Using GIS techniques to obtain a continuous surface of tree crown defoliation

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The issue of whether or not average tree crown defoliation and defoliation dynamics is an interpolable phenomenon at the level of a small test area with detailed information available is analysed in the article in question. Investigations have been carried out in the forests of Dzūkija Integrated Monitoring station in the southern part of Lithuania. It has been found that none of the parameters discussed is spatially autocorrelated. In order to generate defoliation surface from pointwise estimates multiple regression model based on forest, geographic and geologic variables, spatial distribution of which is known has been developed. The most significant variables are the following: the location in relation to water bodies, soil, site index, basal area and the origin of forest stand. The model developed explains up to 45% and 58% of average defoliation and defoliation changes during 3 year period variance, respectively.

Key words: geographic information systems, spatial autocorrelation, multiple regression model, tree crown defoliation.

Introduction

Forests are traditionally represented on a map as groups of discrete polygons the boundaries of which usually correspond to forest stands, soil types, areas of silvicultural activities, etc. However, modern GIS technologies open powerful opportunities to use interpolation techniques for representing forest parameters as a continuous pattern of populations, which are in close dependence on the environmental conditions.

Data, gathered by statistical inventories, can be briefly characterized as the pointwise ones, describing the phenomenon studied at one location. Information for larger areas is obtained summing certain pointwise observations. However, it is often important to have the phenomenon estimate for each point of the territory. Forest health state assessment at Integrated Monitoring Stations (IMS) in Lithuania is carried out using the network of regularly distributed permanent observation plots. The distance between plots averages 200 m. Numerous parameters of every tree, including common tree mensurational characteristics and position in the story as well as the crown defoliation percentage are described. Estimations repeated every second year enable us to find the dynamics both in development and health state changes. The idea to obtain average defoliation estimates over an entire surface aims at the following: (1) integration of different factors, possibly having influence on forest health and its dynamic, spatial distribution of which is known; (2) visualization of forest health spatial distribution. The last may enable the researcher to find some important explanations of the facts what can be quite complicated using traditional techniques. This paper deals with the spatial modeling or representation as a continuous surface of forest parameters, having a clumped pattern. Results of the research conducted to assess spatial interpolability of average tree crown defoliation, estimated on permanent network of observation plots at Dzūkija IMS are used to illustrate the issues discussed.

Interpolation of forest characteristics

Of course, spatial interpolation has existed since long before the computers and related technologies were developed. In a few words it can be described as a tool to obtain estimates over an entire surface for a given variable, which has only been sampled at isolated points

(Lowell, 1996). As an interpolation example development of elevation models, expressed e.g. by contour lines from network of points with known elevations could be taken. However, such simple at first glance case may mask a number of potential problems, which may differ depending both on the nature of phenomenon studied and the methods of interpolation used. There are two assumptions to be satisfied in order to make the resulting interpolation of the phenomenon of interest valid (Lowell, 1996): (1) the phenomenon being studied must behave in an interpolable fashion, i.e. must be truly continuous. If the forest parameters have spatially random occurrence or are effected by some other factors (human activities, damages, etc), then interpolating surface between points will not yield useful results. (2) The point samples must be spaced closely enough to describe the phenomenon being studied.

So, in other words, the objective of this paper is to examine the question of whether or not average tree crown defoliation and its dynamics is an interpolable phenomenon at the level of a small test area with detailed information available. To evaluate these two factors, we must *a priori* measure the amount of spatial autocorrelation.

Spatial autocorrelation

The Tobler's first law of geography tells us, that everything is related to everything, but near things are more related than distant things (Antle and Marshall, 1996). This means that variables estimated at spatially proximal locations are expected to be more similar than those at further distances. Generally, it is recognized that most of the ecological data are spatially dependent by nature. Spatial dependence is often referred to as spatial autocorrelation. Spatial autocorrelation is the tendency for the likely values of a given variable to clump or to repulse non-randomly (Lowell, 1996). Different statistics are used to measure spatial autocorrelation. Geary's ***c*** and Moran's ***I*** indexes have been applied in this study.

