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An analysis of spatial forest structure using neighbourhood-based variables

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Abstract

The study presents an analysis of forest spatial structure and diversity in the Federal State of Durango where the majority of the forests consist of pure pine stands or pine mixed with oak. Natural forests of greater diversity and of high ecological significance are found only in a few isolated localities in the Santa Bárbara valley. These forests, with rare conifers including the genera *Picea*, *Abies* and *Pseudotsuga* are found on particular sheltered, humid sites. For one such rare site, a detailed analysis of forest spatial structure was made, based on three one-quarter hectare plots where all the trees and their coordinates had been assessed. The objective of the study was to provide a quantitative description of the spatial structure of the plots, using new parameters of spatial diversity and to present a method for comparative analysis of the three forest sites. The analysis is using a new approach for describing complex forest structures in a straightforward manner. To evaluate the spatial attributes, it is not necessary to measure distances between trees or to establish tree coordinates. The spatial characteristics can be established merely on the basis of evaluating the immediate neighbourhood of a given number of reference trees. The variables describe the distributions of spatial mingling, size differentiation and contagion, which can be easily interpreted allowing quantitative comparisons between complex forest structures.

Keywords: Mingling; Contagion; Diameter differentiation; Distribution; Forest density

1. Introduction

Durango is one of the most important Federal States in Mexico as far as commercial timber growing and forest conservation are concerned. The forest areas are located along a mountain range known as the Sierra Madre Occidental, a volcanic plateau extending from south of the Tropic of Cancer through western Durango, and northwesterly terminating in southern Arizona. The average elevation of the plateau is 2000 m above sea level, but some areas rise to 3000 m. The highest point in Durango is 3150 m. The landscape is characterized by mature rolling uplands and deep canyons arising on the edge of the plateaus and extending to the summits of the sierras, where they appear as hanging valleys.

The majority of the forests in Durango consist of pure pine stands or pine mixed with oak. Among the forest regions of Durango, the El Salto district stands out because of its economic importance. El Salto comprises an area of about one million hectares of forest land under sustainable forest management.

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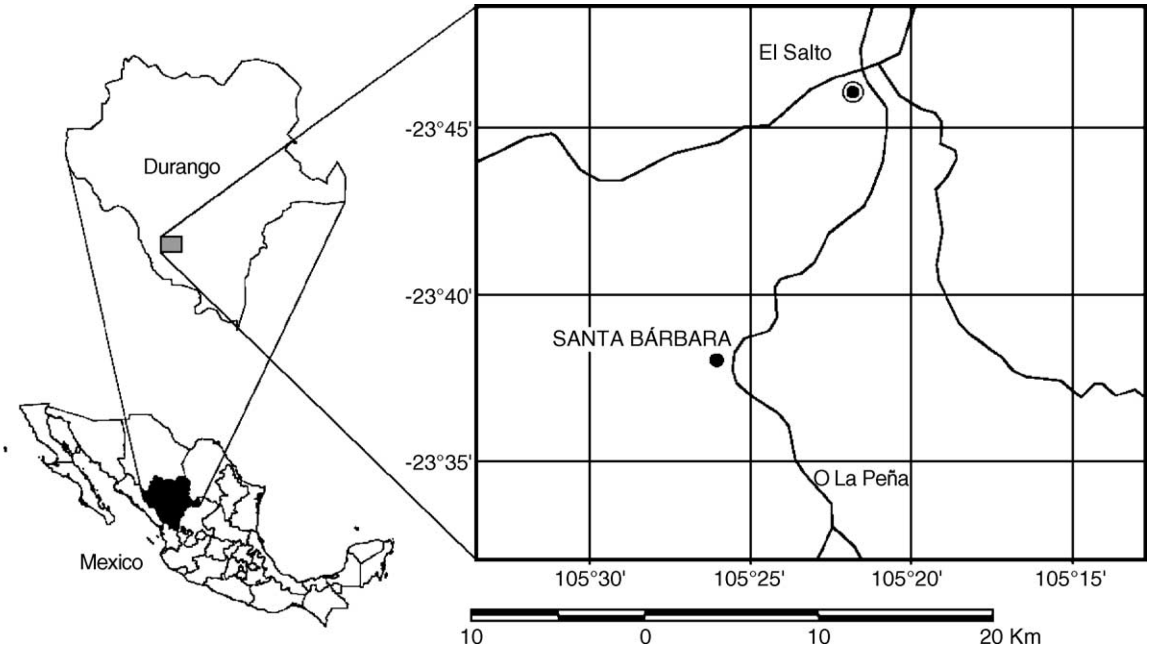


