Assessment and Monitoring of Forest Ecosystem Structure

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Abstract—*Characterization of forest ecosystems structure must be based on quantitative indices that allow objective analysis of human influences or natural succession processes. The objective of this paper is the compilation of diverse quantitative variables to describe structural attributes from the arboreal stratum of the ecosystem, as well as different methods of forest inventory to obtain such indices.*

For the evaluation of the species structure the indices of Shannon H′ and species profile A, segregation S of Pielou and the species mingling index Mi are discussed. The aggregation index R of Clark & Evans and the contagion index Wi, were included in order to describe the horizontal structure of the ecosystem. Finally, for the characterization of the dimensional structure, the homogeneity coefficient H and the indices of diameter differentiation TDi and height differentiation THi were analyzed.

Introduction

One of the aims of the forest management is the search for new inventory and planning methods of the forest ecosystems, particularly in an era in which discussions on the conservation and promotion of biodiversity are rivaled, by the increase in the demand of forest products. A gradual transformation of medium- and long term silvicultural policy is taking place with the abolishment of even-aged pure forests and a greater preference of uneven-aged mixed forests. For such ecosystems indices that quantitatively characterize the structure and diversity are required. Uneven-aged forest management has become an important factor significantly influencing forestry research. The challenge is to obtain the new indicators of sustainability of forest resources.

The indices for characterizing the structure and diversity of the ecosystems allow a better reproduction of the condition of the forest in a given moment and of its evolution in time. Such indices would have to be considered in addition to conventional variables such as diameter, height, basal area, volume, age, and density, in order to achieve a better description of the stands.

The objective of this work is to discuss variables for the quantitative description of the structure and diversity of forest ecosystems. The characterization levels considered include species diversity and structure, spatial structure and the dimensional diversity of the ecosystem. Case studies results of the application of such indices in Mexican forests are presented.

Species Diversity and Structure

Index H′ of Shannon

The Shannon index (Shannon 1948) is one of the most employed variables for the estimation of species diversity; for its determination is employed the formulation:

$$H' = -\sum_{i=1}^{s} p_i \cdot \ln(p_i)$$

S = number of present species
p_i = proportion of the species $p_i = n_i / N$
N_i = number of individuals of the species i
N = total number of trees

As an example of the application of this index the following types of ecosystems with different species composition are presented. These conditions were found in forest ecosystems in the Federal State of Nuevo León, Mexico:

- 100% *Pinus pseudostrobus*; H' = 0.00
- 80% *P. pseudostrobus*, 20% *Quercus rysophylla*; H' = 0.50
- 50% *P. pseudostrobus*, 20% *Q. rysophylla*; H' = 0.69
- 70% *P. pseudostrobus*, 20% *Q. rysophylla*; 10% *Juniperus flaccida*; H' = 0.80

The value H' increases according as a greater number of species occurs and the individuals proportion of the species is more homogeneous. H' depends not only on the number of species present in an ecosystem, but on the frequency with which they are represented (Pommerening 2002).

Species Profile A

To characterize the vertical structure of the species of a forest ecosystem, Pretzsch (1996) based on the index of Shannon, developed the variable profile of species A:

$$A = -\sum_{i=1}^{s} \sum_{j=1}^{z} p_{ij} \cdot \ln\left(p_{ij}\right)$$

S = number of present species

Z = number of height strata (3 in this case)

P_{ij} = proportion of species in the height strata

$$p_{ij} = {n_{ij}}/{N}$$

n_{ij} = number of individuals of the species i in the zone j

N = total number of trees

Pretzsch defines three strata for the application of the index A; stratum I comprises from 80 percent to 100 percent of the maximum height of the trees; stratum II 50 percent to 80 percent and stratum III 0 to 50 percent.

Differing from the index of Shannon, index A characterizes the location of the species in different height strata. A takes values between 0 and a maximum value A. A value A of 0 means that the stand consists of only one species that occurs in one sole stratum. A maximum is obtained when all of the species occur in the same proportion in the stand as well as in the different strata.

