point was marked by a wooden stake in the ground, the upper part of which was painted red. This colour was chosen because it could be seen easily within the forest than other colours such as blue or green. The number of the sampling point was written on the stake, on the red paint, using permanent marker pen. The procedure employed by the two-person team for measuring trees was as follows: one person, who was at the sampling point, carried the vertex, compass and notebook. The other person had callipers, transponder, adhesive tape and permanent marker pens. This person fastened the transponder to a tree and measured the diameter at breast height (dbh, 1.3 m) using the tree callipers. Two perpendicular diameters were measured per tree (Figure 2). This was necessary to record dbh more accurately which was especially important in irregular shaped trees. The value of tree dbh was the mean value of the perpendicular values,

$$\text{dbh} = \frac{(\text{dbh1} + \text{dbh2})}{2}$$

In the case of trees with dbh greater than the size of callipers, measuring tape was used to measure trunk circumference instead of trunk diameter. Thus,

$$\text{dbh} = \frac{\text{trunk circumference}}{\pi}$$

Once measured, the tree was assigned a number, starting with 1, which was written on white tape placed around the trunk. It was important to clearly mark and made visible the already measured trees because it was easy to lose one's bearings in this kind of fieldwork. It was recommended to mark each tree measured because it might be neccesary to return to the tree at a later stage (e.g. to correct measurement mistakes detected in the laboratory). Tape

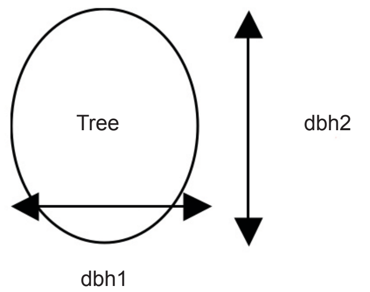

Figure 2 Tree diameter measurements of trunk at breast height (1.3 m)

instead of metallic plates was used because the plot was not permanent. The tape was removed from the trees once the study finished. Person at the sampling point measured the distance, slope and angle from the sampling point to the tree as well as tree height. These values allowed mapping of the exact position of each tree. Any special tree features such as herbivore damage were also registered when found. All trees taller than 1.3 m were inventoried without diameter restriction. At this site, tree trunks were entirely covered with moss, so it was necessary to remove some moss before measurement. For multiple-stem trees, all stems were measured individually but the fact that they were from the same individual was noted in order to recognise it was a single multistem individual. This was important in order to calculate dendrometric values (e.g. basal area) and the number of genetically distinct individuals. There were no trees with large buttresses in this study but if there were, we recommend following the protocol developed by RAINFOR (Phillips et al. 2010).

All trees within a radius of approximately 10–15 m around the sampling point were then measured sequentially following the same procedure. Once all trees had been measured at the first sampling point, the next sampling point was determined at a distance of about 20 m on the ground, double checking the measurements (distance and slope) before the process was repeated until the whole plot had been covered (Figured 1b).

Standing dead trees were also measured in the same way although identifying the species was not possible in many cases. The fallen dead trees found on the soil surface were also mapped and the length and height from both sides in the XYZ plane were measured along with the diameter at both ends. In this way, a projection of the tree can be visualised.

Using this approach, the time required to map all free-standing woody plants (with a height of more than 1.3 m but no diameter limit) in each 1-ha experimental plot was about 1 month per plot (slightly more in the rainy season and 3 weeks in the dry season).

Recruitment subplots in each plot

Forty-two random subplots of 4 m^2 within each 1-ha plot were sampled for recruitment. Each subplot was divided into four quadrats using a 1 m^2 wooden frame. The frame was placed on the forest floor with an east–west orientation, ensuring that the angles were correct (90°). In each subplot, number of seedlings was counted, their height measured and the species recorded. Recruitment was also recorded at each tree sampling point. Due to the likelihood of plants being disturbed or damaged during the tree measurement fieldwork, the recruitment subplots were measured right after marking the sampling point with the stake in the ground but prior to mapping the trees in order to detect the true recruitment pattern in the forest.

