Ecography

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Supplementary material

Appendix 1. Detailed results of literature review

Evaluation of articles

Table A1 shows the different categories we used to describe each study. We first recorded a number of basic descriptors such as the year of publication, the journal, the ecological object (e.g., trees or fire events), the vegetation type, and how SPPA was used (e.g., if specific hypotheses were tested or if the study presented mainly a new method). Next we recorded details on the basic elements of SPPA (i.e., data types, summary statistics, null models, data comparison, and heterogeneity). Finally, we also recorded the software used for the point pattern analysis.

In some cases we simply report the relative proportion of studies that fall into the different categories shown in Table A1; however, in other cases we were interested in the temporal development of the use of different elements of SPPA. In these cases we used an index $C(t, c)$ that gives the proportion of all studies published up to year t that fall within a given category c. We estimate this "proportion of cumulative studies" as $C(t, c) = P(t, c)/a(t)$ where $P(t, c)$ is the number of cases where category c applied up to year t and $a(t)$ is the number of articles in our sample published up to year t. Some of the categories were non-exclusive so that the index $C(t, c)$ may add up to a value larger than one. Because only eleven studies in our sample were published before 1997 (Fig. 1A), we estimated $C(t, c)$ only for years 1997 to 2012.

Results

General descriptors

In the 1980s just a few studies applied modern techniques of SPPA to ecological questions (e.g., Galliano 1982, Sterner et al. 1986, Getis and Franklin 1987, Kenkel 1988). By the 1990s such studies appeared more regularly, becoming increasingly common from 1998 onwards (Fig. A1a). Study sites were spread over most of the globe with some local clusters in central

Europe (Fig. A1b). The 308 Studies on SPPA analyzed here were published in 92 different journals, but the distribution of studies over the journals was highly skewed; nine journals accounted for half of the studies, with *Journal of Vegetation Science* (39 studies), *Forest Ecology and Management* (38), and *Plant Ecology* (21) being the journals where most of the studies were published. When looking at categories of journals publishing more than 5 studies, we found that 71 studies were published in journals focusing on plant ecology, 62 studies were published in forestry journals, and 54 in general ecology journals (e.g., *Ecography*, *Ecology*, or *Acta Oecologica*). The ecological objects studied closely mirrored the subject matter of the respective journals, with an overwhelming number of studies conducted on trees (203), followed by shrubs (26), animal structures or captures (24), herbs (21) and fire events (8). Most of the studies of vegetation were conducted in forests (175), primarily in temperate latitudes (113). A small number of studies were also conducted in areas of semi-arid vegetation (22) and Mediterranean climate (19) (Fig. A1c). Approximately half of the studies analyzed point patterns with relatively few points (< 100), but the other half considered 100 to 800 points (Fig. A1d). Although the analyses were conducted with spatially explicit data, only 62% of the studies contained at least one map of the point patterns.

When looking at the way SPPA was used in the 308 articles, we found that most articles (170) tested a hypothesis, 91 articles addressed specific ecological questions, and 46 articles predominantly presented new methods or tested new methods. The proportion of articles that tested methods decreased after 1998 (blue symbols in Fig. A2a) and those presenting new methods increased after 2000 (green symbols in Fig. A2a).

Data types

Most of the studies examined presented analysis of univariate patterns (82%). In contrast, 44% considered bivariate patterns, 21% qualitatively marked patterns, and only 6% of studies considered quantitatively marked and multivariate patterns (Fig. A2b). The relative proportions of the different types of analyses also did not change much over time (Fig. A2b). A large proportion of the studies analyzed several data types. Thirty-nine percent of the papers analyzed both uni- and bivariate patterns, and 16% analyzed univariate and marked patterns.

Summary statistics

Authors have used a considerable variety of summary statistics, and have often adapted existing ones to better accommodate their specific needs. However, a majority of studies (75%) used *K*- or *L*-functions as summary statistics, 53% of them exclusively (Fig. A2c). In contrast, summary statistics of the pair-correlation function family, which are often more informative, were used in only 27% of all studies. Indices were used in 11% of the studies and nearest neighbor distribution functions in 10% (Fig. A2c). Use of multiple summary statistics was not widespread; 10% of the papers examined combined the *K*- and *g*-families of statistics, but only 6% used *K*- or *g* summary statistics together with other summary statistics (Fig. A2c). Early exceptions are the studies by Sterner et al. (1986) and Barot et al. (1999).

Figures A2d and A2e show how the use of the different summary statistics changed over time. During the last ten years, the proportion of articles using $K(r)$ or $L(r)$ functions has decreased while the number of those using $g(r)$ functions or functions adapted for quantitatively marked or inhomogeneous patterns has increased (Fig. A2d). Regarding the different types of summary statistics, indices and nearest neighbor summary statistics were frequently used before 2000, but their use has strongly declined since then (Fig. A2e).

Edge correction

Roughly one quarter of all studies did not clearly state the edge correction method used (Fig. A2f) and often referred to papers that presented several edge correction methods. In 8% of the studies the authors did not use edge correction, whereas 8% and 4% of studies (mostly old ones) used minus- or plus sampling edge correction, respectively (Fig. A2f). In most of the studies, various pairwise-weighted edge correction (41%) and global edge correction (21%) methods were used. After 2003, the proportion of studies using pairwise-weighted edge correction methods declined somewhat at the expense of global edge correction methods (Fig. A2f), especially within the context of the use of the software *Programita*.

In general, the problem of edge correction, which occupied authors of earlier studies, has been mostly resolved. Recent textbooks (Illian et al. 2008, Wiegand and Moloney 2014) now provide a detailed treatment of the different options for uni- and bivariate patterns. Pairwise-weighted and global edge-correction methods provide generally similar results in the estimation of second-order summary statistics.

