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ORIGINAL PAPER

Spatial autocorrelation based on remote sensing data in monitoring of Norway spruce dieback caused by the European spruce bark beetle *Ips typographus* L. in the Białowieża Forest

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ABSTRACT

Spatial patterns of tree mortality are important factors in the analysis of forest health and sustainable forest management. This study presents the use of spatial autocorrelation techniques in monitoring forest insect outbreaks using individual trees in a 100×100 m resolution grid based on data from 2015 and 2019. The study area was the Hajnówka Forest District (Hajnówka FD) in the Białowieża Forest (BF) in Poland which had an intense bark beetle outbreak from 2015--2019 that killed 38% of all living spruce trees in the upper layer of the stands. The development of a suitable methodology using spatial statistics tools, in particular spatial autocorrelation, allowed the following: (a) describe and compare the spatial structure of the data, (b) assess the magnitude and spatial distribution of the spruce dieback phenomenon in the first and last years of the study, (c) identify the distances at which clustering was most significant for the severity of spruce dieback and show how the size of clusters within a data set varied over the years, (d) to perform a typological classification of the study area according to specific spatial types which identify clusters with a highest intensity of the phenomenon (hot spots), areas with bark beetle-resistant stands (cold spots), and spatial outliers, and (e) to produce a map of spruce mortality local clusters. The methods and results presented in this study serve as baseline information in supporting the efforts to model the spread of bark beetle dynamics for future decision-making.

KEY WORDS

bark beetle, Hajnówka Forest District, Moran's I, LISA, spatial autocorrelation, tree mortality, outbreak

Introduction

Spatial autocorrelation is defined as the principle of the potential of geographic proximity to determine the values of random variables over distances that are similar or dissimilar to randomly associated pairs of observations (Legendre and Legendre, 1998). Researchers have used spatial autocorrelation to describe the dependency of variables within a spatial neighbourhood (Sokal and Oden, 1978a, b; Griffith, 1987; Legendre, 1993; Nelson *et. al.*, 1998; Rossi and Quénéhervé, 1998; Nelson and Boots, 2008, Walker *et. al.*, 2013) which contain useful information but require

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appropriate statistical methods to deal with. Furthermore, spatial autocorrelation analysis has been applied in numerous study areas to improve the quality and reliability of results, primarily by providing the basis for identifying statistically significant high and low clusters. This analytical approach has been used in a variety of fields including ecology (Nelson and Boots, 2008; Jossart *et al*., 2020), epidemiology (Izumi *et al*., 2015) and forestry (Meng and Cieszewski, 2006; Kamińska *et al*. 2020, 2021).

Tree mortality is an important component of all forest ecosystems and their dynamics as well as the principles of sustainable forest development. Therefore, it is important to have sufficient information to predict future forest conditions and understand the historical processes of forest change (Lugo and Scatena, 1996). There are several reasons to expect variability in tree mortality. In recent years, forests have been particularly vulnerable to the effects of extreme weather events such as prolonged droughts or strong winds which directly affect the weakening and subsequent dieback of forest stands (Senf *et al*., 2020, 2021). In addition, hot summers with little rain and warm winters with little snow contribute significantly to the development of insects and pathogens which have a negative impact on tree health (Seidl *et al*., 2017).

Forest insect pests cause tree mortality (Safranyik and Carroll, 2006), defoliation (Whitmire and Tobin, 2006) and forest disturbance (Fleming *et al*., 2002). To understand the characteristics of forests that are particularly susceptible to attack by insects, it is helpful to locate hot spots of insect populations or forest damage (Nelson *et al*., 2007). Understanding bark beetle processes at the landscape level through experimental research is not possible due to practical limitations, therefore we rely on spatial infestation patterns to gain insights into spatial processes. Identifying infestation hot spots can be an important step in analysing spatial and spatio-temporal infestation patterns thereby gaining insight into the spatial processes of the bark beetle. By identifying locations with unusual spatial patterns and studying conditions in these areas, we can develop hypotheses about beetle processes and better understand the conditions that lead to infestation.