Fig. 1. Locality map showing the location of the Santa Bárbara valley near El Salto in the Federal State of Durango.

The silvicultural system attempts to mimic natural processes through selective thinning and regeneration cutting. Natural forests of greater diversity and of great ecological significance (*bosques mixtos incoetáneos*) are found only in a few isolated localities. These forests, with rare conifers including the genera *Picea*, *Abies* and *Pseudotsuga* are found on particular sheltered, humid sites (Fig. 1).

The study area is located in a high protected valley known as Santa Bárbara. The area is situated at 23°39′N and 105°25′W, about 24 km north of the Tropic of Cancer and about 20 km south of the town of El Salto. The Santa Bárbara valley has a permanent stream and is well protected from drying winds. It is surrounded to the south and east by the plateau pine forests, and on the western side empties into the steep, canyon-like gorge known as Quebrada del Infierno. Three tree species, *Picea chihuahuana*, *Abies durangensis* and *Pseudotsuga menziesii*, are found on this particular site and within a limited area of about 20 ha. Trees of these species are rare in Mexico and in Durango. They occur as protected relicts with a high conservation status. Especially significant is the occurrence of *P. chihuahuana*. The proximity of this stand to the Tropic of Cancer provides a warm climate which is uncommon to the genus *Picea*. Only one other species in Asia is known to occur in far south (Gordon, 1968).

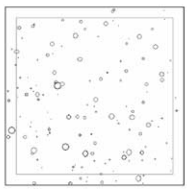
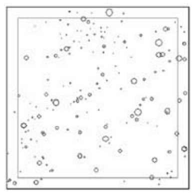
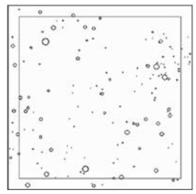
The forest of the Santa Bárbara site is relatively undisturbed. Three permanently marked field plots were established during March 2002 in that virgin forest. Each plot measures 50 m × 50 m square and was given a unique name by the enumeration crew. The three sites were established along an altitudinal gradient at 2595, 2620 and 2685 m above sea level. The data are presented in Table 1.

The objective of this study was to develop and present a method for comparing the spatial structure of different natural forest sites. The analysis is based on a set of permanent field plots in a rare natural forest type which has been withdrawn from management.

2. Description of the spatial forest structure

The ‘‘structure’’ of a forest may be defined by the spatial distribution of the tree positions, by the spatial mingling of the different tree species and by the spatial arrangement of the tree dimensions. The different species and tree sizes may be found in close proximity

Table 1
Spatial distributions, stem numbers (N/ha) and basal areas (G/ha) of the 13 tree species occurring in the three one-quarter hectare plots

Tree species	Chichimoco		Fabián		Coa	
						
	N/ha	G/ha	N/ha	G/ha	N/ha	G/ha
P. chihuahuana	24	8.15	16	2.81	40	3.67
A. durangensis	92	3.32	192	14.87	20	0.68
P. menziesii	68	6.98	120	6.92	80	3.15
C. lindleyi	312	33.18	304	26.44	116	1.35
Quercus rugosa	4	0.20				
Q. castanea	40	0.14	32	1.59		
Q. duriflora	4	0.04			12	4.98
Q. crassifolia			4	0.02		
Prunus serotina	20	0.39				
Pinus ayacahuite			4	0.10	28	0.73
P. durangensis			4	0.27	8	1.22
P. cooperi					212	13.15
Juniperus deppeana			4	0.03	112	3.39
Sum	564	52.40	680	53.05	628	32.32

to each other and thus exhibit a high degree of "mingling", or they may be spatially segregated (Fig. 2). The spatial structure is one of the characteristic attributes of a forest. The problem is to characterize and describe forests with different spatial characteristics more accurately, using affordable assessment techniques.

