DEFINING GROWTH AND QUALITY OF GUADUA BAMBOO CULMS: A CASE STUDY OF GUADUA BAMBOO FORESTS, COLOMBIA

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CAMARGO GARCÍA JC. 2014. Defining growth and quality of guadua bamboo culms: a case study of guadua bamboo forests, Colombia. Guadua (*Guadua angustifolia*) is a bamboo species distributed in north-western South America. In Colombia, it is utilised in construction, handicrafts and flooring. Guadua stands also represent remnants of forest and habitat for animals. Therefore, these forests may provide economical benefits and ecological functions. Attributes of guadua culms were considered as a criterion for managing and harvesting and ultimately for selecting proper raw material. In this study, information on dendrometrics variables as well as physical and mechanical properties of culms was collected from an inventory. Multivariate analyses were performed in order to elucidate factors which properly described the attributes of culms and stands. These factors are useful because they may depict different variables and permit qualifying culms and stands throughout one value. As a result, for guadua culms, two factors were defined which represented growth and quality. For guadua stands, three factors which characterised growth stock, dynamics and quality were determined. These factors eased the process of qualifying culms and stands. Therefore, it might be significant to improve the planning of guadua stands and allow for making decisions on managing these forests in Colombia.

Keywords: Factor analyses, *Guadua angustifolia*, dendrometrics variables, stand variables, physical and mechanical properties

INTRODUCTION

Bamboo is a multipurpose and widely used renewable resource. Particularly in Asia, bamboo is a source of material for construction, tools and implements for agriculture, pulp for paper, handicrafts and is also used for soil conservation (Banik 1999). Bamboo is also popular because its shoots are edible (Razak 2001).

Bamboo species also provide raw material for a wide range of industries. In India, the industry supplied income to 0.5 million people, most of whom were employed in small-scale processing enterprises (Hanumappa 1996).

The bamboo species *Guadua angustifolia* (guadua) is a woody bamboo. In Colombia, especially in the coffee region, it represents an important natural resource, traditionally being used by farmers to build houses, furniture, handicrafts, veneer and flooring (Londoño 1998). Economically, guadua forests can be important for consolidating enterprises (Held 2005), considering that markets in Europe tend to expand which can lead to more possibilities (Becker 2004) with positive effects on social development (Londoño 2009).

Gathering information incurs cost in terms of time and money. Thus, information from inventories should be optimised (Akça 2000) for making better decision on the management of guadua forests (Kleinn 2005). High profitability of guadua forests is a consequence of good forest planning and silvicultural management (Castaño 1987, Morales 2004). In this sense, additional knowledge about culms and stand characteristics is helpful for stand planning and silvicultural management (Camargo et al. 2008a, b, 2009).

According to the last inventory in the coffee region of Colombia, there were about 28,000 ha of guadua (Kleinn & Morales 2006). Its dendrometric attributes, stand variables, stand management options and productivity have been studied (Hincapie & Penagos 1994, García 2004, Morales 2004, Camargo 2006, Kleinn & Morales 2006, Camargo et al. 2007). These studies have pointed out the importance of analysing dynamics by considering an integrated approach which permits better qualification of guadua culms and guadua stand productivity.

Bamboo and tree growth patterns are completely different. Therefore, some aspects should be considered when bamboo growth is expressed through dendrometric variables (Camargo 2006). Guadua is a monocot and lacks vascular cambium. Consequently, each culm emerges with a fixed diameter and achieves final length within 6 or 7 months (Judziewicz et al. 1999). Hence, differences in culm diameter or culm length are not strongly associated with age, as in trees.

The qualification of bamboo culms is usually expressed from dendrometric variables (Camargo 2006, Rijal 2006, Schumacher 2006) as well as physical and mechanical properties (García 2004, Camargo 2006). The above two groups of variables express growth and quality. On the other hand, productivity is defined by new shoots, total number of culms, basal area and total volume (Morales 2004, Camargo 2006). Nevertheless, sometimes the definition of quality, growth or productivity cannot be represented by only one variable. It means that for guadua, a number of variables may influence growth and quality. Consequently, multivariate analyses will be useful to reduce the dimensionality of data. Thus, it is feasible to identify trends on variability of growth and quality and to elucidate groups of variables linked to changes in environmental factors (Garcia 2004, Camargo 2006, Cruz 2009).