Remote sensing techniques have increasingly been used in a wide variety of forestry and ecological applications from monitoring land cover changes to mapping individual trees (Hansen and Loveland, 2012; Fassnacht *et al*., 2016; Stereńczak *et al*., 2020a). In recent years, there have been studies showing the possibility of mapping individual dead standing trees using remote sensing data (Yao *et al*., 2012; Nielsen *et al*., 2014; Polewski *et al*., 2015). Data on these dead trees can provide valuable information for forest ecology and management studies, as it allows monitoring outbreaks from the early stages and modelling the evolution of tree mortality while taking into account various causes. The use of high-resolution remote sensing data in combination with reliable statistical methods enables accurate identification of tree species (Ørka *et al*., 2012) along with information on their health status (either alive or dead) (Kamińska *et al*., 2018), identification of newly infested individual trees (Stereńczak *et al*., 2019), and determination of factors related to the spatial dynamics of tree mortality within a time interval (Grodzki *et al*., 2014; Grodzki, 2016; Kamińska *et al*., 2020, 2021; Stereńczak *et al*., 2020b).

Despite numerous research papers on mortality, there are few studies on the spatial characteristics of tree mortality that consider spatial autocorrelation. Moreover, the spatial distribution of dead trees is an important factor that needs to considered when assessing forest health or developing a forest management and conservation plan. However, knowledge about the importance of spatial distribution of dead trees is still quite insufficient (Rouvinen *et al*., 2002). The objective of this study is to present the use of spatial autocorrelation techniques in monitoring forest insect outbreaks based on remote sensing data. A suitable methodology using spatial statistics tools is applied to analyse the dynamics and spatial extent of the bark beetle outbreak in Hajnówka FD from 2015 to 2019.

Materials and methods

STUDY AREA AND DATA. The study area was the Hajnówka Forest District (Hajnówka FD) in Białowieża Forest (BF) in Poland covering an area of almost 19,000 ha. The Hajnówka FD is a mixture of different forest types and tree species. An analysis of remote sensing data for 2015 looking at the proportion of individual tree species showed that Norway spruce *Picea abies* (L.) H. Karst and Scots pine *Pinus sylvestris* L. were the most abundant in the upper layer of the stand with 23% and 22%, respectively (Kamińska *et al*., 2018). The average age of trees in the forest stands was 85 years with stands over 100 years old covering up to 31% of stands in Hajnówka FD (Hajnówka Forest District, 2022).

Stands of BF are susceptible to infestation by the European spruce bark beetle *Ips typographus* (L.) with massive outbreaks of this insect having been observed since the 1950s (Michalski *et al*., 2004; Boczoń *et al*., 2018). The current bark beetle outbreak started in 2012 and from 2015 to 2019 this infestation worsened with particular intensity. During the entire four year period of the outbreak (2015-2019) 38% of all live spruce in the upper layer of Hajnówka FD stands died, while the proportion of dead spruce in 2015 was only 3% (Kamińska *et al*., 2021).

The data were obtained as part of the LIFE+ – ForBioSensing PL project 'Comprehensive monitoring of stand dynamics in the Białowieża Forest using remote sensing techniques'. Two airborne laser scanning datasets (ALS) and two datasets of color-infrared (CIR) aerial images from 2015 and 2019 were used for the study. Processing of the 2015 dataset included detection of individual trees using the CHM-based method described in Stereńczak *et al*. (2020a). Individual trees were classified by species (spruce, pine or deciduous) and as alive or dead based on structural and intensity characteristics of ALS and spectral characteristics of individual bands of CIR aerial imagery (Kamińska *et al*., 2018). In 2019, trees were classified into live or dead regardless of their species. By assigning information about the tree viability, information was obtained about the dead trees that were classified as alive in 2015. Trees that fell or were cut down in the period between dataset acquisitions were treated as dead trees. Further details on remote sensing data and remote sensing data processing were described in Kamińska *et al*. (2021).

SPATIAL ANALYSIS. Measures of spatial autocorrelation may be either global or local and can be used quantitatively to evaluate the amount of spatial autocorrelation in a dataset. Global measures characterize the nature of spatial autocorrelation for the entire study area using one value that summarizes average trends. The global and local Moran's *I* coefficients are the most commonly used statistics in univariate autocorrelation analyses (Anselin, 1995).

The global Moran's *I* coefficient was calculated using the formula:

$$I = \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \cdot \frac{\sum\sum w_{ij}\,(z_i - \overline{z})(z_j - \overline{z})}{\frac{1}{n}\sum_{i=1}^{n}(z_i - \overline{z})^2} \tag{1}$$

where

n – number of observations (quadrants),
z_i – value of variable for i-th location,
z_j – value of variable for j-th location,
$\overline{z}$ – average value of the variable,
w_{ij} – an element of the spatial matrix **W**.

