QUANTIFICATION OF FOREST STAND STRUCTURE APPLIED TO SCOTS PINE *(Pinus sylvestris* L.) FORESTS

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SUMMARY

The use and the application possibilities of forest structure description are discussed. The quantitative description of forest stand structure is studied by way of three structural characteristics: positioning, mixture and differentiation. Therefore various non-spatial and spatial indices are proposed. Some spatial indices are applied to a mixed oak-pine stand in the Belgian Campine region, and the advantages and disadvantages of the calculated indices are considered. Results indicate the utility of these indices, both in describing the stand structure accurately, and in reflecting the operative processes causing stand evolution.

KEY WORDS: Forest stand structure
Indices
Pinus sylvestris

INTRODUCTION

Use and application of forest structure description

The quantitative description of forest structure can be regarded as one of the most usable working instruments in modern forest management. There are a number of reasons for this:

(i)   Forest structure is directly related with the habitat of many different animal and plant species, and is therefore convenient as an indicator for biodiversity.

In searching for quantitative measures of biodiversity in plant communities, one or more measurable variables should be used. Firstly, such a variable should be ecologically relevant and interpretable, and moreover easy to measure, cheap and repeatable. For this purpose species richness and evenness are often proposed (Magurran, 1988), but in a silvicultural context these measures often cause problems, both in measurement and inter-

pretation (Köhl and Zingg, 1996). Furthermore, important sources of diversity, such as the dimensions of species or their spatial distribution, are not included in the calculation (Innes and Kräuchi, 1995).

Therefore, various researchers have proposed to describe biodiversity, both in plant communities in general and in forests in particular, by measuring the diversity and complexity of their structure (Innes and Kräuchi, 1995; Kuuluvainen *et al.,* 1996). This assumes that a plant or animal species will only be present if the structure of the biotope in question reflects their habitat requirements.

(ii)   Forest structure is a source of relevant information for the forest manager in relation to forest dynamics, aesthetics and wood production.

Forest management practices have a direct impact on forest structure. As the latter can be quantitatively described in a quick and simple way, it is clear that forest structure and its evolution can be used efficiently to estimate the impact of forest management on biodiversity and timber production.

(iii)   The forest structure description of a particular forest type (for example natural stands in forest reserves) defines a set of parameters. In using forest development models for the evaluation of long-term management options, this set of parameters can serve as a reference (Pretzsch,1995).

(iv)   The simple description of forest structure (categorical, or with indices) is sufficient to reconstruct the forest by computer (Pretzsch, 1992; Von Gadow and Hui, 1999). This offers a wide range of possible applications in forest inventory work.

Structure description at the forest and stand level

The structure of forests can be considered at different hierarchical levels. At the landscape level the structure is determined by the variation of stand types (O'Hara, 1998) and the degree of habitat fragmentation (Andrén, 1994). Determining the structural characteristics on the landscape level, Ferris-Kaan and Patterson (1992) suggest the definition of separate patches on the basis of minimum height difference between adjacent stands, from which it becomes possible for patches to be easily mapped. For this and other methods of structure mapping at the landscape level, geographical information systems offer a wide range of possibilities.

However, for the purposes of biodiversity research, forest structure at the stand level is often regarded as more important (Kuuluvainen *et al.,* 1996). For example, the diversity of insect and bird species living in a stand is related to the complexity of the vertical stand structure (MacArthur and MacArthur, 1961; Murdoch *et al.,* 1972; Degraaf *et al.,* 1998). On clear cuts, the abundance of cavity breeding birds decreases with increasing distance to the stand edges (Carlson, 1994). In addition, the spatial distribution and vertical stratification of the trees defines the three dimensional geometry of habitat characteristics for birds, insects, mammals, tree epiphytes, understorey plants and soil micro-organisms (Ratcliffe *et al.,* 1986; Kuuluvainen *et al.,* 1996).

In forest management, forest development research and forest inventory there is also an emphasis on stand structure. Therefore, this paper concentrates on structure definition at this scale. However, if the variables are suitably redefined, the methods for describing stand structure can also be used at larger spatial scales.

Stand structural characteristics

The description of stand structure must be based on a clear definition of 'structure'. Splitting up 'structure' into three structural characteristics, as suggested by Von Gadow and Hui (1999), seems meaningful:

(i) *Positioning*; or the spatial distribution of trees on the stand area. In the so-called *Poisson forest,* where all trees occur independently and do not influence each other, tree positioning is random (Tomppo, 1986). Much research has shown that this rarely occurs since trees in a forest interact and this interaction influences the spatial structure of the forest (Clark and Evans, 1954; Moeur 1993; Frelich *et al.,* 1998). Also management practices (e.g. respacing, thinning) influence positioning. Therefore, trees are seldom positioned at random but rather are clustered or spaced regularly over the area.

