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Effects of Forest Stand Structure in Biomass and Carbon

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Abstract

Biomass has been gaining an increased interest due to its importance in sustainable forest management and in carbon sequestration. Biomass in each forest stand varies according to its structure and influences not only the biomass per area unit but also its distribution in space and time. The structure analysis with absolute stand density measures and structure and diversity measures and indices for the number of trees and basal area does not always reflect the above-ground biomass distribution and variability. The use of above-ground biomass as an absolute density measure and the development of diversity measures and indices derived from it enable further details in the stand structure characterisation. The results of this study highlighted the differences between pure even-aged, pure multiaged, mixed even-aged and mixed multiaged structures. The measures and indices of above-ground biomass are considered primordial as they integrate the horizontal and the vertical distribution, thus enabling a more detailed evaluation of biomass and carbon stocks.

Keywords: stand structure, biomass, density measures, structure and diversity indices

1. Introduction

Forest stands provide a wide range of products and services, from timber and other woody and nonwoody products to services [1, 2]. Traditionally, forest inventories evaluated forest area, crown cover, tree species, number of trees, diameter at breast height and total height [3–6]. National Forest Inventories started to evaluate biomass from the late twentieth century onwards in order to assess wood for timber and bioenergy, carbon stocks and carbon

sequestration and losses [7–12]. Biomass is frequently estimated with indirect methods using tree-level species-specific and site-specific allometric functions [13–28].

The analysis of structure of any forest stand is described in almost all silviculture text books [29–36]. It is a useful tool for stand management, whether they are managed for products or services, as well as for describing the stand or the ecosystem conditions in a long-term monitoring, and for the silvicultural and management practices [33, 36–40]. In any forest system, stand structure is a primordial notion that refers to suite of patterns and interactions between the individuals in a stand. The stand structure can be a result of a planned design or a self-organisation process. In a stand the ongoing processes determine the spatial pattern of the system and thus their structure, but the system properties are also determined by its structure. For example, the spatial arrangement and the tree dimensions in a stand determine their structure in a point in time, but a disturbance either natural (e.g. windstorm or fire) or artificial (e.g. silvicultural practices) determines the future processes and thus the future structure. The variability of stand structure is wide and influences growth, mortality, silvicultural practices, harvests and regeneration, which in turn determine their structure [33–36]. Stand structure is also linked to some heterogeneity, which is associated to diversity, related not only to the number and proportion of species but also to the variability of the tree dimensions and their spatial arrangements [41]. The different stand structures bring to light the variability of the interactions between the trees in a stand. The interactions that occur between a reference tree and its neighbours will define its available growing space and therefore the competition which is also reflected in its growth and consequently biomass and carbon sequestration [33, 41]. Above-ground biomass is frequently used as a proxy to evaluate the carbon stocks [42]. Therefore, to compare stands or to highlight their dynamics, stand structure analysis makes the bridge between the individual tree interactions and the stand.

Stand structure can be described as the spatial and temporal distribution of the trees and other species [33] and encompasses both the horizontal and vertical distributions [9, 33, 35, 43]. It is classified in most silviculture text books [29–36] in two classes: even-aged and multi-aged or uneven-aged. Between two extremes, stands with all the trees with the same age and stands with trees of all ages, a wide range of combinations can be found, hence originating many different stand structures. The variability increases from pure even-aged to mixed multiaged stands, thus enhancing the importance of characterising and analysing structure to evaluate the stands in a point in time, to study their dynamics, to model them or to implement management practices [29–36, 43, 44]. Several methods have been developed and used to describe stand structure, which include tree size distributions, density measures, structure indices and diversity indices. They serve as guides for forest management [29–36, 43].

Structure analysis is frequently done with the number of trees, diameter at breast height, basal area, tree height and number of species. The use of above-ground biomass is not frequent. This study will use absolute density and structure and diversity measures and indices, defined as the function of the former dendrometric variables and those defined as the function of above-ground biomass to evaluate different stand structures. The specific objectives include the analysis of the variability of stand structure between pure and mixed and even-aged and multiaged stands.

2. Materials and methods

A suite of plots that cover a wide range of forest areas and species in Portugal (from north to south) were selected. The plot locations are Mora (central coordinate 8°4'53.98"W and 38°51'16.12"N) of pure *Quercus rotundifolia*, pure *Quercus suber* and mixed *Quercus rotundifolia* and *Quercus suber*; Alcácer do Sal (central coordinate 8°40'28.20"W and 38°27'45.71"N) of pure *Pinus pinea*, pure *Quercus suber* and mixed *Quercus suber* and *Pinus pinea*; Pinheiro da Cruz (central coordinate 38°16'56" N and 8°45'19" W) of pure *Pinus pinaster*; Lousã (central coordinate 40°04'57" N and 8°14'57" W) of pure *Pinus pinaster* and mixed *Pinus pinaster*, *Castanea sativa* and *Quercus robur*; Arcos de Valdevez (central coordinate 41°49'52" N and 8°29'38" W) of mixed *Quercus robur*, *Quercus rubra* and *Betula celtiberica*; Montargil (central coordinate 39°07'08" N and 8°08'49" W) of pure *Quercus suber*; Extremoz (central coordinate 38°54'25" N and 7°37'48" W) of pure *Quercus suber*; Chamusca (central coordinate 39°21'19" N and 8°26'05" W) of pure *Quercus suber*; Coruche (central coordinate 39°06'27" N and 8°21'48" W) of mixed *Quercus suber* and *Pinus pinea* and mixed *Quercus suber*, *Pinus pinea* and *Pinus pinaster*. In the plots of Lousã, several other species were present in a very small number of individuals. The analysis of these plots will be focused in three main species, and all the other species in the plot were grouped in one class, as suggested by [45] since class bias could arise in the results, especially in the diversity indices. The plots used are pure even-aged (53), pure multi-aged (129), mixed even-aged (20) and mixed multiaged (53) in a total of 255 plots. These set of plots was selected to enable the characterisation of different aspects of stand structure, in particular above-ground biomass. The diameter at breast height, total height and four crown radii (north, south, east and west) as well as recorded the species, for all with diameter at breast height ≥ 5 cm. The classification of the plots as pure or mixed was done using the four criteria classification [46] and as even-aged or multiaged using the diameter distributions with 2.5 cm classes [29, 31, 32, 34–36]. Above-ground biomass was calculated per species and per tree with the allometric functions at the tree level (**Table 1**).