Null models

Most of the 254 studies that conducted univariate analysis used CSR as the null model (86%) (Fig. A3a). In contrast, only 15% of all univariate studies used CSR in combination with another univariate null model or point process model. More than half of all studies exclusively used the CSR null model in combination with the *K*-function family of pattern analysis (Fig. A3a). Surprisingly, the use of null models other than CSR has only recently become more frequent in univariate analyses (Fig. A3a). The heterogeneous Poisson process (HP) was used in 15% of all univariate studies, and cluster processes in 8%, while only 5% of the studies analyzing univariate patterns did not clearly state the null model used.

The most frequent null model used in the 135 studies conducting bivariate analysis was the toroidal shift (39% of the studies), followed by bivariate CSR (33%). Both null models were frequently used over the entire period examined by this review (Fig. A3b). One quarter of all bivariate analyses considered structural constraints, such as an antecedent condition, but the bivariate, heterogeneous Poisson process model was rarely used (9.6% of the studies). It is also interesting that 14% of all bivariate studies modified widely used null models to better respond to their specific questions and hypotheses. However, 26% of all studies that conducted bivariate analysis did not clearly state the null model used (Fig. A3b). Sixty-four studies used random labeling correctly for qualitatively marked patterns, but eleven studies confused the null models for independence and random labeling.

Data comparison

The overwhelming majority of studies (93%) used Monte Carlo simulations, and 12% of all studies also used a goodness-of-fit test (GoF) to assess the overall fit of the null model over a distance interval of interest. Several studies mentioned the GoF test, but did not use it because of the exploratory character of the study. Interestingly, the proportion of cumulative studies using the GoF test dropped to 6% in 2003 but since 2004, it has constantly increased up to 12% (Fig A3c). Because the Monte Carlo simulations are stochastic, there is some uncertainty in the assessment of the simulation envelopes, especially if less than 100 simulations are used. The number of simulations used by the authors in the null model strongly varied. In most cases it was between 200 and 1000 (34 % of published articles) or between 20 and 100 (32%). However, 6% of all studies did not provide the number of simulations (Fig. A3d).

Heterogeneity

We found that, up to 1998, approximately 80% of studies were conducted for homogeneous patterns, but this proportion dropped to 50% afterwards (black symbols in Fig. A3e). The proportion of studies that overlooked heterogeneity (blue symbols in Fig. A3e) and studies that recognized it but used homogeneous techniques (yellow symbols in Fig. A3e) accounted for 14% and 13% of all cases, respectively. In contrast, studies considering heterogeneity in the point pattern methods increased after 2005, making up one quarter of all cases (green symbols in Fig. A3e). Finally, studies that exhibited indications of virtual aggregation made up one quarter of all studies. This reached a peak of 33% in 2000, but then declined due to the increasing consideration of techniques accounting for various aspects of heterogeneity (Fig. A3e). Interestingly, out of the 159 studies that conducted the simplest analysis (i.e., used the *K*-function family together with CSR for univariate patterns), 50% were conducted for homogeneous patterns, but 38% of these studies showed virtual aggregation.

Software

Appendix 4 in Supplementary material shows the references and links for the most frequently used software programs. The most used software in the 308 studies examined was *Programita* (56) (Wiegand and Moloney 2004, 2014) and spatstat (46) (Baddeley and Turner 2005), which appeared after 2005. All other packages were used in less than 8% of all studies (Fig. A3f). However, 23% of all studies (71) did not specify the software used.

Additional references

Galliano, E.F. 1982. Pattern detection in plant populations through the analysis of plant-to-all-plants distances. - Vegetatio 49:39–43.

Getis, A. and Franklin, J. 1987. Second-order neighborhood analysis of mapped point patterns. - Ecology 68: 474–477.

Table A1. Descriptors and categories used to characterize how the reviewed studies used the five key elements of spatial point pattern analysis in ecology (bold, numbers 1 to 5). The different categories under each key element are given in italics and normal fonts.

Basic descriptors of papers

- *year of publication*
- *journal*
- *number of points*
- *map of pattern included* (yes, no)
- *location of study area*
- *ecological object**
- *vegetation type †*
- *Use of SPPA*
    - hypothesis testing
    - answer specific question
    - method presentation
    - method test

1) Data types

- unmarked
    - univariate
    - bivariate
    - multivariate
- qualitatively marked
- quantitatively marked

2) Summary statistics

- indices
- *second-order summary statistics*
    - $K(r)$ or $L(r)$
    - $g(r)$ or $O(r)$
    - inhomogeneous versions
- nearest neighbor summary statistics
- mark connection or mark correlation functions
- others
- *Edge correction*
    - minus sampling
    - plus sampling
    - pairwise weighted edge correction
    - global edge correction
    - no edge correction
    - not specified

3) Null models and point process models

- *Univariate*
    - homogeneous Poisson (CSR)
    - cluster processes
    - heterogeneous Poisson (HP)
    - others
    - not specified
- *bivariate*
    - antecedent condition
    - toroidal shift
    - homogeneous Poisson (CSR)
    - heterogeneous Poisson (HP)
    - other
    - not specified
- *qualitatively marked patterns*
    - random labeling
    - not specified
    - wrong selection of independence

4) Data comparison

- *Monte Carlo methods* (yes, no)
- Number of simulations
- *Goodness-of-fit test* (yes, no)

5) Heterogeneity

- homogeneous
- heterogeneous, but not recognized
- heterogeneity recognized, no specific method
- Heterogeneity recognized, specific methods
- *virtual aggregation* (yes, no)

Software

- not specified
- *Programita* (Wiegand and Moloney 2014)
- Spatstat (Baddeley and Turner 2005)
- SPPA (Haase 2001)
- ADE (Thioulouse et al. 1997)
- other

* trees, shrubs, herbs, animal captures or structures, fire events, others

† alpine, boreal forests, dry tropical, Mediterranean, semi-arid land, subtropical forest, temperate forest, wet tropical forest, others, several types.