(ii) *Mixture*; or the description of the mutual position of different tree species within the stand. All tree species within a stand can be randomly mixed, indicating that no preferences in species aggregation exist. On the other hand, as a result of regeneration strategy or management, one species may be present in homogeneous clusters, or seem to avoid other species, thus showing complementarity between species within the stand.

(iii) *Differentiation*; describes the relative dimensions between neighbouring trees. Often a distinction is made between horizontal and vertical differentiation depending on the use of diameter (or circumference), or height, as a means of describing tree size.

Methods to describe the structural characteristics of a forest stand

To describe the three structural characteristics referred to above, the classical stand description (qualitative description of stand closure, mixture, density, etc.) and different graphical methods (diameter distribution, stand height distribution curve, tree map, etc.) can be very useful. However, they may not be sufficient to describe stand structure in detail since subtle differences will often not be revealed.

Classification of quantitative methods

Partial reviews of quantitative methods to determine the three structural characteristics of a stand can be found in Pielou (1977), Gleichmar and Gerold (1998), Kint (1999) and Von Gadow and Hui (1999). Methods can be subdivided in 3 categories:

(i) *Non-spatial indices.* Many extremely varied indices, which try to describe stand structure without taking into account the mutual position of individual trees, are described in the literature. Some may be ecologically useful, but all merely calculate one mean value for the stand; they do not take into account the possible variation within the stand. Therefore their application as a detailed measure of structural diversity appears rather limited (Albert *et al.,* 1995; Jiménez *et al.,* 1998).

(ii) *Spatial indices.* Since stand structure is largely determined by the relative position of the trees, indices based on this approach could be expected to be in a majority. However, development of these indices is quite recent, and their use is still rather limited. Nevertheless the results obtained with some available indices are promising: not only do

they give a detailed insight into the stand structure, but they also can provide information on stand evolution and its underlying processes.

(iii)   *Statistical methods* – different techniques from spatial statistics (e.g. point pattern analysis and geostatistics) can help in describing stand structure. The development of these techniques was inspired by the widespread presence of spatial patterns in forests. Theoretical backgrounds and applications are given in Biondi *et al.* (1994), Kuuluvainen *et al.* (1996), Goovaerts (1997), Mateu and Ribeiro (1998) and Kint (1999). Because of their explicit spatial character, co-ordinates of all trees within the stand need to be known. This makes the statistical methods rather difficult to use in everyday forestry practice and limits its possible applications to specific research areas. Therefore, in this paper no further attention will be paid to this category.

Existing non-spatial indices for stand structure description

Based on the density of trees, a number of non-spatial indices can be defined to describe *positioning.* A review of these is given by Gleichmar and Gerold (1998). Von Gadow *et al.* (1998) propose an angle count sampling technique which enables a fast determination of the positioning within a stand. Unlike spatial indices, these non-spatial indices can at the very most indicate a trend: the degree of clustering or regularity cannot be estimated.

Most of the non-spatial indices for describing *mixture* are based on the relative proportions of species within a stand, e.g. Shannon's H' index (Magurran, 1988). However, H' is a measure for species richness and as such it does not take into account the spatial distribution of species. Contrary to common belief, these indices are therefore not suitable for describing mixture (Von Gadow, 1993; Füldner, 1995).

Horizontal differentiation is sometimes described with the non-spatial homogeneity coefficient of De Camino, in combination with the Lorenz-curve (De Camino, 1976; Aguirre *et al.,* 1998). This method is based on stem distribution data and calculates an indicative value for the mean homogeneity of diameters in the stand.

Different authors, elaborating on the principle of the non-spatial Shannon-index H', have proposed variants to describe *vertical differentiation* in a forest stand. MacArthur and MacArthur (1961) and Murdoch *et al.* (1972) calculated Foliage Height Diversity (FHD), based on the proportion of leaf area per 2m-high horizontal layer. A clear correlation has been shown between FHD and the diversity of birds and insects. However, Petty and Avery (1990) suggest a cautious approach when interpreting FHD indices, since it is possible for many different vegetation structures to generate the same value. As the determination of leaf area is very time consuming, FHD is often replaced by the Tree Height Diversity (THD). This index is based on the proportion of trees in each horizontal layer (Kuuluvainen *et al.,* 1996). Pretzsch (1996) proposes calculating THD, distinguishing within each layer between the different tree species, and renaming the index as a vertical species profile (A). Simple measures such as the number of vegetation layers within a plot can also be used as an index of vertical differentiation (Ferris-Kaan and Patterson, 1992).

As previously mentioned, non-spatial indices have limited power to describe stand structure because structural variation within the stand is not taken into account. This limits their applicability to evaluating the impact of silvicultural practices upon biodiversity if structural features are to be used as a surrogate measure of the latter. In addition, many

of these indices are well known and have often been applied in forest stands. Therefore, their application will not be discussed further.

