Universitatea Ştefan cel Mare Suceava

Stefan cel Mare University of Suceava

Faculty of Forestry

Research on the Evaluation of Stands Regeneration by Computer Means

DOCTORAL THESIS

Suceava, June 2009

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Abstract: The regeneration of forest resources is one of the main objectives of modern forest management. The present thesis aims to identify detailed features of the regeneration process and the characteristics of sapling interaction. The research involved evaluation of regeneration structure, dimensional differentiation of saplings, spatial pattern analysis – sapling aggregation and species association, and sapling competition using distance-dependent methods. A new distance-dependent dimensional differentiation index (IDIV) and a new geometrical criterion for selecting neighbouring competitor saplings were created and applied. Appropriate methods and techniques were identified for investigating regeneration and computer technology was used intensively. Nine stand-alone software programs were produced in order to achieve the objectives of the thesis.

Keywords: stand regeneration, forest models, dimensional diversity, competition, spatial pattern analysis, sapling aggregation, area potentially available.

Introduction

Sustainable forest management requires comprehensive knowledge about forest growth and development. This knowledge is often encapsulated in models and forecasting tools. The regeneration process is essential to preserve forest resources but because of its complexity is rather difficult to model. In my research I focussed on the characteristics of stands regeneration and the main features of sapling interaction that might help to create a forest regeneration model.

I present the evolution of concepts concerning stand regeneration and I review the literature covering theoretical aspects of forest cybernetics. I point out aspects regarding general elements of modelling, features of forestry modelling and model categories. I also mention trends in forestry modelling with respect to neural networks, spatial analysis, three-dimensional modelling and satellite images and remote sensing. At the end of the first part of the thesis I deal with the characteristics of forest regeneration modelling and software used to simulate forest regeneration.

Objectives

The objectives were set taking into account the recent trends in regeneration studies. The main lines of the thesis consider four levels of regeneration evaluation:

- The evaluation of regeneration structure. What are the characteristics of the horizontal and vertical structure of regeneration? What is the type of sapling size (diameter, height and crown) distribution? Which biometric attribute is the most expressive parameter of the regeneration structure? Are biometric attributes influenced by sapling density?
- The evaluation of saplings' dimensional diversity. What is the intensity of saplings' dimensional heterogeneity? What is the most appropriate method to assess saplings' dimensional diversity? Can we incorporate spatial information in the process of evaluation?
- The evaluation of saplings' spatial pattern. Can we establish that saplings' spatial distribution follows a non-random pattern? Are the saplings and seedlings aggregated? Is there any association or segregation of species or sapling categories? Can we determine the dimensional particularities of the aggregation and association or segregation?
- The evaluation of competition between saplings. Does competition influence sapling growth? What are the most suitable methods of selecting neighbour competitors?

An additional objective was to create personal software tools for the analysis of regeneration data.

Materials

The study area is located in Flămânzi Forest District, Production Unit I Flămânzi and parcel 50A, near Cotu, a small settlement situated in Botoşani County. The topography is almost flat, with a slope average of 2-3% and the altitude is around 140 meters.

The area of the stand studied is 21.5 hectares and the species composition consists of 30% sessile oak, 20% oak, 30% common hornbeam, 10% small-leaved linden and 10% common ash. The area is regenerated naturally and the regeneration gaps were created in 2001-2002 and were enlarged in 2007. Within this stand a 2.5 hectare homogenous area covered in saplings was selected for further investigation.

I installed a network of ten permanent rectangular sampling plots (7 x 7 m) where I measured the characteristics of all saplings and seedlings. I used a Geographic Positioning System (GPS) in order to record the coordinates of the centre of each plot and I labelled every sapling and seedling inside the plot. The features of 7253 individuals were determined. The attributes assessed are: species, location of the individuals (x, y Cartesian coordinates), basal diameter, total height, crown insertion height, two crown diameters along the directions of axes and the latest annual height growth.

Because of the large amount of data, specialised computer software was used: Microsoft Excel, StatSoft Statistica, Stand Visualization System, ESRI ArcView, SpPack (Perry, 2004), SPPA (Haase, 1995), SILVASTAT (Popa, 1999).

I created additional software programs in order to achieve the thesis objectives (using Microsoft Visual Basic development kit): CARTOGRAMA, BIODIV, DIFDOM, IDIV, SPATIAL, VORONOI, SVS Export, HEGYI and SCHUTZ.

Methods

The current study involved different data analysis methods. Each of the methods was comprehensively explained and adequate references were provided.