In an ecosystem constituted by 11 arboreal species, values of A = 2.07 and Amaximum = 3.50 were obtained.

Segregation Index S of Pielou

The segregation index S of Pielou (1961) describes the combination or mingling of two species, that is, the spatial classification of a species in relation to the other. This index is based on the ratio between the observed and the expected number of mixed pairs. To obtain it the species of all the trees of a given surface and that of their nearest neighbor is determined, obtaining the number of individuals of the species 1 and 2 (m, n), as well as the number of trees with neighbors of the same species (a, d) and neighbors of different species (c, b). The index S is obtained then as:

$$S = 1 - \frac{\text{observed number of mixed pairs}}{\text{expected number of mixed pairs}}$$

S is calculated as of the following data:
nearest neighbor
species 1species 2total
reference treespecies 1abm
reference treespecies 2cdn
vwN

through the formulation:

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

S takes values of -1 to 1; -1 represents the maximum possible mutual attraction among the two species, 0 shows an independent distribution and 1 corresponds to the maximum possible positive segregation. Values of $S < 0$ mean an association between the species; $S > 0$ corresponds to a segregation, this is, spatial separation of the species.

In figure 1 two fractions of ecosystems with different distribution of the species are presented. In the area a) S = - 0.72, by it the species present an evident association; opposite to the foregoing, in the area b) with a value of S = 0.79, a clear segregation of the species is observed.

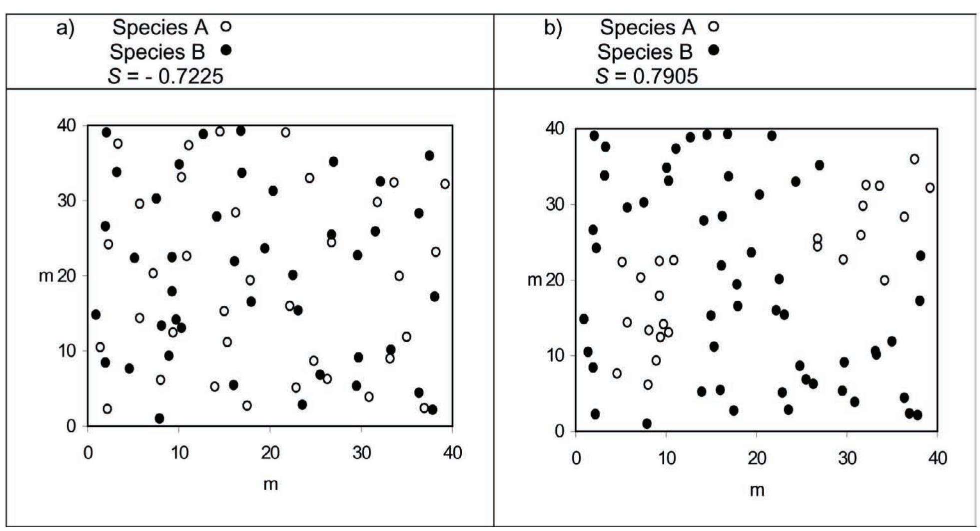

Figure 1. Index of segregation S of Pielou for two fractions of ecosystems.

Species Mingling Index M_i

The species mingling index M_i is defined for a reference tree and its four nearest neighbors as the relative proportion of neighboring trees of different species (Gadow 1999). This index was developed in order to avoid the limitation of the index of Shannon, which does not allow inferring information on the spatial distribution (vertical and horizontal) from the species. Forests with equal H' can present a very different spatial distribution of the trees.

The species mingling index is obtained from the function:

$$M_i = \frac{1}{n}\sum_{j=1}^{n} m_{ij}$$

m_{ij} takes a value 0 when the neighbor belongs to the same species of the reference tree; otherwise it has a value of 1.