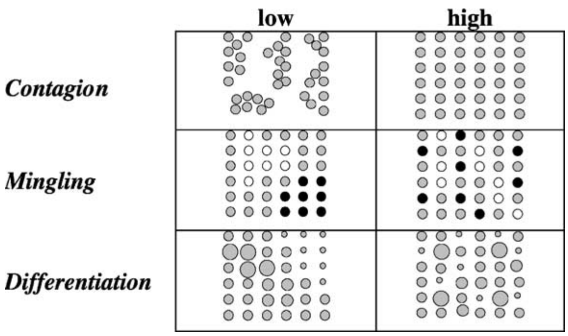


Fig. 2. The main elements of forest spatial structure are regularity of tree locations, spatial species mingling and spatial size differentiation.

L-und pair correlation functions are useful for describing forest structures, but they require datasets with known tree positions (Stoyan and Stoyan, 1992; Pretzsch, 2001; Pommerening, 2002). Such data are hardly ever available in practice and this precludes the use of these otherwise elegant methods. Aggregate indices, such as the spatial index proposed by Clark and Evans (1954), can provide a first general impression of the structure of a particular forest, but they cannot be used to describe the great variety of spatial arrangements (Zenner and Hibbs, 2000). This deficit is especially serious in very irregular forests where small-scale structural characteristics are highly variable (Albert, 1999).

For this reason, we propose a set of three types of neighbourhood-based parameters: contagion, mingling and differentiation. The parameters can be used to provide a comprehensive description of the spatial structure of a forest. Assessment and description may be tree-based or point-based. In the tree-based approach a sample tree closest to a sample point is chosen as reference tree and the attributes of its immediate neighbours (size, species) and the regularity of

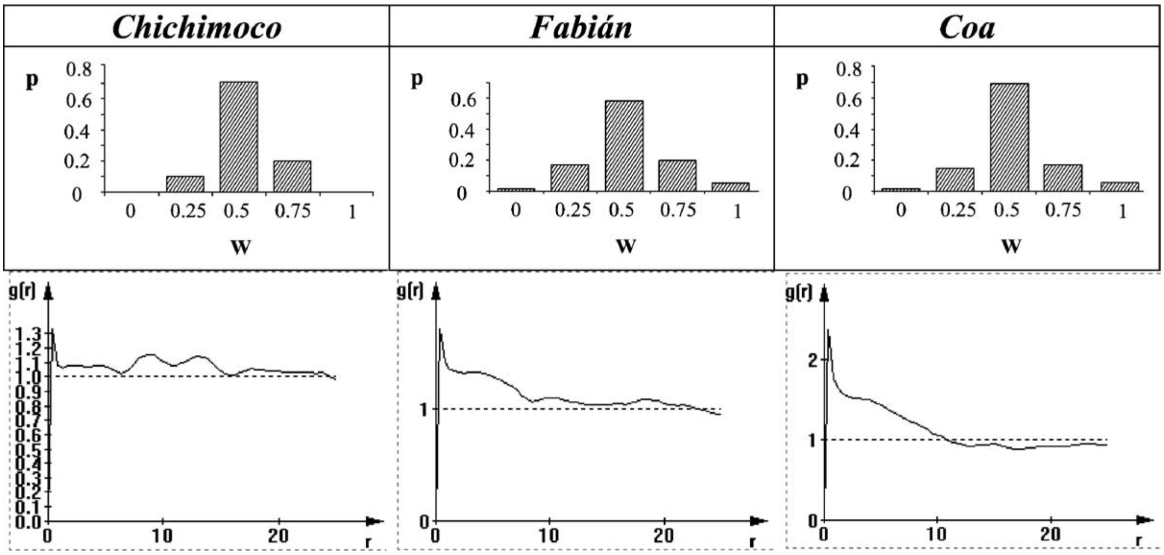


Fig. 3. Contagion distributions in the three research plots with corresponding graphs of the pair correlation functions below.