It is not possible to describe stand structure with only one criterion; inversely, the combination of several criteria is needed. The stand structure has to be described with the characterisation of the spatial distribution, both horizontal and vertical, of the trees with their dendrometric parameters. From the latter, the use of the number of trees, the diameter at breast height and the total height are frequent. Less commonly used are the height of the beginning of the crown, the crown radii and the tree locations is frequent [29–36, 41, 43]. Seldom biomass is used [9].

The measures to analyse stand structure can be divided in three groups: (i) density measures, (ii) structure indices and (iii) diversity measures and indices. In even-aged stand structure, characterisation can be done using the first two groups, while for mixed stands, diversity measures and indices should be included as the former are not able to fully characterise it.

Density measures are stand-level parameters which are a proxy for competition between individual trees and growing space allocated to each tree. The *absolute stand density measures* are a unique measure for a stand usually obtained as the count, sum or average of a dendrometric parameter, frequently calculated for a standard area, typically the hectare.

Quercus rotundifolia and *Quercus suber* [20]

$$ww = 0.164185 \times d^{2.011002}$$

$$wb = 0.600169 \times d^{1.355957}$$

$$wc = 1.909152 \times d^{1.200354}$$

$$W = ww + wb + wc$$

Pinus pinea [22]

$$ww = 18.85 \times c^{1.68} \times h^{0.95}$$

$$wbr = 184.94 \times c^{3.03}$$

$$wl = 22.27 \times c^{1.76} \times \left(\frac{h}{d}\right)^{-0.5}$$

$$wb = 8.08 \times c^{1.55} \times h^{0.47}$$

$$W = ww + wbr + wl + wb$$

Quercus robur, *Quercus rubra* and *Betula celtiberica* [48]

$$ww = e^{(-3.323 + (0.950 \times \ln(d^2 \times h))}$$

$$wc = e^{(-14.246 + (2.248 \times \ln(d^2 \times h)) - 0.01972 \times (lc \times h))}$$

$$W = ww + wc$$

Castanea sativa [47]

$$ww = 0.02044 \times d^{1.76603} \times h^{1.16402}$$

$$wbr = 0.00440 \times d^2 \times h$$

$$wb = 0.06574 \times d^{1.84096}$$

$$W = ww + wb + wbr$$

Pinus pinaster [47]

$$ww = 0.0146 \times d^{1.94687} \times h^{1.106577}$$

$$wbr = 0.0308 \times d^{2.75761} \times \left(\frac{h}{d}\right)^{-0.39381}$$

$$wl = 0.09980 \times d^{1.39252} \times \left(\frac{h}{d}\right)^{0.71962}$$

$$W = ww + wbr + wl$$

where d is the diameter at breast height (in cm), h is the total height (in m), c is the circumference at breast height $c = (\pi \times d)/100$ (in m), lc is the crown length (in m), W is the total above-ground biomass (in kg), ww is the wood biomass (in kg), wbr is the branch biomass (in kg), wl is the leaf biomass (in kg) and wc is the crown biomass (in kg).

Table 1. Above-ground biomass allometric functions.

The most frequently used density measures are the number of trees per hectare, the basal area per hectare, the volume per hectare, crown cover and mean quadratic diameter [29–36, 43]. Of interest is also above-ground biomass, per hectare, and their mean, which are not usually used. In pure stands each absolute density measure results frequently in one value per stand. Conversely, in mixed and multiaged stands, evaluation should also be done per species and per height layer, respectively [46].

When tending a stand, there is the need to select the trees that will be maintained and removed in silvicultural practices [29, 31, 32, 34, 35] and thus to have a suite of tools for their selection. The *structure indices*, which are derived from dendrometric variables, are able to evaluate potential photosynthetic ability, potential tree growth, vigour and stability. From the indices described in literature, the most frequently used index to evaluate tree or stand stability and vigour is hd ratio [6, 36, 43, 49–52]; for the ability to withstand disturbances such as the windstorms is the linear crown ratio [4, 6, 31] and for the potential photosynthetic ability and growth rate are the crown length and the crown ratio [6, 33, 34, 36]. The tree stability and growth are usually evaluated as the function of threshold values. It should be noticed that variability is expected between tree species and between even-aged and multiaged stands. For even-aged stands, ageing and crown closure might increase instability and reduce growth

and vigour. The multiaged systems tend to have higher stability and vigour, due to their wider variability of diameter, total height and crown diameters [35, 38, 51].

The hd ratio (hd) is the relation between the tree total height and its diameter at breast height, with both variables in the same metric units [6, 29, 36, 43]. It is usually calculated per tree and at the stand level with their mean value. It allows an evaluation of the tree stability but gives also some insights to the competition pressure that the tree was subjected in the past. The higher the competition the higher hd and the lower is stability [36, 43]. This can be explained by the distribution of photoassimilates, which are allocated first to height growth and only then to diameter [33], and consequently trees under stronger competition grow more in height and less in diameter and thus will have higher slenderness [43]. There is a straight link between hd and windthrow, the higher the first the higher the probability of wind damages [33, 36, 43]. For silviculture, the definition of thresholds for tree stability is of importance. Several authors [36, 49, 51, 53, 54] report that $hd \leq 85$ indicates stable trees and stands, $hd > 85$ unstable and $hd > 100$ very unstable. Trees with $hd < 45$ correspond to trees in free growth [49]. Nonetheless, the tree stability should not be analysed separately, as it also depends on the dimension of the tree crowns and stand density. Trees with large crowns have potentially higher stability than those with smaller crowns. Dense stands of trees with small crowns are potentially more affected by disturbances due to the higher hd and smaller crowns [36]. In even-aged stands, this can originate windthrow of large forest areas [38–40]. Multiaged stands tend to have smaller hd [38, 55] due to the variability of tree height, diameter and crowns, originating potentially greater stability [43].

The linear crown diameter (lcr) is defined by the ratio between the crown diameter and the diameter at breast height, with both variables in the same metric units [4, 6, 31]. In general, lcr has the tendency to increase in time in young stands, especially before crown closure. Also, lcr depends mainly on the aerial growing space, increasing from dominated to dominant trees, and tends to diminish with crown closure, as trees continue to increase in stem diameter, but not in crown diameter due to the lateral confinement of the crowns by their neighbours [31, 33]. [31] for even-aged stands reports a lcr of about 22 for broadleaved species and 12–18 for conifers.

The crown length (lc), defined as the difference between the total height and the height of the beginning of the live crown (in m), is a proxy for the evaluation of the trees' past competition pressures. Strong competition increases the death and fall of the inferior branches, phenomena known as crown shyness [6, 34, 36]. The threshold interval of lc for trees of good growth and vigour is between $\frac{1}{3}$ and $\frac{1}{2}$ of the total height of the tree [34, 36].