The formulas for calculating the Moran's ***I*** and the Geary's ***c*** indexes and their interpretation in WinNT Arc/Info module Grid (the software used for calculations) are the following:

$$I = \Sigma\Sigma w_{ij} c_{ij} /(\Sigma\Sigma w_{ij})(\Sigma(z_i - z_m)^2 / n$$

where $\Sigma\Sigma w_{ij} = 4 * n$

$$c = \Sigma\Sigma w_{ij} c_{ij} /(2(\Sigma\Sigma w_{ij})(\Sigma(z_i - z_m)^2 /(n-1))$$

where $\Sigma\Sigma w_{ij} = 4 * n$

The notation, used in spatial autocorrelation formulas: n - the total number of cells in a grid; i, j - any two adjacent cells; z_i - the value of the attribute of cell i; c_{ij} - the similarity of i's and j's attributes – $(z_i-z_j)^2$; w_{ij} - the similarity of i's and j's locations, $w_{ij}=1$ if cells i and j are directly adjancent and 0 otherwise; σ^2 - the sample variance: $\Sigma(z_i-z_m)^2/(n-1)$,where z_m is the mean cell value for the grid.

There may be several reasons why the spatial autocorrelation indices do not indicate the possibilities to generate surface of phenomenon studied by interpolation techniques – an interpolable continuum of forest characteristics may not be present or they change abruptly both between and within forest stands. The only solution to get locally reliable parameter estimates is to use ancillary information on parameters, spatial distribution of which is known and they are in close relation with phenomenon under analyses. Modern GIS techniques enable us to develop spatial models using different maps as arguments. Thus, necessary surfaces can be generated without using traditional interpolation algorithms.

Materials and methods

The forests of Dzūkija Integrated Monitoring Station have been chosen as the testing polygon. It is a part of Dzūkija National Park, where pine forests prevail. Total area of the station – 380 ha. A 200x200 m square grid of 58 permanent plots has been established and up to date two observations have been made – in 1993 and 1996. The following plotwise characteristics are used in this study: average age (usually for pine) and defoliation estimates in percents for all and dominant trees (Fig. 1).

Various GIS information for the test area have been made available: geomorphology, soils, litology, vegetation (imported from the databanks of Joint Research Center, Ministry of Environment), forest stands as well as all descriptive stand characteristics, digital elevation model (DEM). Forest stand boundaries have been digitized from forest compartment maps (scale 1:10000). To develop the DEM KRIGING algorithm (available in NT Arc/Info) has been used. The root mean square error of DEM was estimated to be 0.32 m. Slope and aspect were generated basing on DEM.

In order to measure the spatial autocorrelation Thiessen polygons were constructed around the plots and each polygon was assigned the defoliation value,

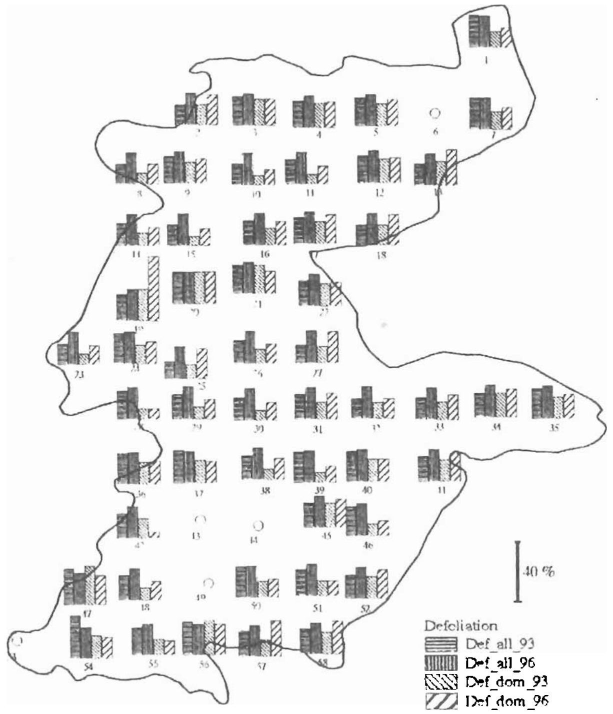

Figure 1. Defoliation estimates on permanent observation plots at Dzūkija IMS

measured at a given plot. For the sake of comparison several additional data sets have been analysed for spatial autocorrelation. Tree age, volume per ha, basal area on an observation plot were treated in the same manner as the defoliation. Elevation data for the plot have been extracted from DEM and random values (ranging in the interval of the defoliation values) were assigned to the polygons too. The last two data sets were intended to serve to some extent as the examples of interpolable phenomenon (elevation) and the non-interpolable one. Moran's ***I*** and Geary's ***c*** indices were calculated for each of the data sets.

