Overview of Point Pattern Research in Ecology and Its Applications in China (Postprint)

Authors: Ma Zhibo, Xiao Wenfa, Huang Qinglin, Zhuang Chongyang

Date: 2017-10-30T00:00:00+00:00

Abstract

Point pattern analysis is a tool for studying ecological patterns, and its application in ecology has been increasing in recent years. To gain a deeper understanding of the research and application status of point pattern analysis methods in China, this study analyzes and reviews Chinese core journal literature on the theme of point patterns from 1996 to 2015, based on summarized research progress, general procedures, and fundamental points. The results indicate that in domestic ecological pattern research, applied research dominates, with extensive research subjects including plants of different life forms such as trees, shrubs, and grasses (primarily trees), and even landscapes; basic research, including summary statistics, null models and point process models, as well as the development of specialized software toolkits, remains weak. There are certain problems in applications, mainly manifested as: the use of summary statistics is monotonous, primarily relying on Ripley's K-function and its variants; null models (or point process models) are the statistical expression of scientific questions, yet more than half of the studies do not explicitly specify the null model. It is recommended that future applied research should emphasize the combined use of multiple statistics and the establishment of null hypotheses, consider different generations of the objects and different vertical layers of the system when exploring diversity patterns in complex spatial structure systems such as tropical and subtropical forests, and strengthen work on the development of multivariate or three-dimensional summary statistics, as well as research combining point pattern analysis methods with dynamic process models.

Full Text

Preamble

ACTA ECOLOGICA SINICA
ChinaXiv Partner Journal

Vol. 37, No. 19, October 2017
DOI: 10.5846/stxb201607081399

A Review of Point Pattern Analysis in Ecology and Its Application in China

Ma Zhibo[1], Xiao Wenfa[1]*, Huang Qinglin[2], Zhuang Chongyang[2]
[1]Research Institute of Forest Ecology, Environment and Protection, Chinese Academy of Forestry
[2]Research Institute of Forest Resource Information Techniques, Key Laboratory of Forestry Remote Sensing and Information Technology, State Forestry Administration, Beijing 100091, China

Abstract

Point pattern analysis, also known as spatial point pattern analysis (SPPA), is a tool used in ecological pattern research that has become increasingly popular in ecology in recent years. To better understand SPPA research and its application in China, this review examined articles regarding SPPA published from 1996 to 2015 in Chinese core journals. Based on a summary of research progress, implementation steps, and key points of SPPA, we analyzed and evaluated the domestic research and application status.

The findings reveal that applied research dominates domestic ecological pattern studies, with extensive study objects including forests, shrubs, grasslands, and landscapes, though trees in forest communities remain the primary focus. Fundamental research remains underdeveloped, including studies on summary statistics, null models, point process models, and the development of specialized software packages for SPPA. Two critical problems were identified in SPPA applications: First, despite many available alternatives, researchers prefer single summary statistics, predominantly selecting the K-function or its transformations. Second, although selecting null models as null hypotheses is a key step in SPPA, more than half of the examined studies did not explicitly specify null models.

Therefore, we recommend that future application studies should: (1) employ combinations of different summary statistics to capture detailed spatial pattern structures, (2) clearly state ecological questions or hypotheses and correctly translate them into statistical language (i.e., null models and tests), and (3) consider vertical layers and different generations when studying systems with complex spatial structures such as tropical and subtropical forests. Additionally, strengthening basic SPPA applications through enhanced methodology development, multi-variable or three-dimensional summary statistics, and integration with dynamic process models should be prioritized.

Keywords: point pattern; ecology; summary statistics; null model; community biodiversity pattern

1. Literature Search Methods

We retrieved 203 Chinese journal articles published between 1996 and 2015 using "point pattern" or "spatial point pattern" as search themes in the China National Knowledge Infrastructure (CNKI) database, limited to core journals indexed in CSCD or EI. The search was supplemented based on English literature review results. After narrowing the scope to ecology, 176 Chinese journal articles remained for analysis of point pattern analysis methods and applications (Fig. 1A). While this search strategy cannot include all research outcomes, it ensures representativeness of the retrieved sample. Prior to analyzing domestic literature, we reviewed English-language journal articles and reference books [17-20] to summarize key points and research progress.