Existing spatial indices for stand structure description

Spatial indices for describing *positioning* are generally based on the distance between neighbouring trees and density. The index of Clark and Evans (1954) is often used in forest practice. Spatial indices for describing *mixture* not only account for relative proportions of trees within a stand, but also indicate relations between species such as aggregation or segregation. The segregation index of Pielou (1977) is well known for this purpose, and has often been applied in forests. A recent alternative is the mixture index of Von Gadow (1993). Both *horizontal and vertical differentiation* can be described through the differentiation index of Von Gadow (1993). No other spatial indices have been developed for this purpose. These spatial indices are described in some detail in material and methods.

Objective

The aim of this paper is to provide a description and application of some existing spatial indices that show promise for use in forest practice. Their utility in describing stand structure in Scots pine forests and its evolution over time will be illustrated by an example of a mixed oak-pine stand in the Belgian Campine region.

MATERIAL AND METHODS

Experimental stand in Ravels

The state-owned forest of Ravels is situated in the north of the province of Antwerp, in the centre of the Campine region. The soil type is a humid to wet degraded podzol (types Zcg, Zdg and Zeg - Soil map of Belgium, National Geographical Institute). The variation of soil humidity can be explained by the explicit micro-relief.

The study area is a compartment (no. 10) with an area of 13.2 ha, in which Scots pine *(Pinus sylvestris)* was planted in 1908. Eventually, an even-aged spontaneous regeneration of pedunculate oak *(Quercus robur)* and red oak *(Q. rubra)* established beneath the canopy of Scots pine. Growth ring analysis in 1992 revealed that the pedunculate oaks were about 50 years old and the red oaks were only about 40 years old. Subsequently, a shrub layer consisting of black cherry *(Prunus serotina)* spontaneously developed.

Data about the treatment of the stand are available since 1957. Treatment was always intensive: between 1960 and 1992, approximately 160 m³ha⁻¹ (on average 5 m³ha⁻¹yr⁻¹) was harvested in thinnings. In 1993 a very heavy thinning was carried out removing more than 40 % of the standing volume. The total basal area fell from 25.6 m² ha⁻¹ in 1992 to 18.3 m² ha⁻¹ in 1998. The 1993 thinning mainly removed Scots pine trees that were ham-

pering the development of broadleaved trees, but all black cherries were also felled (followed by glyphosate treatment of the stumps).

At present, the stand is dominated by pedunculate oak and red oak, beneath a thin canopy of Scots pine. Since the elimination of black cherry in 1993, no new shrub layer or soil vegetation has developed. Although the stand has the potential for further vegetation development, hardly any natural regeneration has taken place, which is mainly the consequence of ungulate grazing.

Five strip transects were established, each of which had a length of 100 metres and a width of 20 metres. Within each transect, all trees with a circumference of more than 15 cm were measured, both in 1992 and 1998, for the following parameters: species, circumference at 1.30 metres, height, and position. In 1992 transects were established independently of each other, without a clear definition of relative position. In order to allow detailed analysis of the stand, Kint (1999) measured the relative position of the transects and recalculated the position of all trees relative to a common reference point (Fig. 1).
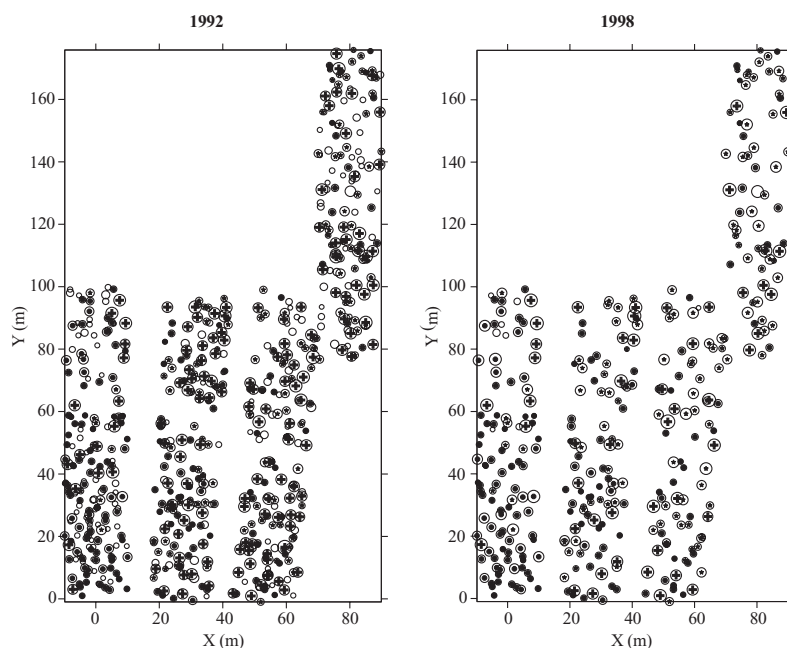

Fig. 1.–Relative position of four transects and of the measured trees in compartment 10 in Ravels in 1992 and 1998. The fifth transect is not shown because of its remote location from the others. The radius of circles is proportional to the circumference of trees

Posición relativa de cuatro transectos y de los árboles medidos en el tramo 10, en Ravels, en 1992 y 1998. El quinto transecto no se muestra debido a su localización más lejana respecto de los demás. El radio del círculo es proporcional a la circunferencia de los árboles

● = pedunculate oak; * = red oak; + = Scots pine; open circle = other species

In Figure 1, the effect of the heavy thinning in 1993 is evident. Distances between trees, which are necessary for determining nearest neighbour relations, were not measured in the field but were calculated from the locational co-ordinates of trees within the transects.