In order to provide proper information and contribute to guadua bamboo forest management, the aim of this work was to develop factors, which could integrate a set of variables for qualifying growth, quality and productivity of guadua. The possibility of obtaining values for each culm or stand will be of advantage, especially when information on planning or harvesting is required.

MATERIALS AND METHODS

Study area and sampling

The study sites were located in the coffee region of Colombia, with a total area of 1029.5 ha and elevation between 900 and 2000 m above sea level. This vertical range corresponds to the elevation range of guadua there. Mean annual temperature is between 20 and 27 °C and precipitation, between 950 and 2500 mm per year with bimodal distribution. Most of the soils are Andisols from volcanic ashes, slightly acidic and have good physical properties such as good structural stability, high effective depth, low apparent density and high porosity (García 2004).

Systematic two-stage sampling was applied. In the first stage, the entire study area was subdivided into primary units of 10 km × 10 km. Of these primary units, 103 units were randomly selected. In the centre of each selected primary unit, a square plot of 3 km × 3 km was established on aerial photographs. In these aerial photo sample plots, all guadua stands were mapped. A total of 16 aerial photo sample plots were selected for field sampling and 101 field plots of 10 m × 10 m were randomly selected within these mapped guadua stands.

Within each 10 m × 10 m field plot, diameter at breast height (middle of the internode at breast height) of all culms was measured. Culm length was measured on three culms that were randomly selected on the plot and cut. These culms were used to calculate volume by the Smalian equation (Dieguez et al. 2003) and for measuring other culm variables. Stand variables were extrapolated from the sample plot data such as basal area (based on diameter measurement), number of culms and the quadratic mean diameter.

Following standardised methods (ISO 2004, NTC 2007), six samples corresponding to internodes above and below the middle of the culm were taken from each felled culm. Samples were used to measure shear strength τ_{ult} (N mm^{-2}) and compression strength σ_{ult} (N mm^{-2}). A total of 909 samples were tested. The basic density ρ (g cm^{-3}) was also determined from samples used in the analysis of strength variables. Culm hardness (H_{dr}) was measured using a hardness tester on 10 mature culms (5 years old), which were randomly chosen from each field plot. Measurements were done around the culm from the middle part of the internode at breast height (1.3 m).

Analyses

To define stand dynamics, growing stock and quality, a factor analysis was performed (Johnson 2000). First, factors were obtained for qualifying culms growth and quality. Thereafter, factors that described stand productivity and quality were also defined. The factor procedure (PROC FACTOR) for factor analysis of the SAS/STAT® statistical program was used. The definition of factors was done according to chi-square test, value of root mean square off-diagonal residuals and eigenvalues of each factor (Johnson 2000).

RESULTS AND DISCUSSION

Qualification of culm growth and culm quality

After performing the PROC FACTOR, the multivariate test of chi-square showed that at least one factor was common ($p < 0.0001$). Therefore, factor analysis was a suitable approach. In this sense, two factors were sufficient (chi-square: $p = 0.091$; value of root mean square off-diagonal residuals: 0.0341 and eigenvalues of 8.8 and 5.7 respectively) (results not shown). The original variables and rotated axes of the factors were highly correlated. Thus, Factor 1 showed a larger load of dendrometric culm variables and Factor 2 exhibited a larger load of physico–mechanical variables. Thus, Factor 1 could describe culm growth, whereas Factor 2 represented culm quality (Table 1).

Studies have shown how groups of variables are related to growth and strength (physical and mechanical properties) of culms (García 2004, Camargo et al. 2007). However, these grouping are related to areas spatially defined, where site conditions may have significant effect on dendrometric and physico–mechanical variables of guadua culms. Therefore, high variability of culms features is associated with site conditions and the possibility of qualifying culms through a value which represents a set of features is really useful.

Each factor can be calculated and expressed through a value. Therefore, culms can be qualified in terms of growth and quality. The calculation is possible using the standardised scoring coefficients multiplied by the standardised value of each variable (Johnson 2000). Standardised scoring coefficient for calculating factors are shown in Table 2.

