

Anisotropy analyses of population distribution patterns

WANG Benyang, YU Shixiao (✉), WANG Yongfan

School of Life Sciences, Sun Yat-sen University, Guangzhou 510275, China

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Abstract Direction-dependence, or anisotropy, of spatial distribution patterns of vegetation is rarely explored due to neglect of this ecological phenomenon and the paucity of methods dealing with this issue. This paper proposes a new approach to anisotropy analysis of spatial distribution patterns of plant populations on the basis of the data resampling technique (DRT) combined with Ripley's L index. Using the ArcView Geographic Information System (GIS) platform, a case study was carried out by selecting the population of *Pinus massoniana* from a needle- and broad-leaved mixed forest community in the Heishiding Nature Reserve, Guangdong Province. Results showed that the spatial pattern of the *P. massoniana* population was typically anisotropic with different patterns in different directions. The DRT was found to be an effective approach to the anisotropy analysis of spatial patterns of plant populations. By employing resampling sub-datasets from the original dataset in different directions, we could overcome the difficulty in the direct use of current non-angular methods of pattern analysis.

Keywords population, spatial distribution pattern, anisotropy analysis, data resampling technique, Ripley's L index

1 Introduction

The spatial distribution pattern that many ecological datasets have rendered reveal both scale dependence and direction dependence (directionality, or anisotropy), with the former referring to changing characteristics at multiple scales, and the latter, different patterns in different directions. Numerous researches on vegetation pattern have been carried out with emphasis on its scale dependence, which roughly fall into two aspects: one is to develop multi-scale pattern analysis

methods for solving scale dependent problems, and the other is to probe scale effects or to analyze spatial patterns at multiple scales (Wang and Yu, 2005).

The scale dependence of spatial patterns is increasingly recognized by modern ecologists, and quantitative research on spatial heterogeneity at multiple scales is considered as the first step towards exploring relationships between pattern and process (Wu et al., 2002). However, the direction dependence (directionality), or anisotropy, of spatial patterns has received little attention (Rosenberg, 2004). Related studies are still rare (Rosenberg, 2004; Wu et al., 2002).

Although the effects of changing direction on pattern analysis have long been recognized in vegetation analysis when using blocked quadrant variance methods and geostatistical analysis of anisotropy, few researches have been carried out that directly and systematically address the question of how changing directions affect pattern analysis (Wu et al., 2002). The underlying reasons are probably the neglected situation of direction dependence, and the paucity of applicable methods for anisotropy analysis. With its semivariance that is closely related to direction, geostatistical analysis method, which was mainly utilized for analysis of anisotropic spatial heterogeneity of plant populations, can also be adapted in anisotropic spatial pattern analysis for exploring relationships between direction and pattern. Rosenberg (2004) proposed that wavelet analysis and his adapted angular wavelet analysis can be used for detecting anisotropic spatial patterns. However, neither geostatistical analysis nor wavelet analysis can be simply applied to ecological field datasets, and sometimes a professional software package (e.g. geostatistical analysis software) is indispensable.

The objective of this paper was to present a new approach for anisotropy analysis of spatial distribution patterns by employing a data resampling technique (DRT) combining with Ripley's L index, which was carried out on the ArcView Geographic Information System (GIS) software package by selecting the *Pinus massoniana* population in a needle-broadleaved mixed forest in the Heishiding Nature Reserve of Guangdong as a case study.

2 Study site and methods

2.1 Study site

The study site is located in the Heishiding Nature Reserve, Guangdong Province. For its detailed descriptions and vegetation classification scheme, refer to Yu et al. (2000).

At the northwest site of Jiaqiaokeng, Shimentang village of the Heishiding Nature Reserve (23°26' N, 111°53' E), a 64 m × 64 m sample plot was set up, and each tree or shrub species with the diameter at breast height (DBH) greater than 1 cm was surveyed, and items recorded include species name, DBH, height, crown width and coordinates within the plot. The community concerned was a *P. massoniana* dominated needle-broadleaved mixed forest type, the most widespread needle-broadleaved mixed forest type in the Heishiding Nature Reserve (Yu et al., 2000). Its forest physiognomy was typical of a needle-broadleaved mixed forest type, with the upper layer dominated by *P. massoniana*, and the middle and lower layers by both *P. massoniana* and broadleaved tree species.

