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Use of unmanned aerial vehicles (UAVs) for the dasometric analysis of bamboo plantations from the genus *Guadua* spp.

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ABSTRACT

Objective: bamboo is a forest resource that, due to its rapid growth, requires frequent evaluations (monitoring) to define the most appropriate management strategies; however this entails a high cost and a great investment of time. This study presents an analysis of the use of unmanned aerial vehicles (UAVs) to generate information on the crown cover of *Guadua* spp. bamboo strains, and relates it to other of its dasometric parameters.
Methodology: the areas of the bamboo strains were defined based on generated aerial images, where each strain was delimited by differentiating it from its environment, for which four types of thresholds were defined.
Results: the relationship of the crown area with each dasometric parameter suggests that there is a positive trend, where in most cases there was an adequate significance ($P<0.05$): height $R^2=0.67$ ($P=0.0222$); diameter 1.3 m $R^2=0.56$ ($P=0.0367$); culm diameter 0.3 m $R^2=0.57$ ($P=0.0313$); and number of culms $R^2=0.54$ ($P=0.130$).
Conclusions: in this way, the results showed that with the UAV it was possible to determine the coverage area of individual bamboo strains and that some of their dasometric parameters could be estimated based on their allometric relationship.

Keywords: drone, orthoimages, biomass, photogrammetry, allometric equations.

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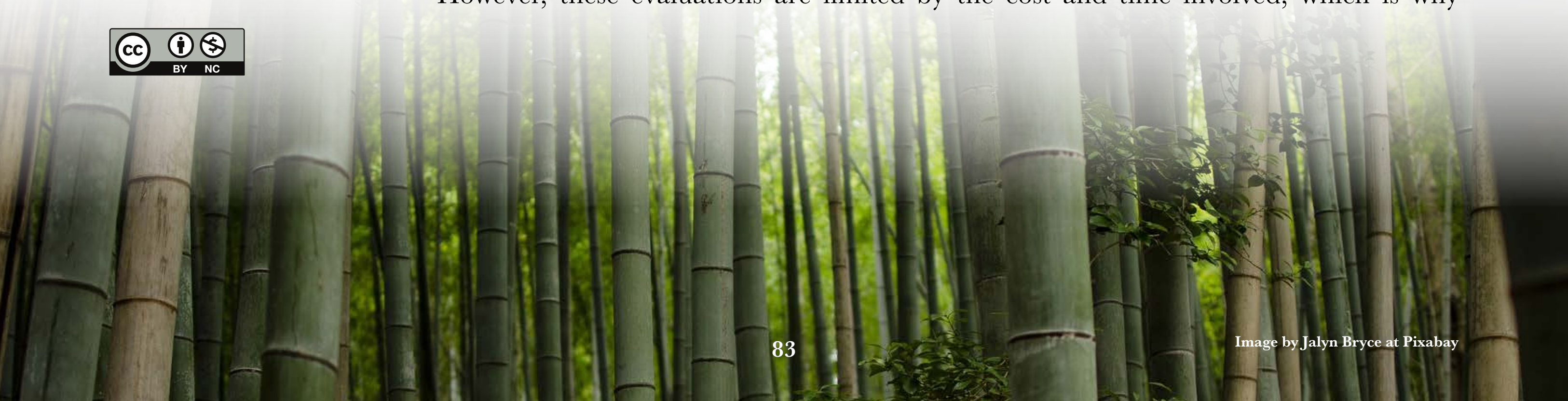
INTRODUCTION

The specific characteristics of bamboo, such as the quality of its wood and its fast growth (Ruiz-Sánchez, 2019), define it as a promisory species of high ecologic, economic and social value. Because of this, its production has been supported through commercial plantations, where its fast growth must be considered to define the most adequate management strategies, which implies conducting frequent evaluations (height, number of culms, volume, condition) of the growth dynamics (Ruíz-Sánchez *et al.*, 2015). However, these evaluations are limited by the cost and time involved, which is why



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alternatively they can be carried out remotely, through the use of satellite images (Dash *et al.*, 2018). However, they have a low resolution and lose sharpness when there is an intention to work at the level of individual strains. As an alternative, aerial photographs can be generated through the use of unmanned aerial vehicles (UAVs), at specific intervals of time and of high spatial resolution (Surový *et al.*, 2018). This way there can be a historical file of the changes in the plantation with the passing of time (Mohan *et al.*, 2017), with which its structural dynamics can be determined (Tang and Shao, 2015). The use of UAVs is complemented with field evaluations (Panagiotidis *et al.*, 2017), and allows generating information for an intensive management of the plantation. However, there is scarce information regarding bamboo. Therefore, the purpose is to evidence the use of UAVs in bamboo plantations as a practical alternative, in the management of bamboo plantations. This is illustrated with information generated in a commercial bamboo plantation located in the state of Colima, Mexico.