The crown ratio (cr) is the percent of the crown length in relation to the total height. This index is used as a surrogate for the photosynthetic rate and is strictly related with the stand management, for example, with stem height free of branches and hd [6, 33, 34]. The threshold for vigorous growth is $cr > 30\%$ and for stability should be $cr > 50\%$ [34]. Well-balanced crowns have cr between 30 and 50% [33].

The stand structure and its complexity can be evaluated by *diversity measures* and *indices*, enabling to predict the growth and growth patterns' dynamics [33]. Frequently, one measure

or index is not able to quantify the different stand characteristics; thus, it is common to use more than one. The most frequently used measures are related to the number of species, the species proportions and their distribution, and are based on the number of trees, basal area and tree height [41, 52, 56–63]. They are selected so that the horizontal and vertical distributions are characterised. These indices are frequently applied to mixed and/or multiaged stands. The commonly used indices are species richness, relative density, relative basal area, Simpson index, Shannon and Weaver index for the horizontal distribution and A index for the vertical distribution [41, 52, 56–63]. Some can also be used in even-aged stands to evaluate the tree horizontal and vertical distribution.

Species richness (SR) refers to the number of species in a stand. The higher the number of species the richer is the stand [56, 59]. It gives insights regarding diversity, but it lacks information in what concerns the frequency of each species and/or their dimensions. Thus, stands with the same number of species are included in the same class, though they can have different proportions of species [45, 56, 59, 64, 65].

Other indices enable the heterogeneity quantification [56] through the importance of each species in the mixture; the relative density (R_N) quantifies the number of individuals of a species in relation to the total number of individuals in a stand, relative basal area (R_C) the proportion of the basal area of a species in relation to the total basal area in a stand [45, 56, 59, 64, 65] and the relative biomass (R_{AGB}) the proportion of above-ground biomass of each species in relation to the total above-ground biomass in a stand [9]. These measures can also be applied to tree dimensions, such as height layers or diameter at breast height or above-ground biomass classes.

Another two indices that characterise the heterogeneity are the Simpson index and Shannon and Weaver index. The Simpson index (D) measures the probability of two individuals belonging to the same species, assuming they were chosen randomly [56, 59]. This index varies between 0 and 1. It is 1 for stands with only one species and decreases with the increase of both the number of species and the similarity between their frequencies. Shannon and Weaver index (H) measures the probability of one individual chosen randomly to belong to a certain species. The inclusion of the Napierian logarithm in its formula results in a disproportional variation of their values, enabling larger increases for the rare species than for the abundant ones [61, 66]. This index increases with the increase of both the number of species and the equality of their frequencies [45, 61, 65–67].

The formula of Shannon and Weaver index enables its division in additive components [60, 61, 66, 68, 69]. While some authors considered diameter at breast height classes [61, 68, 69], others used basal area [60] and height [66] classes. The A index, based in Shannon and Weaver index, enables the characterisation of the vertical profile of the stand in a number of individuals. It considers the vertical profile divided in three height zones, defined as proportions of the maximum height of the stand, namely, inferior zone 0–50% of the maximum height, intermediate zone between 50 and 80% and superior zone >80%. It is 0 for pure one-layer stands and increases with the increase of the number of species and their equality per layer, reaching the higher values in mixed multiaged stands [66, 67].

Structure indices		Diversity measures and indices			
Name	Formula	Name	Formula	Name	Formula
hd ratio	$hd = \frac{h}{d}$	Species richness	$SR = \sum_{i=1}^k Sp_i$	Simpson index	$D = \sum_{i=1}^N \left(\frac{N_i(N_i-1)}{N(N-1)} \right)$
Linear crown ratio	$lcr = \frac{d_c}{d} \times 100$	Relative density	$R_N = \frac{N_i}{N} \times 100$	Shannon and Weaver index	$H = -\sum_{i=1}^k p_i \times \ln p_i$
Crown length	$lc = h - h_c$	Relative basal area	$R_G = \frac{G_i}{G} \times 100$	A index	$A = -\sum_{i=1}^k \sum_{j=1}^z p_{ij} \times \ln p_{ij}$
Crown ratio	$cr = \frac{lc}{h} \times 100$	Relative above ground biomass	$R_{AGB} = \frac{AGB_i}{AGB} \times 100$		

where d is the diameter at breast height, h the total height, lc the crown length, dc the crown diameter, h_c the height of the beginning of the life crown, Sp_i the species i , N_i the number of individuals of species i , N the total number of individuals, G_i the basal area of specie i , G the total basal area, AGB_i the above-ground biomass of species i , AGB the total above-ground biomass, p_i the probability of an individual belonging to the i th species, p_{ij} the probability of an individual belonging to the i th species and the j th height zone.

Table 2. Structure and diversity measures and indices.

For each plot the following absolute density measures were calculated: number of trees per hectare (N), basal area per hectare (G), basal area of the average tree (gm), mean quadratic diameter (dg), above-ground biomass per hectare (AGB) and its arithmetic mean ($AGBm$). Four structure and seven diversity measures and indices were used (**Table 2**). In order to better characterise above-ground biomass in the horizontal and vertical planes, Simpson, Shannon and Weaver and A indices were adapted to G and AGB , and the former two were also adapted to classes of 500 kg. The plots were grouped in four structure classes: pure even-aged (PE), pure multiaged (PM), mixed even-aged (ME) and mixed multiaged (MM). To understand better the variability between the different stand compositions, plots were grouped in the following classes: pure *Quercus rotundifolia* (QR); pure *Quercus suber* (QS); pure *Pinus pinea* (PP); pure *Pinus pinaster* (PPI); mixed *Quercus rotundifolia* and *Quercus suber* (QRS); mixed *Quercus suber* and *Pinus pinea* (SP); mixed *Quercus suber*, *Pinus pinea* and *Pinus pinaster* (SPP); mixed *Pinus pinaster*, *Castanea sativa* and *Quercus robur* (PCR); and mixed *Quercus robur*, *Quercus rubra* and *Betula celtiberica* (RRB). The comparison between the different measures and indices and between pure, mixed, even-aged and multiaged plots was carried out with non-parametric Wilcoxon test for paired and independent samples, respectively [70]. The statistical analysis was implemented in R [71].