Since small m_{ij} it is a discrete binary variable, capital M_i can take the following values:

0.0 when all the individuals of the group (five) belong to the same species;

0.25 when one of the neighbors of the reference tree belongs to other species;

0.50 if two of the neighboring trees belong to other species

0.75 if three of the neighbors of the reference tree belongs to other species and

1.00 if the neighboring four of the reference tree belong to different species

The middle species mingling value is calculated through:

$$M = \frac{1}{N}\sum_{i=1}^{n} Mi$$

N = number of trees in the stand

Figure 2 shows species mingling values for a stand of *Picea chihuahuana*, *Abies durangensis* and *Cupressus lindley* in the Federal State of Durango, Mexico. The mingling distribution of *Picea chihuahuana* shows that the species is surrounded by either three or even four neighbors that belong to a different species. In contrast, *Cupressus lindleyi* occurs in a variety of mingling constellations: either in pure groups (about 10 percent), in groups where half of the trees are *Cupressus lindleyi* (about 35 percent) and in groups where none of the neighbors is *Cupressus lindleyi* (about 10 percent). *Abies durangensis* does not form pure or almost pure groups, but occurs most frequently as a single tree among other species.

Spatial Structure

Index of Aggregation R of Clark & Evans

The aggregation index R of Clark & Evans (1954) describes the degree of regularity in the distribution of tree positions. This index is based on the relationships of distance between neighboring trees and, although widely used in botany and vegetation science, is rather unknown in the practice of forestry. It is simply calculated as the ratio between the observed and expected average distance for a random distribution between neighbouring trees:

$$R = \frac{\text{r observed}}{\text{r expected}}$$

R takes on a value of 1 if the distribution of tree positions is random and trends toward zero with increasing aggregation. The maximum possible value is 2.15. Values greater than 1 indicate increasing tendency to regularity.

The index of Clark & Evans is based on the relationships of distance between neighboring trees. For all the trees N of a surface A the distances r_i, i = 1. N to their nearest neighbor are obtained. The mean distance is calculated through:

$$\text{r observed} = \frac{\sum_{i=1}^{N} r_i}{N}$$

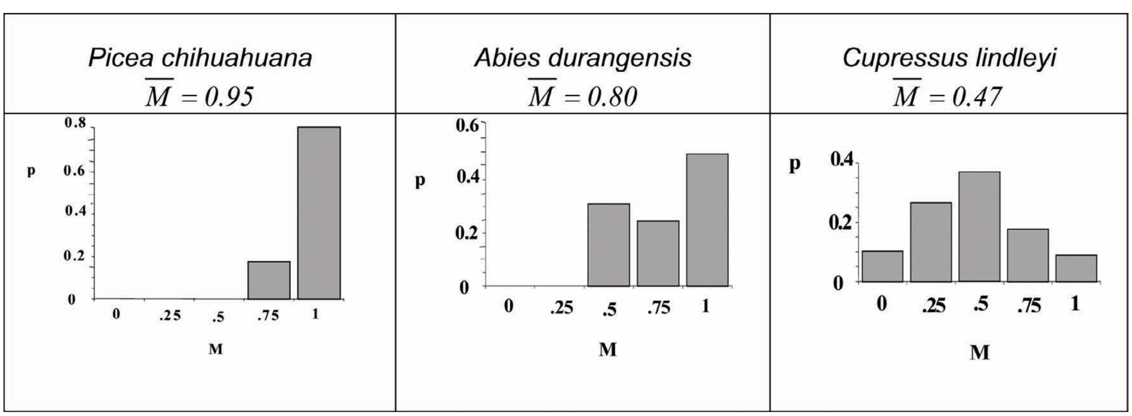

Figure 2. Distribution of the species mingling index in a mixed ecosystem.

r observed is related to the mean distance expected for the random distribution of the trees:

$$\text{r expected} = \frac{1}{2\sqrt{N/A}}$$

An example is presented in the figure 3, showing the distribution of the trees in fractions of two stands of pine-oak in Northeastern Mexico's. Stand a) has a value of R = 0.98, that indicates a random distribution of the trees. In stand b) R is 0.89, thus presents a distribution with trend to the conformation of groups.