MATERIALS AND METHODS

Study area

An experimental bamboo plantation was evaluated (10,000 m^2), which is located in the state of Colima, Mexico: 18° 57' 56" N, 103° 50' 18" W, at an altitude of 40 m. The climate in this region is warm sub-humid, with mean annual temperature of 26 °C, and mean annual precipitation of 690 mm. The bamboo plantation is two years old and made up by 210 plants of four species of bamboo: *Guadua aculeata* Rupr. ex E. Fourn., *Guadua inermis* Rupr. ex E. Fourn., *Guadua amplexifolia* J. Presl and *Guadua angustifolia* Kunth.

Generation of orthoimage

The aerial images, required to generate the orthoimage, were taken using a multirotor DJI Phantom 4 Pro UAV, with a CMOS sensor of 20M pixels and a RGB chamber. Programming the flight with this device was done through the DJI Go™ Pro software. The frontal superposition between the images was established in 80%, while the lateral superposition was of 70%, for which the Pix4D Capture software was used.

Delimitation of individual strains

Each of the georeferenced bamboo strains was associated with the field measurements: a) number of culms; b) basal diameter (cm), taken at 30 cm of height; c) normal diameter (cm), taken at 1.30 m of height, d) height (m), e) health, and f) survival. To delimit individually each bamboo strain in the orthoimage, firstly, they were differentiated from their environment, for which the thresholds of the following coverages were defined (Li *et al.*, 2020): a) young foliage; b) mature foliage; c) soil; and d) shade. Once the coverages were located, a photographetric segmentation process was conducted (Kaartinen *et al.*, 2012) to define the limits of foliage of each, with which their area could be calculated (m^2).

Allometric equations

With the integration of field information and information that can be generated with the UAV, the study sought to estimate parameters which are difficult to measure with simpler estimation variables (Dong *et al.*, 2020). The corresponding allometric equations were generated, where the area of each strain (obtained with the UAV) was correlated with each of its dasometric parameters (number of culms, basal diameter, normal diameter and height). Finally, an estimation table was generated, where specific area classes are related with the dasometric parameters.

RESULTS AND DISCUSSION

Dasometric characterization

The average number of culms was 16, where the largest population was between 10 and 20 culms (6,000 culms/ha) (Figure 1). These results agree with those obtained for *G. angustifolia*, with densities between 3,000 and 8,000 culms/ha (Londoño, 1998). However, other species of woody bamboo, such as *Bambusa oldhamii* Munro (Castañeda *et al.*, 2005) and *G. angustifolia* (Camargo, 2014), report higher densities (between 5,000 and 11,000 culms/ha approximately), which can be due to various factors, such as their adaptability, growth speed, type of growth, maturity, environmental conditions, etc.

In general, the dasometric characteristics of the strains indicate that it is a heterogeneous plantation. However, in the case of the basal diameter at 30 cm (DC), there is a slight dominance of the category of 2.4 cm, with a range found of 0.28 to 3.43 cm, while for the diameter at 1.30 cm of height (DAP) the class of 2 cm predominates slightly, within a range from 0 to 2.86 cm. This implies that the basal part is slightly thicker and denser than the rest of the stem, which is adequate for construction purposes, as is the case of the wood of *G. angustifolia*, since it tends to be a natural cylindrical element (Sánchez-Medrano *et al.*, 2016). In this regard, Camargo (2014) informed about similar values in the increase in average DAP of 5.1 (±1.7) cm, at seven years since establishment in *G. angustifolia* plantations in Colombia. However, the dimensions in diameter were smaller (up to 50%) than those found in guadales in Colombia (Camargo, 2014); this indicates that the plants have still not reached their maximum growth, as cited by Castañeda-Mendoza *et al.* (2005) and Daquinta *et al.* (2007). In terms of height, two classes dominate (1.5 and 3.5 cm), within a range that goes from 0.72 to 4.9 m. This variation of heights is because the young bamboo strains (1 to 7 years of age) still have not reached the maximum height or their maximum growth potential. Carmargo (2014) mentions that species of the genus *Guadua* reach 25-30 m of height in 5 or 6 months in strains older than 7 years.