their positions are related to the reference tree. In the point-based approach, the structural attributes of a neighbourhood group of trees (variation of tree species and sizes; regularity of tree positions) is assessed at each sample point (Staupendahl, 2001).

2.1. The contagion

The contagion W_i describes the degree of regularity of the spatial distribution of the four trees nearest to a reference tree i.[1] W_i is based on the classification of the angles α_j between these four neighbours. A reference quantity is the standard angle α_0, which is expected in a regular point distribution. The binary random variable v_j is determined by comparing each α_j with the standard angle α_0. The contagion is then defined as the proportion of angles α_j between the four neighbouring trees which are smaller than the standard angle α_0:

$$W_i = \frac{1}{4}\sum_{j=1}^{4} v_j \quad \text{with}$$

$$v_j = \begin{cases} 1, & \alpha_j < \alpha_0 \\ 0, & \text{otherwise} \end{cases} \quad \text{and} \quad 0 \le W_i \le 1 \tag{1}$$

[1] For details refer to Gadow et al. (1998). Four neighbours have proved to be most suitable based on practical considerations in connection with the field assessment methods (Albert, 1999; Hui and Hu, 2001).

$W_i = 0$ indicates that the trees in the vicinity of the reference tree are positioned in a regular manner, whereas $W_i = 1$ points to an irregular or clumped distribution. With four neighbours, there are five possible values that W_i can assume. The estimator for the contagion of a given forest is $\bar{W}$, the arithmetic mean of all W_i-values. Although the contagion mean value $\bar{W}$ is quite informative for characterizing a point distribution, it is often advisable to study the distribution of the W_i-values which reveals the structural variability in a given forest (Fig. 3). The pair correlation function does reveal a clumping of trees at inter-tree distances between 0 m and 10 m in Coa and Fabián. The contagion index also shows clumping in about 20% of the cases.

The contagion distributions in the three research plots differ with regard to their means and variances. The contagion mean values are 0.504, 0.528 and 0.515 in Chichimoco, Fabián and Coa, respectively. Based on the work by Hui and Gadow (2002), all three spatial distributions may be characterized as random. Fabián is the closest to a clumped distribution.

2.2. Species mingling

Species diversity has become a very important aspect of forest management and conservation and a number of parameters are available to describe it.