2.2 Methods

2.2.1 Point map

Point map is a kind of scatter map that treats plant individuals as points, with locations determined by coordinates within sample plot, which visualizes population distribution patterns intuitively, and thus is an auxiliary tool for quantitative ecological research (Wang and Yu, 2005). Point map helped carry out qualitative visual analyses of population distribution patterns, and the roughly appraised outlook of anisotropic distribution pattern on the technical platform of the ArcView GIS software package, the input coordinate datasets of which were also the data source for quantitative anisotropy analyses of population distribution patterns.

The number of individuals of *P. massoniana* in the sampled plot was 172, and the point map of it is illustrated in Fig. 1. From Fig. 1, it could be visually determined that there were different numbers of individuals in different directions, and thus, the population *P. massoniana* demonstrated a somewhat anisotropic distribution pattern.

2.2.2 Data resampling technique

Comparisons of sampling techniques, especially those involved in same plot but different analysis methods, or different plot areas, were usually constrained by insufficient manpower and material resources. The DRT is a kind of technique that extracts sub-datasets from original source datasets (e.g. surveyed dataset of a plot) according to a set of predefined professional specifications on such computer platforms as the GIS.

Although the application of computer technology in the process of vegetation sampling was rather limited, researches

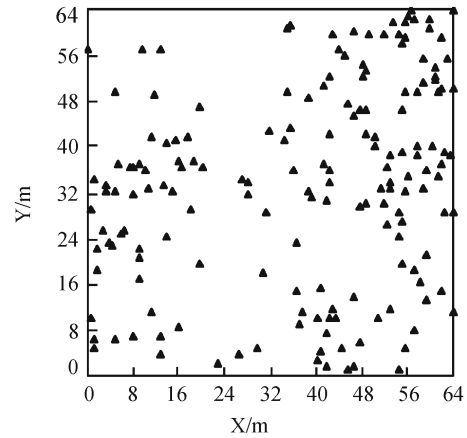


Fig. 1 Mapped point pattern of *Pinus massoniana* population

indicated that it was applicable and promising (Yu et al., 1998). DRT based on plot dataset increases the reusability of original basic datasets, and helps to reveal much more ecological information and explore the in-depth ecological nature of studied objects. At the same time, DRT decreases costs in manpower and material resources. Compared with computer-based simulated sampling technique (Yu et al., 1998), DRT is in nature alike.

For a square plot, its rectangular sub-plots can be determined in different directions, typically in those directions shown in Fig. 2. The angles from the horizontal direction till the longer edges of D1, D2, D3 and D4 are 45°, 135°, 90° and 0°, respectively, and D1 or D2 is laid parallel to the rectangle's corresponding diagonal, D3 to the vertical, and D4 to the horizontal, with all central coordinates at the center of the square plot.

Hereafter, the resampling ratio is defined as the ratio of the number of individuals in the sub-plot to that of the original plot. The resampling ratios of *P. massoniana* population in four typical directions as those defined in Fig. 2 are listed in Table 1.

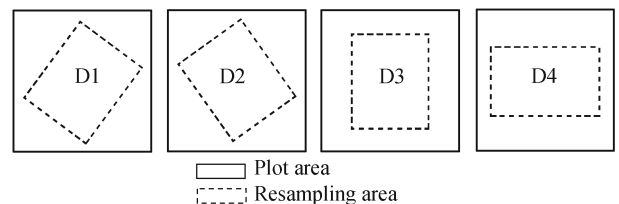


Fig. 2 Sketch maps for resampling in four typical directions

Table 1 Resampling ratio of *Pinus massoniana* in Heishiding Nature Reserve, Guangdong Province

Resampling D1		Resampling D2		Resampling D3		Resampling D4	
NOI	RR /%	NOI	RR /%	NOI	RR /%	NOI	RR /%
79	45.9	74	43.0	64	37.2	74	43.0

NOI: Number of Individuals; RR: Resampling Ratio

2.2.3 Ripley's L index

Ripley's $K(d)$ function has been widely applied to study spatial distribution patterns of plant populations. Ripley defined the estimator $K(d)$ as (Ripley, 1977)

$$K(d) = A \sum_{i=1}^n \sum_{j=1}^n \frac{\delta_{ij}(d)}{n^2} \quad i, j = 1, 2, \dots, n; i \neq j, d_{ij} \leq d \quad (1)$$

where A is the plot area and n is the number of individuals within the plot, d is the current distance scale, and d_{ij} is the distance between individual pair i and j , $\delta_{ij}(d) = 1$ (if $d_{ij} \leq d$) or $\delta_{ij}(d) = 0$ (if $d_{ij} > d$).