To find out the spatial distribution of average crown defoliation estimates on the area of Dzūkija IMS, multiple regression model was developed using parameters of the GIS database as the independent variables. To evaluate the defoliation surface, generated according to the developed model the following techniques were applied. A total of 57 plots were used for model calculation and 1 for the validation. The procedure was repeated with the other validation plot until all plots have been used. It was not possible to divide all plots into calibration and validation subsets because the exclusion of even several plots from the model development resulted significantly in a decrease in the multiple regression correlation coefficient. The difference of true and modeled values was calculated. These two values were regressed against each other – perfect agreement will result in a correlation coefficient equal to 1, a slope of 1, an intercept of 0 and a root mean square error (RMSE) of 0.

Results

Spatial autocorrelation

It is apparent that none of parameters discussed is spatially autocorrelated (Table 1). For data, to be spatially correlated, Moran's ***I*** index should be over 1 and Geary's ***c*** should approach 0. The topographic data can be distinguished from the rest as indicating some tendency to be spatially continuous, but too poor resolution used (similar to the plot density) for sampling limits well-founded conclusions. Thus, it should be concluded, that both average values of defoliation and its changes in observation plots are distributed randomly or spatially independent (for a given density of observation plots). This eliminates the opportunity to have defoliation surfaces from the pointwise estimates by traditional interpolation techniques.

Table 1. Results of spatial autocorrelation assessment

Object	Indices of spatial autocorrelation	
	Moran's *I*	Geary's *c*
Random values	0.12	0.86
Elevation	0.75	0.21
Average crown defoliation in 1993	0.01	0.82
Average crown defoliation in 1996	0.11	0.76
Average crown defoliation of dominant trees in 1993	0.05	0.77
Average crown defoliation of dominant trees in 1996	0.05	0.77
Change in average crown defoliation during 1993-1996	0.20	0.56
Change in average crown defoliation of dominant trees during 1993-1996	0.08	0.68
Age	0.14	0.69
Volume per ha	0.15	0.64
Basal area	0.26	0.68

Relating crown defoliation to mapped forest, geologic and geographic parameters

It can be hardly possible to expect to have an interpolable continuum of parameters, including crown defoliation if growing conditions change abruptly both between and within forest stands. The only solution to have surface from pointwise estimates seems to be relating crown defoliation (or other parameters) to other forest, geologic and geographic characteristics. It is necessary that information on the above listed characteristics would be available at all points on test region. So, the research was further focused only to those parameters, which were available in the GIS database of Dzūkija IMS.

The following parameters were tested as independent variables to model the defoliation:

1. Elevation (ELEV), i.e. digital elevation model;
2. Aspect (ASPECT), calculated according to the DEM;
3. Slope (SLOPED), calculated according to the DEM and expressed in degrees;
4. Distance from the water bodies (DISTANCE), in particular case from the rivulet;
5. Azimuth of each point to the closest water body (AZIMUTH);
6. Litology (LITOLOG);
7. Soils (SOIL);
8. Origin of the stand (OR);
9. Main tree species of the stand, usually pine (MTSP);
10. Site index (SI);
11. Volume in m^3 per ha (VOL);
12. Relative basal area (BA);
13. Share of the main tree species in the story (KF1);
14. Age of the main tree species (AGE1);
15. Height of the main tree species (H1);
16. Diameter of the main tree species (D1).

To find the values of independent variables the corresponding coverage was overlaid with the locations of sample plots. Some categorical parameters available in the GIS database were not used in the model development, when all their values were not reflected on sample plots. Categorical variables were made available to the procedure as sets of binary "dummy" variables. The following are the predictive models for crown defoliation and its changes, which have been constructed using multiple linear regression.

Average defoliation in 1996 (underlined regression coefficients indicate p-level under 0.05):

$$DEFAVG96 = -1780.86 - 0.09718ELEV - 0.01533ASPECT + 0.116444SLOPED + \underline{0.027931}AZIMUTH + 0.0000564DISTANCE - 1.93039SOIL - 1.24452LITOLOG + 1.57109OR + 0.068281MTSP + \underline{12.52516}SI - 0.16563VOL + 2.261101BA + 1.59419KF1 - \underline{0.89395}AGE1 + \underline{0.523162}H1 + 0.853769D1; (R^2=0.45)$$

Average defoliation of dominant trees in 1996:

$$DEFDOM96 = 601.894 - 0.01949ELEV - 0.01901ASPECT + 0,021225SLOPED + \underline{0.019621}AZIMUTH + 0.003696DISTANCE - 1.57667SOIL - 0.3732LITOLOG - 0.59009OR + 0.04614MTSP + \underline{9.762598}SI - 0.12052VOL + 2.417944BA + 2.202099KF1 - 0.60426AGE1 + \underline{0.299312}H1 + 0.586397D1; (R^2=0.44)$$