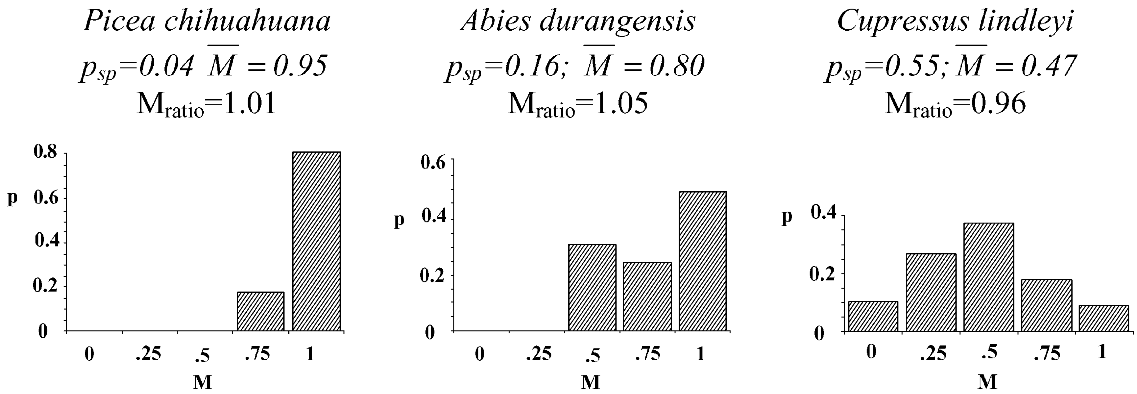


Fig. 4. Species-specific mingling distributions for three tree species in the Chichimoco plot; p_{sp} is the proportion of the number of trees that the species contributes to the stand as a whole, $\bar{M}_{sp}$ the average mingling value of a given species, $M_{ratio} = 1 - p_{sp}/\bar{M}_{sp}$.

An example is the Shannon–Weaver index which has been used in ecological applications by Pielou (1977, p. 293). We propose to evaluate the species diversity in the vicinity of a reference tree and define mingling as the proportion of the n nearest neighbours that do not belong to the same species as the reference tree (Füldner, 1995), specifically:

$$M_i = \frac{1}{4}\sum_{j=1}^{4} v_j \qquad (2)$$

with

$$v_j = \begin{cases} 1, & \text{neighbour } j \text{ belongs to the same species as reference tree } i \\ 0, & \text{otherwise} \end{cases}$$

and $0 \leq M_i \leq 1$.

With four neighbours, the mingling attribute M_i can assume five values. Of particular interest is the species-specific mingling. Fig. 4 presents the distribution graphs for three species in the Chichimoco plot.

The mingling distribution of *P. chihuahuana* shows that the species is either surrounded by three or even four neighbours that belong to a different species. In contrast, *Cupressus lindleyi* occurs in a variety of mingling constellations: either in pure groups (about 10%), in groups where half of the trees are *C. lindleyi* (about 35%) and in groups where none of the neighbours is *C. lindleyi* (about 10%). *A. durangensis* does not form pure or almost pure groups, but occurs most frequently as a single tree among other species.

We may express the relationship between the average mingling value of a given species ($\bar{M}_{sp}$) and the proportion of the number of trees that the species contributes to the stand as a whole (p_{sp}) by the following ratio:

$$M_{ratio} = \frac{1 - p_{sp}}{\bar{M}_{sp}}$$

Graz (2002) found that low values of M_{ratio} indicate a high degree of clumping of a particular species within the forest, while values close to 1 indicate a more even distribution. This potentially interesting aspect will be subject of further investigation in the future.

2.3. Size differentiation

The tree attribute dominance of neighbours was proposed by Hiu et al. (1998) to relate the relative dominance of a given tree species to the immediate neighbourhood.[2] We define dominance as the proportion of the n nearest neighbours of a given reference tree which are smaller than the reference tree, which is calculated in the same way as the previous tree-based structural parameters:

$$U_i = \frac{1}{4}\sum_{j=1}^{4} v_j \qquad (4)$$

[2] The original German designation is Umgebungsmass.

