

STAND STRUCTURE DIVERSITY IN *PINUS SYLVESTRIS* L. WOODLANDS IN THE CENTRAL MOUNTAIN RANGE (SPAIN)

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SUMMARY

The purpose of this study was to assess the structure of Scots pine (*Pinus sylvestris* L.) stands at different developmental stages through the altitudinal range of its distribution area in Valsaín forest, located in the Central Mountain Range of Spain. Trees were mapped and their diameter, height and crown height measured in 0.5 ha plots. Gadow's differentiation, Shannon index and structure complexity index (SCI) were used in order to describe the vertical structure. The highest vertical diversity was found in the plots located near the upper limit of the altitudinal range, where high mountain shrubs replace the Scots pine forest, and near the lower limit where the Pyrenean oak (*Quercus pyrenaica* Willd.) appears mixed with the Scots pine, as well as during the regeneration stage. The results found may support managers an objective analysis in order to include diversity in decision-making.

INTRODUCTION

The vertical structure of forest ecosystems depends on intra and inter specific competition, site conditions, shade tolerance and disturbance regimes and is widely acknowledged to characterize forest biodiversity (MacArthur and MacArthur 1961, North et al. 1999). It offers the advantage of being easily measured in the field and at the same time it provides a large amount of valuable information.

One of the most widely used methods to assess the vertical structure diversity consists on calculating the Shannon index (Shannon, 1949) with the foliage distribution in vertical strata. This index is denominated foliage height diversity index or FHD (MacArthur & MacArthur, 1961). The FHD requires a specific sampling method to assess the vertical arrangement of the vegetal layers (Ferris-Kaan et al., 1998), and it is not straight forward to apply when there are not well defined

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vegetal layers. Some authors have used Shannon's diversity index by diameter classes (Buongiorno *et al.*, 1994; Staudhammer & LeMay, 2001). Recently, some new methods have been developed to characterize the pattern of the vertical structure. Gadow's differentiation index (Gadow, 1993; Gadow & Hui, 1999) extends the nearest neighbor methods to the vertical structure analysis. Other index based on the distance between the top of neighbour trees is the structure complexity index (SCI) proposed by Zenner and Hibbs (2000).

Stand structure has been largely studied in managed forests recently but few studies have dealt with this issue in Mediterranean forests. This study aims to compare how different methods to assess height heterogeneity capture the vertical structure in Scots pine forest to obtain quantitative measures that can be used to evaluate the vertical structure across the stand life and at different ecological conditions.

MATERIAL AND METHODS

Data collection

The data of this study derives from *Pinar de Valsaín*, a managed Scots pine forest located in the North facing slopes of the *Sierra de Guadarrama* in the Central Mountain Range in Spain. The altitude ranges between 1200 and 2200 m, with mean annual temperature around 9° C and over 730 mm of annual rainfall. Group shelterwood system is followed in this forest, allowing regeneration to take place naturally in a 40 years period.

Eight rectangular 0.5 ha plots were installed through the altitudinal growth range of Scots pine. Six of them were established including all the current age classes in the forest, from 1-20 years (plot V1) to 101-120 years (plot V6), where rotation length is 120 years. The other two plots were placed at uneven stands near the lower and upper limits of Scots pine spectrum. Plot V7 was located at 1300 m where Scots pine appears mixed with Pyrenean oak (*Quercus pyrenaica*) and plot V8 was situated at 1800 m where Scots pine appears mixed with alpine shrubs (*Juniperus communis ssp nana*).

Diameter at breast height (dbh) and height (H) were measured for all trees. Stems higher than 1.30 m were located through their xy coordinates while saplings below 1.30 m in height were recorded in a 2 x 2 m² grid situated over the plots.

Table 1. Stand level variables in the experimental plots (extent 0.5 ha) in *Valsaín* forest (V1, V2, V3, V4, V5, V6, V7 and V8): Plot size in m²; Age class (years); N ≥ 10 cm and N < 10 cm, tree number per ha with dbh ≥ 10 cm and dbh < 10 cm respectively; dbh ≥ 10 cm and dbh < 10 cm, mean diameter at breast height (cm) of tree with dbh ≥ 10 and dbh < 10 cm respectively; BA, basal area (m²/ha); H > 10 cm and H < 10 cm, mean height (m) of tree with dbh ≥ 10 and dbh < 10 cm respectively.