A significant value of *I* greater than 0 indicates a positive autocorrelation which means that objects have similar values of variables (a high value of a variable in location *i* tend to be clustered with

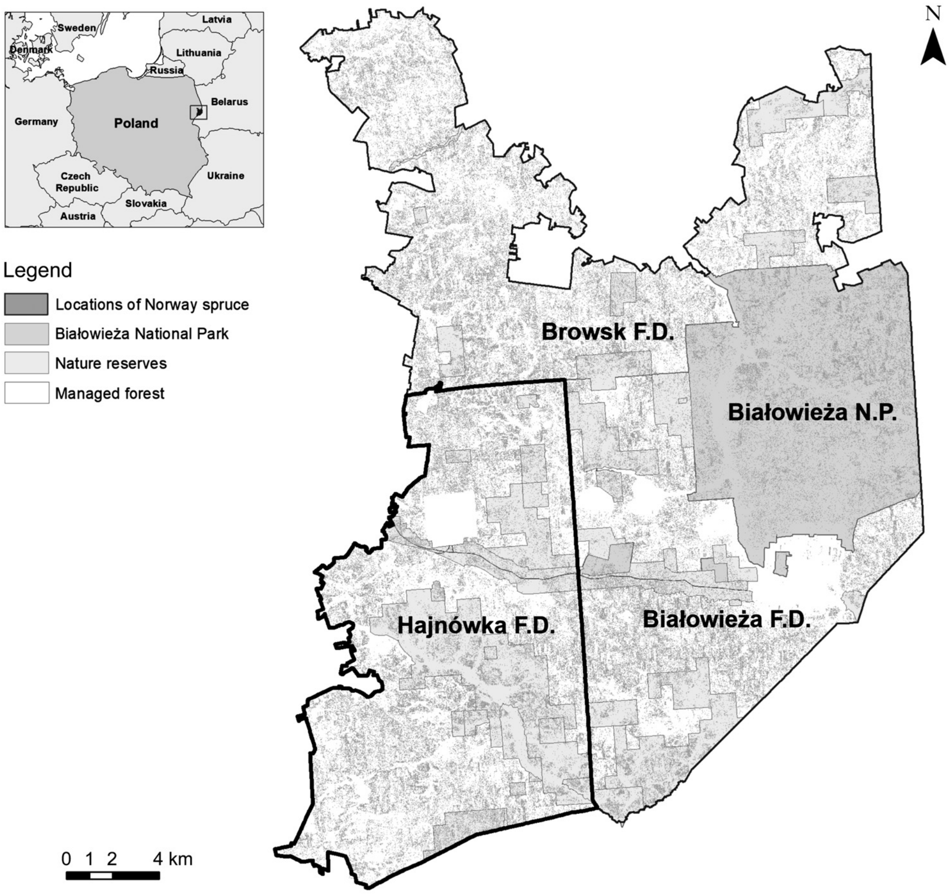

Fig. 1.
Study area – Hajnówka Forest District in the Białowieża Forest

high values of the same variable in locations that are neighbors of *i*, and vice versa). A value of *I* less than 0 denotes a negative autocorrelation which means that big differences existed between the values of neighboring objects (a high value of a variable in location *i* tend to be co-located with lower values in the neighboring locations). A value of *I* equal to 0 or close to 0 means random spatial distribution. Significance tests for global and local Moran's *I* statistics were presented in Cliff and Ord (1981).

Testing of significance of autocorrelation was based on the empirical value of the Z statistic which follows normal distribution using the following formula:

$$Z_I = \frac{I - E(I)}{\sqrt{Var(I)}} \sim N(0,1) \quad (2)$$

where

$E(I)=-1/(n-1)$,

$Var(I)=E[I^2]-E[I]^2$.

The spatial weight matrix W characterizes the dependence and association of the spatial units. However, it cannot be estimated and needs to be set in advance (Leenders, 2002; Li *et al.*, 2019). Weight can be based on contiguity relations or distance. In a weight matrix based on contiguity, a value unequal to zero in the matrix represents pairs of elements with a certain contiguity relation while a zero represents pairs without a contiguity relation. Two examples of contiguity relations are 'rook case' and 'queen case'. The first takes only full neighbours into account and the latter all eight surrounding cells while the complete matrices contain the contiguity relations of all pairs of points. Besides this contiguity principle, it is also possible to make weight matrices based on geographic distances such as inverse distance. The spatial weights are standardized by row and each weight is divided by the sum of its row. In a row-standardised matrix the values are represented as fractions so that the sum of all values in a row of the weight matrix equals one.

Correlogram calculated with Moran's I was used to quantify the spatial dependency per distance class (Li *et al.*, 2019). Correlogram calculates the Moran's I index at multiple distances for a single dataset. The fixed distances analysed were derived from each possible distance between one data point and all other data points.