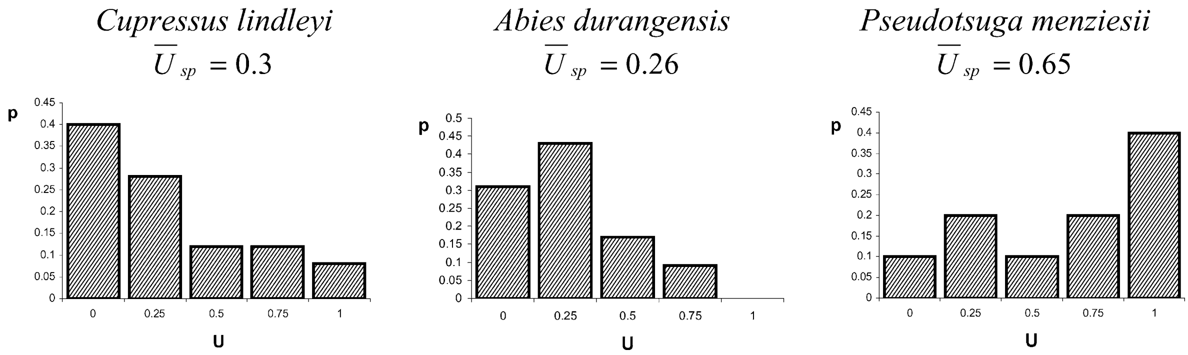


Fig. 5. Species-specific dominance distributions for three tree species in the Chichimoco plot. $\bar{M}_{sp}$: average dominance value of a given species.

with

$$v_j = \begin{cases} 1, & \text{neighbour } j \text{ is smaller than reference tree } i \\ 0, & \text{otherwise} \end{cases}$$

and $0 \leq U_i \leq 1$.

With four neighbours, U_i can assume five values. Fig. 5 presents the distribution graphs for three species in different plots.

The dominance criterion is useful if we wish to describe the relative dominance of a particular tree species. The distribution of *C. lindleyi* is left-skewed, which shows that only a few reference trees are dominant in their immediate vicinity while the majority are surrounded by at least three bigger neighbours. A similar interpretation can be provided for *A. durangensis* whereas *P. menziesii* is a more dominant species. All three species occur as dominant, codominant and suppressed trees in the Chichimoco plot. These analyses were made for all the tree species in each of the three plots.

3. Quantifying differences between the populations

One of the objectives of characterizing tree populations more accurately, is to be able to compare them. Comparisons are made, for example, when we need to evaluate the difference between two natural forests occurring on the same site, or between a managed and an unmanaged forest. For this purpose, we define the variable absolute discrepancy which measures the amount of a particular attribute of population A that needs to be exchanged between the two populations to make it identical with population B. For example, the discrepancy of number of trees between Chichimoco and Fabián is equal to $(680 - 564)/2 = 58$ trees which would have to be exchanged so that both would have the same number of trees. The corresponding basal area discrepancies are: for Chichimoco–Fabián, 0.32; for Chichimoco–Coa, 10.04 and for Fabián–Coa, 10.36. This is a useful concept which can be extended to include the diameter distributions and the contagion distributions of the three populations.

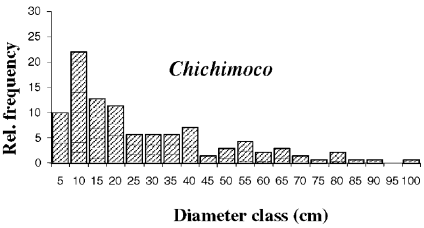
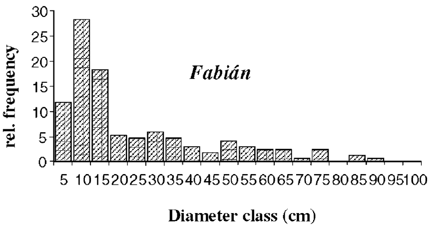
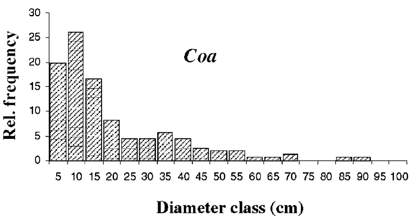
3.1. Discrepancy of diameter distributions

The absolute discrepancy of the diameter distributions may be defined as follows (Gregorius, 1974; Pommerening, 2002):

$$\mathrm{rDD} = \frac{1}{2}\sum_{i=1}^{n}|D_{1i} - D_{2i}|$$

where D_{1i} is the relative frequency of the ith diameter class in population 1, D_{2i} the relative frequency of the ith diameter class in population 2, n the number of diameter classes, rDD represents the relative proportion which must be exchanged between the classes if the empirical distribution 1 is transformed into distribution 2. Correspondingly, $1 - \mathrm{rDD}$ is the proportion common to both distributions. A value of $\mathrm{rDD} = 1$ means that both distributions have no common class, whereas $\mathrm{rDD} = 0$ signifies that the distributions are absolutely identical. The diameter discrepancies are presented in Table 2.