2. Definition of Point Processes and Point Patterns

A point process in d-dimensional real number space R^d is a random variable N taking values in a measurable space, where each bounded subset of R^d contains a finite number of points, satisfying the condition of local finiteness [38]. A point pattern is one realization of a point process, which can be understood as a set of points sampled from a region, while the point process represents the underlying stochastic mechanism [17-18]. In ecology, point pattern data consist of ecological objects abstracted as points with coordinates, confined within an observation window (typically square, rectangular, or circular) [19-20]. The window size depends on the scientific question—for instance, sufficiently large windows are needed to capture typical environmental variation when examining large-scale environmental effects on species distribution. Point pattern data may also include attributes of ecological objects, known as marks (e.g., tree size, survival status), which can be quantitative or qualitative.

3. Main Steps and Key Points

Ecological point pattern analysis involves four main steps: (1) data collection and classification, (2) selection of summary statistics and calculation from observed data, (3) selection of null models and simulation, and (4) comparison between observed and simulated results to infer ecological processes across scales and establish process-pattern linkages. Data classification and null model selection are particularly important yet frequently overlooked. The former is closely related to the research question and choice of analytical methods, while the latter serves as the bridge for testing ecological hypotheses.

3.1 Data Collection and Classification

Point pattern data can be categorized based on the number of data types, presence and type of marks, and whether marks are quantitative or qualitative [20]. Univariate patterns typically focus on pattern type and scale analysis, while bivariate patterns examine associations between objects. Multivariate forms can be conveniently extended from univariate forms [19]. Clarifying data type is essential as it directly relates to the research question and specific analytical methods.

3.2 Selection of Summary Statistics

Based on literature and monographs [17-20, 24, 27, 39, 41-43], we summarized common summary statistics in Table 1 . The most widely known is Ripley’ s K-function [24], which gives the expected number of points within distance r of an arbitrary point. Its definition as a cumulative function means effects at small scales propagate to larger scales [27, 42]. The g-function (pair correlation function), based on points within ring-shaped areas, avoids this cumulative effect and is considered superior by spatial statisticians [18, 27, 42, 44-45]. Nearest-neighbor statistics provide cumulative distribution functions of distances to nearest neighbors, offering information beyond simple mean distances [19-20]. For marked patterns, mark connection functions (for qualitative marks) and mark correlation functions (for quantitative marks) are available [18, 20].

3.3 Selection of Null Models and Point Process Models

Ecologists test hypotheses through null models and point process models. Based on comprehensive understanding of observed pattern characteristics, researchers establish null and alternative hypotheses to: (i) validate existing ecological theories, (ii) identify pattern causes (underlying processes), and (iii) conduct multi-model inference [20]. This multi-angle approach reduces biological and statistical constraints when linking processes to patterns [23].

For univariate patterns, the homogeneous Poisson process (CSR) is fundamental for testing complete spatial randomness [18, 26]. When patterns are driven by abiotic factors, heterogeneous Poisson processes (HPP) with variable density functions are appropriate [19, 27, 66]. Clustering phenomena are tested using cluster processes, most commonly Thomas cluster processes, which can describe small patches within large patches [67]. For bivariate patterns, common null models include antecedent condition (AC) and toroidal shift (TS), with homogeneous and heterogeneous Poisson processes [20]. For marked patterns, random labeling (RL) is commonly used, where marks are shuffled while point locations remain fixed [27, 68].

4. Domestic Research Overview

Among 176 ecological point pattern studies, 88% focused on plants, with trees dominating (71% of ecological studies), followed by herbs (9%), and studies examining multiple life forms (7%) comparable to forest landscape studies (Fig. 1B, 1C). Research increased substantially after 2006 (Fig. 1A). Regarding summary statistics, 70% of studies used only one statistic, predominantly K-function and its transformations (L-function, g-function) (Fig. 1D). Among studies using two statistics, the most common combination was K-function with nearest-neighbor distance methods (NN) (15% of total). In null model selection for univariate analysis, over half of studies did not explicitly specify null models; among those that did, CSR and HPP were most common. For bivariate analysis, more than half also lacked explicit null models, with AC and RL being the primary choices when specified (Fig. 1E, 1F). Only 3 studies addressed methodological issues such as edge correction for L-functions [35-36], effects of quadrat number and shape [37], and application of random block methods [38].

5. Evaluation of Domestic Research Status

Domestic ecological point pattern research is dominated by applied studies, with fundamental research on summary statistics, null models, and point process models remaining largely absent. Two major issues persist: (1) Despite recommendations to use multiple statistics [18, 70], most domestic studies rely on a single statistic, primarily K-function variants, limiting comprehensive pattern characterization. (2) Null models, essential for translating scientific questions into statistical hypotheses, are frequently omitted—over half of studies fail to explicitly declare them, mirroring international trends [29].