Plot	Plot size	Age class	N ≥ 10 cm	N < 10 cm	dbh ≥ 10 cm	dbh < 10 cm	BA	H ≥ 10 cm	H < 10 cm
V1	100 x 50	1-20	584	7468	20.2	2.4	34.4	13.6	3.1
V2	85 x 58.8	20-40	1668	936	16	4.9	41	14.3	6.3
V3	100 x 50	40-60	1322	0	20.5	≠	48.5	16.4	≠
V4	100 x 50	60-80	686	0	30.5	≠	53.3	23.5	≠
V5	70.7 x 70.7	80-100	550	0	34.6	≠	54	22.1	≠
V6	100 x 50	100-120	334	318	38.3	1.5	41.4	24	2.1
V7	70.7 x 70.7	Uneven	608	964	18.8	1.6	25.2	11.5	2.4
V8	100 x 50	Uneven	578	244	19.9	3.6	22.7	10	3.3

Vertical structure analysis

-Distance independent indices

Shannon's index (Shannon 1949) was used to estimate the height diversity using it with basal area by height classes:

$$FHD' = - \sum_{i=1}^s p_i \ln p_i \quad \text{with:} \quad p_i = \frac{\sum_{j=1}^N G_{ji}}{\sum_{i=1}^s \sum_j G_{ji}} \quad (1)$$

where s is the number of height classes at 5 m intervals (being the lower limit of the first class 0) in the plot and p_i is the ratio between the basal area of the i th tree and the total basal area.

Height distribution's diversity was also measured using the structure index based on the variance:

$$STVI = \sum_{i=1}^n \sum_{j=1}^n p_i p_j (H_i - \bar{H})^2 \quad (2)$$

where n is the number of trees in the sample, p_i is the ratio between the basal area of the i^{th} tree and the total basal area, H_i is the height of tree i^{th} tree and n/N is the sampled fraction. This structure index based on the variance proposed by Staudhammer and LeMay (2001) was somewhat more complex, because it was standardised to be 0.5 when the distribution is uniform over half of the total range and when the distribution is bimodal with half the values uniformly distributed over the lower quartile and the other half uniformly distributed over the upper quartile, and was also constrained to equal to 0.1 for a distribution with half of the values equal to the lowest and half equal to the highest (maximum variance).

-Distance dependent indices

Gadow's differentiation index (DHn) has been used to measure small-scale variability in the height size distribution (Gadow 1993, Gadow and Hui 1999). The DHn is given by:

$$DHn = \frac{1}{N} \sum_{i=1}^n DHni \quad \text{with:} \quad DHni = \frac{1}{n} \sum_{j=1}^n \left(1 - \frac{x_{\min}}{x_{\max}} \right)_j$$

where DHn is the mean differentiation calculated for n neighbours, N the number of trees per plot and $DHni$ the differentiation index for tree i calculated with n neighbours, and where $x_{\min}$ and $x_{\max}$ are the smallest and the largest height among tree i and its n neighbours. Values close to 0 indicate that the neighbours are of a very similar size, whereas values close to 1 reflect high differentiation. In this study three neighbours were included ($n = 3$), this being the usual practice (Füldner 1995).

Another index used to characterize the neighbourhood height differentiation is the structure complexity index (SCI) developed by Zenner and Hibbs (2000). This index integrates tree height and horizontal spatial pattern. Points marking the top of each three neighbouring trees are connected, constructing a 3- dimensional continuous tessellation of non-overlapping triangles. This triangular irregular network satisfies the Delaunay criterion (Fraser and van den Driessche, 1971) (i.e., a circle drawn through the three nodes of a triangle contains no other point, the triangles are as equi-angular as possible and the triangulation is independent of the order in which the points are processed).

$$SCI = \frac{\sum_{i=1}^N \frac{1}{2} |a_i \times b_i|}{A_T}$$

where A_t is the sum of the projected areas of the triangles, $i=1...N$ is the number of triangles in the test plot, and $\frac{1}{2}|a_i \times b_i|$ represents the surface area in 3-dimensions connecting x , y and z coordinates of trees. SCI is at its minimum when it is equal to one, when all the trees in the stand have the same height.