Table 2
Histograms of the three diameter distributions and the discrepancies between them

		Fabián	Coa
	Chichimoco	0.20	0.17
	Fabián		0.09
	Coa		

The difference between the diameter distributions are relatively small when we compare Fabián with Coa, but much bigger when Chichimoco is compared with one of the two other plots. More trees of a larger size and less trees of small dimensions are found in Chichimoco. Fabián and Coa both have a relatively large population of small trees.

3.2. Relative discrepancy of contagion distributions

We can compare the differences in the spatial arrangement of the trees in a similar fashion, using the relative discrepancies of the contagion distributions rDW as $\mathrm{rDW} = (1/2)\sum_{i=1}^{n}|W_{1i} - W_{2i}|$. The results are presented in Table 3. The contagion distribution histograms are presented again to facilitate comparison.

Table 3
The three contagion mean values and the distribution discrepancies

Contagion mean $\bar{W}$	Plot	Fabián	Coa
0.504	Chichimoco	0.15	0.08
0.528	Fabián		0.10
0.515	Coa		

The absolute discrepancy measures the size of the difference, not the direction. The direction is easily established by comparing the distribution means. In the case of the contagion, the mean values are all within the range of a random distribution, found by Hui and Gadow (2002). The Fabián distribution is very close to being classified as clumped.

4. Discussion

The analysis presented in this paper evaluates the density, species diversity and spatial structure using traditional and new approaches. The traditional approach includes comparisons of basal areas and stems per hactare as a measure of density. With more than 50 m^2/ha basal area, the Chichimoco and Fabián are each very dense when compared with Coa's 32 m^2/ha. The biomass levels of Chichimoco and Fabián are both rather high, but their stem numbers differ considerably. Fabián has 20% more trees and these differences reflect clearly in the diameter distribution, which is another traditional measure of forest structure.

Spatial attributes provide further information about the field plots. The tree-based contagion W_i can be used to characterize the spatial distribution of tree positions without the necessity to measure distances between trees. It describes the degree of regularity of the spatial distribution of the four trees nearest to a reference tree i based on the classification of the angles α_j between the neighbouring trees. The dominance which measures the proportion of the n nearest neighbours of a given reference tree which are smaller than the reference tree, provides information about the relative status of a species within the population. Species diversity is evaluated by the tree attribute mingling which measures the proportion of the n nearest neighbours that do not belong to the same species as the reference tree.

Sometimes, a comparison needs to be made between different tree populations, for example, between a managed and an unmanaged forest. The absolute discrepancy which measures the size of the difference between distributions, is a useful quantity which allows easy interpretation of differences in the distribution of size classes, mingling values and contagion values. The direction of the differences is easily established by comparing the distribution means. Regarding the contagion, the mean values in the three field plots are all within the range of a random distribution. This observation is supported by previous work. The Fabián distribution is very close to being classified as clumped.

Using the example of a very special forest with rare tree species, the analysis is using a new approach for describing complex forest structures in a straightforward manner. To evaluate the spatial attributes, it is not necessary to measure distances between trees or to establish tree coordinates. The spatial characteristics have been established merely on the basis of evaluating the immediate neighbourhood of a given number of reference trees. They can be easily interpreted. However, further work is needed to evaluate the potential of the neighbourhood variables in comparison with traditional methods, such as pair correlation functions. The system for describing forest spatial structure presented in this paper is (a) more comprehensive than the traditional approaches (including species, size and point pattern simultaneously) whereas the classical methods are usually limited to describing point patterns and (b) more easily assessed in the field whereas the classical methods require costly measurement of tree positions, either by complete enumeration or on sample plots.

Acknowledgements

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