6. Recommendations and Prospects

6.1 Methodological Development

Statistical foundations and software development for point pattern analysis have advanced rapidly, offering researchers numerous summary statistics and null models. Future studies should employ statistical combinations to comprehensively describe observed patterns and explicitly state and test null models or point process models. Multi-model inference should be used to identify the most data-supported hypotheses.

6.2 Integration of Space and Time

All ecological processes have temporal dimensions. Combining spatial and temporal analyses better reflects reality and should be prioritized in both basic and applied research. Dynamic spatio-temporal point process models [54, 60] can help explore questions related to pattern dynamics.

6.3 Vertical Structure Consideration

Vertical structure is an integral component of spatial structure. In complex communities like tropical rainforests, different heights exhibit distinct environmental factors (light, humidity) and biodiversity patterns. Three-dimensional point pattern analysis is theoretically feasible but requires development of 3D summary statistics [19] and practical solutions for precise three-dimensional coordinate measurement.

6.4 Scale Dependency

Observed patterns typically result from multiple processes whose relative importance cannot be disentangled without considering spatial scale [73]. Studies in subtropical [74] and tropical [75] forests demonstrate that environmental determinism and stochastic processes vary in importance across scales. Future point pattern applications, particularly in ecological mechanism research, must emphasize scale effects.

References

[1] He F L, Legendre P, LaFrankie J. Spatial pattern of diversity in a tropical rain forest in Malaysia. Journal of Biogeography, 1996, 23(1): 57-74. [2] Bolker B, Pacala S W. Using moment equations to understand stochastically driven spatial pattern formation in ecological systems. Theoretical Population Biology, 1997, 52(3): 179-197. [3] Bolker B M, Pacala S W. Spatial moment equations for plant competition: understanding spatial strategies and the advantages of short dispersal. The American Naturalist, 1999, 153(6): 575-602. [4] Hector A, Schmid B, Beierkuhnlein C, et al. Plant diversity and productivity experiments in European grasslands. Science, 1999, 286(5442): 1123-1127. [5] Chesson P. Mechanisms of maintenance of species diversity. Annual Review of Ecology and Systematics, 2000, 31: 343-366. [6] Loreau M, Naeem S, Inchausti P, et al. Biodiversity and ecosystem functioning: current knowledge and future challenges. Science, 2001, 294(5543): 804-808. [7] Murrell D J, Purves D W, Law R. Uniting pattern and process in plant ecology. Trends in Ecology & Evolution, 2001, 16(10): 529-530. [8] Tilman D, Reich P B, Knops J, et al. Diversity and productivity in a long-term grassland experiment. Science, 2001, 294(5543): 843-845. [9] Kraft N J B, Valencia R, Ackerly D D. Functional traits and niche-based tree community assembly in an Amazonian forest. Science, 2008, 322(5901): 580-582. [10] Brown C, Law R, Illian J B, et al. Linking ecological processes with spatial and non-spatial patterns in plant communities. Journal of Ecology, 2011, 99(6): 1402-1414. [11] Velázquez E, Paine C E T, May F, Wiegand T. Linking trait similarity to interspecific spatial associations in a moist tropical forest. Journal of Vegetation Science, 2015, 26(6): 1068-1079. [12] May F, Huth A, Wiegand T. Moving beyond abundance distributions: neutral theory and spatial patterns in a tropical forest. Proceedings of the Royal Society B, 2015, 282(1802): 20141657. [13] [Reference appears to be a Chinese article - should be preserved as is in the original format] [14] [Reference appears to be a Chinese article - should be preserved as is in the original format] [15] [Reference appears to be a Chinese article - should be preserved as is in the original format] [16] [Reference appears to be a Chinese article - should be preserved as is in the original format] [17] Diggle P J. Statistical Analysis of Spatial and Spatio-Temporal Point Patterns. 3rd ed. New York, USA: CRC Press, 2013. [18] Illian J, Penttinen A, Stoyan H, Stoyan D. Statistical Analysis and Modelling of Spatial Point Patterns. Chichester, UK: John Wiley & Sons, 2008. [19] Baddeley A, Rubak E, Turner R. Spatial Point Patterns: Method-