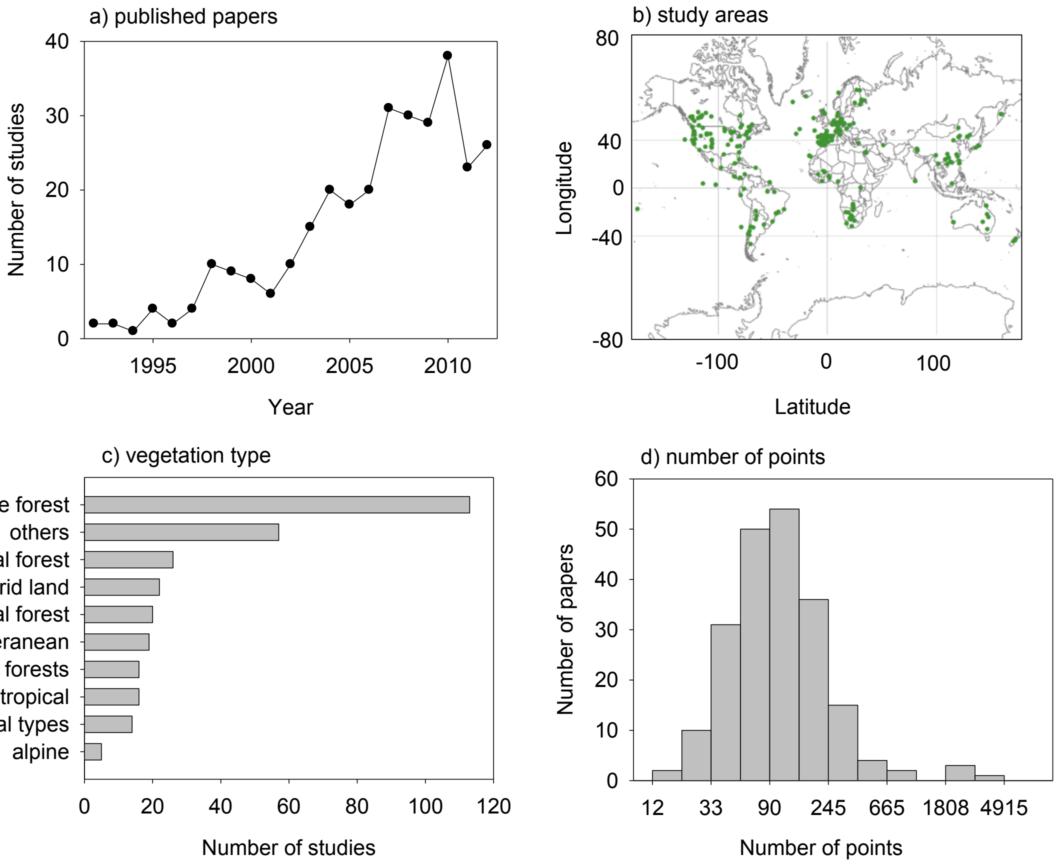

Figure A1. Basic descriptors of the 308 articles using point pattern analysis in ecology and related disciplines over the 1992-2012 study period. (a) Number of studies published per year included in our analysis. (b) Geographical location of the 308 articles using point pattern analysis in ecology and related disciplines. (c) Number of studies performed in different vegetation types. (d) Frequency distribution of the number of points in the patterns.