RESULTS AND DISCUSSION

Table 2 shows the evolution of the different vertical indices obtained for the experimental plots in *Valsaín*. The vertical differentiation shows a decreasing trend over the life of the stand with a slight increase in the oldest plot. The values for all the analysed vertical structure diversity indices were greater for the stages from regeneration to the first thinning under low intensive silviculture (V1) and in the plots located at the upper (V8) and lower limits (V7) of the distribution limits of Scots pine.

Table 2. Vertical structure indices in the experimental plots in *Valsaín* forest (V1, V2, V3, V4, V5, V6, V7 and V8): H', Shannon's index; STVI: structure index based on the variance; DH3, Gadow's index for height and 3 neighbours; SCI, structure complexity index.

Plot	FHD	STVI	DH3	SCI
V1	1.55	74.32	0.19	2.89
V2	1.21	17.14	0.13	2.05
V3	0.93	8.25	0.12	1.80
V4	0.73	9.94	0.07	1.42
V5	0.59	7.00	0.07	1.30
V6	0.89	8.19	0.07	1.25
V7	1.34	196.05	0.17	1.79
V8	1.06	119.11	0.25	1.87

A decreasing trend of Shannon index was clear over the life of the stand, with a slight increase in the oldest plot. The behaviour of the STVI index over the life of the stand is even more evident. The vertical differentiation (DH3) shows a decreasing trend over the life of the stand, and asymptotizes when the stand reaches the stem exclusion stage. SCI showed the same general trend as DH3. The plots located at the upper and lower limits of the distribution area of the species showed high values for all the analysed vertical structure diversity (Table 2).

The vertical structure diversity is commonly estimated by using the foliage height diversity index (FHD), which consists of applying the Shannon index to the height distribution of foliage. This index has been largely used in ecological studies and has been proved to be a good indicator of structure complexity of the forest (Kuuluvainen *et al.*, 1996). The relative frequency (estimated through the number of contacts within each layer) can be substituted in the Shannon index for the proportion of basal area corresponding to each height class (Staudhammer & LeMay, 2001). The basal area is approximately proportional to the space occupied by the tree crown. However, this index is dependant on the class size width and there is no agreement in literature about what class width or how many classes should be used, and of how sensitive the index is to the change of class width (Ferris-Kaan *et al.*, 1998; Varga *et al.*, 2005). The use of indices based on the variance, such as STVI (Staudhammer & LeMay, 2001), has the advantage that their value does not depend on the artificial set of the class boundaries. Nevertheless, diversity indices based on the variance behave quite different than those derived from the Shannon's index, because the variance is maximum when the distribution is binomial with half of the trees in the lower class and the other in the upper class, whereas the diversity reaches a maximum when all the classes are evenly represented (Magurran, 1988). Height diversity must be referred to the scale of the study to be used in analysis of vegetation dynamics or comparative studies.

The distance dependant indices of vertical structure analysed give a picture of the height variability at micro-scale, i.e., a tree and its neighbours. Gadow's differentiation index was used to describe patterns at microstructure level, because it operates only for the immediate neighbourhood of each tree, and it assigns an index value to each tree of the stand. The differentiation index has been used for structural characterization of forests (Aguirre *et al.*, 2003), but as it quantifies the variability of height between neighbor trees, its utilization to link structural changes, silviculture applied and competition may be promising (Montes *et al.*, 2004). Nevertheless, the neighborhood scale assessment gives little information about the stand structure and many processes that take place at larger scales. The SCI index proposed by Zenner and Hibbs (2000) integrates the horizontal spatial pattern and tree height, giving us a complexity measure of the 3-dimensional structure, and additional information about heights distribution in our stands, but is mainly influenced by the micro-scale vertical structure.

These height diversity indices give a picture of height variability at micro-scale and can be used to compare or monitor height structure complexity at a determined scale, although the height distribution must be analysed to avoid misinterpretations of the results. This study showed that very different vertical structures can result in similar values for height diversity indices. The calculation of the distant independence indices at different scales, dividing the plot into smaller plots may show

how height diversity varies with the size of the plot, and could therefore allow us to see the trend at larger scales and to study the strength of the relationship between horizontal pattern and vertical structure.

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