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RESEARCH ARTICLE

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Structural diversity of forest communities on Baihuashan Mountain, Beijing

Abstract The structural diversity of forests on Baihuashan Mountain, Beijing, was surveyed by a plotless method combined with branch and leaf coverage estimation in the different layers. New structural indices were constructed, calculated and compared among different communities. On the basis of previous work, structural diversity of forest communities at the stand level was described by a vertical complexity index and a horizontal heterogeneity index. From a correlational analysis among the new indices and other commonly used biodiversity indices, we concluded that the new indices are closely related to a tree height inequality index and the Shannon-Wiener index of the tree and shrub layer, which indicated that the new indices were good at indicating structural diversity in the different forests on Baihuashan Mountain. The results show that, in natural forests, structural diversity of pioneer communities is much lower than in late successive communities. In plantations, structural diversity is determined by the stage of development and tree species. Tending would increase horizontal heterogeneity and decrease vertical complexity.

Keywords structural diversity, Baihuashan Mountain, forests, tending

1 Introduction

Structure and diversity of forest communities form the basis from which we can understand the ecosystem functions of forests and carry on sustainable forest management. The results of many micro-scale studies show that communities with high spatial heterogeneity contain more animal and plant species and that this diversity is often closely the related to diversity of micro-habitats, especially in the forests (MacArthur and MacArthur, 1961; Gao et al., 1992). At the same time, the structure of the forest community is correlated with many functional characteristics of the forest, such as interception of precipitation, modification of the micro-climate, promotion of tree growth and enhancement of community stability (O'Hara et al., 1996; Chen et al., 1997). However, it is not easy to distinguish definitely between spatial structure and species biodiversity in plant communities, since both affect some ecological processes simultaneously. Furthermore, community structures change over the course of forest development according to modern forest ecology. Therefore, structural diversity of a community can be regarded as a criterion for dividing developmental stages as well as a substitute for species diversity in a forest community (Kohm and Franklin, 1996; Oliver and Larson, 1996). Given this knowledge, a corresponding ecosystem management strategy could be designed to enhance the development of forest stand structures, promote biodiversity and upgrade the provision of ecosystem services by the forest (Lahde et al., 1999; Bordelon et al., 2000). In short, the study of structural diversity of forest communities deserves strong support in both theoretical ecology and ecosystem management practices.

For our study, we surveyed the structural diversity of forests on Baihuashan Mountain, Beijing, by means of a plotless method combined with estimates of branch and leaf coverage in different layers. Structural diversity indices were amended on the basis of previous works (Zheng and Luo, 2003) and calculated for each forest community for comparison and analysis of the differences among various communities in order to provide theoretical support for forest management in this region.

2 Methods

2.1 Natural conditions in study area

The Baihuashan Mountain at the northern end of the Taihang Mountains is situated between 39°49′–39°53′N, 115°30′–115°38′E west of Beijing, China. The elevation of

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the main body of the mountain is relatively high and the ridges stretch very far. The highest peak is 2035 m. The region has a typical monsoon climate with an average temperature of -10°C during the coldest month and 21°C during the hottest month. The annual precipitation in this region is over 700 mm, with most of it occurring in June, July and August. Parent rock material of Baihuashan Mountain is lava which erupted during the Mesozoic and Jurassic eras. Andesite is common. There are three main soil types in the region. Meadow soils occur in the area above 1900 m elevation, brown soils are between 1200–1900 m and cinnamon soils are found below 1200 m elevation (Pan, 1988).

Although the original vegetation in the region is a typical temperate deciduous broad-leaved forest, the present forests are composed of secondary forests and plantations because of long-term human activities. Major plant communities in the natural forests are dominated by *Betula platyphylla*, *Quercus wantaishanica* and *Populus davidiana*. Plantations consist largely of *Larix principis-rupprechtii*, *Pinus tabulaeformis*, etc. (Liu and Ren, 1992).

3 Study method

3.1 Field survey

Sample plots were established in the research area. Each plot covers 3600 m^2. We surveyed plots by a plotless point-centered quarter method combined with an estimate of coverage of branches and leaves in plant layers in order to investigate the structural diversity of communities. At the same time, a representative plot was measured as a control for tree information in each community. The basic characteristics of five sample plots surveyed are presented in Table 1 (tree indices are based on control plots).