Information system of the plantation

From the incorporation of all the information of the bamboo plantation that was taken in the field, a specific geographic information system was structured, where each of the strains was georeferenced in relation to the orthoimage of the bamboo plantation. Therefore, given that the location of each of the strains refers to an exclusive number of registry, this allows managing the information referred to the dynamics of each strain where, for example, the following is known: their location (coordinates), number of culms, height, stem diameter, crown diameter, among other factors, which can be aggregated to the system. Specific data of each strain can also be analyzed through the application, for

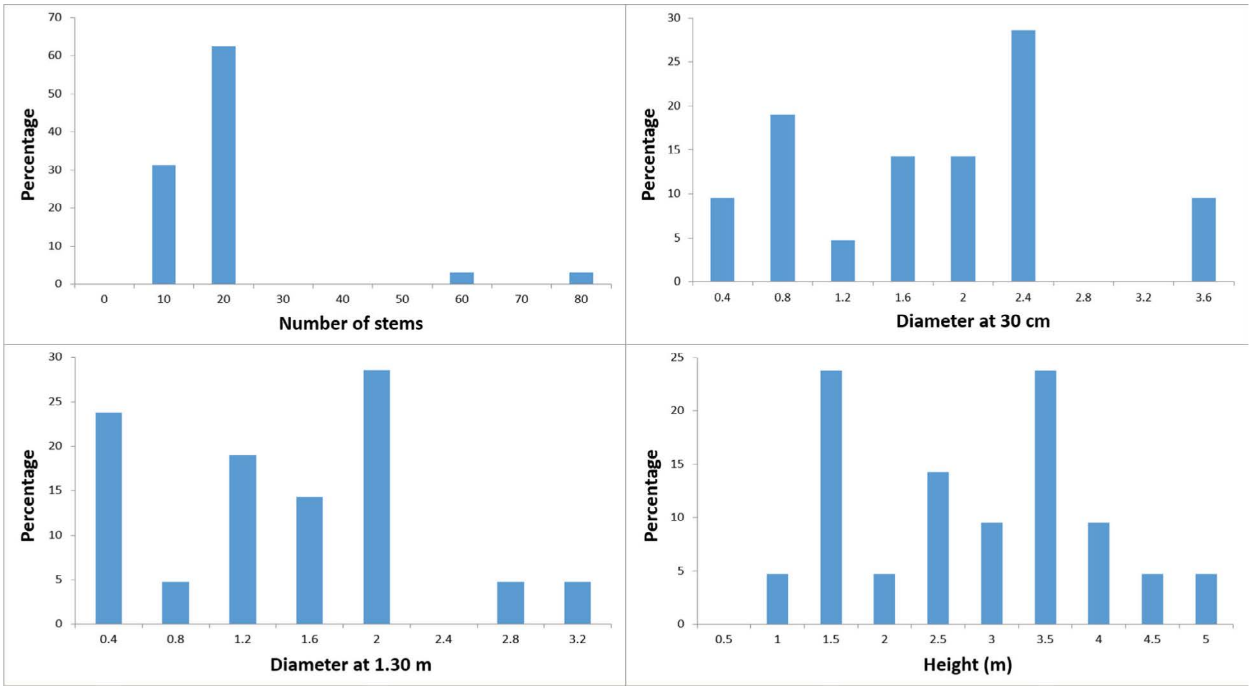

Figure 1. Percentage of dasometric parameters of the bamboo plantation in the Experimental Field in Tecomán, Colima.

example, of a filter per height, which allows graphically locating the place where strains of a certain range of height are found.

Coverage thresholds and delimitation of bamboo strains

To delimit each of the strains, the analysis of the thresholds of the values of the spectral bands of the image allowed differentiating the following coverages (Figure 2): a) shade; b) soil; c) young foliage; and d) mature foliage. Based on this, binary images were generated for each of these coverages (Dong *et al.*, 2020), where, for the case of the bamboo strain, the images corresponding to young foliage and mature foliage were integrated.

Delimitation of bamboo strains

In the photogrammetric segmentation process (Figure 3), it is observed that, in general, the individual outline of the strains is well-defined. Some external portions of young foliage can also be seen, which can be confused with the soil coverage, since the latter considered some zones with herbs. Although it was possible to have better detection in the areas of young bamboo, it was difficult to detect very small bamboo strains. This is important since the ideal composition of a strain in a plantation of *G. angustifolia* must be considered to be 10% of new shoots, 30% of new culms, 60% of mature culms, and to avoid having over-mature culms (Londoño, 1998). This cannot be appreciated only with information from the foliage, as is the case of this study, so better results would be expected in the delimitation of the strains when the plantation has reached maturity (5-7 years).