Assessment of topographical and environmental factors

To assess light conditions, hemispherical photographs were taken using a camera attached with a fish-eye lens. The camera was placed in the middle of the recruitment subplots. It was levelled horizontally and oriented towards true north using a compass with spirit level. The camera was placed 20 cm above the ground because understorey foliage attenuated light near the forest floor (Montgomery 2004). The photographs were analysed for visible sky, direct site factor, indirect site factor and global site factor.

Six receptors were installed at a height of 1.3 m in the centre of the subplots to measure relative humidity and absolute temperature. One of the receptors was a reference-measuring device, recording humidity and temperature from a point that was considered as the reference value. That receptor remained fixed at the same point during the entire study. The rest were repositioned every 2 days, moving from the centre of one subplot to the centre of another until all subplots were covered. Humidity and temperature values assigned to each subplot were the values of the reference measurement minus the values recorded in the subplot. For humidity and temperature, absolute values relative to the control measurement were expanded to plot level using geostatistical methods (Creesie 1993, Ledo et al. 2013).

To determine elevation, slope, curvature and aspect, a digital elevation model of each plot using X, Y, Z coordinates of the measured woody plants, with approximately 5000 points for each plot, was built using the software ArcMap® v9.2. Elevation, slope, curvature and aspect were derived from the digital elevation model in a 2 m × 2 m grid.

The initial intention was also to analyse pH, C, N, P, K and Al in the middle of the subplots. However, due to problems associated with mining activity which was beginning in the area, permission was denied to perform these analyses. For detailed inventory micronutrients analysis see Arellano (2013). Nevertheless, a simplistic but very useful observation was carried of soil characteristics. The observed soil-surface rockiness was recorded for each subplot as continuous variable ranging from 1 (big fixed rocks, parent rock) to 4 (clay). Similarly, the organic matter coverage was codified using a continuous variable from 1 (parent material) to 8 (total coverage with substantial layer of organic matter). Intermediate levels were based on the quantity and trade-offs between organic matter and stones. This vague classification later yielded significant results during the analysis.

Botanical collection and species identification

In order to correctly identify each species, samples of woody plants were collected during the fieldwork and compared with catalogued specimens in the main official herbaria of the region. This was a continuous process conducted during all fieldwork. This task was performed in the following way: botanical collection started during a 5-day intensive inspection of the forest prior to the study itself. To separate and identify different species or suspected species, pictures of all the species were taken. For each species we recorded the pictures of leaves, trunk, branches, architecture of the species, any special features, flowers and fruits where applicable, and smell if characteristic. Drawings of leaves were also made. A database was then developed using this information. The information was also recorded in a notebook which was brought to the field for purpose of comparison. Botanical samples of branches of the species were taken, except for rare species (to avoid disturbing rare and probably endemic plants). All samples were pressed. All recognised herbaria of the region were visited and most of the species were identified on site and confirmed by herbaria experts. With each inventory we continued adding to the notebook, the electronic database and the botanical collection all new species found and updating information of the existing records. Unidentified species were termed as morphospecies.

RESULTS AND DISCUSSION

Using this inventory, all standing woody plants of heights ≥ 1.3 m were mapped and their heights, dbhs and species recorded. A diameter tape or pi tape could be used instead of the tree calipers. The pi tape is smaller and easier to transport than tree callipers, but it would take a little longer to perform the diameter measurements. Hence, the tree callipers is still preferable. The vertex hypsometer seemed to be the perfect tool to measure distances and tree height. Distances and tree height could have been measured with a laser device or a total station device. However, both tools are difficult to use in dense tropical forest and are also very expensive to acquire. Furthermore, they are sensitive and were not designed for use in the forest. The whole inventory was completed in 4 months (working mainly during the rainy season), with a two-person team at total cost of less than 4000€, excluding salary. With this inventory we were able to study the spatial distribution of all woody plants in the forest, spatial relationships among them, microscale habitat associations and finally recruitment patterns and spatial strategies (Ledo 2012).