The standardised value for each variable is defined as follows:

$$Z_{rj} = \frac{x_{rj} - \hat{\mu}_j}{\sqrt{\hat{\sigma}_{jj}}}$$

Table 1 Correlations between original variables and rotated axes of the factors

Variable	Culm growth (Factor 1)	Culm quality (Factor 2)
Diameter dbhi	**0.913**	0.0008
Wall thickness	**0.796**	0.2120
Culm length	**0.751**	-0.0413
Compression strength	0.074	**0.9176**
Culm hardness	0.119	**0.3870**
Basic density	-0.140	**0.3756**
Shear strength	-0.201	-0.2160

dbhi = Diameter measured at the middle of the internode at breast height

Table 2 Standardised scoring coefficients for culm growth (Factor 1) and culm quality (Factor 2)

Variable	Culm growth (Factor 1)	Culm quality (Factor 2)
Diameter dbhi	0.590	-0.080
Wall thickness	0.256	0.058
Culm length	0.187	-0.039
Compression strength	-0.036	0.852
Culm hardness	0.0084	0.064
Basic density	-0.0245	0.066
Shear strength	-0.020	-0.030

Dbhi = Diameter measured at the middle of the internode at breast height where Z_{rj} = standardised value of the j-th variable for the r-th culm, x_{rj} = observed value, $\hat{\mu}_j$ = estimated mean value of the respective variable x and $\hat{\sigma}_{jj}$ = standard deviation. Thus, the values of the factors for individual culms may be calculated as

$$\text{Growth} = 0.590Z_d + 0.256Z_t + 0.187Z_h - 0.036Z\sigma_{ult} \ \ldots - 0.020Z\tau_{ult}$$

$$\text{Quality} = -0.080Z_d + 0.058Z_t - 0.039Z_h + 0.852Z\sigma_{ult} \ \ldots - 0.030Z\tau_{ult}$$

After calculating Factors, the growth value was between 2.5 and -1.7 and the quality value, between 3.6 and -1.8. High values represented culms with excellent development or good quality. On the contrary, low or negative values represented poor growth and/or bad quality. However, a factor value is neither dimensional nor comparable with other individual values of growth or quality variables. Comparisons should be done only between factor values.

Qualification of growth, dynamics and quality of guadua stands

In order to develop factors which described characteristics of guadua stands, variables included were those describing the average of stands (i.e. the average of total culms per ha, average diameter of culms, etc). The statistics used for obtaining a factor from stand variables suggested that at least one factor was common (chi-square test for multivariate data = $p < 0.0001$, root mean square off-diagonal residual = 0.09597) and consequently the factor analysis was appropriate. The eigenvalues for the first, second and third factors with eight variables included were 12.3, 3.4 and 2.3 respectively

According to the correlation between the factors and the original variables, Factor 1 showed the strongest correlations with variables that expressed stand growing stock such as average on the internode at breast height (about 1.3 m) and average culm length (Table 3). Basal area might also be important, although the correlation observed here was weak. Factor 2 could be interpreted as an expression of stand dynamics and exhibited strong correlation with harvest intensity, percentage of shoots and percentage of young culms. The negative correlation observed between the percentages of dry and/or damaged culms with Factor 2 is also important as it shows that these variables are affected in an opposite manner under conditions which favour the development of shoots and young culms. Factor 3 had stronger correlations with physical and mechanical properties, especially with average compression strength. Thus, this factor may be interpreted as an expression of stand quality or stand culm quality per stand.

Table 3 Correlations between original variables and rotated axes of factors that express growing stock (Factor 1), stand dynamics (Factor 2) and stand quality (Factor 3)

Variable	Factor 1	Factor 2	Factor 3
Average culm diameter	**0.929**	0.147	-0.164
Average culm length	**0.764**	-0.101	-0.0291
Basal area	**0.383**	-0.139	0.140
Harvest intensity	0.052	**0.690**	-0.150
Percentage of shoot	-0.046	**0.494**	-0.426
Percentage of young culm	-0.0750	**0.447**	0.266
Percentage of damaged culm	0.143	**-0.561**	-0.027
Percentage of dry culm	-0.050	**-0.645**	0.075
Average compression strength	-0.028	0.190	**0.682**
Average hardness	0.145	-0.145	**0.586**
Average basic density	-0.178	-0.199	**0.383**
Average shear strength	-0.425	-0.085	**-0.456**

The variables include factors which represent stand dynamics, growing stock and stand quality have also been identified after cluster analyses as those with higher influence on this classification (García 2004, Camargo 2006) and have also shown high variability within stands under silvicultural management (Morales 2004, Camargo 2006, Camargo et al. 2009).