3. Results and discussion

The absolute density measures show a wide variation, larger for N and AGB than for G for all the plots. Variability is larger in the MM, as reported by several authors [29–37]. In general it increases from the pure to the mixed and from the even-aged to the multiaged plots (**Figure 1**). Similarly, gm , dg and $AGBm$ are larger for multiaged than for even-aged plots though with less variability (**Figure 1**). Nonetheless, there are significant differences between the absolute density measures for the structure classes, except for N between ME and MM ($W = 514$, $p = 0.85$)

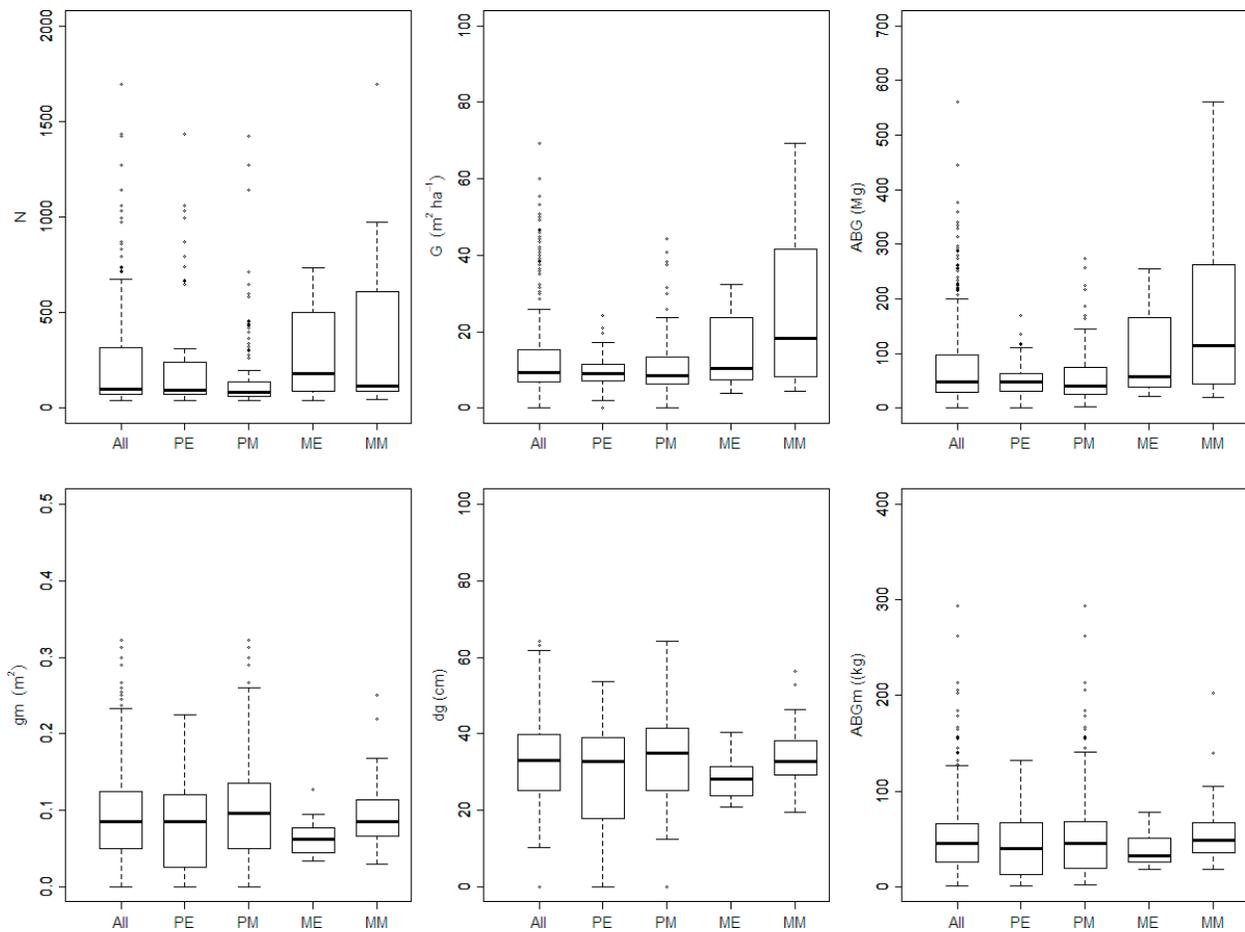


Figure 1. Boxplots of N , G , AGB , gm , dg and $AGBm$ for all plots and per structure classes.

and for G and AGB between PE and PM ($W = 3776$, $p = 0.27$; $W = 3828$, $p = 0.21$, respectively). In spite of the similar trends, there are significant differences between N and G , G and AGB and N and AGB , for all structure classes (*all*, $p < 0.001$). In fact the absolute density measures encompass different aspects of stand structure that are complementary. While N reports only to the number of individuals, G relates to their stem diameter and AGB to the relation between diameter at breast height and total height, incorporating both the horizontal and the vertical dimensions in the absolute density measure.

The lowest variability is found in the plots managed as agroforestry systems with lower N , G and AGB but larger gm , dg and $AGBm$. This is characteristic of management systems focused on stem and crown diameter growth [44] and is especially visible for PP (**Figure 2**). Inversely, the plots where management is directed towards timber production have higher N , G and AGB , but the individual trees have lower diameter at breast height and smaller $AGBm$, though considerably larger AGB (**Figure 2**). Noteworthy are QS plots that have a rather high variability. This is due to the development stage of the stands, while some are young with higher N , G and AGB and smaller gm , dg and $AGBm$; in the adult plots, the opposite is observed (**Figure 3**).

The values of hd are indicative of good stability (**Figure 4**) with most values < 80 [36, 49, 51, 53, 54]. Many plots have $hd \leq 45$ indicative of trees in free growth, which is the case of most