Description of positioning: CE

The commonly used index of Clark and Evans (CE) expresses the extent to which a forest stand deviates from the Poisson forest: the mean distance between a tree and its nearest neighbour (r_A) is compared to the expected mean distance if trees were randomly positioned (r_E).

For a mathematical derivation of r_E, the reader is referred to Clark and Evans (1954). Some major adaptations of r_E, that also take into account the surface and the circumference of the sample plots and therefore minimise edge effects, are summarised by Füldner (1995). Thus, the index of Clark and Evans can be calculated as follows:

$$CE = \frac{r_A}{r_E} = \frac{\frac{1}{N}\sum_{i=1}^{N} r_i}{0.5 \cdot \sqrt{\frac{A}{N}} + 0.0514 \cdot \frac{P}{N} + 0.041 \cdot \frac{P}{N^{3/2}}} \tag{1}$$

where
r_i = distance between tree i and his nearest neighbour (m)
N = total number of trees in the sample plot
A = surface of the sample plot (m²)
P = circumference of the sample plot (m)

In the case of a completely randomised distribution of trees within the stand, CE equals 1. If clumping occurs, the mean distance between neighbouring trees (r_A) will decrease and CE assumes a value smaller than 1. In regular positioned stands CE becomes larger than 1, with a maximal value of 2.1491 for a hexagonal arrangement of trees.

In order to test the calculated CE values against a significant deviation of 1, the proposed statistic of Clark and Evans (1954) is applied. They test the null hypothesis (H_0: CE = 1 and H_1: CE ≠ 1) using a standard, normally-distributed test value:

$$c = \frac{r_A - r_E}{\sigma_{r_E}} \quad \text{with} \quad \sigma_{r_E} = \frac{0.26136}{\sqrt{N \cdot \rho}} = \frac{0.26136}{\sqrt{N^2 / A}} \tag{2}$$

where
σ_{r_E} = standard deviation of r_E in a Poisson-forest of density ρ
N = total number of trees in the sample plot
A = surface of the sample plot (m²)
ρ = density of the sample plot = N/A

Description of mixture: S and DM

The *Segregation index* of Pielou (S) is often used, and is based on the relationship between the observed mixture and that expected under random conditions. Thus a distinction can be made between aggregation (intimate mixture, association between species), segregation (spatial separation) or neutral relation (random mixture) between two tree species.

When calculating S for two species, A and B, the number of trees of species A and species B which have a conspecific nearest neighbour has to be determined (a and d), as well as the number of trees of species A or B which are neighbours to species B or A (b and c) (see Table 1).

TABLE 1

DEFINITION OF THE PARAMETERS FOR THE CALCULATION OF S (SEGREGATION INDEX)

Definición de los parámetros para el cálculo del índice de segregación (S)

species	number of nearest neighbours of		sum
	species A	species B	
species A	a	b	m
species B	c	d	n
species A + species B	v	w	N

In stands with more than two species, the sum of a and b, or c and d, does not necessarily have to equal the number of trees of species A and species B, respectively. This is because each tree can be a neighbour to a tree other than either of the two species being examined. Using the parameters in Table 1, the segregation index S can be calculated as follows:

$$S = 1 - \frac{N \cdot (b + c)}{(v \cdot n + w \cdot m)} \tag{3}$$

The value of S is theoretically situated between –1 and 1. If the two tree species A and B are spatially separated, the number of observed mixed pairs will be smaller than would be expected if trees were randomly mixed, and S approaches the value 1. The index S equals 0 if both species are randomly mixed within the stand. Negative values for S are possible, but according to Pielou (1977) this is unlikely in plant communities, as this would indicate association between the two species.

A second commonly used index is the *Durchmischung* (DM) or mixture index of Von Gadow (1993), which was adjusted and applied for the first time by Füldner (1995). This index features two significant differences with the segregation index of Pielou: (i) not only the first, but multiple neighbours are accounted for and (ii) the index is not restricted

to the mixture of two species but can be determined for all the species together as well as for each species separately.