Descriptive statistics methods were used to support the description of the regeneration structure. The dimensional and density distributions of the saplings were modelled with theoretical statistical distributions such as Weibull, Beta and Gamma. I used the Pearson's chi-square (χ^2) and Kolmogorov–Smirnov test to assess how well the statistical models fitted. The structural characteristics of the saplings were modelled and the relationship between the biometric parameters of saplings and their density was analysed. Simple and multiple regression models were used. The accuracy of the models was estimated by analysing the mean squared error, absolute and relative mean bias and mean percent error.

To enhance the structure information, a computer-based environmental data visualization system – SVS *Stand Visualization System* (McGaughey, 1997) was used. In order to produce SVS compatible files, I developed SVS Export application software.

The spatial distribution of the dimensional sapling attributes was analysed and represented by a newly created software application – CARTOGRAMA.

The dimensional diversity of the saplings was evaluated by classic diversity indices such as Simpson (1949), Shannon (1948), Pielou (1969), Brillouin (Magurran, 2004), Berger-Parker (1970), McIntosh (1967), Margalef (1958), Menhinick (1964) and Gleason (1922) index. The values of the indices were calculated with BIODIV, a computer program that I developed. Göttingen's indices – the dimensional differentiation index and the dominance index (Gadow and Hui, 1999) were also used. DIFDOM software (a personal program) was used to compute the values of the indices. I developed a new spatial diversity index (IDIV) and produced a computer program to evaluate the values of this index.

The analyses of sapling spatial distribution were performed using two different types of techniques - distance-dependent and distance-independent methods.

Distance-independent methods consisted of a statistical evaluation of quadrate method indices – dispersion index (the ratio of the variance to the mean), index of clumping (David and Moore, 1954), Morisita (1962) and Green (1966) indices.

Distance-dependent methods included nearest neighbour analysis –Fisher (1922) index, index of aggregation Clark-Evans (1954), Donnelly (1978), Pielou (1959) and Skellam (1952) indices, refined nearest neighbour analysis (Diggle, 1979), k^{th} nearest neighbour analysis (Thompson, 1956) and the second order spatial statistics analysis - univariate and bivariate Ripley's K function analysis (Ripley, 1976, 1977). The $L(t)$ function was used, a transformation of the K function, proposed by Besag (1977), that linearises $K(t)$ and stabilises its variance. For the bivariate analysis the $L_{12}(t)$ function (Lotwick and Silverman, 1982; Upton and Fingleton, 1985) was used. To test the statistical significance of the results and evaluate the CSR (*Complete Spatial Randomness*) hypothesis and the spatially independent hypothesis, the $L(t)$ and respectively $L_{12}(t)$ values were examined by comparing with confidence envelopes ($P=0.05$) generated by Monte Carlo simulations. SpPack (Perry, 2004), SPPA (Haase, 1995) and SPATIAL (Palaghianu, Horodnic, 2006) were the computer programs used to analyse the data by distance-dependent and independent methods.

The spatial information was used to evaluate the competition between saplings. Two versatile distance-dependent competition indices were used: Hegyi (1974) and Schutz (1989). The Schutz index uses an individual criterion for selecting competition neighbours, but the Hegyi index does not provide such a condition. In order to solve the problem of selecting neighbours I developed a geometrical criterion for selecting neighbouring competitor saplings. The criterion is based on a mathematical condition that estimates the crown shading of a sapling by a direct competitor.

The Hegyi index formula usually uses the ratio of the diameters of the neighbouring trees. Because of the particularities of regeneration, the values of the Hegyi index were computed taking into account the ratio of the heights, crown volumes and exterior surfaces of the crown (the sapling's crown was assimilated with an ellipsoid).

The concept of APA (*area potentially available* to a tree) is also presented, and its implication in selecting the neighbours of an individual. Voronoi polygons or Dirichlet cells represent the mathematical solution of identifying APA so I developed a software application based on Ohyama's algorithm (2008) that constructs simple and weighted Voronoi diagrams.

Results and Discussion

The regeneration structure is characterised by a large dispersion of size and density (the average coefficient of variation values is greater than 55-60%). The sapling size frequency distributions are unimodal and right-skewed. The probability density function of the Gamma and Weibull distributions provided the best solutions in fitting the experimental distributions according to the Chi-square (χ^2) and Kolmogorov–Smirnov tests.

Because of the particularities of regeneration structure and considering the difficulty of measuring sapling size parameters, the total height should be considered the central parameter of the structure because of its simplicity and accuracy of evaluation and its active influence on sapling growth. The basal diameter is not easy to determine and the accuracy of measuring is a problem.