Detailed survey methods were as follows. Four sample lines were established within each plot. The distance between lines was 15 m and six points were arranged on the line with 10 m between each point. At each point, one tree with a diameter at breast height (DBH) over 4 cm, nearest to the center point in each of the four quadrats was measured. And we recorded species, DBH, height, crown width and height to the lowest branch. The same information was also recorded for the control plot. At each point, one 2 m × 2 m shrub quadrat and two 1 m × 1 m grass quadrats were established along the line. Species, number of plants of each species, height and cover of shrubs and grass were recorded separately. A temporary 5 m × 5 m quadrat centered on each point was used to estimate the cover of the layer of branches and leaves. The space over this quadrat was considered as a three-dimensional object, with five layers divided as follows: 0–0.5 m, 0.5–1.5 m, 1.5–5.0 m, 5.0–12.0 m and >12.0 m, which corresponded to the grass layer, the shrub layer, a layer of saplings, a succession layer and the crown layer of the dominant species, respectively. In order to avoid unnecessary errors, two people conducted the cover estimation in each layer together. The cover data of the layers were classified into ordinal numbers for further analysis given the following criteria: 1, when cover < 5%, 2, 5%–25% cover, 3, 25%–50% cover, 4, 50%–75% cover and 5, cover > 75% (Zheng and Luo, 2003).

3.2 Data analysis

1) Structural diversity indices. Structural diversity includes two aspects, one is vertical complexity and the other is horizontal heterogeneity. The vertical complexity can be described as a difference in branch and leaf density at successive heights. This index was calculated as the average weighted cover of each layer. The formula for the vertical complexity index in each sample plot is (Zheng and Luo, 2003):

$$C_V = \frac{1}{24}\sum_{i=1}^{24} V_i \tag{1}$$

where C_V is the vertical complexity index, and V_i the weighted cover of the layer at the ith point and calculated as follows:

$$V_i = \sum_{i=1}^{5} CS_j \cdot CW_j \tag{2}$$

where CS_j is the ordinal number of the jth layer and CW_j the weight of the jth layer.

The other aspect of structural diversity, i.e., horizontal heterogeneity, can be described as the difference of plant coverage at the 24 points in each sample plot. Since there

Table 1 Basic characteristics of sample plots

plot	community	aspect	slope/°	tree density/individual·hm^{-2}	average DBH/cm	average height/m	management
1	birch forest	north-west	5	1100	20.6	16.8	
2	oak forest	south-west	35	783	16.6	10.7	
3	larch plantation	north-east	30	750	18.5	14.6	established in 1975, tending in 1991
4	pine plantation	north-east	20	800	20.2	10.5	established in 1975, tending in 1991
5	larch plantation	north	15	1033	19.2	12.8	established in 1969, no tending

were five layers at each point, similar to five attributes and each attribute had 24 pieces of information in one plot, the horizontal heterogeneity index could be calculated as the difference in the average layer cover between two points (total number of pairs: $C_{24}^2 = 276$). For our study we defined the difference index as a Euclidean distance, calculated as (Zhang, 2005):

$$C_H = \frac{1}{C_{24}^2} \sum_{i=1}^{24} d_{jk} \quad (3)$$

where C_H is the horizontal heterogeneity index, d_{jk} the Euclidean distance between points j and k and is calculated as:

$$d_{jk} = \sqrt{\sum_{i=1}^{5} (x_{ij} - x_{ik})^2} \quad (4)$$

where x_{ij} and x_{ik} are the ordinal numbers between jth point and kth point with five different layers each.

2) Other biodiversity indices commonly used in the literature are the Shannon-Wiener index and the Gini index. We calculated the Shannon-Wiener index for species diversity of the shrub and grass layers as follows (Ma, 1994):

$$H = -\sum P_i \cdot \ln P_i \quad (5)$$

where H is the Shannon-Wiener index and P_i the ratio of the number of individuals of the ith species to the total number of individuals.

We used the Gini index to describe the inequality of tree heights in the sample plot. The Gini index is the average difference of an attribute between two individuals in a plot. The Gini index ranges between 0 and 1. This index proved to be effective in describing tree height diversity in a forest community (Wiener and Solbrig, 1984; Dixon et al., 1987; Latham et al., 1998). The formula for the Gini index is:

$$G = \frac{1}{\sum_{i=1}^{n} X_i(n-1)} \sum_{i=1}^{n} (2i - n - 1) X_i \quad (6)$$

where G is the Gini index, X_i height of the ith tree, i the index of tree height ordered from the bottom up and n is the number of trees in the plot.

The Gini index is one of the most successfully used indices for plant height inequality. We used it to show the inequality of tree height in one sample plot, i.e., as tree height diversity.

All indices were calculated with EXCEL and the data analyzed by SPSS 11.0.

4 Results

4.1 Structural diversity of natural forests and plantations

Previous studies have shown that the point-centered quarter method, combined with an estimation method for coverage, is useful in evaluating the effect of anthropogenic disturbance to forest structures (Zheng and Luo, 2003). The estimation of layer coverage is a qualitative method used in the evaluation of forest structures and habitat quality in the landscape (Lahde et al., 1999; Drapeau et al., 2000). We have used this method to describe the structure of forest communities for the purpose of an easy forest survey and for management evaluation. The formula of indices in this paper have been amended on the basis of our previous studies (Zheng and Luo, 2003).