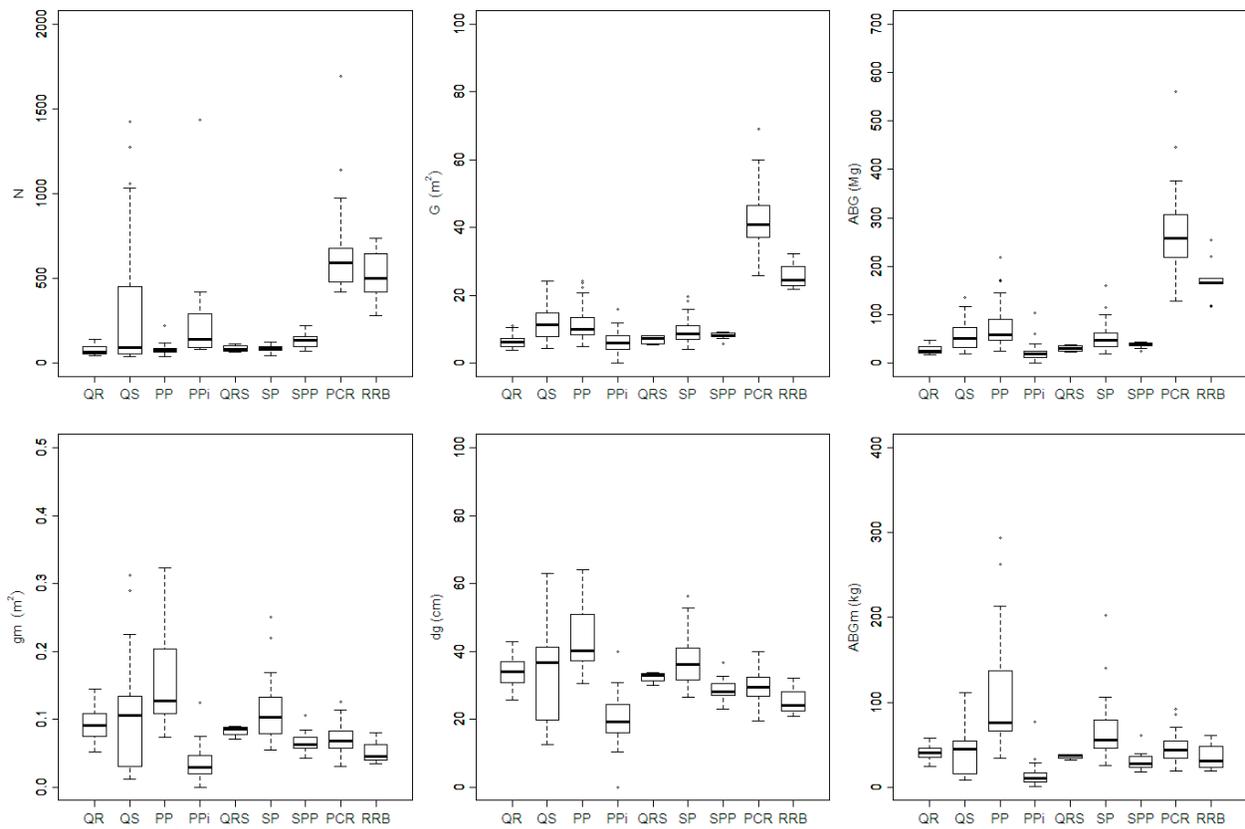


Figure 2. Boxplots of N , G , AGB , gm , dg and $AGBm$ per composition classes.

QR, QS and PP plots that are managed in agroforestry systems. The stands managed for timber PPI, PCR and RRB have higher hd (Figure 5). There is a decrease of hd from even-aged to multiaged plots [38, 43, 49, 55] and an increase from pure to mixed plots, though the latter show a wider variability (Figure 4), denoted by the significant differences between PE and ME and PM and MM (*all*, $p < 0.001$). The analysis per composition classes outlines the differences between the plots managed in agroforestry systems (QR, QS, PP, QRS, SP and QSP) and those managed for timber (PPI, PCR and RRB), with the former with $hd < 45$ indicative of many trees in free growth [49] and the latter for most trees $hd < 85$, thus indicating good tree and stand stability [36, 49, 51, 53, 54]. Another source of variability is the tree and/or stand development stage; young individuals and stands have higher hd as a result of the high growth rates in height and low in stem diameter [54].

For all plots and per structure classes, lcr is larger than the inferior threshold [31], though with larger variability for MM (Figure 4), denoted by the significant differences between PE and ME and PM and MM (*all*, $p < 0.001$). Conversely, no significant differences were found between PE and PM ($W = 3402$, $p = 0.96$) and ME and MM ($W = 659$, $p = 0.11$). In the multiaged structures, as trees develop their crowns in different height layers, crown horizontal confinement is not as strong as in the even-aged ones; thus, the crown lateral growth still continues in the former opposite to what happens when crown closure occurs in the latter [33, 35]. The analysis per composition classes (Figure 5) shows larger variability for the plots managed for

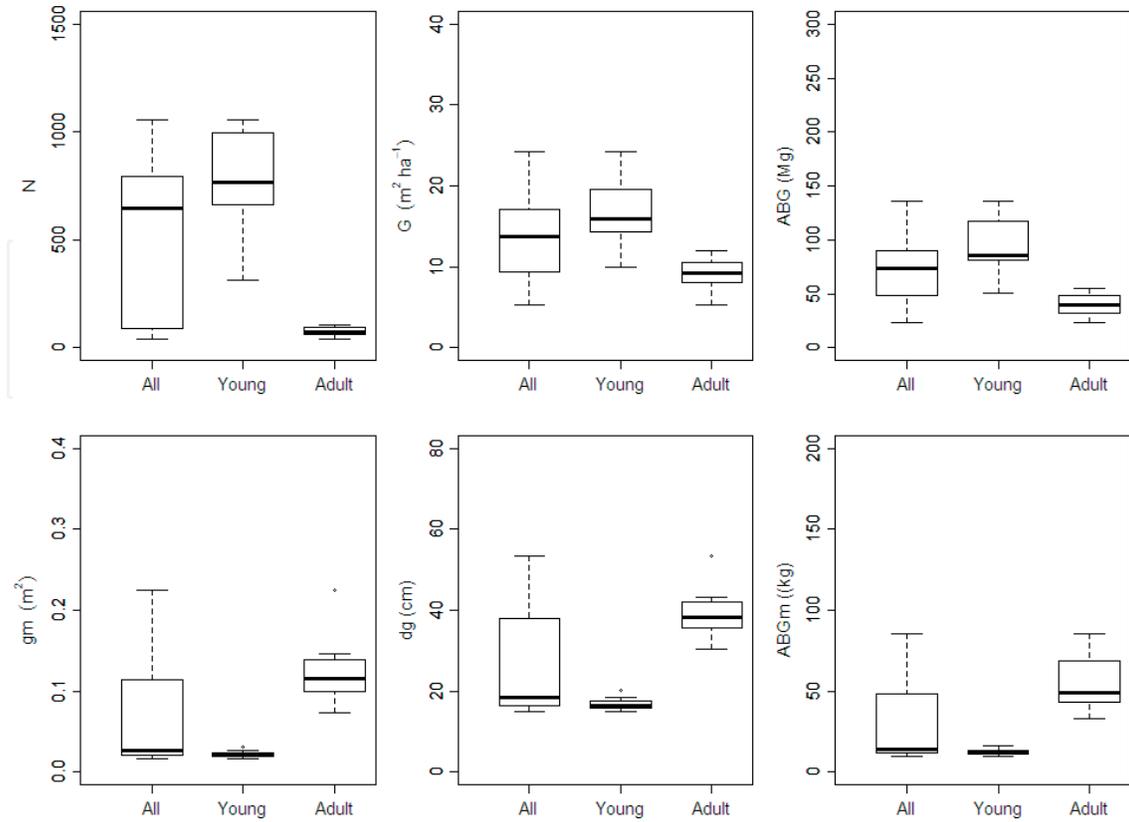


Figure 3. Boxplots of N , G , AGB , gm , dg and $AGBm$ for all young and adult QS plots.