Change in average defoliation during 1993-1996:

$$DEFAVGCH = 1317.187 + 0.287065ELEV - 0.00404ASPECT - 0.04773SLOPED + 0.008032AZIMUTH - \underline{0.00725}DISTANCE + 1.431892SOIL - 0.30809LITOLOG - 1.2343OR + 0.019351MTSP - 3.6902351SI - 0.04314VOL + \underline{3.236558}BA + 1.735655KF1 + 0.069561AGE1 - 0.08691H1 + 0.233807D1; (R^2=0.58)$$

Change in average defoliation of dominant trees during 1993-1996:

$$DEFDOMCH = 1213.908 + 0.108193ELEV - 0.01553ASPECT - 0.43368SLOPED + 0.010944AZIMUTH - 0.00245DISTANCE - 2.18729SOIL + 0.321311LITOLOG - 1.1094OR + 0.043617MTSP - 4.6829SI - 0.12001VOL + \underline{4.464032}BA - 0.72823KF1 + 0.354431AGE1 - 0.02119H1 - 0.42614D1; (R^2=0.44)$$

These models were implemented in special NT Arc/Info AML macros modules to generate maps of defoliation and defoliation dynamics. If one of the regression members equals 0 on a certain location, defoliation for it was not calculated. In such a way non-forest compartments and young forest stands (age under 20 years) were eliminated from surface generation.

Maps, presented in Fig. 2, visualize spatial distribution of average defoliation (of all and dominant trees) in coniferous stands at Dzūkija IMS in 1996 as well as the changes in defoliation during 1993-1996. It can be clearly seen that the assessed parameter changes abruptly on the border between forest compartments.

Evaluation of generated surfaces indicates that expected errors are within the accuracy of visual assessment in the field (Table 2).

Table 2. Results of modeled crown defoliation assessment (based on the difference between true and modeled values on the observation plots)

Assessment criteria	Average crown defoliation in 1996	Change in average crown defoliation during 1993-1996	Average crown defoliation of dominant trees in 1996	Change in average crown defoliation of dominant trees during 1993-1996
	Values of assessment criteria			
Differences:				
Min	-27.4	-10.4	-23.1	-21.4
Max	8.2	8.6	12.1	9.5
Average	-9.8	0	-0.1	-0.2
RMSE	8.0	4.3	6.7	5.3
Correlation coefficient	0.51	0.62	0.52	0.62
Linear regression:				
Slope	0.43	0.42	0.33	0.37
Intercept	9.82	3.41	17.03	3.00