The mixture index for each individual tree i (DMn_i) can be defined as the probability that none of the n nearest neighbours is of the same species as tree i. The mean value for all trees (DMn) represents the index value for the stand. In Ravels forest the index was calculated for the three nearest neighbours (n = 3), according to Füldner (1995):

$$DM3_i = \frac{1}{3} \cdot \sum_{j=1}^{3} V_{ij} \quad V_{ij} = \begin{cases} 0 \rightarrow \text{tree i and neighbour j of the same species} \\ 1 \rightarrow \text{tree i and neighbour j of different species} \end{cases} \quad (4)$$

and

$$DM3 = \frac{1}{N} \cdot \sum_{i=1}^{N} DM3_i \quad (5)$$

where N = total number of trees in the sample plot

Depending on relative frequency and positioning of a certain species within a stand, the DM index can take values between 0 and 1: strongly represented or clustered species will result in low DM-values (indicating that homogeneous groups of tree species occur), whereas less frequent or regularly positioned species will have rather high DM-values (indicating their complete mixture within stand). To facilitate interpretation, the relative frequency of trees in each DM-class can be calculated and presented graphically. Equation (4) shows that the DM_i-value for each individual tree can only equal the following: 0 – 0.33 – 0.67 – 1, i.e. every value represents one DM-class.

Description of horizontal and vertical differentiation

To calculate his *Differenzierung* index (T), Von Gadow (1993) used circumference (TC) as well as height (TH). The principle of T will be explained by the example of TC, as described by Füldner (1995). In Ravels, both TC and TH were calculated.

The circumference differentiation of a single tree i (TCn_i) calculates, for the n nearest neighbours, an average of the ratio of the smallest over the largest circumference. The mean value for all trees (TCn) represents the index value for the stand. In Ravels forest the index was calculated according to Füldner's (1995) method, for the three nearest neighbours.

$$TC3_i = \frac{1}{3} \cdot \sum_{j=1}^{3} \left[1 - \frac{\text{MÍN} (C_i, C_j)}{\text{MÁX} (C_i, C_j)} \right] \quad (6)$$

and

$$TC3 = \frac{1}{N} \cdot \sum_{i=1}^{N} TC3_i \quad (7)$$

where
Ci   = circumference of tree i, for which the index is calculated
Cj   = circumference of the jth neighbour of tree i
N   = total number of trees in the sample plot

Values for TC range between 0 and 1, with values close to 0 for stands with a very low differentiation, since neighbouring trees have similar circumferences. High values indicate a high degree of circumference heterogeneity between neighbours. Aguirre et al. (1998) proposed splitting T-values into five categories, in order to facilitate inter-stand comparison:

(i) low differentiation – values from 0 to 0.2
(ii) moderate differentiation – values from 0.2 to 0.4
(iii) clear differentiation – values from 0.4 to 0.6
(iv) strong differentiation – values from 0.6 to 0.8
(v) very strong differentiation – values from 0.8 to 1

Since, for each individual tree, a differentiation value is known, the relative frequency of trees per category can be calculated and graphically presented, thus showing small-scale structural differences in the stand. Furthermore, this information reveals the underlying operative processes (as thinning or competition) causing stand evolution (Albert *et al.,* 1995; Aguirre et al., 1998; Kint, 1999).

RESULTS

An overview of the results after calculation of the various indices in Compartment 10 in Ravels forest, is given in Table 2.

The positioning-index of Clark and Evans (CE)

Values of CE clearly indicate that none of the species present are clumped at the stand level. It is important to note that this does not exclude the presence of individual clusters in the stand as Figure 1 would suggest for pedunculate oak. Both pedunculate oak and red oak are randomly positioned. Scots pine, as well as all trees considered together, show a very significant tendency towards regularity as a result of the various selective thinnings since the origin of the stand. Lastly, it is interesting that the values obtained in 1998 are higher than for 1992 (although the difference is never significant). This could be interpreted as a slight shift towards greater regularity in the stand. These results seem to confirm the findings of Warrington (1994), Füldner (1995) and Gleichmar and Gerold (1998) that in managed stands there is often a tendency towards regularity as a result of management practices that are focused on freeing future trees and thinning clusters.

The segregation-index of Pielou (S)

The S-index most frequently shows values close to zero indicating a random mixture of trees. The only S-value for which a significant difference from zero can be assumed with sufficient certainty is that for the mixture between pedunculate oak and red oak. The high index value suggests spatial separation between these two species, which is logical

TABLE 2

**RESULTS OF THE CALCULATION OF THE INDICES CE, S, DM, TC AND
TH IN COMPARTMENT 10 IN RAVELS IN 1992, IN 1992 WITHOUT BLACK
CHERRY AND IN 1998**