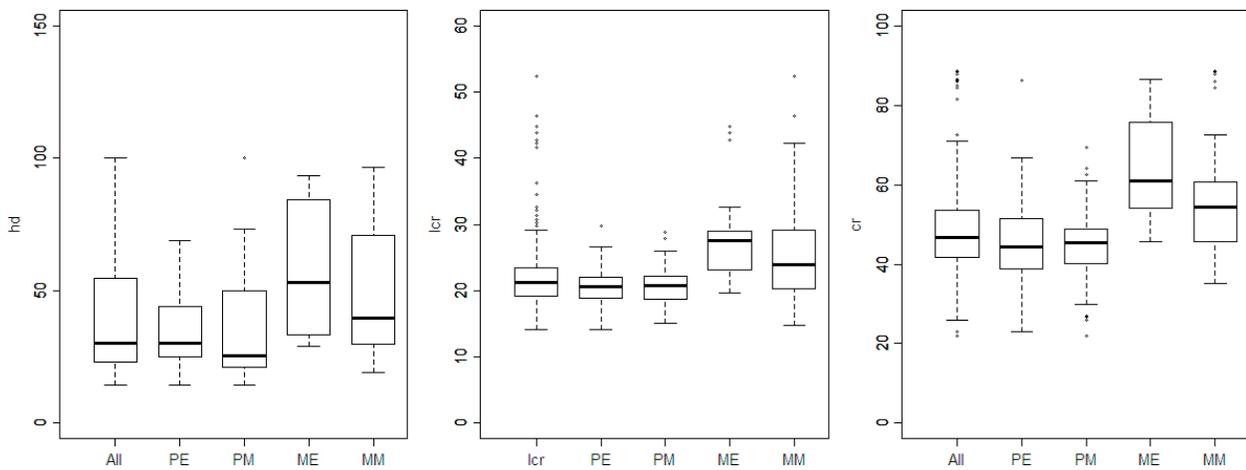


Figure 4. Boxplots of hd , lcr and cr for all plots and per structure classes.

timber both pure and mixed (PPI, PCR and RRB) and for QS. The former is due to the presence of different cohorts (PCR) and to the high density (RRB), and the latter as aforementioned is due to the difference in development stage (young *vs.* adult). The lower variability of QR, QS and PP is a reflection of low density where stem and crown diameter growths are promoted and as the trees are frequently in free growth, denoted by the hd .

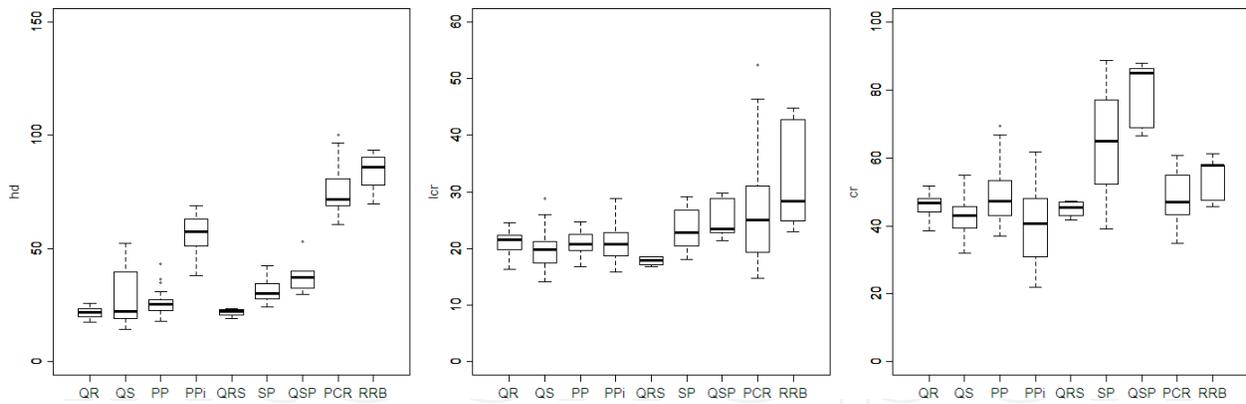


Figure 5. Boxplots of *hd*, *lcr* and *cr* per composition classes.

In 95% of the plots, $lc > \frac{1}{3}$ of the total height and the remaining 5% have $lc > 22\%$, indicating good tree and stand, growth and vigour [33–35]. Likewise, $cr > 30\%$ for most individuals and plots, increasing from pure to mixed plots and from multiaged to even-aged plots, though with larger variability in the mixed plots (**Figure 4**), indicates vigorous growth and well-balanced trees [33, 34], and $cr > 50\%$ good stability [34]. The variability between structure classes is denoted by the significant differences between PE and ME, PM and MM and ME and MM (all, $p < 0.05$). The smaller cr and variability are found for QR, QS and QRS plots, which are a reflection of management, where trees are periodically pruned to promote fruit production, especially adult stands [44]. In contrast, the mixtures of broadleaved and conifer species (SP, QSP, PCR) or of broadleaved species (RRB) have higher cr and larger variability (**Figure 5**). A possible explanation can be the effect of competition between trees, as these stands have higher densities, shade and branch abrasion phenomena can happen and the trees with competition advantages tend to expand their growing space, thus reducing the cr of those trees with fewer advantages and hence increasing the variability [33–35].

Species richness is lower in pure than in mixed plots [46, 56, 59]. Pure plots have one (55%), two (37%) or three or more species (8%). The mixed plots have two or three (40% each) or four or more species (20%). PE and PM with more than one species correspond to 43% and 45% of the total number of plots. Though N , G and AGB of the secondary species are much smaller than that of the main species, their presence is reflected in the relative density measures (**Table 3**). Consequently, as referred by several authors [45, 56, 59, 64, 65], other indices should be used to evaluate diversity. D and H variability in the pure plots is derived from the presence of more than one species. Thus, diversity can increase with only a few individuals (**Figures 6 and 7**), though in mixed plots is higher, denoting both the number of species and the equality of their proportions [45, 64, 65]. For D_N , D_G and D_{AGB} , significant differences were found between PE and PM and between PM and MM and for D_{AGB} also between ME and MM (all, $p < 0.001$). When comparing the different formulations of this index, significant differences are found between D_N and D_G for MM, between D_N and D_{AGB} for PM and MM and between D_G and D_{AGB} for the four structure classes (all, $p < 0.05$). A possible explanation is the number of individuals of the secondary species and the dimensions of their individuals. D_G does not account for the tree