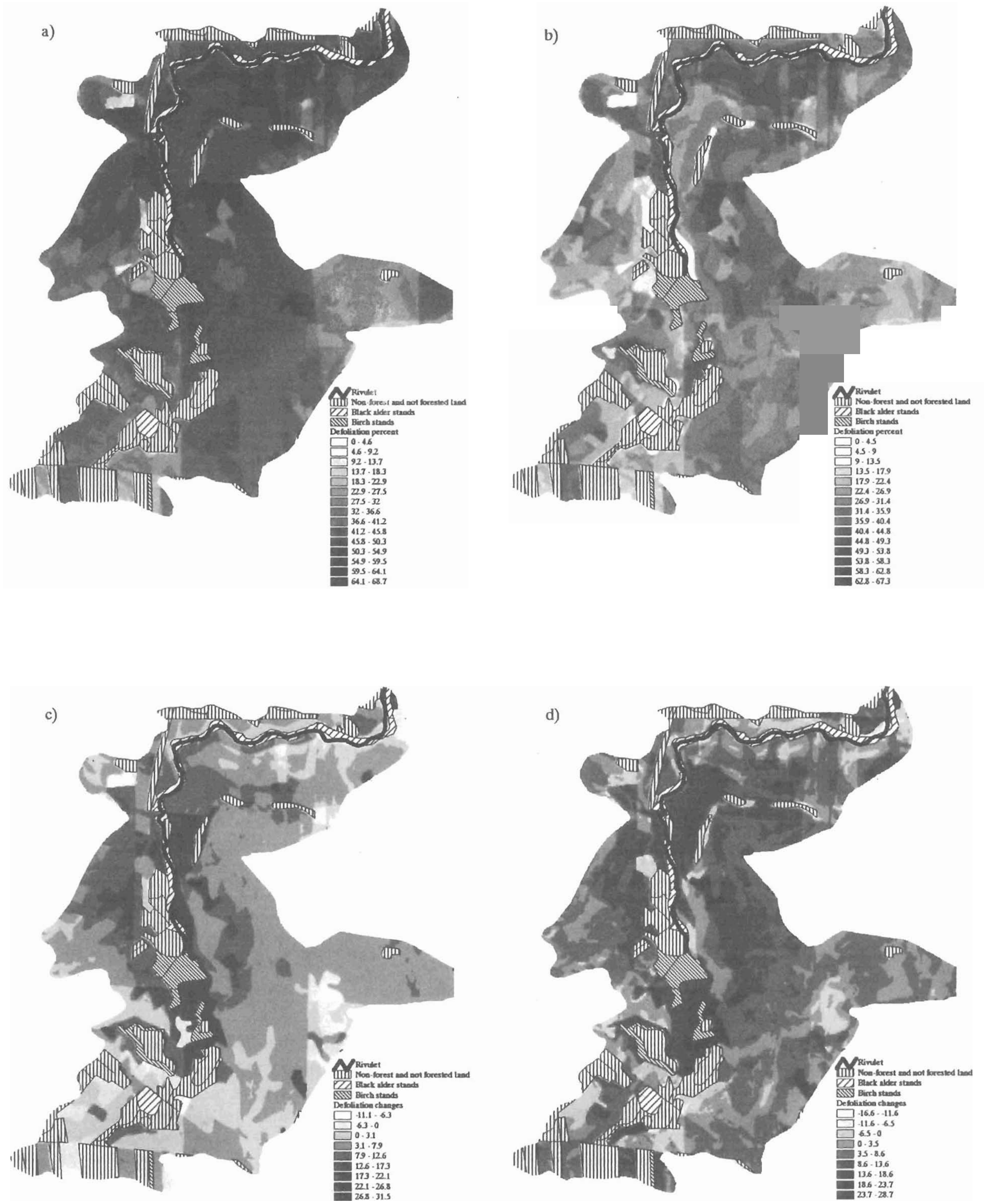

Figure 2. Defoliation and its dynamics of coniferous stands in Dzūkija IMS, a) average defoliation of all trees, b) average defoliation of dominant trees, c) changes in average defoliation of all trees during 1993-1996, d) changes in average defoliation of dominant trees during 1993-1996

Discussion and conclusions

The idea of this paper was to present the forest research people with the solution to obtain surface from pointwise forest characteristic estimates. Crown defoliation was chosen as an example, but the principles described should be similar to other forest parameters. To conclude this research the following could be noted:

1. Values of tree crown defoliation and its changes in permanent observation plots in Dzūkija IMS (network density 200x200 m) are spatially independent. Spatial autocorrelation Moran's ***I*** and Geary's ***c*** indices are close to those of random values (respectively $I = 0.01$-0.11 and $c = 0.77$-0.82). This eliminates the opportunity to obtain defoliation surface by interpolating pointwise estimates.

2. In order to obtain the surface of defoliation and its changes for all territory analysed multiple regression model should be developed basing on forest, geographic and geologic variables, spatial distribution of which is known. Largest multiple regression correlations are achieved while using all variables of the GIS database. The most significant are the location in relation to water bodies, soil, site index, basal area and the origin of forest stand. The model developed explains 45% and 44% of average all and dominant tree crown defoliation variance and 58% and 44% of defoliation changes during 1993-1996, respectively.

3. The root mean square error of defoliation surface of all trees, generated using the methods discussed, equals 8.0%, the one for dominant trees – 6.7% and for defoliation changes during 1993-1996 – 4.3% and 5.3%, respectively.

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ИСПОЛЬЗОВАНИЕ ГИС ДЛЯ РАЗРАБОТКИ ТЕРРИТОРИАЛЬНОЙ МОДЕЛИ ДЕФОЛИАЦИИ КРОН ДЕРЕВЬЕВ

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Резюме

В статье расматривается вопрос о возможности интерполяции дефоляции кроны и ее изменении в ограниченной, изучаемой територии используя всю доступную информацию. Исследования проводились в лесном массиве на станции интегрального мониторинга в южной части Литвы, в национальном парке Дзукии. Установленно, что не один из изучаемых параметров пространственно не автокорялирован. С целю установить уровень дефоляции на каждой точке изучаемой территории создана многорегрессионная модель дефоляции на основе данных пробных площадок и географических переменных, величины которых известны. Наибольшее значение на уровень дефоляции имели следующие переменные: место нахождение древостоя или расстояние от реки, почва, площадь сечения, бонитет и происхождение древостоя. Сосданная модель описывает соответственно 45: и 58: вариации средней дефоляции и ее изменении в течении 3 летнего периода.

Ключсвыс слова: географические информационные системы, пространственная автокореляция, многочисленная регрессионная модель, дефоляция кроны дерева.