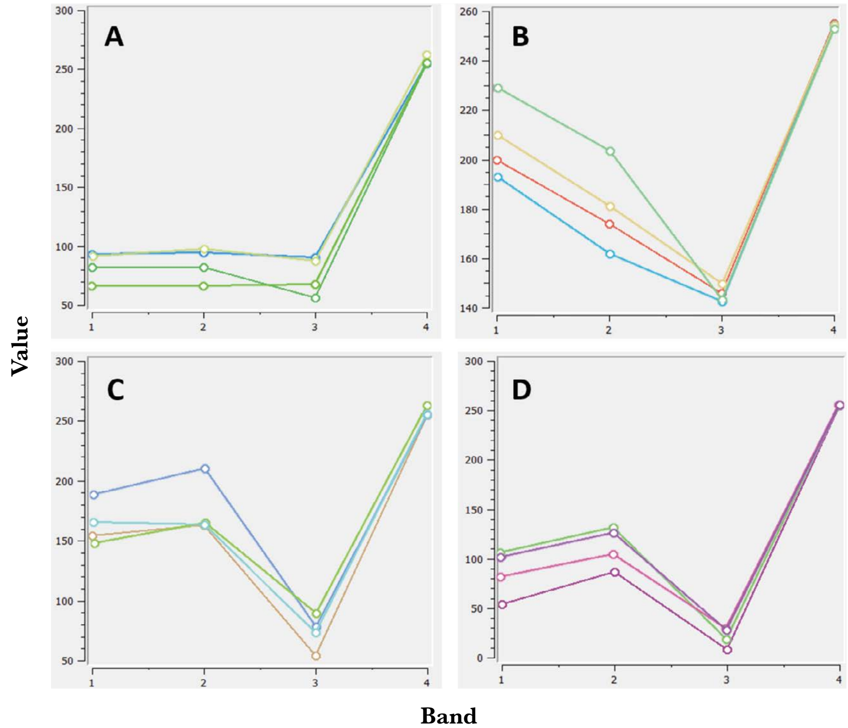

Figure 2. Thresholds of the values of the bands of the orthoimage, corresponding to: A=Shade; B=Soil; C=Young foliage; and D=Mature foliage.