Contagion Index W_i

The contagion index W_i (Hui and Gadow, 2002, Aguirre and others 2003) describes the regularity of the distribution of the neighboring trees to a reference tree. The determination of this index is based on the measurement of the angles between two neighbors of the reference tree and its comparison with a standard angle obtained through:

$$\alpha_o = 360/n \pm 360/10n$$

n = number of neighboring trees considered

The contagion index W_i is then defined by the proportion of the smaller angles α to the standard angle $\alpha 0$:

$$Wi = \frac{1}{n}\sum_{j=1}^{n} w_{ij}$$

w_{ij} has a value = 1 when the jth angle between two next neighboring trees is smaller or equal to the standard angle $\alpha 0$, otherwise it takes a value of 0.

If n = 4, W_i can present the following values:

0.0 if none of the angles is smaller to standard angle,

0.25 if one of the angles is smaller to standard angle,

0.50 when two of the angles α are smaller to standard angle,

0.75 if three of the angles α are smaller to standard angle, and

1.0 when the four angles α are smaller to standard angle.

The average value of the contagion index is calculated through:

$$\overline{W} = \frac{1}{N}\sum_{i}^{N} w_i$$

Values of $\overline{W}$ 0.5 correspond to a random distribution of the trees, those greater to this value represent a grouping trend. Smaller values indicate a trend towards regularity. For the ecosystems of figure 4 $\overline{W} = 0.53$ indicates a random distribution of the trees while $\overline{W} = 0.59$ corresponds to a trend to a grouping of the trees.

Dimensional Diversity

Homogeneity Coefficient H

The homogeneity of a stand can easily be described through the employment of the homogeneity coefficient (H) of De Camino. H is expressed through the percent relationship between number of trees and volume by diameter classes (De Camino 1976). In a totally homogeneous forest all the trees have the same volume; in heterogeneous one a high percentage of trees represent a small proportion of volume, while few individuals contribute with the greater proportion of the volume.

The homogeneity coefficient H is determined through:

$$H = \frac{\sum_{i=1}^{n-1} SN\%}{\sum_{i=1}^{n-1} SN\% - SV\%}$$

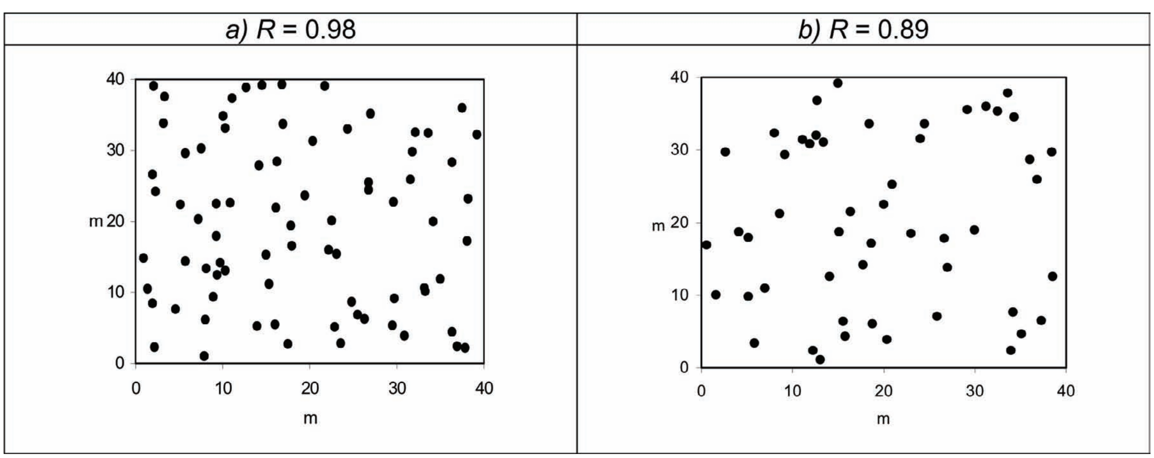

Figure 3. Index of Clark & Evans for two ecosystems with different horizontal structure.