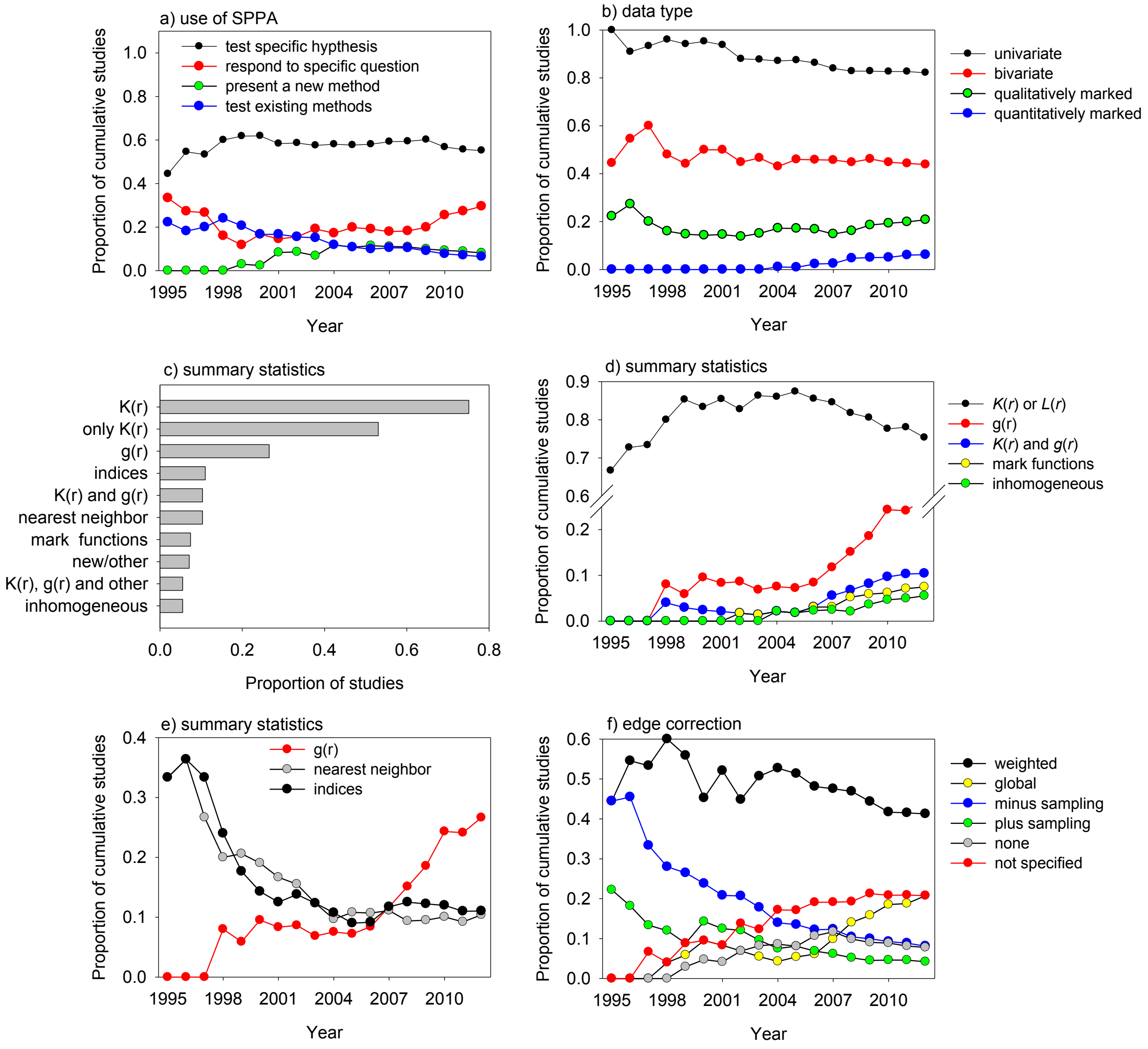

Figure A2. Use of spatial point pattern analysis, data types, summary statistics, and edge correction methods in the 308 studies analyzed. Temporal change in the proportion of articles; (a) that tested hypotheses, answered specific questions, or presented/tested new methods, (b) that analyzed different data types. (c) Proportion of articles that used a given summary statistic or a combination of summary statistics; inhomogeneous refers to inhomogeneous second-order summary statistics, and mark functions to mark correlation and mark connection functions. (d) Temporal change in the proportion of articles using different types of summary statistics. (e) Same as d), but only for indices, nearest neighbor statistics and the pair correlation function. (f) Temporal change in the proportion of articles using different edge correction methods; weighted and global indicate pairwise weighted edge correction and global edge correction, respectively.