Moran's I values, calculated for a series of increasing distances, measure the intensity of spatial clustering for each distance. The intensity of clustering is determined by the returned z-score. Typically, as the distance increases so does the z-score which indicates intensification of clustering. At some particular distance, however, the z-score generally peaks which reflects distances where the spatial processes promoting clustering are most pronounced.

Global spatial autocorrelation may not pick up aberrant local spatial patterns that cause some local patterns to be opposite of the global spatial trend (Wang *et al.*, 2016). Local Indicator of Spatial Association (LISA) represents a set of localized statistical approaches that typically measure the relationship between individual locations and their surrounding neighbours to uncover patterns of spatial clustering.

LISA or local Moran's I was calculated for each observation unit using the following formula:

$$I_i = \frac{z_j - \overline{z}}{\sum_{i=1}^{n} \frac{(z_i - \overline{z})^2}{n}} \cdot \sum_{j=1, j \neq i}^{n} [w_{ij} \, (z_j - \overline{z})] \tag{3}$$

For each location, values of I_i allowed the computation of its similarity with its neighbours and testing of its significance. The following five classes were observed (Zhang *et al.*, 2008):

– locations with no significant local autocorrelation,
– locations with high values with similar neighbours (named 'high-high'),
– locations with low values with similar neighbours (named 'low-low'),
– locations with low values with high-value neighbours (named 'low-high'),
– locations with high values with low-value neighbours (named 'high-low').

An extension of LISA is the bivariate local Moran's I_i in which variable z of observation i is compared to variable y of neighbourhood j. The modified equation for bivariate local Moran's I_i takes the following form:

$$I_i = \frac{z_j - \overline{z}}{\sum_{i=1}^{n} \frac{(z_i - \overline{z})^2}{n}} \cdot \sum_{j=1, j \neq i}^{n} [w_{ij} \, (y_j - \overline{y})] \tag{4}$$

The bivariate Moran's I_i facilitates the examination of multi-temporal data relating to the intensity of spruce decline. Examining the relationship between tree mortality at a location in a specific year versus tree mortality in the neighbourhood in subsequent years results in a severity rating that incorporates change. In the study, severity at a location in 2015 was compared to severity in its neighbourhood in 2019 to determine spatial and temporal patterns of beetle spread according to the following classes:

– Constant class – the location had above average severity in 2015 and above average severity in the neighbourhood in 2019 (named as 'HH')
– Decline class – the location had above average severity in 2015 and below average severity in the neighbourhood in 2019 (named as 'HL')
– Increase class – the location had a low severity in 2015 and above average severity in the neighbourhood in 2019 (named as 'LH')
– Null class – the location had zero to minimal severity in 2015 and its neighbourhood had zero to minimal severity in 2019 (named as 'LL')

In the study, ArcGIS software (ArcMap 10.5; ESRI, 2017) and GeoDa (version 1.12; Anselin *et al.*, 2006), a GIS-based application focused on estimating local and global spatial relationships in the attributes presented in GIS, were used for conducting spatial analysis. For the spatial analysis the study area was divided into cells with an edge length of 100 m and the severity of bark beetle attack was calculated as a percentage of dead spruce within each grid cell according to the formula:

$$\textit{Proportion of dead spruce} = \frac{\textit{Number of dead spruce}\ (2019) - \textit{Number of dead spruce}\ (2015)}{\textit{Number of dead spruce}\ (2015)} \cdot 100\%$$

Spatial statistics (global Moran's I and local/bivariate local Morans's I_i) were calculated with weights based on 'queen' contiguity (where the definition of neighbour was based on sharing a common boundary). Additionally, spatial autocorrelation testing was conducted of the percentage of dead spruce in 2015 and 2019 and for a series of increasing distances which measured the intensity of spatial clustering for each lag .

Results

As shown in Figure 2, Moran's I-correlograms (distances from 150 m to 1500 m of a lag) of dead spruce percentages in 2015 and 2019 are presented. The observed spatial autocorrelation was used to describe and compare the spatial structure of the data. The correlograms showed differences in Moran's I between years. All percentages of dead spruce shown in Figure 2 had positive spatial autocorrelation that gradually decreased. Comparing Moran's I values for both years showed spatial autocorrelations for spruce mortality as stronger in 2019 (ranging from 0.16 to 0.56), while Moran's I values ranged from 0.03 to 0.39 in 2015.