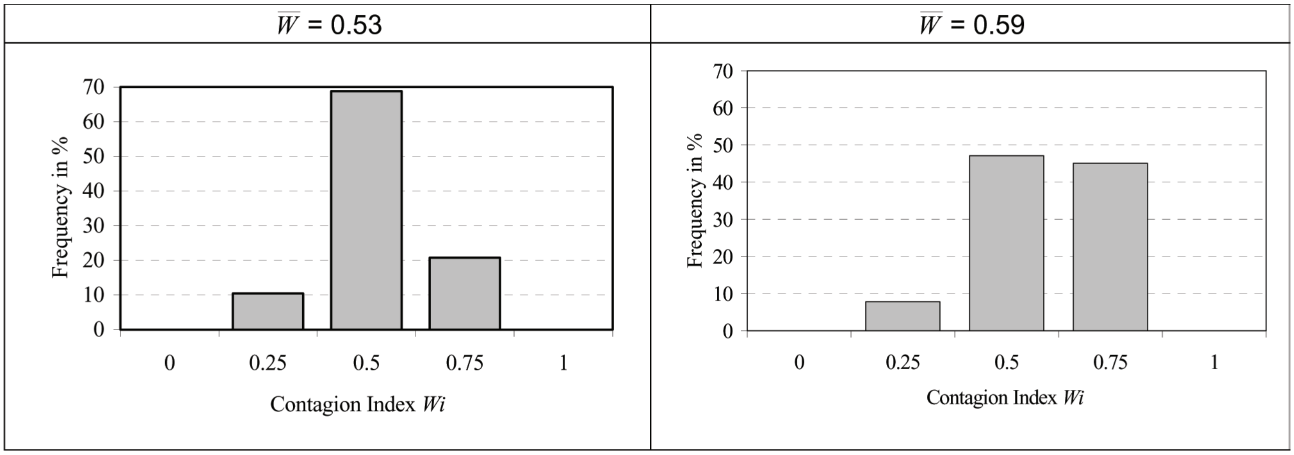

Figure 4. Distribution of the trees in the contagion index W_i, in two stands with different horizontal distribution.

SN% = sum of the percentages of number of trees to the diameter class i

SV% = sum of the percentages of volume to the diameter class i

Figure 5 shows the homogeneity coefficients (H) obtained in the unthinned and thinned fractions of a stand of *Pinus cooperi* and *P. leiophylla*, as well as the corresponding Lorenz curves. A greater homogeneity of the thinned area is observed here, the H value is greater (6.03) and the Lorenz curve is found accordingly nearer the reference line.

Dimension Differentiation Indices

The dimension differentiation indices describe the relationship between a given tree and its nearest neighbor and are defined by the quotient between a dimensional variable of the smaller tree and the corresponding of the bigger tree, subtracted form 1. The diameter differentiation TD_i, for example, is obtained through the function:

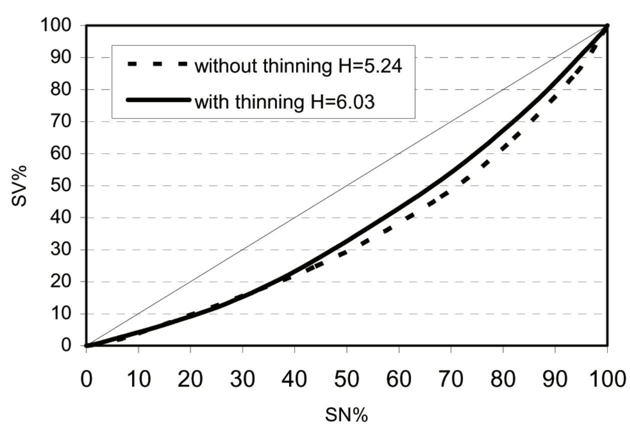

Figure 5. Homogeneity coefficients and Lorenz curve for the unthinned and thinned fractions of an ecosystem.

$$TDi = \frac{1}{n}\sum_{j=1}^{n} td_{ij}$$

td_{ij} is derived from the relationship of the diameters from neighboring trees deducted from 1:

$$td_{ij} = 1 - \frac{smaller\left(d_{1.3i}, d_{1.3j}\right)}{bigger\left(d_{1.3i}, d_{1.3j}\right)}$$

The middle diameter differentiation value is:

$$TD = \frac{1}{N}\sum_{i=1}^{N} TD_i$$

N = number of trees of the stand

A TD*i* value of 0 means that both trees have the same diameter. As the difference of the diameters increases, the value of TD*i* also grows.