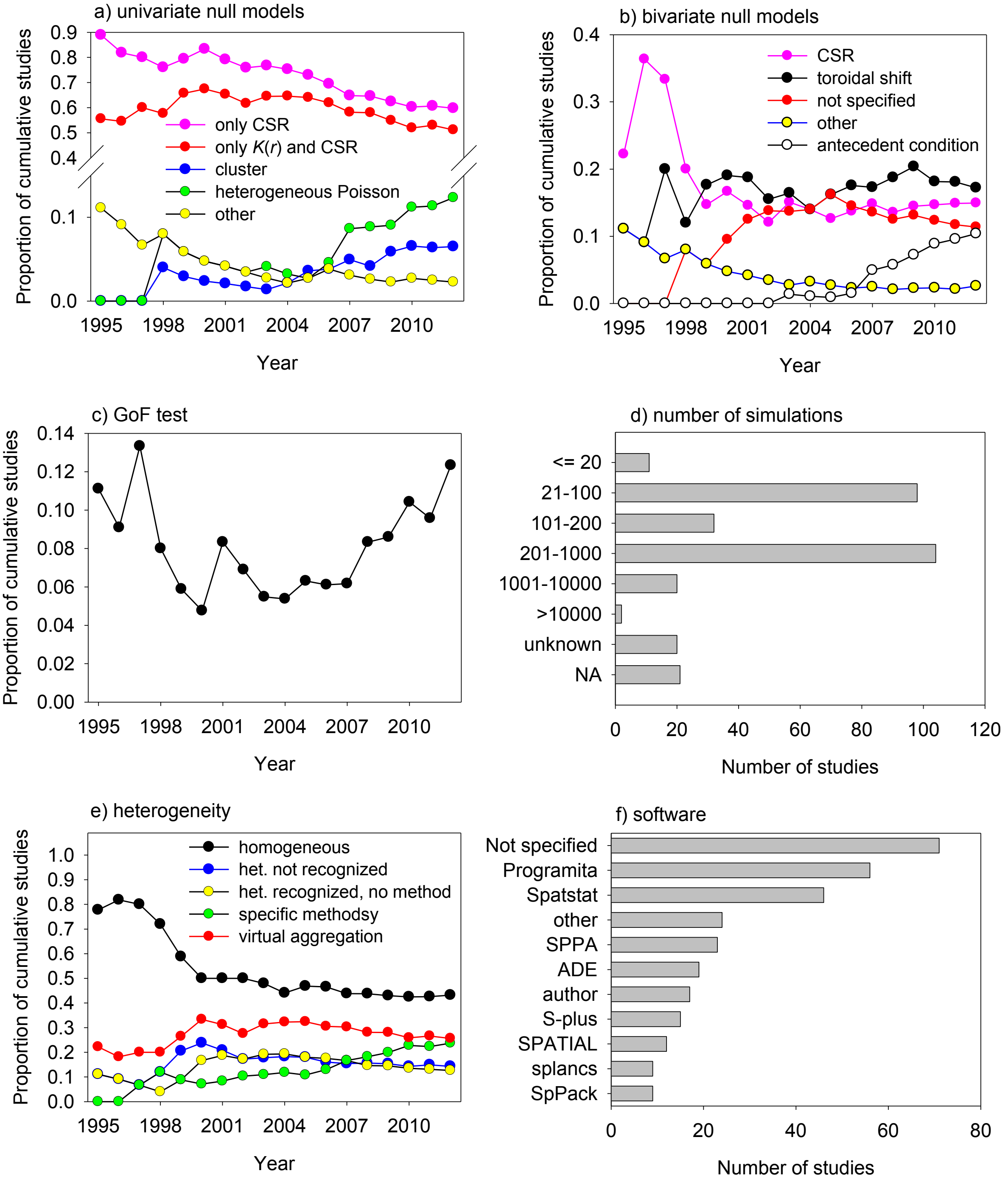

Figure A3. Null models, data comparison, heterogeneity, and software as used in the 308 articles analyzed. Temporal change in the proportion of articles using; (a) different univariate and (b) bivariate null models, (c) a goodness-of-fit test, (d) a certain number of simulations of the null model, (e) different methods to deal with heterogeneity. (f) Number of articles using different software packages. References for software are given in Appendix 4 in Supplementary material.

Appendix 2. Additional results of global envelopes

Global envelopes $S^+(r)$ and $S^-(r)$ that are variable in r were proposed by Myllymäki et al. (in press) in their section 5 as “global scaled maximum absolute difference (MAD) envelopes”. They have the desired property that the null model can be rejected over a given distance interval with significance level α if the observed summary statistic $S(r)$ wanders at one or more distances r outside the global simulation envelopes. Note that the pointwise envelopes do not have this property because of the problem of multiple inference (Loosmore et al. 2006).

The global envelopes $S^+(r)$ and $S^-(r)$ are constructed in three steps. First, the summary statistics $S_i(r)$ are estimated from the observed data ($i = 0$) and from the s realizations of the null model ($i = 1,.. s$), and the mean $\bar{S}(r)$ and the standard deviation $\hat{\sigma}_S(r)$ of the $S_i(r)$ are estimated for $i = 1,.. s$. Then, the original summary statistics $S_i(r)$ are student transformed:

$$S_i^{ses}(r) = \frac{S_i(r) - \bar{S}(r)}{\hat{\sigma}_S(r)}, \qquad (1)$$

In ecology this transformation is called standardized effect sizes. Notably, the pointwise simulation envelopes $G_p^-(r)$ and $G_p^+(r)$ of the student transformed summary statistics (e.g., for $\alpha = 0.05$ the 5th lowest and highest values of $S_i^{ses}(r)$ taken from $i = 1, .., 199$) approximate for all distances r the critical value $G_p^-(r) = -z_\alpha$ and $G_p^+(r) = z_\alpha$ with $z_\alpha = 1.96$ for $\alpha = 0.05$. Thus, we have constant pointwise simulation envelopes. This works if the distribution of the $S_i(r)$ for $i = 1, \ldots s$ approximates for fixed values of r a normal distribution. This assumption can be tested by comparing the $G_p^-(r)$ and $G_p^+(r)$ with the critical values z_α and $-z_\alpha$. If the distribution is not symmetric for some values of r one can either use upper and lower quantiles proposed by Myllymäki et al. (2015a) or exclude these distances from the distance interval where the global envelope test is applied.

Second, the standard “maximal absolute difference” (MAD) test introduced by Diggle (1979) and Ripley (1979) is applied for the studentised summary statistics $S_i^{ses}(r)$. This test makes sense because the variance of the $S_i^{\text{ses}}(r)$ under the null model is the same for all distances r. The functional summary statistic $S_i^{\text{ses}}(r)$ of the ith simulation of the null model is reduced to its minimum and maximum value $S_i^{\min}$ and $S_i^{\max}$, respectively, taken over the distance interval $r = r_{\min}, .., r_{\max}$ of interest. The kth largest value of the $S_i^{\max}$ is the upper global envelope G^+, and the kth smallest value of the $S_i^{\min}$ is the lower global envelope G^-. Note that this test conducts only one test for the entire interval. For this reason, the problem of multiple inference (Loosmore et al. 2006) does not occur and we can reject the null model with significance level α if $S_0^{\text{ses}}(r) > G^+$ or $S_0^{\text{ses}}(r) < G^-$ for one or more distances r ($r \geq r_{\min}$ and $r \leq r_{\max}$).

Third, to obtain the desired global simulation envelopes $S^+(r)$ and $S^-(r)$ that are variable in r we apply the inverse transformation of (1) to G^+ and G^- (see eq. 17 in Myllymäki et al. *in press*):

$$\begin{aligned} S^+(r) &= \bar{S}(r) + \hat{\sigma}_S(r)G^+ \\ S^-(r) &= \bar{S}(r) - \hat{\sigma}_S(r)G^- \end{aligned} \qquad (2)$$

The global envelopes $S^+(r)$ and $S^-(r)$ are implemented in the software *Programita*, which can be accessed at www.programita.org, and as R library spptest which can be obtained at https://github.com/myllym/spptest.

Additional references

Ripley, B.D. 1979. Tests of randomness for spatial point patterns. - Journal of the Royal Statistical Society B 41:368-374.

Diggle, P.J. 1979. On parameter estimation and goodness-of-fit testing for spatial point patterns. - Biometrics 35:87-101.