Spatial autocorrelation was repeated for different distances, and each distance was assigned a z-score value indicating a statistically significant level (Fig. 3). Moran's I z-scores plotted by distance revealed the distances at which clustering was most significant for the percentage of dead spruce and showed the variability of cluster size within a data set in Hajnówka FD over the years (1250 m – maximum peak in 2015; 5400 m – maximum peak in 2019).

Figure 4 illustrates the clustering trend as to the extent of bark beetle infestation in 2015 and 2019 in Hajnówka FD. The values of global Moran's I for both years (I_{2015}=0.39 and I_{2019}=0.58) proved a significant positive spatial autocorrelation and indicated a dynamic increase in spruce mortality during bark beetle infestation. In 2019, a significant intensification of spruce dieback was already being observed throughout the study area as well as a significant expansion of clusters. Furthermore, the territorial spread of areas with bark beetle-infested spruce to other forest areas was clearly visible with many newly emerging outbreaks of different sizes registered. In 2015, 1017 hotspots were identified (5.6% of the whole study area), while four years

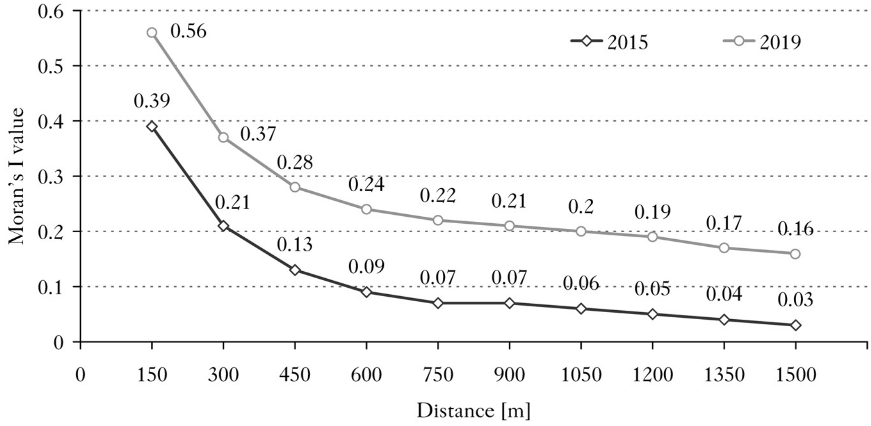

Fig. 2.

Correlograms of Moran's I of the percentage of dead spruce in years 2015 and 2019

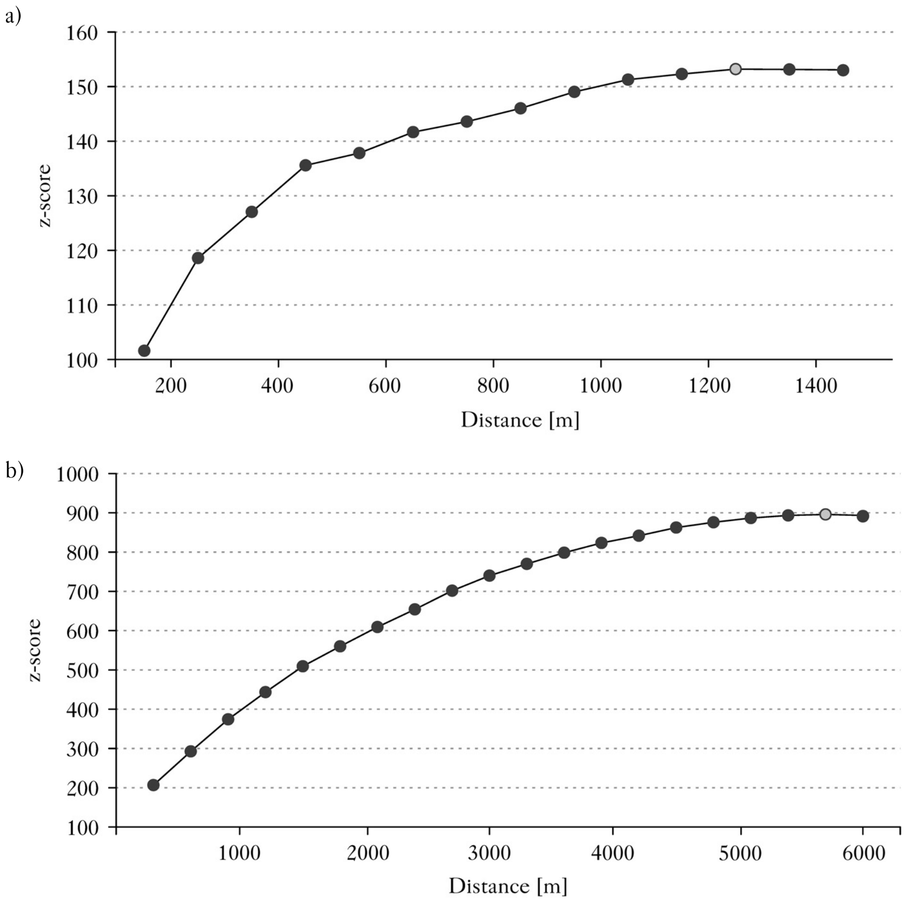

Fig. 3.