*Resultado del cálculo de los índices CE, S, DM, TC y TH en el tramo 10 de Ravels en
1992, en 1992 sin incluir el cerezo negro, y en 1998*

year	species[a]	CE[b]	S			DM	TC	TH
			red oak	Scots pine	bl. cherry			
1992	pedun. oak	0.999	0.373	−0.012	−0.104	0.644	0.254	0.175
	red oak	0.957	~	−0.167	0.197	0.645	0.26	0.159
	Scots pine	1.154**	~	~	−0.194	0.797	0.122	0.085
	black cherry	1.016	~	~	~	0.810	0.268	0.292
	total	1.069**	~	~	~	0.722	0.419	0.317
	tot. min bc.[c]	1.072**	~	~	~	~	0.388	0.253
	pedun. oak	~	0.327	−0.005	~	0.504	~	~
1992 min bc. [d]	red oak	~	~	−0.174	~	0.6	~	~
	Scots pine	~	~	~	~	0.726	~	~
	total	~	~	~	~	0.691	~	~
	pedun. oak	1.019	0.417	0.043	~	0.42	0.274	0.19
1998	red oak	0.969	~	0.07	~	0.426	0.269	0.12
	Scots pine	1.148**	~	~	~	0.89	0.117	0.105
	total	1.099**	~	~	~	0.501	0.339	0.203

(a) species: pedun. oak = pedunculate oak; tot. min bc. = total stand without black cherry.

(b) A significant difference from 1 is indicated by the symbol ** for a level of significance of 1%. CE>1 indicates a tendency towards regular spacing; CE<1 indicates a tendency towards clumping.

(c) For CE, TC and TH, two total values are calculated in 1992: one with and another without black cherry. Thus the impact of this species on the total value for these indices is estimated.

(d) For S and DM, the mixture in 1992 is also calculated on a data set from which black cherry has been removed. Thus the impact of this species on the mixture is estimated.

since red oaks appear to be about 10 years younger than pedunculate oaks and would therefore have mainly become established in open patches within the stand.

It is surprising how many negative S-values occur, especially when considering the remark from Pielou (1977) that this should rarely be the case. A negative value, though probably never significant in this case, suggests a tendency towards association of species. In an intensively managed stand, however, this is a very improbable process. Therefore we suggest these negative values to be a result of management practices being focused on the liberation of future trees from conspecific competitors. This creates the effect that each species will have more often a different species as nearest neighbour than expected under random mixture. As S is calculated using only one nearest neighbour for each tree, this effect is reflected in negative index values. In conclusion, negative values for S in Ravels forest clearly do not indicate association between species, but only prove an artificially induced alternation of species over small distances.

The mixture-index of Von Gadow (DM)

The similar values of DM for all species in Ravels forest (Table 2) indicate that each was mixed with the others to roughly the same extent. The decrease in DM between 1992 and 1998 showed a general decline in the mixing of species within the stand. Scots pine was the only exception to this. The reason is clarified through an examination of its DM_i-distribution, separated into four classes as mentioned earlier (Fig. 2):
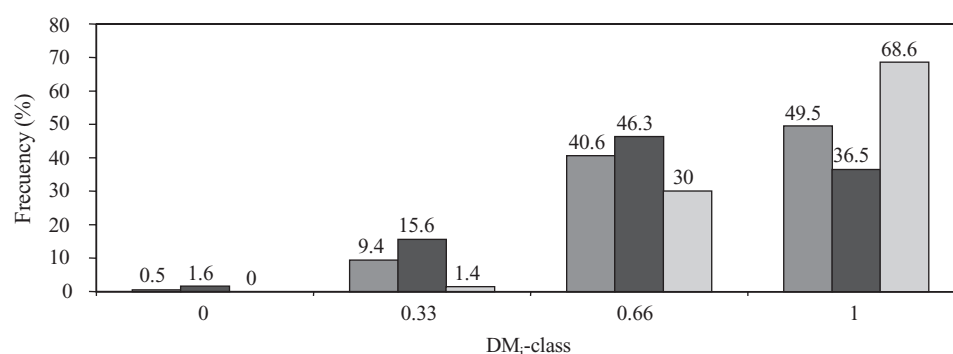

Fig. 2.–DM_i-distribution (%) of Scots pine in compartment 10 (Ravels) over four classes in 1992 (left), 1992 without black cherry (middle) and 1998 (right).
(For the definition of the classes: see text)
Distribución (%) de DM_i, de Pino silvestre en el tramo 10 de Ravels en cuatro clases, en 1992 (izquierda), en 1992 sin incluir al cerezo negro (medio) y en 1998 (derecha).
(Para la definición de las clases: ver el texto)

When analysed in its separate components, the 1993 thinning affected the DM-value of pine in two opposite ways. If no pine trees had been removed, the total elimination of black cherry would have caused a decline of DM for pine – as was the case for the other species – by increasing its relative frequency within the stand. However, the heavy thinning of pine trees further increased the relative frequency of all other species, thereby accentuating the general decline of DM. But for pine itself, the opposite effect occurred so that the 1998 DM value exceeded that found before thinning.

The differentiation-index of Von Gadow (T)

No substantial differences are found between results for TC and TH, so they can be considered together. In general a low to moderate differentiation exists and this tendency is even more pronounced for TH than for TC. This means that neighbouring trees show only very small differences in dimensions.