Besag (1977) suggested using $L(d)$ instead of $K(d)$ to linearize the expected values and stabilize the variance. Under the assumption of a Poisson distribution, the expected value of $L(d)$ is 0, with the calculation equation as

$$L(d) = \sqrt{\frac{K(d)}{\pi}} - d \quad (2)$$

The figurative $d-L(d)$ relations can be employed in detecting spatial distribution patterns at multiple scales. If $L(d) < 0$ (i.e. less than the expected value of a Poisson distribution), a uniform distribution pattern is assumed; or if $L(d) > 0$ (i.e. greater than the expected value of a Poisson distribution), a clumped distribution pattern is assumed; otherwise, an assumption of a random distribution pattern cannot be rejected.

When a clumped distribution is detected, such information as intensity and scale of a clump can be further inferred from the figurative $d-L(d)$ relations (Stamp and Lucas, 1990; Zhang, 1998). The clump intensity is indicated by the scale at which the maximum deviation from confidence envelopes appears, and the clump scale, by a circle with a radius of the scale indicating clump intensity.

Two problems come along with the application of Ripley's $K(d)$ function in population distribution pattern analyses. One is edge effects correction, and the other is significance tests. Tang et al. (2003) believed that the method of edge effects correction is the key problem in applying Ripley's $K(d)$ function. Four comprehensive cases were summarized. The equation for $K(d)$ can be now calculated as (Tang et al., 2003)

$$K(d) = A \sum_{i=1}^n \sum_{j=1}^n \frac{w_{ij}(d)}{n^2} \quad i, j = 1, 2, \dots, n; i \neq j, d_{ij} \leq d \quad (3)$$

where $w_{ij}(d)$, the weighting factor for edge effects correction, is equal to the inverse of the proportion of the circumference of the circle with center at i and radius d_{ij} lying within the plot, and other symbols are the same as those defined in Eq. (1).

Either analytical methods or the Monte Carlo simulation technique can be applied to significance tests of Ripley's L index. Because all the researchers in China are using Monte Carlo techniques (Hou and Han, 1997; Zhang, 1998; Tang et al., 2003; Zhang and Meng, 2004), this paper used the

analytical method, taking $1.42A^{0.5}/N$ as the critical value for estimating 95% confidence envelopes (Stamp and Lucas, 1990).

2.2.4 Technical approach

Technically, anisotropy analyses of population distribution patterns can be carried out in one of two broad approaches (Rosenberg, 2004). First is the method-driven approach, which directly employs those methods that include a direction-related parameter, such as the geostatistical analysis method for direction-related problems. Second is the sampling-driven approach, which employs traditional analysis methods on datasets sampled in different directions, and then summarizes results in different directions for anisotropic distribution pattern analyses.

This paper took the second approach. First the sub-datasets in different directions were resampled through DRT, and then Ripley's L index was employed for analyses of distribution patterns in different directions, at multiple scales.

The sub-datasets were resampled through DRT in four typical directions as those shown in Fig. 2, and $K(d)$ was evaluated according to Eq. (3) with the edge effects correction method of Tang et al. (2003), and then Ripley's L index was employed according to Eq. (2) in four typical directions for the anisotropy analyses of distribution patterns of the population of *P. massoniana*. The key step for the analysis process was the resampling of sub-datasets in different directions through DRT.

2.2.5 Anisotropy analyses extension on ArcView GIS

Anisotropy analyses were automatically carried out through the extension of anisotropy analyses on ArcView GIS platform developed by the authors. The core functionality of the extension of anisotropy analyses includes two parts:

(1) Data Resampling: This part implements such data preparations for the second part as specification determining for sub-plot, coordinates extracting from original dataset according to the specification, and data transforming for calculations. The rectangular sub-plot for resampling in this paper was 50 m in length, and 40 m in width, which was the biggest within the original 64 m × 64 m square plot. The original community survey datasets were resampled in four typical directions as those shown in Fig. 2 for constructing sub-datasets for the *P. massoniana* population.

(2) Ripley's L index analyses: This part accomplishes anisotropy analyses of population distribution patterns following the methods described in the preceding sections.