We take sample plot 2 as an example to show how the structural diversity indices were calculated. After briefly surveying the height of layers of the different forest communities in Baihua Mountain, we found that the height of three layers, i.e., the major crown layer of the dominant tree species, the shrub layer and grass, were similar in the different natural forests. So, we decided to divide layers into five fixed height classes (see 3.1), representing crown, succession layer, sapling layer, shrub layer and grass layer, respectively. According to equation (1), C_V was calculated with different weights of the layers, where the weight was the ratio of layer height to average tree height in the plot. The length of the highest layer was the difference in height between the tallest tree and the lowest limit of this layer to emphasize different dominant trees in each community. After summing the weighted layers of 24 covers, we obtained its average as the vertical complexity index of plot 2, i.e., 4.294. The calculation of the horizontal heterogeneity index was also based on the ordinal numbers of the cover layer. According to equations (3) and (4), the Euclidean distances of 276 point pairs were calculated (data omitted from Table 2). The average of the distance

Table 2 Structural diversity indices and other diversity indices of the five sample plots

diversity indices	birch forest	oak forest	larch plantation (north-east slope)	pine plantation	larch plantation (north slope)
vertical complexity (C_V)	2.883	4.294	3.650	3.794	3.820
horizontal heterogeneity (C_H)	1.668	2.291	2.360	2.549	1.970
tree height inequality (G)	0.099	0.153	0.100	0.112	0.130
tree species diversity (H_t)	0.546	0.801	0.613	0.563	0.683
shrub species diversity (H_s)	2.203	1.140	2.257	1.981	1.800
grass species diversity (H_g)	2.360	2.447	2.332	2.189	2.331

was used as the horizontal heterogeneity index, which was 2.291, of plot 2.

The structural diversity indices of the other four plots surveyed were calculated as explained earlier. The results are shown in Table 2.

4.2 Correlations among indices

Few studies have been carried out on structural diversity in China so far. We calculated other commonly used biodiversity indices for communities at the same time to probe their relationships. These indices included species diversity index (Shannon-Wiener index) for trees, shrubs and grasses and the Gini index for tree height diversity. The results of these biodiversity indices are also shown in Table 2. Correlations among the different indices were analyzed by Spearman coefficients (see Table 3).

Table 3 Correlation coefficients among six diversity indices

diversity indices	C_V	C_H	G	H_t	H_s	H_g
vertical complexity (C_V)	1.00					
horizontal heterogeneity (C_H)	0.20	1.00				
tree height inequality (G)	1.00**	0.20	1.00			
tree species diversity (H_t)	0.90*	0.1	0.90*	1.00		
shrub species diversity (H_s)	−0.90*	0.1	−0.90*	−0.70	1.00	
grass species diversity (H_g)	0.10	−0.50	0.10	0.30	−0.20	1.00

Note: **significant at 0.01 level; *significant at 0.05 level.

The results show that the vertical complexity index is highly correlated with the tree height diversity index. Because C_H was good in describing the vertical layer of community while the Gini index was also used to demonstrate inequality of tree height, the high correlation between the two indices is easy to understand. There are only a few indices used to indicate the variety of plant heights, the Gini index is one of most accepted indices and is regarded as a good reference in the analysis of vertical forest structures. However, it should be pointed out that the Gini index is different from the vertical structure complexity index (C_V) since it only demonstrates the diversity of tree heights and not that of all layers of the community. The results show that both C_V and G are positively correlated with the tree diversity index ($P<0.05$) but negatively correlated with the shrub diversity index ($P<0.05$), which again demonstrates, as suggested earlier, that C_V and G are similar aspects of a community. Therefore, the vertical structure and the complex vertical structure can affect the development of the shrub layer. We can also find the effect of vertical structure on the development of the shrub layer from the correlation coefficients −0.7 between the species diversity index of the shrub layer and the tree layer. On the other hand, the correlation coefficient of the horizontal heterogeneity index and the grass diversity index is 0.5, which suggests that diversity of grass in the forest maybe be affected by gaps or microclimates in the community. No significant correlations were found among the other indices.