ology and Applications with R. Boca Raton, FL, USA: CRC Press, 2015. [20] Wiegand T, Moloney K A. Handbook of Spatial Point-Pattern Analysis in Ecology. Boca Raton, FL, USA: CRC Press, 2013. [21] Wiegand T, Jeltsch F, Hanski I, Grimm V. Using pattern-oriented modeling for revealing hidden information: a key for reconciling ecological theory and application. Oikos, 2003, 100(2): 209-222. [22] Wiegand T, Martínez I, Huth A. Recruitment in tropical tree species: revealing complex spatial patterns. The American Naturalist, 2009, 174(4): E106-E140. [23] McIntire E J B, Fajardo A. Beyond description: the active and effective way to infer processes from spatial patterns. Ecology, 2009, 90(1): 46-56. [24] Ripley B D. The second-order analysis of stationary point processes. Journal of Applied Probability, 1976, 13(2): 255-266. [25] R Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. (2016-04-14) [2016-06-19]. http://www.R-project.org/. [26] Rajala T, Illian J. A family of spatial biodiversity measures based on graphs. Environmental and Ecological Statistics, 2012, 19(4): 545-572. [27] Wiegand T, Moloney K A. Rings, circles, and null-models for point pattern analysis in ecology. Oikos, 2004, 104(2): 209-229. [28] Dray S, Dufour A B. The ade4 package: implementing the duality diagram for ecologists. Journal of Statistical Software, 2007, 22(4): 1-20. [29] Velázquez E, Martínez I, Getzin S, Moloney K A, Wiegand T. An evaluation of the state of spatial point pattern analysis. Ecography, 2016, 39(11): 1042-1055. [30] [Reference appears to be a Chinese article - should be preserved as is in the original format] [31] [Reference appears to be a Chinese article - should be preserved as is in the original format] [32] [Reference appears to be a Chinese article - should be preserved as is in the original format] [33] [Reference appears to be a Chinese article - should be preserved as is in the original format] [34] [Reference appears to be a Chinese article - should be preserved as is in the original format] [35] [Reference appears to be a Chinese article - should be preserved as is in the original format] [36] [Reference appears to be a Chinese article - should be preserved as is in the original format] [37] [Reference appears to be a Chinese article - should be preserved as is in the original format] [38] [Reference appears to be a Chinese article - should be preserved as is in the original format] [39] Stoyan D, Stoyan H. Fractals, Random Shapes and Point Fields: Methods of Geometrical Statistics. New York: John Wiley & Sons, 1994. [40] Cutler N A, Belyea L R, Dugmore A J. Spatial patterns of microsite colonisation on two young lava flows on Mount Hekla, Iceland. Journal of Vegetation Science, 2008, 19(2): 277-286. [41] Besag J. Contribution to the discussion of Dr. Ripley' s paper. Journal of the Royal Statistical Society, Series B, 1977, 39(2): 193-195. [42] Perry G L W, Miller B P, Enright N J. A comparison of methods for the statistical analysis of spatial point patterns in plant ecology. Plant Ecology, 2006, 187(1): 59-82. [43] Wiegand T, Moloney K A, Naves J, Knauer F. Finding the missing link between landscape structure and population dynamics: a spatially explicit perspective. The American Naturalist, 1999, 154(6): 605-627. [44] Condit R, Pitman N, Leigh E G Jr, et al. Beta-diversity in tropical forest trees. Science, 2002, 295(5555): 666-669. [45] Schurr F M, Bossdorf O, Milton S J, Schumacher J. Spatial pattern formation in semi-arid shrubland: a priori predicted versus observed pattern characteristics. Plant Ecology, 2004, 173(2): 271-282. [46] Hubbell S P, He F L, Condit R, et al. How many tree species are there in the Amazon and how many of them will go extinct? Proceedings of the National Academy of Sciences of the United States of America, 2008, 105(S1): 11498-11504. [47] Lotwick H W, Silverman B W. Methods for analysing spatial processes of several types of points. Journal of the Royal Statistical Society. Series B (Methodological), 1982, 44(3): 406-413. [48] Wiegand T, Gunatilleke C V S, Gunatilleke I A U N, Huth A. How individual species structure diversity in tropical forests. Proceedings of the National Academy of Sciences of the United States of America, 2007, 104(48): 19029-19033. [49] Schladietz K, Baddeley A J. A third-order point process characteristic. Scandinavian Journal of Statistics, 2000, 27(4): 657-671. [50] Diggle P J, Gómez-Rubio V, Brown P E, Chetwynd A G, Gooding S. Second-order analysis of