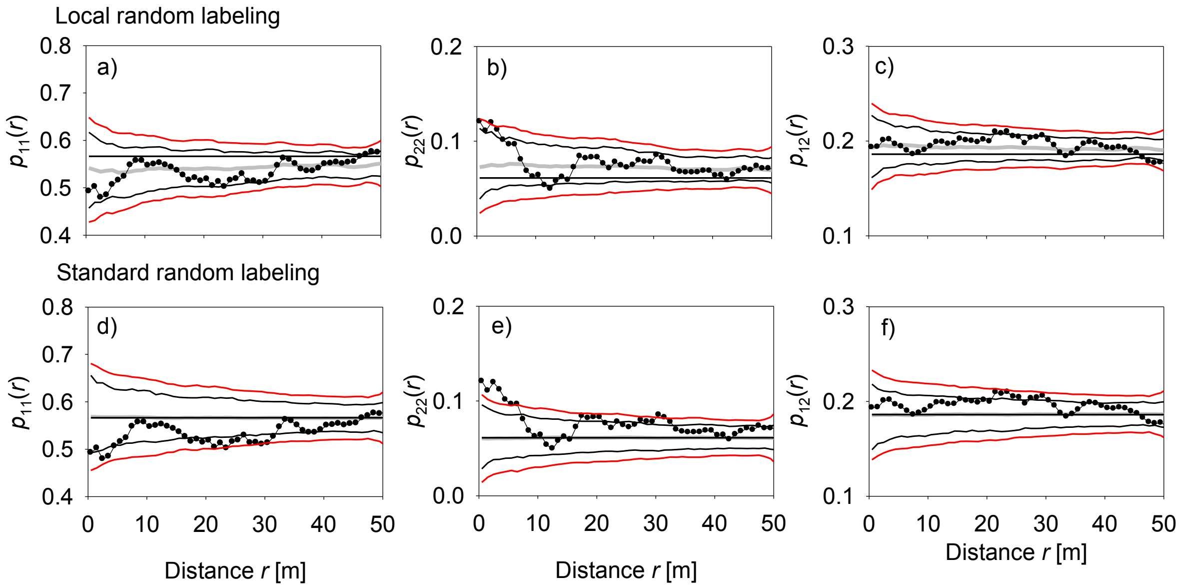

Figure A4. Comparison of the results of standard random labeling and local random labeling for the data of surviving and dead saplings of *E. galalonensis* shown in figure 1D. a) - c) Results for local random labeling (where a given mark is not moved more than 100m), they are the same as in Figs. 3C - E. The horizontal black line shows the expectation of standard random labeling. Comparison with the expectation of local random labeling (grey bold line) shows that mortality of *E. galalonensis* shows spatial trends. d) -f) Same as a) - c), but for standard random labeling where the marks are randomly shuffled among all saplings.

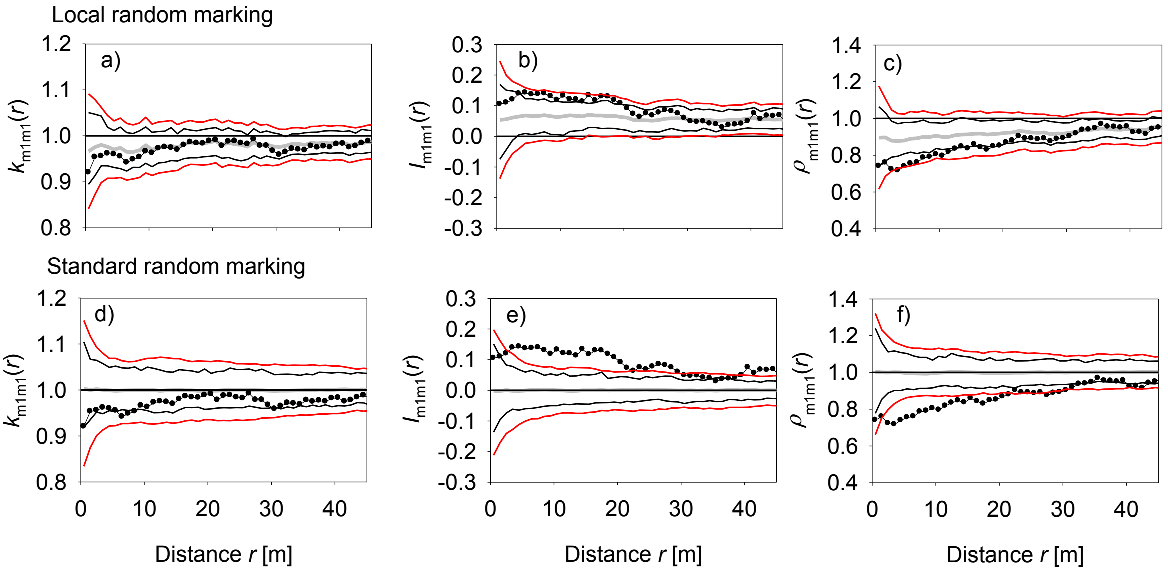

Figure A5. Comparison of the results of standard random marking and local random marking for the quantitatively marked pattern of large trees (dbh > 10cm) of the mid-story tree *Trichilia pallida* shown in figure 1E. a) - c) Results for local random marking (where a given mark is not moved more than 100m). a) is the same as Fig. 5A and b) the same as Fig. 5C, and in c) we show additionally the mark variogram. Comparison with the expectation of local random marking (grey bold line) shows that sizes of *T. pallida* shows spatial trends. d) -f) Same as a) - c), but for standard random marking null model where the marks are randomly shuffled among all large trees.

Appendix 3. List of papers analyzed

Aakala et al. 2007. Trees dying standing in the northeastern boreal old-growth forests of Quebec: spatial patterns, rates and temporal variation. Canadian Journal of Forest Research 37: 50-61.

Aakala et al. 2012. Spatially random mortality in old-growth red pine forests of northern Minnesota. Canadian Journal of Forest Research 42: 899-907

Akhavan et al. 2012. Spatial patterns in different forest development stages of an intact old-growth Oriental beech forest in the Caspian region of Iran. European Journal of Forest Research 131: 1355-1366.