Percentage of dead spruce z-scores plotted by distance band for 2015 (a) and 2019 (b). The peaks have been highlighted.

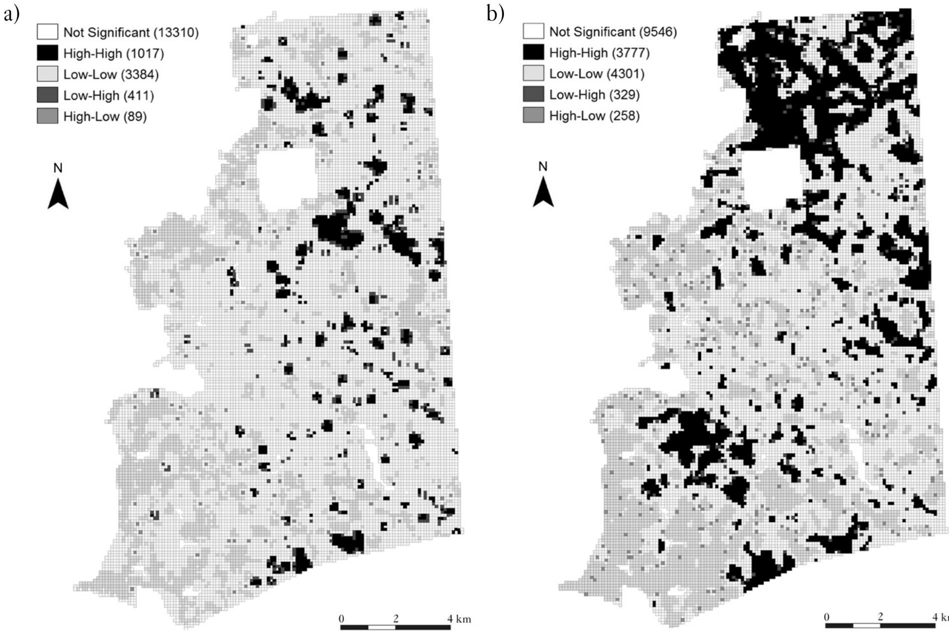

Fig. 4.

Area types by spatial relationship of spruce dieback dynamics in 2015 (a) and 2019 (b). 'High-High' spatial class means heavily infested spruce stands in a similar neighbourhood; 'Low-Low' spatial class means low or not infested spruce stands in similar neighbourhood; 'High-Low' spatial class means heavily infested spruce stands in a neighbourhood with low mortality; 'Low-High' spatial class means low or not infested spruce stands in a neighbourhood with high mortality.

later 'high-high' sites accounted for 20.7% of Hajnówka FD (3,777 cells). The largest hotspot identified during the four-year outbreak was in the northern part of the district area. In the vicinity of hot clusters, there were 'low-high' outliers where the tree mortality was significantly lower than in neighbouring areas. Among them, stands were observed to be infested with bark beetles during the initial phase of the outbreak, and in these areas the process was saturated during the analysed period. However, some of the 'low-high' areas were not infested in 2015, and spruce dieback had spread there during the four-year outbreak.

Cold clusters of bark beetle-resistant spruce were also observed, and no significant outbreak centre was detected there. It is worth noting that most cells (56%) were not infested in 2015. As a result of the high dynamics of spruce mortality between 2015 and 2019, only 11.6% of the cells had no dead trees in 2019. However, it is noteworthy that many 'high-low' outliers were observed which indicated the dieback of individual spruce trees with most located near cold clusters.