Species composition	R_N		R_G		R_{AGB}	
	min	max	min	max	min	max
Pure even-aged						
QR	96.6	100.0	96.9	100.0	96.8	100.0
QS	83.0	100.0	87.2	100.0	90.5	100.0
PP	80.0	100.0	84.2	100.0	87.4	100.0
PPi	100.0	100.0	100.0	100.0	100.0	100.0
Pure multiaged						
QR	87.5	100.0	85.4	100.0	85.7	100.0
PP	83.3	100.0	85.4	100.0	85.7	100.0
PPi	93.8	100.0	95.1	100.0	99.9	100.0
PCR	85.3	100.0	97.3	100.0	98.6	100.0
Mixed even-aged						
Cr	32.7	80.0	42.1	80.0	45.8	91.3
Mixed multiaged						
PPi	39.1	80.0	77.7	80.0	80.9	99.7

Table 3. Minimum and maximum proportion of R_N , R_G and R_{AGB} per species for pure plots and per main species for mixed plots.

height contrary to what happens with D_{AGB} (cf. **Table 1**). Therefore, it can be said that D_{AGB} enables the incorporation of two dimensions, thus discriminating stands where the secondary species have the similar diameter but different height distributions. The Shannon and Weaver index shows the same trends as Simpson's [60, 61, 66, 68, 69], as denoted by the significant differences between PE and ME and PM and MM for H_N , H_G and H_{AGB} and between ME and MM for H_G and H_{AGB} (all, $p < 0.001$). The comparison of the three formulations of H shows significant differences for PM, ME and MM between H_N and H_G for PM and MM between H_N and H_{AGB} and for PE and MM between H_G and H_{AGB} (all, $p < 0.01$).

Simpson and Shannon and Weaver indices formulated for 500 kg AGB classes enable further details of the differences between structure classes. A general decreasing trend for the former and increasing for the latter are observed from PE to MM, though with wider variability (**Figure 8**), which is clearer than with the formulation per plot. Hence, it enables to differentiate further the structure according to the proportions of AGB per structure classes (cf. **Figure 6**). A similar trend was found by [69].

Most plots have trees in all height zones (**Table 4**). The even-aged plots have more than 67, 86 and 86% of N , G and AGB in the superior and intermediate layer. Inversely, the multiaged plots have between 46 and 49% of N in the inferior layer, corresponding to 8–15% of G and 5–16% of AGB . This distribution is also reflected in the A index, though differently for A_N , A_G and A_{AGB} (**Figure 6**). In general, it increases from PE to MM, in accordance to several authors

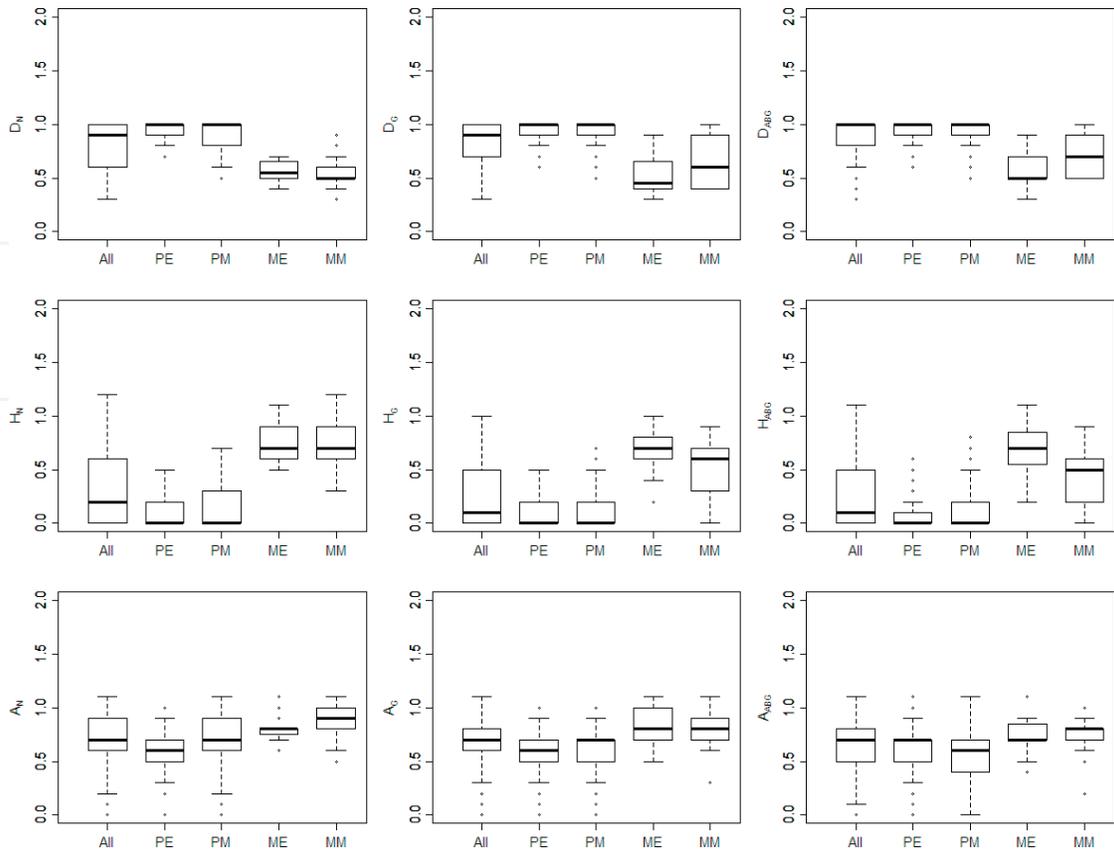


Figure 6. Boxplots of D_N , D_G , D_{AGB} , H_N , H_G , H_{AGB} , A_N , A_G and A_{AGB} for all plots and per structure classes.