Values of factors growing stock, stand dynamics and stand quality were also calculated by multiplying the coefficient (Table 4) by the standardised value (Z) of each variable (Johnson 2000).

The factor values for an individual stand were calculated as follows:

$$\text{Growing stock} = 0.789Z_{(\text{average culm diameter})} + 0.158Z_{(\text{average culm length})} + 0.047Z_{(\text{basal area})} - 0.027Z_{(\text{harvest intensity})} \ldots\ldots - 0.075Z_{(\text{average shear strength})}$$

$$\text{Dynamics} = 0.126Z_{(\text{average culm diameter})} - 0.101Z_{(\text{average culm length})} + 0.045Z_{(\text{basal area})} + 0.323Z_{(\text{harvest intensity})} + 0.185Z_{(\text{percentage of shoots})} \ldots - 0.046Z_{(\text{average shear strength})}$$

$$\text{Quality} = -0.174Z_{(\text{average culm diameter})} + 0.022Z_{(\text{average culm length})} + 0.054Z_{(\text{basal area})}\ 0.031Z_{(\text{harvest intensity})} \ldots\ldots - 0.233Z_{(\text{average shear strength})}$$

Values for the growing stock factor varied between -1.84 and 2.7 whereas for stand dynamics, between -2.80 and 2.25, and between -1.57 and 2.062 for the stand quality factor (results not shown). High values for each factor may represent better conditions of stand productivity, stand dynamics and stand quality. Interpretations of factors and subsequent suggestions about subjacent variables that these may represent have been done based on the mean of variables used to calculate these factors (growth, stand and quality variables). These interpretations were carried out in an attempt to be coherent with the different aspects that might characterise guadua stands. The subjacent factors obtained measured unique and independent characteristics of the population from which the sample was taken (Johnson 2000). Consequently, the factors obtained in this study should only be used to describe the characteristics of sampled *G. angustifolia* stands. However, this approach may be employed for other bamboo species including the same variables although with their specific range of values.

For a better description of guadua stands using the new factors obtained here, it is important to incorporate all factors and not each one independently because the solution proposed is for all factors. In addition, it is important to note that the variables included in the multivariate analyses also represent a number of important stand characteristics that should be individually analysed before interpreting them as a group such as those obtained from the multivariate analyses.

Table 4 Standardised scoring coefficients for factors: growing stock (Factor 1), stand dynamics (Factor 2) and stand quality (Factor 3)

Variable	Factor 1	Factor 2	Factor 3
Average culm diameter	0.789	0.126	-0.174
Average culm length	0.158	-0.101	0.022
Basal area	0.047	-0.045	0.054
Harvest intensity	-0.027	0.323	-0.031
Percentage of shoot	-0.044	0.185	-0.177
Percentage of young culm	-0.011	0.165	0.121
Percentage of damaged culm	0.033	-0.211	-0.035
Percentage of dry culm	0.019	-0.265	-0.005
Average compression strength	0.024	0.142	0.392
Average hardness	0.050	-0.028	0.262
Average basic density	-0.0004	-0.039	0.120
Average shear strength	-0.075	-0.046	-0.233

CONCLUSIONS

Although guadua culms and stands could be characterised by individual variables, the factors developed in the present study might be used as an overall measurement to obtain integrated information about the culm condition. Factors that described the growing stock, stand dynamics and stand quality were helpful in the assessment of guadua stand conditions. Therefore, this may be a useful tool for planning silvicultural and management practices in guadua bamboo forests.

The multivariate analyses carried out in this study provided an important approach for reducing data dimensionality and also for providing information about groups of variables which described a specific condition. Considering the complexity of guadua stands associated with their growth, stand dynamics and the number of variables required to qualify culms, factors are an important tool for foresters responsible for the management of this natural resource.

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