Other dimensional variables may similarly be employed in addition to the diameter differentiation TD*i*. These would include, for example, the indices of height differentiation TH*i*, and of crown cover differentiation TKS*i* (Aguirre and others 1998, Jiménez and others 1998, Del Río and others 2003).

Figure 6 shows the distribution of the trees of a mixed forest in the classes of diameter differentiation 0.0-0.2, 0.2-0.4, etc. For *Pinus pseudostrobus* a greater proportion of the trees present a scarce diameter differentiation with respect to their neighbors (class 0.0-0.2); *Quercus rysophylla* shows a similar frequency, which has more than half of the cases with a diameter difference to their next neighbor smaller than 20 percent. *Juniperus flaccida* behaved differently in that the greater proportion of trees shows differences of diameter between 40 and 60 percent (class 0.4-0.6).

The frequency of height differentiation classes for the previous species is observed in here. P*inus pseudostrobus* presents smaller height differentiation that the rest of the species, about 60 percent of the trees has values smaller

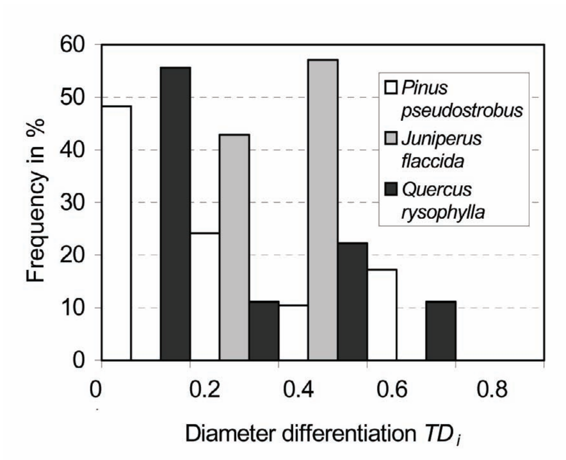

Figure 6. Distribution of the trees in the classes of diameter differentiation.

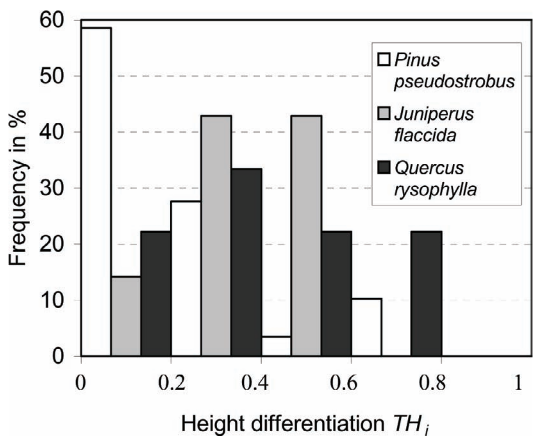

Figure 7. Distribution of the trees in the classes of height differentiation.

than 0.2 (fig. 7). In contrast to diameter differentiation, *Juniperus flaccida* showed a minor height differentiation, while for *Quercus rysophylla* the tree frequency in the class 0.6-0.8 is increased, this is, more than 20 percent of the trees showed a height differentiation greater than 60 percent.

Concluding Remarks

The indices considered in this paper constitute an alternative for the evaluation and monitoring of the structure and diversity of forest ecosystems on quantitative grounds. The application of such indices in an integral method of forest inventory allows a better description, reproduction and monitoring of ecosystems, as well as the development of indicators of sustainability of forest resources management.

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