Tree mortality at a given location in 2015 was compared to tree mortality in its neighbourhood in 2019 to determine the spatial and temporal patterns of bark beetle spread over a four-year period (Fig. 5). HH locations were heavily infested spruce stands in 2015 with similar neighbouring stands in 2019 corresponding to the hotspots on the 2015 LISA map (Fig. 4). Neighbouring LH locations had low or no infested spruce stands in 2015 and a neighbourhood with high mortality in 2019. They illustrate bark beetle infestation within a 4-year period. HH and LH sites from the bivariate LISA map form hot spots in 2019 (Fig. 4). HL sites had heavily infested spruce stands in 2015 and a low mortality neighbourhood in 2019. These were areas where dieback did

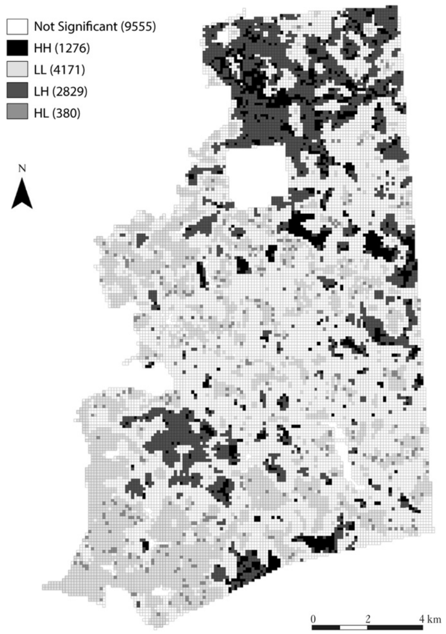

Fig. 5.
Bivariate LISA cluster map for percentage of dead spruce. 'HH' spatial class means heavily infested spruce stands in 2015 with similar neighbouring stands in 2019; 'LL' spatial class means low or no infested spruce stands in 2015 and similar neighbouring stands in 2019; 'HL' spatial class means heavily infested spruce stands in 2015 and neighbourhood with low mortality in 2019; 'LH' spatial class means low or no infested spruce stands in 2015 and a neighbourhood with high mortality in 2019.

not spread to surrounding areas and had individual dead spruce in non-spruce stands. LL locations had low or no infestation of spruce stands in 2015 and similar neighbouring stands in 2019. These were areas with stands that were resistant to mortality caused by bark beetle infestation.

Discussion and conclusion

The purpose of this study was to present the use of spatial autocorrelation techniques in monitoring forest insect outbreaks based on remote sensing data. The study area was the Hajnówka Forest District in the Białowieża Forest in Poland, where an intense bark beetle outbreak occurred between 2015-2019 killing 38% of all living spruce trees in the upper layer of stands (Kamińska *et. al*., 2021). Infested areas greatly increased starting from several initial infestation spots as the beetles spread to reach new food sources.

The development of a relevant methodology using spatial statistics tools, in particular spatial autocorrelation, allowed for the following:

- describe and compare the spatial structure of the data,
- to evaluate the amount and spatial distribution of the phenomenon of spruce tree dieback in the first and last years of the study,
- identify the distances at which clustering was most significant for the severity of spruce dieback and to show how the size of clusters within a dataset varies over the years,
- perform a typological classification of the study area according to specific spatial types as well as to identify clusters with a highest intensity of phenomenon (hot spots), areas with bark beetle resistant stands (cold spots), and spatial outliers,
- generate a map of local clusters of spruce dieback.

Spatial patterns of tree mortality are important factors in analysing forest health and sustainable forest management as there are many causes for tree mortality. In this study, we focused on bark beetle induced mortality and explored their spatial distributions. In an aggregate area of any kind of damage, it is important to consider and analyse the damage in detail in order to reveal the progression and patterns of tree mortality. However, the total amount of dead wood in forest ecosystems is affected by many factors. Multidirectional studies on the influence of selected habitat, stand and topographic factors on spruce mortality were conducted by Kamińska *et al.* (2020, 2021) and Stereńczak *et al.* (2020b). Analysis of dead spruce occurrences in 2015 made it possible to consider crown closure and stand age as the most important predictors in the initial phase of spruce mortality in BF. More open and older spruce stands were most susceptible to dieback during this period (Stereńczak *et al.*, 2020b).

It is worth noting that spatial autocorrelation results are sensitive to cell size and neighbourhood size (Harris *et al.*, 2017). While it is difficult to assess how best to use local Moran's *I*, it is advisable to consider all of the above factors until reasonable and stable results are obtained (Zhang *et al.*, 2008). A focal cell size of 1 ha was suitable for spatial analysis for the proportion of dead spruce according to previous studies by Kärvemo *et al.* (2014) and Kamińska *et al.* (2021). There is inevitably an element of subjectivity in choosing an appropriate value for the neighbourhood distance. As neighbourhood size increases, hotspots become fewer and larger, and smaller neighbourhood sizes are more likely to capture localised trends (Harris *et al.*, 2017). Neighbourhood size in local Moran's I_i should be representative of the distance over which a location exhibits a relationship with its surroundings. In terms of bark beetle dispersal, this means that a neighbourhood is defined based on the distance the insect typically flies during its summer dispersal period. The presented methodology and results can provide important support for conducting an analysis to assess the mortality risk of stands affected by outbreaks in large forest areas based on high-resolution multitemporal remote sensing data.