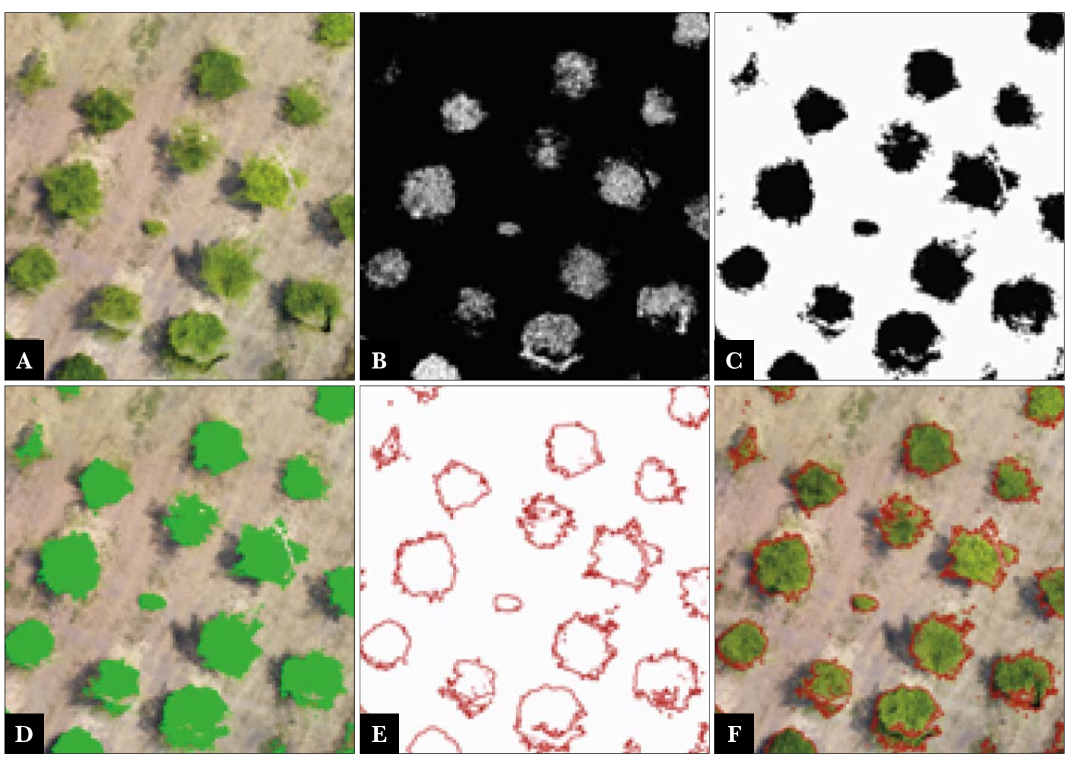

Figure 3. Photogrammetric process to delimit the bamboo strains: A=Orthoimage; B=Image of a band; C=Binary image; D=Area of softened strains; E=Delimitation of bamboo strains; and F=Superposition of polygons on orthoimage.

The remote analysis of the aerial biomass of bamboo is still considered difficult, because there is still a lack of adequate comprehension of the integration mechanisms of the growth characteristics of bamboo forests and data from remote sensors (Yuyun Chen *et al.*, 2019). However, as the bamboo strains grow, the development of the density of the plantation can be monitored through the methodology proposed, in relation to the land coverage and the superposition of the crowns of the strains. Thus, the appropriate moment for the application of clearing in the plantation can be defined, from a silviculture perspective, as: a) sub-dense, when not all the space is used in the best way, leaving many empty spaces; b) over-dense, when there is a large amount of individuals in insufficient space, fostering competition over light and nutrients; and c) optimal density, where all the space of the plantation is used without exposing the trees to competition over resources. Furthermore, when understanding the coverage dynamics of the bamboo strains, through the use of UAVs, growth and yield models can be defined (Letourneau *et al.*, 2011).

Allometric analysis

Figure 4 shows that there is a clear positive trend in the relationship between the area of the bamboo strains and their dasometric parameters, where the relationships of the area with height and diameter at 30 cm were the ones that showed lower variability, grouped more towards the line of defined trends. On the other hand, the relationship with the diameter at 1.30 m was the one that presented the greatest data dispersion.