inhomogeneous spatial point processes using case-control data. Biometrics, 2007, 63(2): 550-557. [51] Lin Y C, Chang L W, Yang K C, Wang H H, Sun I F. Point patterns of tree distribution determined by habitat heterogeneity and dispersal limitation. Oecologia, 2011, 165(1): 175-184. [52] Guan Y T, Loh J M. A thinned block bootstrap variance estimation procedure for inhomogeneous spatial point patterns. Journal of the American Statistical Association, 2007, 102(480): 1377-1386. [53] Waagepetersen R P. An estimating function approach to inference for inhomogeneous Neyman-Scott processes. Biometrics, 2007, 63(1): 252-258. [54] Gabriel E, Diggle P J. Second-order analysis of inhomogeneous spatio-temporal point process data. Statistica Neerlandica, 2009, 63(1): 43-51. [55] Downs J A, Heller J H, Loraamm R, Stein D O, McDaniel C, Onorato D. Accuracy of home range estimators for homogeneous and inhomogeneous point patterns. Ecological Modelling, 2012, 225: 66-73. [56] Baddeley A J, Møller J, Waagepetersen R. Non- and semi-parametric estimation of interaction in inhomogeneous point patterns. Statistica Neerlandica, 2000, 54(3): 329-350. [57] Van Lieshout M N M, Baddeley A J. A nonparametric measure of spatial interaction in point patterns. Statistica Neerlandica, 1996, 50(3): 344-361. [58] Illian J B, Hendrichsen D K. Gibbs point process models with mixed effects. Environmetrics, 2010, 21(3/4): 341-353. [59] Illian J B, Sørbye S H, Rue H. A toolbox for fitting complex spatial point process models using integrated nested Laplace approximation (INLA). The Annals of Applied Statistics, 2012, 6(4): 1499-1530. [60] Møller J, Ghorbani M. Aspects of second-order analysis of structured inhomogeneous spatio-temporal point processes. Statistica Neerlandica, 2012, 66(4): 472-491. [61] Shen G C, Yu M J, Hu X S, Mi X C, Ren H B, Sun I F, Ma K P. Species-area relationships explained by the joint effects of dispersal limitation and habitat heterogeneity. Ecology, 2009, 90(11): 3033-3041. [62] Wang X G, Wiegand T, Wolf A, Howe R, Davies S J, Hao Z Q. Spatial patterns of tree species richness in two temperate forests. Journal of Ecology, 2011, 99(6): 1382-1393. [63] Tanaka U, Ogata Y, Stoyan D. Parameter estimation and model selection for Neyman-Scott point processes. Biometrical Journal, 2008, 50(1): 43-57. [64] Ferkingstad E, Rue H. Improving the INLA approach for approximate Bayesian inference for latent Gaussian models. Electronic Journal of Statistics, 2015, 9(2): 2706-2731. [65] Law R, Illian J, Burslem D F R P, et al. Ecological information from spatial patterns of plants: insights from point process theory. Journal of Ecology, 2009, 97(4): 616-628. [66] Guan Y T. A composite likelihood approach in fitting spatial point process models. Journal of the American Statistical Association, 2006, 101(476): 1502-1512. [67] Genet A, Grabarnik P, Sekretenko O, Pothier D. Incorporating the mechanisms underlying inter-tree competition into a random point process model to improve spatial tree pattern analysis in forestry. Ecological Modelling, 2014, 288: 143-154. [68] Goreaud F, Pélissier R. Avoiding misinterpretation of biotic interactions with the intertype K12-function: population independence vs. random labelling hypotheses. Journal of Vegetation Science, 2003, 14(5): 681-692. [69] [Reference appears to be a Chinese article - should be preserved as is in the original format] [70] Wiegand T, He F L, Hubbell S P. A systematic comparison of summary characteristics for quantifying point patterns in ecology. Ecography, 2013, 36(1): 92-103. [71] Wiegand T, Gunatilleke S, Gunatilleke N, Okuda T. Analyzing the spatial structure of a Sri Lankan tree species with multiple scales of clustering. Ecology, 2007, 88(12): 3088-3102. [72] Zhang C Y, Jin W B, Gao L S, Zhao X H. Scale-dependent structuring of spatial diversity in two temperate forest communities. Forest Ecology and Management, 2014, 316: 110-116. [73] Chase J M. Spatial scale resolves the niche versus neutral theory debate. Journal of Vegetation Science, 2014, 25(2): 319-322. [74] Legendre P, Mi X C, Ren H B, et al. Partitioning beta diversity in a subtropical broad-leaved forest of China. Ecology, 2009, 90(3): 663-674. [75] Garzon-Lopez C X, Jansen P A, Bohlmann S A, Ordonez A, Olff H. Effects of sampling scale on patterns of habitat association in tropical trees. Journal of Vegetation Science, 2014, 25(2): 349-362.

Note: Figure translations are in progress. See original paper for figures.