These results could have important implications for practical forest management and conservation. It is very important to consider disturbances caused by bark beetles in practical forest management as a dynamic and advanced outbreak stage is difficult to control. The spread of *I. typographus* during the outbreak did not follow strictly defined patterns. The methodology presented in this study could be a suitable tool for analysing relatively large areas of insect outbreaks in other regions and can be successfully used to produce operational risk maps for tree mortality caused by bark beetles in large forest areas based on multitemporal high-resolution remote sensing data. Such detailed risk assessment maps would be of great value to foresters. For example, providing forest owners with these maps during an outbreak could be a routine procedure in the future which could improve assessments and control measures by allowing foresters to focus on identified high-risk stands.

In summary, spatial autocorrelation statistics are useful tools for multivariate regional analyses, especially in monitoring forest insect outbreaks. They provide information on the nature and strength of spatial dependence, allow associations between objects to be determined, and identify spatial structure better than conventional methods.

Competing interests

Author declares there is no conflict of interest.

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STRESZCZENIE

Zjawisko autokorelacji przestrzennej z wykorzystaniem danych teledetekcyjnych w monitorowaniu zamierania drzewostanów świerkowych powodowanego gradacją kornika drukarza *Ips typographus* (L.) w Puszczy Białowieskiej

Zamieranie drzew jest naturalnym i niezbędnym procesem zachodzącym w ekosystemach leśnych i jednym z najważniejszych elementów zrównoważonego rozwoju lasu. Spodziewane zwiększenie intensywności i częstotliwości susz oraz ekstremalnych zjawisk pogodowych może przyczynić się do nasilenia zamierania drzew na całym świecie. Dlatego ważne jest dysponowanie wystarczającymi informacjami, aby przewidzieć przyszłe warunki w lesie i zrozumieć historyczne procesy zachodzących w nim zmian.

Analiza autokorelacji przestrzennej umożliwia poznanie stopnia intensywności danego zjawiska w obiektach przestrzennych. Celem pracy było przedstawienie wykorzystania technik autokorelacji przestrzennej w monitorowaniu zamierania świerków z użyciem danych teledetekcyjnych. Obiektem badań były drzewostany Nadleśnictwa Hajnówka (ryc. 1), gdzie w latach 2015-2019 wystąpiła intensywna gradacja kornika drukarza, podczas której zamarło 38% wszystkich żywych świerków w górnej warstwie drzewostanów.

Do opracowania wykorzystano 2 zestawy danych lotniczego skanowania laserowego (ALS) oraz 2 zestawy danych zdjęć lotniczych barwnych w podczerwieni (CIR): z 2015 i 2019 r. Poszczególne drzewa zostały sklasyfikowane według gatunków (świerk, sosna lub liściaste), a także jako żywe lub martwe na podstawie cech strukturalnych i intensywności ALS oraz charakterystyki spektralnej poszczególnych pasm zdjęć lotniczych CIR. W 2019 r. drzewa zostały sklasyfikowane jako żywe i martwe, bez względu na gatunek.

Zastosowanie autokorelacji przestrzennej pozwoliło:

– opisać i porównać strukturę przestrzenną danych (ryc. 2);
– ocenić poziom oraz rozkład przestrzenny zjawiska zamierania świerków w pierwszym i ostatnim roku badań (ryc. 2, 4);
– określić zasięg oraz dynamikę lokalnych skupień mających największe znaczenie dla nasilenia zamierania świerków (ryc. 3, 5);
– dokonać typologicznego podziału obszaru badań według określonych typów przestrzennych, ukazując klastry o największym nasileniu zjawiska (hot spoty) oraz obszary z drzewostanami odpornymi na działalność kornika (cold spoty) (ryc. 4);
– wygenerować mapy lokalnych skupisk zamierania świerka (ryc. 4).

Prezentowane w pracy wyniki mogą stanowić istotne wsparcie dla gospodarki leśnej i ochrony lasu. Przedstawiona metodyka może być odpowiednim narzędziem do analizy stosunkowo dużych obszarów występowania szkodników w innych regionach i może z powodzeniem służyć do tworzenia operacyjnych map ryzyka śmiertelności drzew powodowanej przez korniki na dużych obszarach leśnych w oparciu o wieloczasowe dane teledetekcyjne o wysokiej rozdzielczości.