The evolution of T-values between 1992 and 1998 has different causes. The differentiation of pedunculate oak, for example, may have increased as a result of the selective thinning in 1993 (see Fig. 3 for TC). The importance of this change is not known, but if
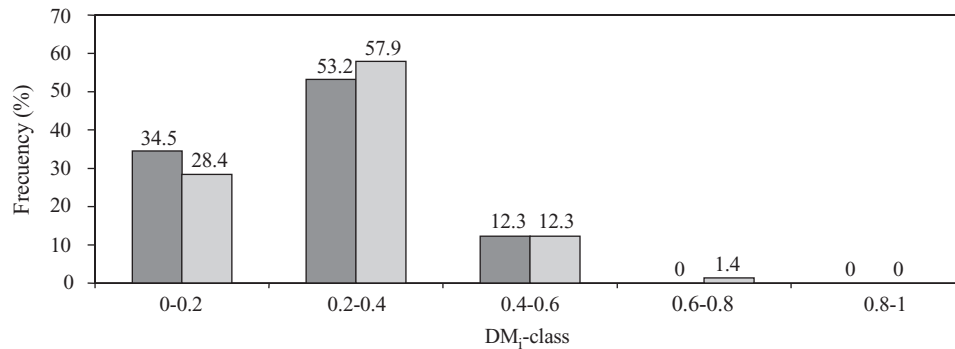
Fig. 3.–TC$_i$-distribution of pedunculate oak in compartment 10 in Ravels over five classes in 1992 (left) and 1998 (right). (For the definition of the classes: see text)

Distribución del TC$_i$ del roble pedunculado en el tramo 10 de Ravels, en 5 clases en 1992 (izquierda) y 1998 (derecha). (Para la definición de las clases: ver el texto)

confirmed, the reason may be that freed trees often find a previous competitor of similar dimensions replaced by a much smaller tree from the shrub layer.

The decrease of total differentiation is mainly due to the complete elimination of black cherry from the stand. The T$_i$-distribution can be a very useful tool for interpreting the evolution of T-values between 1992 and 1998, especially if more than one process is influencing the evolution in opposite directions.

When interpreting T-values it must be borne in mind that this index only describes local differentiation: heterogeneity is only considered within the immediate vicinity of a tree. Thus, a low differentiation does not exclude the presence of spatial autocorrelation, but can even be an indication of it (Kint, 1999).

DISCUSSION

The usefulness of the CE-index in describing positioning is clearly shown by the example in Ravels forest. The index is easy to calculate, although the determination of the distances between neighbouring trees can seem quite laborious. The reliability of the results is significantly higher with a correction for edge effects (Füldner, 1995). According to Gleichmar and Gerold (1998) who made an extensive comparative study of existing positioning indices the index of Clark and Evans has the greatest practical application in managed forest stands. They particularly emphasise the simplicity of calculation and the limited index range (between 0 and 2.1491), which simplifies the comparison between different stands. In stands where clumping of tree species can be expected, CE is less reliable because of its calculation depending only on one nearest neighbour for each tree (Pielou, 1977; Smaltschinski, 1998). In that case, Kotar (1993) and Gleichmar and Gerold (1998) offer some valuable alternatives to CE.

Both indices S and DM complement each other in describing tree mixtures. S provides specific information about the mutual mixture of two species, allowing species complementarity to be studied. DM describes whether one species is intimately mixed with all the others or not, although by retaining only two species and calculating DM on this reduced data set, information about the mutual mixture of these two species can also be obtained (Kint, 1999). Therefore, the description of mixture can possibly be limited to the calculation of DM, without the loss of much information.

As S only takes into account one nearest neighbour for each tree, Füldner (1995) states that it is possible to draw incorrect conclusions in intensively managed and complex mixed stands. This was confirmed in Ravels forest, through an analysis of the calculated negative S-values. This disadvantage of S is rectified by DM, which takes into account three neighbours. Finally, the possibility through the DM_i-distribution of achieving a clear insight in the processes within a stand that determine the mixture and its development, makes the DM index a better choice.

The T-index not only gives an accurate indicative value for the degree of heterogeneity between dimensions and of its change over time, it also provides a detailed insight in the development processes within the stand through calculation of the T_i-distribution (see also Albert *et al.,* 1995; Füldner, 1995; Aguirre *et al.,* 1998).

For CE a statistical test exists (Clark and Evans, 1954), and its application in Ravels forest substantially simplifies the interpretation. For S, a χ^2-test may be used to judge whether the observed mixture departs significantly from that under random conditions (Pielou, 1977). One of the major disadvantages of DM and T is the absence of any statistical test: it is impossible to know whether index values between species or over time significantly differ from each other.