This proposed inventory is applicable to all kinds of tropical forests as well as temperate and boreal forests. Montane cloud forests have great abundance and diversity of epiphytes such as bromeliads but there is almost a complete absence of lianas. The opposite pattern occurs in rainforests, where density of lianas is generally high. A refined protocol for liana census can be found in Schnitzer et al. (2006).

Networking and sharing data is important and currently on the increase (Reichman et al. 2011). The use of similar inventories facilitates interchange of data and comparison of data/results.

One final and very important recommendation is to visit the area with local people, if possible, before the study begins in order to gain their cooperation. Local people know the area and, more importantly, they probably understand the dangers associated with the area and how to avoid them. For example, local people will have more ideas of how to react when encountering wild animals.

Comparison with existing inventory methods

The main parameters in inventory design are plot size, tree diameter cut-off (minimum diameter considered to include trees in the inventory), tree variables measured and additional variables measured such as soil nutrients, environmental conditions and inclusion of epiphytes. The choice of the characteristics included in each inventory will depend on the final aim. The inclusion of mapped trees implies a lot of effort and may not always be worthwhile. For example, Gentry, a pioneer in large tropical inventories, used 0.1-ha plots in transects (Gentry 1988). His main aim was to study diversity across a large latitudinal and altitudinal gradient. Similarly, trees were not mapped in the plots of the RAINFOR network (Lewis et al. 2013, Slik et al. 2013), which was a large-scale network for the study of species richness and biomass in the Amazon. Talbot et al. (2014) and Arellano (2013) also provided discussion on plots where the trees were not mapped. However, in some cases the use of mapped plot is required such as if the aim of the study is to develop a spatial individual based model or the study of spatial distribution of trees. The first large project in which trees are mapped is probably the Smithsonian Tropical Research Institute network (Condit 1998, Hubbell et al. 1999). Not all the initially proposed plots remain but new plots have been incorporated in recent decades, making this database an important source of information on tropical forests.

Apart from the Smithsonian Tropical Research Institute plots, several research projects have used mapped plots (Table 1). In terms of diameter cut-off, two groups of inventories can be distinguished, namely, those that use 10 cm and those that use 1 cm. In the first case, the inventory focuses on the study of large trees which form the canopy. A cut-off of 10 cm reduces inventory time drastically. In this study, about 80% of woody plants had dbh values of < 10 cm. This dbh excluded short-lived understorey species and also young individuals of canopy species. If the aim of the research is to study canopy layer, 10 cm can be used as diameter cut-off. If the aim is to study canopy-forming species as a whole, the use of 10 cm cut-off may lead to biased results. However, in this study, more than 80% of the species with dbh < 10 cm were understorey or mid-canopy species (Ledo 2012). In terms of plot size, three main groups can be distinguished, namely, 50-ha, 1-ha and 0.5-ha plots. In the smaller plots, heterogeneity gradients could

Table 1 Comparisons between tropical inventories using mapped plots, including plot size, diameter cut-off at 1.3 m height (dbh) and type of forest

Reference	Plot size (ha)	Dbh (cm)	Type of forest
Arévalo and Fernandez-Palacios (2003)	0.06	4	Cloud forest
Batista and Maguire (1998)	0.5	10	Atlantic Brazilian forest
Lawes et al. (2008)	1	10	Moist tropical forest
Li et al. (2009)	20	1	Subtropical forest
Pelissier (1998)	0.4	30	Rainforest
Condit (1998)	1 to 50	1	Rainforest, moist forest
Wiegand et al. (2007)	25	1	Rainforest
Proposed method	1	0.5	Cloud forest

not be found. Hence, we recommend using the largest plots that time and budget allow. We used three separate plots instead of one large plot in order to encompass the full heterogeneity of the forest. This would not be necessary if a 50-ha plot was available.

ACKNOWLEDGEMENTS

This research was funded through a PhD grant from the Universidad Politécnica de Madrid. The fieldwork in Peru was partially supported by the Consejo Social de la Universidad Politécnica de Madrid. WE Caba helped in the fieldwork. I wish to thank A Collins for the English language revision.

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