3 Results

The curves of Ripley's L index in four typical directions (Fig. 3) demonstrated that, the spatial distribution pattern of the *P. massoniana* population was typically anisotropic, with

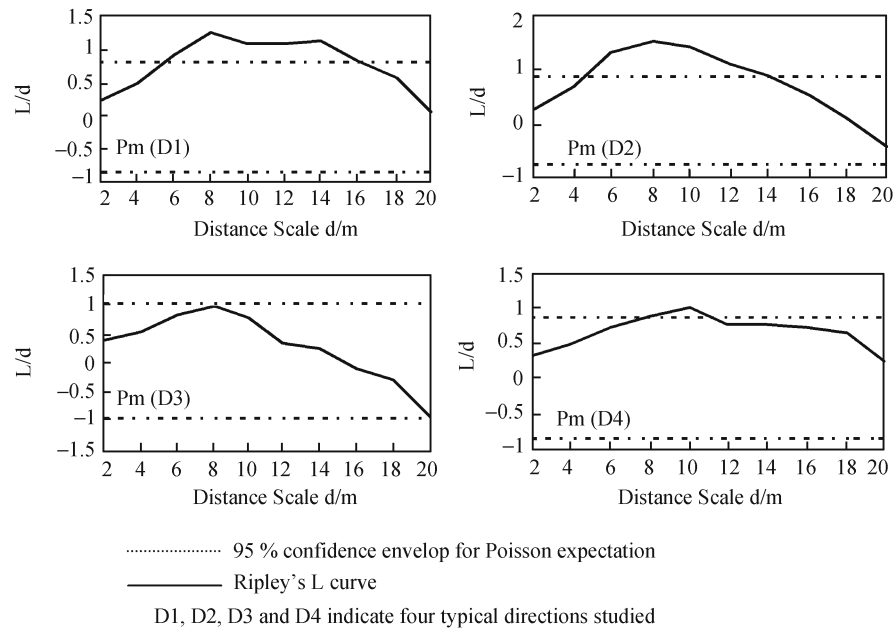


Fig. 3 Ripley's L curve for anisotropic pattern analysis of *Pinus massoniana* (Pm)

different patterns in different directions, and similar patterns in symmetrical directions.

The resampling ratio of the *P. massoniana* population ranged from 43% to 46% (Table 1), about half of the individuals distributed in four typical directions. Judging from Fig. 3, in directions D3 and D4, the curves of Ripley's L index fell within the 95% confidence envelope, indicating a significant random distribution pattern at a scale range from 2–20 m. While in symmetrical directions D1 and D2, the population of *P. massoniana* was clumped at the scale ranges of 2–16 m and 4–14 m, respectively; and exhibited maximal deviation from the confidence envelope at a scale of 8 m, indicating maximal clump intensity at this scale, and a clump scale of 200 m² or so.

4 Discussion

4.1 Anisotropic distribution pattern of plant population

Environmental factors such as soil nutrients distribution, prevailing wind direction, and animal dispersal patterns, can all exhibit direction dependence; and pattern forming processes can be strongly direction dependent and are not necessarily isotropic (Keitt, 2000). Therefore, the anisotropic distribution pattern is a comprehensive manifestation of both environmental spatial heterogeneity and the biological characteristics of the population, and anisotropy is the primary characteristic of population distribution pattern.

The case study of this paper showed that, the distribution pattern of the *P. massoniana* population was anisotropic, with different distribution patterns in four different typical directions. Its causal factors were possibly the biological

characteristics of *P. massoniana*, and its surrounding environmental factors the soil nutrients distribution patterns. The Heishiding Nature Reserve is located in the southern subtropical region, and forest communities within this region are generally in a trend of successional process from the forest of *P. massoniana* to the evergreen broadleaved forest. The forest community embracing the sample plot was a needle-broadleaved mixed forest dominated by a population *P. massoniana*. It was midway of the successional stages, where *P. massoniana* was declining, while other broadleaved tree species such as *Castanopsis nigrescens*, and *Itea chinensis* were gradually occupying much more space in the upper layer of the community. The spatial heterogeneity of habitats resulted in differences in regeneration conditions for the seedlings of *P. massoniana*, a strong heliophytic tree species, which in turn made possible differences in the position and quantity of random individual deaths, and eventually brought about differences in distribution patterns in different directions, or anisotropic distribution patterns. However, further validating researches are needed.

The results also showed that the curves in four typical directions could be roughly grouped into two, i.e. D1 and D2 in one group, and D3 and D4 in the other (Fig. 3). This suggests that the population might exhibit symmetrical distribution patterns, with similar distribution patterns in symmetrical directions. The presence of anisotropy proved that spatial heterogeneity within the studied region, and the symmetry of spatial heterogeneity should be the most probable causal factor for an anisotropic distribution pattern, though further research is necessary for validating the truths, or quantifying the symmetry.