The regression equations of basal diameter, height to crown insertion and average crown diameter in relation to height were examined and it was established that total height represents a good predictive parameter of sapling size attributes. The predictive parameter explained 61% of diameter variance and 44% of average crown diameter. Significant negative correlations were found between sapling density and basal diameter, crown diameter, crown volume and crown exterior surface. The height is less influenced by density so both parameters were used to improve the accuracy of a multiple regression model that forecast the other dimensional attributes.

The analysis of the dimensional diversity of the saplings revealed two bunches of classic diversity indices, grouped by similarity - the first collection is formed by Simpson, Shannon, Pielou, Brillouin, Berger-Parker and McIntosh indices; the second one consists of the Margalef, Menhinick and Gleason indices.

The results show that height parameter attains the highest dimensional diversity – frequencies are the most regularly distributed in classes of height distribution. The maximum diversity related to dimensional attributes was found in common hornbeam and small-leaved linden saplings.

The dimensional differentiation index points up for a low to medium height differentiation (using the evaluation scale proposed by Pommerening, 2000) in groups of 2 up to 6 saplings. The dominance index in respect to height also has low values.

The diversity indices do not usually take into account information about spatial distribution of dimensional attributes. To correct this problem I developed a new spatial diversity index (IDIV) based on sapling position and their size parameters. The IDIV index includes two axial components IDIV_Ox and IDIV_Oy (used to evaluate gradient phenomenon) and the extreme values IDIV_min and IDIV_max (used to evaluate diversity intensity). There were no differences between IDIV_Ox and IDIV_Oy so there is no evidence of a gradient phenomenon.

The values of the IDIV index were computed on a three dimensional scale, with 25, 50 and 100 cm evaluation steps. Values for diversity are higher as the evaluation step increases, showing the influence of the observation scale on spatial analysis (Hurlbert, 1990). In the IDIV the values increase close to the maximum evaluation step, a fact that can be explained by the aggregation tendency of saplings.

IDIV and IDIV_max are strongly influenced by sapling density – positively correlated, but IDIV_min is not related to density. IDIV and conventional diversity indices are medium correlated, the same situation being observed in the case of IDIV relation to the dimensional differentiation index and the dominance index. The above-mentioned correlations prove the IDIV's capacity to record dimensional heterogeneity.

Sapling spatial distribution was studied by different methods. Distance-independent techniques (quadrate method indices) revealed deviation from Poisson's spatial distribution in the direction of aggregation. The intensity of clustering decreases as density augments. Distance-dependent indices (Fisher index, Clark-Evans index of aggregation, Donnely, Pielou and Skellam indices) support the above-mentioned aspect.

The refined nearest neighbour analysis and k^{th} nearest neighbour analysis offer a greater number of details, showing aggregation tendencies at distances between 10 and 30 cm, respectively clustering of 2-3 saplings (plots 1, 7 and 9), up to 6-7 saplings (plots 2 and 10) or even more than 16 saplings (plots 3,4,5,6).

Univariate Ripley's K function analysis indicates aggregation in all the plots studied –maximum clustering is present at 30-90 cm and 220-310 cm intervals. The spatial pattern shows smaller groups of saplings included in larger ones. Bivariate analysis demonstrates that seedlings are associated positively with medium height saplings and the tallest saplings repulse seedlings and medium height saplings. Analyses of interspecific spatial distribution patterns show spatial segregation between wild cherry and field maple. Positive association was observed between common hornbeam and oak along with small-leaved linden and common ash.

Competition process shapes forest dynamic and growth. The different competition indices (based on the Hegyi and Schutz indices) revealed similar centres of high intensity of competition. All the indices variants can be used in predictive models of growth, but some of them have superior forecasting capabilities – the Hegyi variants that use crown exterior surface and height. The criterion developed for selecting competition neighbours is versatile and sensitive and provided better results than the Schutz criterion. Finally, the area potentially available to a tree (and the Voronoi diagrams implementation) can be used to select competition neighbours or to asses the spatial pattern of sapling distribution.

Conclusions

Forest regeneration is a complex process with numerous unknown variables. Forest modelling can find hidden relations between these variables and can predict the regeneration dynamic based on characteristics of the relations that have been identified.

This study examined some of the regeneration features associated with sapling dimensional distribution, spatial patterns and competition. A large amount of input data was used and the research findings may be incorporated in simple regeneration models. Modern investigation techniques were used and several practical software solutions (nine computer programs) were produced. New methods suited to investigating forest regeneration were created and applied.

The results of this study may be useful to ecologists or forest researchers since they provide detailed and complex information about the forest regeneration process.

Note: The thesis "*in extenso*" (Romanian version) may be consulted on the web at: `www.farado.ro/teza`

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