Aldrich et al. 2003. Spatial dispersion of trees in an old-growth temperate hardwood forest over 60 years of succession. Forest Ecology and Management 180: 475-491.

Ali et al. 2009. Long-term fire frequency variability in the eastern Canadian boreal forest: the influences of climate vs. local factors. Global Change Biology 15: 1230-1241.

Andersen 1992. Spatial analysis of two-species interactions. Oecologia 91: 134-140.

Arévalo and Fernández-Palacios 2003. Spatial patterns of trees and juveniles in a laurel forest of Tenerife, Canary Islands. Plant Ecology 165: 1-10.

Arévalo et al. 2005. Regeneration in a mixed stand of native *Pinus canariensis* and introduced *Pinus pinea species*. Acta Oecologica-International Journal of Ecology 28: 87-94.

Atkinson et al. 2007. Investigating spatial structure in specific tree species in ancient semi-natural woodland using remote sensing and marked point pattern analysis. Ecography 30: 88-104.

Awada et al. 2004. *Picea glauca* dynamics and spatial pattern of seelings regeneration along a chronosequence in the mixedwood section of the boreal forest. Annals of Forest Science 61: 789-794.

Barbeito et al. 2009. Response of pine natural regeneration to small-scale spatial variation in a managed Mediterranean mountain forest. Applied Vegetation Science 12: 488-503.

Barot et al. 1999. Demography of a savanna palm tree: predictions from comprehensive spatial pattern analyses. Ecology 80(6): 1987-2005.

Batista and Maguire 1998. Modelling the spatial structure of tropical forests. Forest Ecology and Management 110: 293-314.

Batllori et al. 2010. Current regeneration patterns at the tree line in the Pyrenees indicate similar recruitment processes irrespective of the past disturbance regime. Journal of Biogeography 37: 1938-1950.

Bayard and Elphick 2010. Using spatial point pattern assessment to understand the social and environmental mechanisms that drive avian habitat selection. The Auk 127(3): 485-494.

Beghin et al. 2010. *Pinus sylvestris* forest regeneration under different post-fire restoration practices in the northwestern Italian Alps. Ecological Engineering 36: 1365-1372.

Béland et al. 2003. Structure, spatial distribution and competition in mixed jack pine (*Pinus banksiana*) stands on clay soils of eastern Canada. Annals of Forest Science 60: 609-617.

Belinchón et al. 2011. Fine spatial pattern of an epiphytic lichen species is affected by habitat conditions in two forest types in the Iberian Mediterranean region. Fungal Biology 115:1270-1278

Berg and Hamrick 1994. Spatial and genetic structure of two sandhills oaks: *Quercus laevis* and *Quercus margaretta* (Fagaceae). American Journal of Botany 81(1): 7-14.

Beverly et al. 2008. Assessing spatial attributes of forest landscape values: an internet-based participatory mapping approach. Canadian Journal of Forest Research 38: 289-303.

Biganzoli et al. 2009. Fire-mediated interactions between shrubs in a South American temperate savannah. Oikos 118: 1383-1395.

Bilek et al. 2011. Managed vs. unmanaged. Structure of beech forest stands (*Fagus sylvatica* L.) after 50 years of development, Central Bohemia. Forest Systems 20: 122-138.

Birkhofer et al. 2010. Assessing spatiotemporal predator-prey patterns in heterogeneous habitats. Basic and Applied Ecology 11: 486-494.

Boudreau et al. 2010. Population dynamics of *Empetrum hermaphroditum* (Ericaceae) on a subarctic sand dune: Evidence of rapid colonization through efficient sexual reproduction. American Journal of Botany 97:770-781

Bourgignon et al. 2011. Are the spatio-temporal dynamics of soil-feeding termite colonies shaped by intra-specific competition? Ecological Entomology 36: 776-785.

Boyden et al. 2005. Spatial and temporal patterns in structure, regeneration, and mortality of an old-growth ponderosa pine forest in the Colorado Front Range. Forest Ecology and Management 219: 43-55.

Burke et al 1998. Effect of density on predation rate for turtle nests in a complex landscape. Oikos 83: 3-11.

Camarero et al. 2000. Spatial pattern of subalpine forest-alpine grassland ecotines in the Spanish Central Pyrenees. Forest Ecology and Management 134: 1-16.

Camarero et al. 2005. Spatial patterns of tree recruitment in a relict population of *pinus uncinata*: forest expansion through stratified diffusion. Journal of Biogeography 32: 1979-1992.

Carcaillet et al. 2009. Spatial variability of fire history in subalpine forests. Ecoscience 16: 1-12.

Castagneri et al. 2010. Diachronic analysis of individual-tree mortality in a Norway spruce stand in the eastern Italian Alps. Annals of Forest Science 67: 304.

Castilla et al. 2012. Disturbance-dependent spatial distribution of sexes in a gynodioecious understory shrub. Basic and Applied Ecology 13: 405-413.

Castillo-Núñez et al. 2011. Delineation of secondary succession mechanisms for tropical dry forests using LiDAR. Remote Sensing of Environment 115: 2217-2231.

Caylor et al. 2003. Tree spacing along the Kalahari transect in southern Africa. Journal of Arid Environments 54: 281-296.

Chen and Bradshaw 1999. Forest structure in space: a case study of an old growth spruce-fir forest in Changbaishan Natural Reserve, PR China. Forest Ecology and Management 120: 219-233.

Christopher and Goodburn 2008. The effects of spatial patterns on the accuracy of forest vegetation simulator (FVS) estimates of forest canopy cover. Western Journal of Applied Forestry 23: 5-11.