Using several different landscapes in North America, Wu et al. (2002) found that, generally, most landscape metrics

showed large differences at smaller extents among the four directions, i.e. northwest \rightarrow southeast, southwest \rightarrow northeast, southeast \rightarrow northwest and northeast \rightarrow southwest, indicating anisotropy at the landscape level, and that those differences became smaller and eventually disappeared as the overlapped area continued to increase.

Wu et al. (2002) also found pronounced anisotropy in landscape metrics in their North America study, with four response curves forming two groups: NW \rightarrow SE and SW \rightarrow NE as one group, and SE \rightarrow NW and NE \rightarrow SW as the other, with curves within a group resembling each other rather closely. They believed this was indicative of the relatively symmetric landscape pattern, because the response curves of all metrics should be identical if landscape patterns were isotropic, i.e. same pattern in different directions.

At the population level, spatial distribution pattern means the arrangement of individuals of a population in a given time and space. Numerous methods have been proposed for determining whether a population distribution falls into one of the three common recognized types, i.e. random, uniform or clumped pattern. Actually, most traditional studies assumed an isotropic distribution pattern, supposing either no differences in different directions or those possible differences could be neglected. This assumption certainly decreased the rationality of the conclusions arrived at. Both theoretical analyses and practical research showed that the habitats and the pattern-forming ecological processes are generally anisotropic. Therefore, results of pattern analysis through traditional methods could be otherwise called mixed pattern, or overall pattern, since it was isotropy-assumed.

Scale dependence and direction dependence are two important spatial attributes of population distribution pattern, therefore the multi-scale analyses and anisotropy analyses of these two attributes are two important fields in population distribution pattern research. Anisotropy analyses help lead to an in-depth understanding of the characteristics of population distribution patterns and its relations with environmental factors, and are fundamental to research on the relationships between population distribution patterns and its principal controlling ecological processes. With the newly defined paradigm of spatial autocorrelation in ecology, anisotropy is also an important factor for constructing new ecological models (Lichstein et al., 2002). For its capability of separating characters related to temporal scales from those related to spatial scales, anisotropy analyses also help construct more accurate pattern-process analysis models (Keitt, 2000). With increasingly deepened researches of pattern analyses, the aspect of anisotropy of pattern analyses will receive deserved emphasis.

4.2 Methods of anisotropy analyses

Exclusive professional methods of anisotropy analyses have not been devised yet. Existing methods of pattern analysis do not include direction-related parameters, thus cannot be employed directly in anisotropy analyses. As to methods

borrowed from other disciplines, such as semivariance in geostatistics, or adapted from existing methods for anisotropy analyses, their practical applications are rather restricted. Therefore, developing professional methods of anisotropy analyses is of great methodological importance, and deserves further research.

By employing DRT and resampling sub-datasets in different directions, this paper carried out anisotropy analyses of the distribution pattern for the *P. massonian* population, precluding the problem of absent direction-related parameters in existing methods of pattern analysis. The technical approach is fairly practicable, and is an effective tool in the anisotropy analyses of population distribution patterns. DRT is a new form of application of computer-based vegetation resampling technique, which simplifies data preparations for anisotropy analyses through resampling sub-datasets in different directions. DRT extracts much more ecological information from original basic datasets, enhances reusability of the basic datasets, and decreases costs in manpower and material resources in field work.

4.3 Ripley's L index analysis

The method of Ripley's L index analysis was first introduced into home by Hou and Han (1997) and Zhang (1998), and employed in vegetation pattern analysis. Hou and Han (1997) pointed out that this method was capable of detecting patterns, in that there was no information loss compared with index-based methods that converted two dimensional coordinates into either a one-dimensional plot index, or one-dimensional distance index. When using Ripley's L index in analyzing population distribution patterns and inter-specific relationships at multiple scales, Zhang (1998) found that this method could detect population patterns and inter-specific relationships at multiple scales with results that were plain and intuitive, and that were better in accordance with actuality. Point pattern analysis can detect clump scale, and reveal more truthful characteristics of distribution patterns for a population at finer scales, and thus is more effective than such methods as Variance/Mean ratio, Morisita dispersion index or nearest neighbor analysis. However, few researches applying point pattern analysis have been reported (Zhang and Meng, 2004) at home. The underlying reasons are probably its complex process of edge effects correction, or its daunting Monte Carlo techniques for significance tests coming with this method.

Therefore, when analyzing the anisotropic distribution pattern of *P. massoniana* populations by employing Ripley's L index, this paper obtained its multi-scale characteristics in different directions, and carried out synergic analyses of direction dependence and scale dependence. The paper also used an analytical method for determining the 95% confidence envelopes so as to simplify the process of significance tests.

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