4.3 Analysis of structural diversity in different forests

By comparing the structural diversity of the various natural forests and plantations with different management histories, we can find some hints on how structural diversity changed in this region. A comparison of plots 1 and plot 2 indicates structural diversity changes during succession. Although the average DBH and tree height of the birch forest are larger than those of the oak forest (see Table 1), the vertical complexity index and horizontal heterogeneity index of the pioneer community markedly exceed those of the late succession community. This reveals that during the succession of forests in our study region, the original community was composed of fast growing, high density, heliotropic plants with but low structural diversity, while the late succession community is dominated by slow growing neutral tree species low density but with high structural diversity. The Gini indices of the two communities were 0.153 and 0.099 respectively, which means that the variation of tree heights in the birch forest is much higher than that of the oak forest. The Shannon-Wiener index of trees also suggests a similar conclusion. Comparatively, the species diversity of the shrub layer was higher in the birch forest than in the oak forest, which may be caused by environmental differences between the two communities.

The Baihuashan Mountain is the green barrier west of Beijing. Many larch and Chinese pines were planted at a density of 1.5 m × 1.5 m in the late 1960s. Since plantations in this region were regarded as an engineering project for public benefit, thinning was seldom carried out and tree density in the forest always remained high. Over time, natural broad-leafed trees invaded the plantations and tree densities kept increasing. By checking the density and structural diversity indices of plots 3, 4 and 5, we can find indications of this process.

Tending affects the structure of a forest community and changes its structural diversity. When comparing the indices of plots 3 and 5, it could be seen that vertical complexity decreased after tending while horizontal heterogeneity increased. Tending causes a decline in tree density while it creates a greater variety in the microclimate of the community which leads to the invasion of natural broad-leafed trees in the stand. Differences in forest structures are also affected by dominant tree species. When comparing the indices of plots 3 and 4, we find that the structural diversity indices of the Chinese pine plantation are higher than those of the larch plantations. Because the tending techniques applied to both types of plantations were similar in intensity, this pattern can be attributed with a high level of confidence to different habitats of dominant tree species. Chinese pines grow slower than larch and are more shade-tolerant, which may cause the divergence in differentiation time of trees and stand pattern formation with high initial tree density. Within the same developmental period, the Chinese pine plantation was apt to produce a more complex structure than the larch plantations. Considering C_V, C_H and G indices together, we concluded that plantations can produce relative high structural diversity similar to natural pioneer communities given sufficient time and tending. However, their structural diversity still cannot be as high as that of late succession communities. The stability of late succession communities is often regarded as high as the spatial heterogeneity within it. However, a comparison of the structural diversity among plantations and natural communities indicates that tending can increase horizontal heterogeneity while decreasing vertical complexity. An increase in horizontal heterogeneity only does not mean structural optimization and enhancement of stability in a forest community.

5 Discussion

There are many advantages using estimation of layer coverage as the basis for the calculation of structural diversity indices as we have done. Diversity indices of branches and leaves are useful in evaluating bird habitats (MacArthur and MacArthur, 1961). Leaf density at different height layers has greater effect on insects than do plant identities in different layers in forest (Gao et al., 1992). Communities with complex vertical structures can play more important roles in soil and water conservation through interception of precipitation (Chen et al., 1997). Thus, by comparing species diversity indices that can only indicate a small aspect of a forest structure, layer coverage-based structural diversity indices illustrate the structure of forest communities more thoroughly. Previous studies on structural diversity in the Changbai Mountains in northeastern China show that structural diversity indices could be used to distinguish the difference in structures between the original and secondary forests. These indices are better than species diversity indices in describing the change of structural diversity by human activities (Luo et al., 1997; Zheng and Luo, 2003). In this study, we have validated the methods in northern China. With a typical plot of 600 m^2 as control, our point-centered quarter method (24 points) combined with coverage estimation of layers was used to survey the structure of forest communities on the Baihuashan Mountain. The survey area and number of points met the requirements of our research in biodiversity of forest communities in the region (Pan, 1988; Liu and Ren, 1992). Our results of community similarity indices between the two methods also validated our new method (calculations omitted).

Studies in forest structures before focused on tree height division and coverage of different life forms (Chen et al., 1997; Zang et al., 2001; Song et al., 2003), with little attention paid to horizontal heterogeneity. However, gaps and micro-habitats in forest are important characteristics at the stand level. Ignoring these would surely lead to an incomplete description of community structures (Franklin, 1994). Furthermore, in previous studies, vertical layers were often divided in a way of fixed length, which were suspected not reflect natural plant layer patterns because different communities have various layers in addition to the effect of community composition on the number of species (Zhi, 2001). We have divided the layers in a way that, as closely as possible, simulates nature, and we use information of coverage, not species, to construct the structural diversity indices which improve the general and comparative applicability of the method. Of course, our division of the layers is also related to the stage of forest developmental. Each stage is characterized by its own unique structure, which was presented in the new theory of forest stand dynamics (Kohm and Franklin, 1996; Oliver and Larson, 1996). When dividing the layers in different forest communities, we should take community and its developmental stage into consideration to find a suitable way. Because of variable regional vegetation conditions and labor requirements for surveys, detailed studies should be conducted in the future.

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