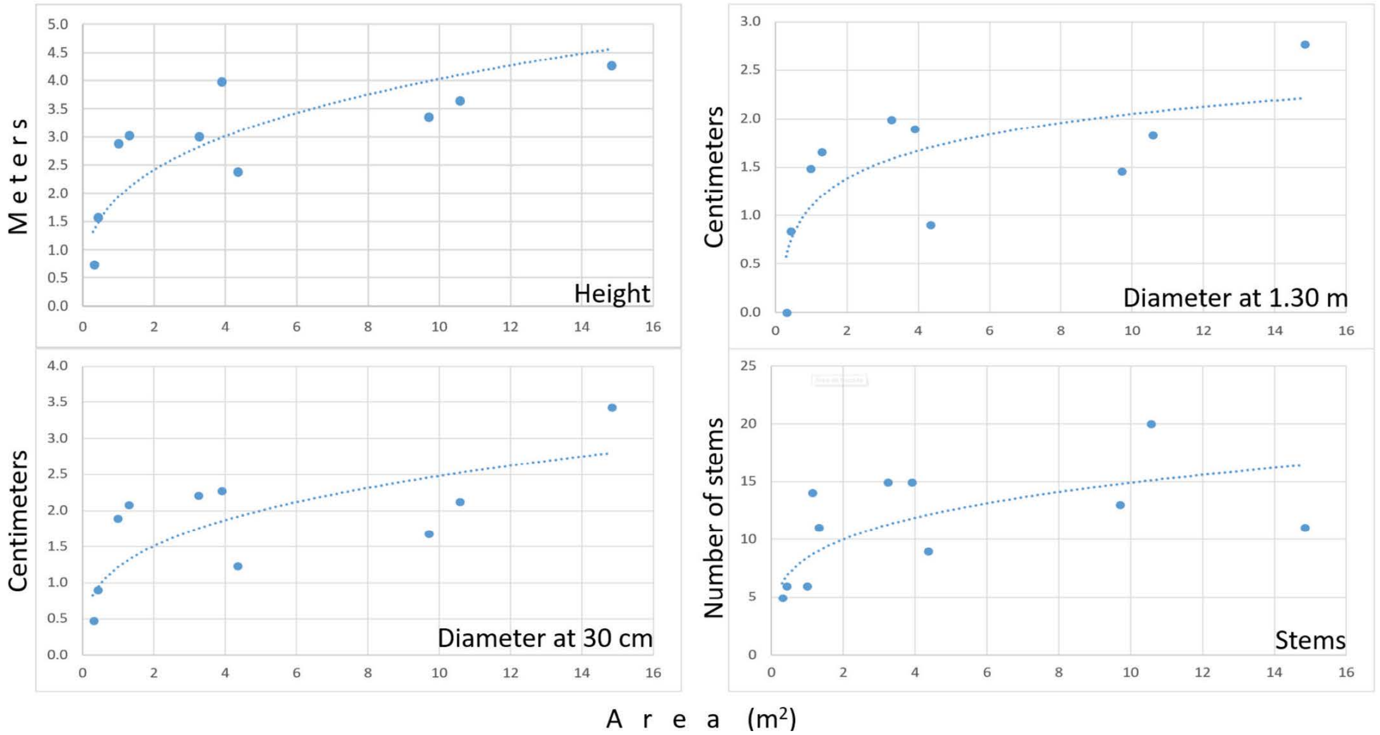

Figure 4. Trend of the relationship of areas of strains with several dasometric parameters.

The allometric equations corresponding to these trends are shown in Table 1, where the exponential models prevail, with the exception of the relationship of the area with diameter at 1.30 m, whose best adjustment was defined with a logarithmic model. On the other hand, the determination of the model's adjustment to estimate the dasometric parameters and the proportion of the variation of the results defined by the model, was rather low. However, the models were significant (p-value), with the exception of the model that estimates the number of stems, which implies that there is a significant relationship between the coverage area of the strain with the dasometric variables.

Estimation rate

As a result of the application of allometric equations, Table 2 shows a table for the estimation of the dasometric parameters. Based on this rate, it is enough to understand the area (m^2) of coverage of a bamboo strain, to be able to estimate, for example, the height or the diameter at 1.30 m. Therefore, the sum of the values of the individual strains allows making estimations of the productivity of the entire plantation, in a more practical way. However, it must be considered that because *Guadua* spp. presents an open sympodial rhizome growth, the use of allometric models generated in this study is restricted to this genus.

Table 1. Allometric equations for the estimation of parameters of *Guadua* spp. bamboo strains, in relation to their coverage area.

Variable	Equation	R^2	p-value
Height	$=1.94 * (Area^{0.317})$	0.67	0.0222
DAP	$=0.4146 * (\ln(Area)) + 1.0949$	0.56	0.0367
DC	$=1.2188 * (Area^{0.3085})$	0.57	0.0313
NC	$=8.4308 * (Area^{0.2471})$	0.54	0.1301

NC=Number of stems; DC=Diameter of stem at 30 cm; DAP=Diameter at 1.30 m.

Table 2. Estimation rate of dasometric parameters of bamboo strains, based on the coverage area.

Area (m^2)	Height (m)	DAP (cm)	DC (cm)	NC
1	1.940	1.095	1.219	8.431
2	2.417	1.382	1.509	10.006
3	2.748	1.550	1.711	11.060
4	3.011	1.670	1.869	11.875
5	3.231	1.762	2.002	12.548
6	3.424	1.838	2.118	13.127
7	3.595	1.902	2.221	13.636
8	3.750	1.957	2.315	14.094
9	3.893	2.006	2.401	14.510
10	4.025	2.050	2.480	14.893

DAP=Diameter at 1.30 m; DC=Diameter at 30 cm; NC=Number of culms.

CONCLUSIONS

The results showed that it was possible to determine the coverage area of individual strains of bamboo with the technology of unmanned aerial vehicles (UAVs). The estimation of dasometric parameters of bamboo strains is possible based on the allometric relationship with the area of crown coverage of these strains. The use of UAVs facilitates the capture of aerial images, of quality for the tridimensional digitalization of forest plantations. Through the use of a geographic information system, it is possible to associate forest parameters of the tree cover taken in the field with the georeferenced location of the existing and eliminated tree coverage. Processes were defined in a geographic information system to locate bamboo strains in a plantation, based on specific criteria, as for example: species, condition, area, height, number of stems, diameter, as well as combinations between these criteria. The use of UAV technology facilitates evaluation work and monitoring of the bamboo plantation, since it can help to keep a historical record of its condition, which can be consulted without the need to return to the site in the field.

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