Chung et al. 2006. Fine-scale genetic structure among genetic individuals of the clone-forming monotypic genus *Echinospora koreensis* (Fabaceae). Annals of Botany 98: 165-173.

Condit et al. 2000. Spatial patterns in the distribution of tropical tree species. Science 288: 1414-1418.

Cornullier and Bretagnole 2006. Assessing the influence of environmental heterogeneity on bird spacing parameters: a case study with two raptors. Ecography 29: 240-250.

Cousens et al. 2008. Small-scale spatial structure within patterns of seed dispersal. Oecologia 158:437-48

Couteron and Kokou 1997. Woody vegetation spatial patterns in a semi-arid savanna of Burkina Faso, West Africa. Plant Ecology 132: 211-227.

Couteron et al. 2003. A test for spatial relationships between neighbouring plants in plots of heterogeneous plant density. Journal of Vegetation Science 14: 163-172.

Curzon and Keeton 2010. Spatial characteristics of canopy disturbances in riparian old-growth hemlock - northern hardwood forests, Adirondack Mountains, New York, USA. Canadian Journal of Forest Research 40: 13-25.

Cutler et al. 2008. The spatiotemporal dynamics of a primary succession. Journal of Vegetation Science 96: 231-246.

Dagley 2008. Spatial pattern of coast redwood in three altitudinal flat old-growth forests in Northern California. Forest Science 54: 294-302.

Dale and Powell 2001. A new method for characterizing point patterns in plant ecology. Journal of Vegetation Science 12: 597-608.

De Luis et al. 2008. Temporal and spatial differentiation in seedling emergence may promote species coexistence in Mediterranean fire-prone ecosystems. Ecography 31: 620-629.

de Soto et al. 2010. Release of *Juniperus thurifera* woodlands from herbivore-mediated arrested succession in Spain. Applied Vegetation Science 13: 15-25.

Debski et al. 2002. Habitat preferences of Aporosa in two Malaysian forests: implications for abundance and coexistence. Ecology 83: 2005-2018.

Deckers et al. 2005. Effects of landscape structure on the invasive spread of black cherry *Prunus serotina* in an agricultural landscape in Flanders (Belgium). Ecography 28: 99-109.

Dickinson and Norton 2011. Divergent small-scale spatial patterns in New Zealand's short tussock grasslands New Zealand. Journal of Ecology 35: 76-82.

Djossa et al. 2008. Land use impact on *Vitellaria paradoxa* C.F. Gaerten. Stand structure and distribution patterns: a comparison of Biosphere Reserve of Pendjari in Atacora district in Benin. Agroforestry Systems 72: 205-220.

Dolezal et al. 2006. Neighborhood interactions influencing tree population dynamics in nonpyrogenous boreal forest in northern Finland. Plant Ecology 185: 135-150.

Dolezal et al. 2004. Tree growth and competition in a *Betula platyphylla-Larix cajanderi* post-fire forest in Central Kamchatka. Annals of Botany 94: 333-343.

Dolezal et al. 2004. Neighbourhood interactions and environmental factors influencing old-pasture succession in the Central Pyrenees. Journal of Vegetation Science 15: 101-108.

Dounavi et al. 2010. Spatial patterns and genetic structures within beech populations (*Fagus sylvatica* L.) of forked and non-forked individuals. European Journal of Forest Research 129: 1191-1202.

Duckenbrod et al. 2005. Spatial pattern and process in forest stands within the Virginia piedmont. Journal of Vegetation Science 16: 37-48.

Duvall 2007. Human settlement and baobab distribution in south-western Mali. Journal of Biogeography 34: 1947-1961.

Dwyer et al. 2010. Neighbourhood effects influence drought-induced mortality of savanna trees in Australia. Journal of Vegetation Science 21: 573-585.

Eccard et al. 2006. Use of large Acacia trees by the cavity dwelling black-tailed tree rat in the Southern Kalahari. Journal of Arid Environments 64: 604-615.

Eccles et al. 1999. Spatial pattern analysis in Namaqualand desert plant communities: evidence for general positive interactions. Plant Ecology 142: 71-85.

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Appendix 4. Key references and links for software packages appearing in Figure A3f.

Software	Key reference	Link
ADE	Thioulouse, J., D. Chessel, S. Dolédec, and J. M. Olivier. 1997. ADE-4: a multivariate analysis and graphical display software. Statistics and Computing 7:75-83.	http://pbil.univ-lyon1.fr/ADE-4/
SPATIAL	Duncan, R. P. 1990. SPATIAL analysis program. Department of Plant Science, Lincoln University, New Zealand.	
Programita	Wiegand, T., and K.A. Moloney. 2014. *Handbook of spatial point pattern analysis in ecology*. Chapman and Hall/CRC press, Boca Raton, FL.	www.Programita.org
Spatstat	Baddeley, A., E. Rubak, and R. Turner. 2015. Spatial point patterns: methodology and applications with R. Chapman and Hall/CRC Press	http://spatstat.github.io/
splancs	Rowlingson, B. and Diggle, P. 1993 Splancs: spatial point pattern analysis code in S-Plus. Computers and Geosciences 19: 627-655	www.maths.lancs.ac.uk/ ~rowlings/Splancs/
S-plus	INSIGHTFUL CORPORATION. 2005. S-Plus 7 for Windows user' guide. Insightful Corporation, Seattle, WA.	
SPPA	Haase 2001. Can isotrpy vs anisotropy in the spatial association of plant species reveal physical vs biotic facilitation? Journal of Vegetation Science 12: 127-136.	
SpPack	Perry, G.L.W. 2004. SpPack: spatial point pattern analysis in Excel using Visual Basic for Applications. (VBA). Environmental Modelling & Software 19:559-569	