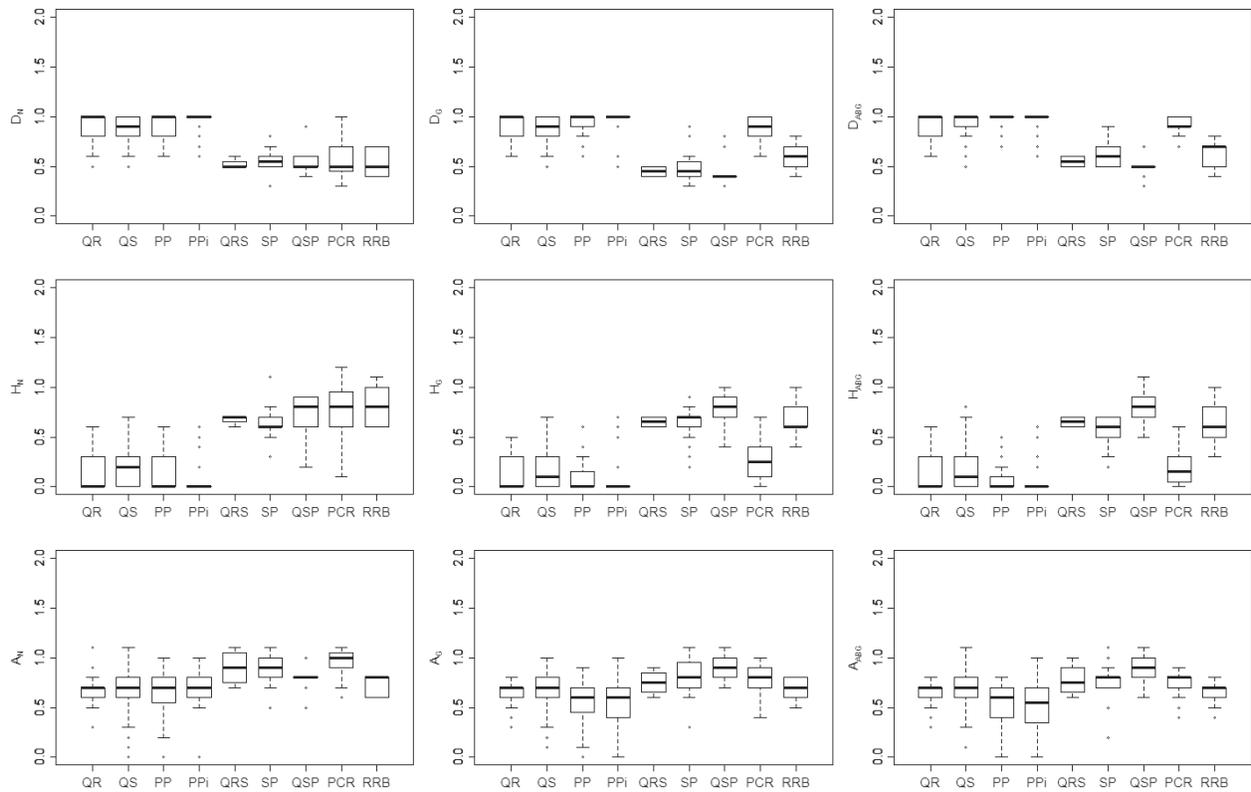


Figure 7. Boxplots of D_N , D_G , D_{AGB} , H_N , H_G , H_{AGB} , A_N , A_G and A_{AGB} per composition classes.

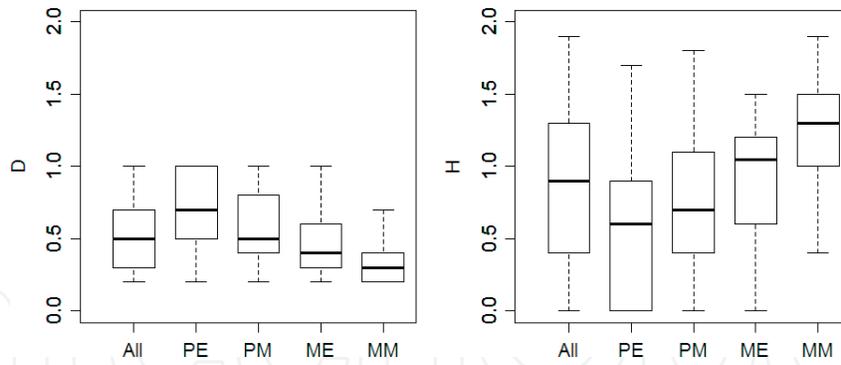


Figure 8. Boxplots of D and H per 500 kg AGB classes for all plots and per structure classes.

Structure class	Height zone								
	N			G			AGB		
	1	2	3	1	2	3	1	2	3
All	41.9	36.8	21.2	11.4	47.1	41.5	8.2	46.9	44.9
Pure even-aged	32.6	47.1	20.3	13.8	50.0	36.2	13.9	52.9	33.3
Pure multiaged	49.4	31.2	19.3	15.2	40.4	44.4	15.7	40.3	44.0
Mixed even-aged	13.0	49.3	37.7	7.8	45.9	46.3	4.5	43.4	52.1
Mixed multiaged	46.5	34.2	19.2	8.2	51.4	40.4	4.5	49.3	46.1

where 1 is the inferior zone, 2 the intermediate and 3 the superior.

Table 4. Mean proportion of N, G and AGB per height zone, for all plots and per structure class.

[45, 64–67]. Also, it is denoted by the significant differences between the four structure classes for A_N and between PE and ME and PM and MM for A_G and A_{AGB} (*all*, $p < 0.001$). The analysis per composition classes shows the increase of diversity from pure to mixed plots, though the variability within each group is rather wide, consequence of the number of individuals per height zone as well as their dimensions. Similarly to the former, higher values are attained for A_N than for A_G and A_{AGB} (Figure 7). This variability can be explained by the dimension of the individuals of the inferior layer. Though they can be in a rather high number, their diameter at breast height and total height are much smaller than those of the individuals of the two upper layers; thus, both the basal area and the above-ground biomass are also much smaller. This variability is also denoted by the significant differences for all formulations between PM and MM (*all*, $p < 0.001$). As expected PE and ME present no significant differences for A_N and A_G ($V = 259$, $p = 0.34$; $V = 44$, $p = 0.90$, respectively), for A_N and A_{AGB} ($V = 397$, $p = 0.37$; $V = 104$, $p = 0.43$, respectively) and for A_G and A_{AGB} ($V = 52$, $p = 0.38$; $V = 43$, $p = 0.13$, respectively). This can be, at least partially, explained by the small proportions of individuals in the inferior layer (cf. Table 4).

4. Conclusions

Structure analysis is of primordial importance for the study and modelling of forest stands as well as for their management. The most frequently used measures and indices characterise the stands with the number of individuals, stem diameter and total height. Above-ground biomass, as by their formulation incorporates both diameter and total height, is able to incorporate in the measures and indices the horizontal and the vertical dimensions. Also, forest biomass can give further insights to the carbon sequestration.

The results revealed that there are significant differences between the measures and indices calculated with the number of trees and basal area, when compared with those calculated with above-ground biomass. The latter can be of importance when there is the need to discriminate stands with similar number of trees but with different dimension proportions.

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