The absence of any correction for edge effects is a substantial disadvantage of all indices, apart from CE. The calculated nearest neighbours for a tree standing near the edge of a transect are not necessarily the effective nearest neighbours. As a result, a distortion of the correct index value can arise. For clarity we should mention that, to calculate the discussed indices, other types of plot besides the transects used in Ravels can be used, e.g. square or circular plots. It should however be emphasised that the error caused by edge effects is bigger when small sample plots are used, and that the edge effect correction for CE is not valid in the case of circular plots.

The indices presented in this paper are all easy and fast to calculate, which is often seen as an advantage for their practical use in forests. Nevertheless, many researchers are put off by the large amounts of data necessary as it is often supposed that co-ordinates of all trees have to be measured. However, analysing each of these indices, it becomes clear that only the relative position of trees with respect to their neighbours is required. Therefore, a sampling technique was developed by Füldner (1995), with a variable number of sample trees according to the degree of detail required. For each of these trees the distance to their three nearest neighbours is measured, as well as the dimensions of these four trees. This so-called *structural group of four* is a practical and fast technique, which has been shown to produce very accurate results for CE, DM and T (Albert *et al.,* 1995; Aguirre *et al.,* 1998; Jiménez *et al.,* 1998). We have not yet found an application for the calculation of S.

A great advantage of the *structural group of four* technique is that the problem of edge effects is avoided. In terms of time for the fieldwork, Füldner (1995) mentions that 75 minutes were required to measure 40 points in a stand of 11ha. This time could be reduced further if no calculation of CE was necessary, as no distance measurements would

have to be carried out. Furthermore, in existing data sets the technique allows a sub-sample of points to give a valuable indication of index values.

CONCLUSIONS

The quantitative description of forest structure has a wide range of possible applications in modern forest management, biodiversity research and forest inventory. In these applications, it is mainly the structure at the forest stand level which is relevant. Stand structure is described in a complete and simple way using three structural characteristics: positioning, mixture and differentiation. In order to quantify this, many non-spatial and spatial indices have already been developed.

The Ravels forest example clearly demonstrates the usefulness of the indices presented (CE, S, DM and T) in describing stand structure. In Table 3 the major characteristics of each of the discussed indices are summarised.

TABLE 3

OVERVIEW OF THE MAJOR CHARACTERISTICS OF THE DISCUSSED INDICES

Síntesis de las principales características de los índices analizados (para una explicación detallada, ver el texto)

index	data requirements for each sample tree i	edge effect correction[a]	statistical test[a]	distribution[a]
CE	distance to the first nearest neighbour of tree i	+	+	–
S	species of tree i and of its first nearest neighbour	–	(+)	–
DM	species of tree i and of its three nearest neighbours	–	–	+
T	dimension of tree i and of its three nearest neighbours	–	–	+

(a) + = existing; – = not existing
For detailed explanation: see text.

The positioning index CE is easy to calculate, can be corrected for edge effects, and offers a statistical test. The mixture index S describes the mutual mixture between two species, but can lead to wrong conclusions in intensively managed and complex mixed stands. Therefore it seems better to use DM in describing a mixture. The differentiation index T has proved to be accurate and simple in use. In addition to providing a description of the present structure, its evolution in time can also be analysed. The indices DM and T give information about stand evolution processes by means of their respective distributions. For S, DM and T a distortion of the correct index value can arise as a result of edge effects. This is avoided by using the structural group of four sampling technique, which offers a practical and fast alternative to measuring all trees within plots.

The link between structure and biodiversity in forests is obvious: tree positioning significantly affects light regimes within the stand; the number and distribution pattern of different tree species determines deposition and litter composition and thereby controls a

variety of biotic and abiotic processes; vertical and horizontal differentiation, resulting from positioning, mixture, age distribution and competition, directly and indirectly affects animal and vegetation species richness. It therefore seems relevant to propose the indices for positioning, mixture and differentiation discussed above as possible tools for indirectly quantifying biodiversity through habitat characteristics. For the moment though, no reference values for these indices exist, thereby making it impossible to interpret them in terms of biodiversity. It would therefore be relevant to develop such reference values, e.g. by outlining typical index values for different types of natural forest stands within a particular region. Such values could then serve as possible target-values in management plans for Scots pine stands where biodiversity is one of the main objectives.

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RESUMEN

Cuantificación de la estructura de los rodales aplicada a masas de Pino silvestre (*Pinus sylvestris* L.)

En este trabajo se discute el uso y las posibilidades de aplicación de la descripción de la estructura de las masas. La descripción cuantitativa de la estructura del rodal se estudia por medio de tres características estructurales: posición, mezcla y diferenciación. Se proponen varios índices espaciales y no espaciales. Se aplican varios índices espaciales a rodales mixtos de pino y roble en la región belga de Campine, y se consideran las ventajas y desventajas de los índices calculados. Los resultados señalan la utilidad de estos índices, tanto para describir exactamente la estructura del rodal, como para reflejar los procesos operativos que causan la evolución del rodal.

PALABRAS CLAVE: Estructura del rodal
Índices
Pinus sylvestris

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