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Original Research Article

Individual-based model of spatio-temporal dynamics of mixed forest stands

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ABSTRACT

This research presents the results of constructing and parameterizing an individual-based model of spatiotemporal dynamics of mixed forest stands. The model facilitates computerized experiments with forest stands having different combinations of species and age structures. These forest stands grow on temperate areas where light is the main system-forming factor that shapes and develops forest ecosystems. The model TEMFORM (TEMperate FORests Model) is developed with few equations and parameters, most of which can be estimated using standard forest inventory data. Parameterization of the model used the growth tables of a set of basic forest-forming species in Far East Russia. Simulation results of the development of the natural single- and mixed-species stands and the effects of different types of disturbances on the stand dynamics and compositions are presented.

1. Introduction

Various types of forest ecosystem models are being developed (Botkin et al., 1972; Liu and Ashton, 1995; Chertov et al., 1999; Bugmann, 2001; Porte and Bartelink, 2002; Busing and Mailly, 2004; Bolliger et al., 2005; Xi, 2009; Fontes et al., 2010; Kolobov, 2012; Borges et al., 2014) to study natural forest dynamics, the effects of different felling systems, disturbances (forest fires, clear felling, insect invasions, etc.) on stand dynamics, carbon balance, and climatic changes. The main difficulties in simulating the dynamics of forest ecosystems are the complexity of the systems and the constrained availability of empirical data to estimate model parameters. Forest inventory databases are one of the available sources of quantitative information to simulate forest dynamics. Many forest inventory data of Russian forests include growth tables, biological productivity tables, and general tables of growth and mortality of different types of forest stands. These data are standard and cover the majority of Russia's forest fund, including a description of major forest-forming species that influence different forest types and site conditions (e.g., Koryakin, 1990; Shvidenko et al., 2008; Usoltsev, 2007).

An uncomplicated individual-based model of spatiotemporal dynamics of multi-species and uneven-aged forest stands that compete for light during development is proposed in this paper. The model is developed with few equations and parameters, most of which can be estimated using standard forest inventory data. In particular, eco-physiological parameters of equations and functions that describe tree growth and death because of competition for light are estimated. Results are correlated with Russian forest inventory data, which has not been done thus far (Korzukhin and Korovin, 2012). Applications of the model are limited to temperate forests where light is the main limiting factor of tree growth. Other factors such as mineral nutrition and soil moisture are considered constant throughout the modeling cycle. Parameterization of the model employed growth tables of a set of basic forest-forming species in Far East Russia. Studies on forest ecosystems in the Far Eastern region employing simulation tools are few probably because of limited empirical data. The FAREAST model (Zhang et al., 2009) was used to simulate the responses of Far Eastern forests to climate change. Existing Russian simulation models were developed mainly for the forest simulations in European Russia, such as EFIMOD (Komarov et al., 2003) and FORRUS (Chumachenko et al., 2003).

The proposed model in the present study describes the dynamics of the stock and provides formation on the spatial distribution, age structure, and species composition of mixed stands as a result of intraspecific and interspecific competition for light among individual trees. This model may be used to determine the effect of different types of disturbances (fires, windfalls, insect outbreaks, clear-cutting, etc.) on stand dynamics and composition.

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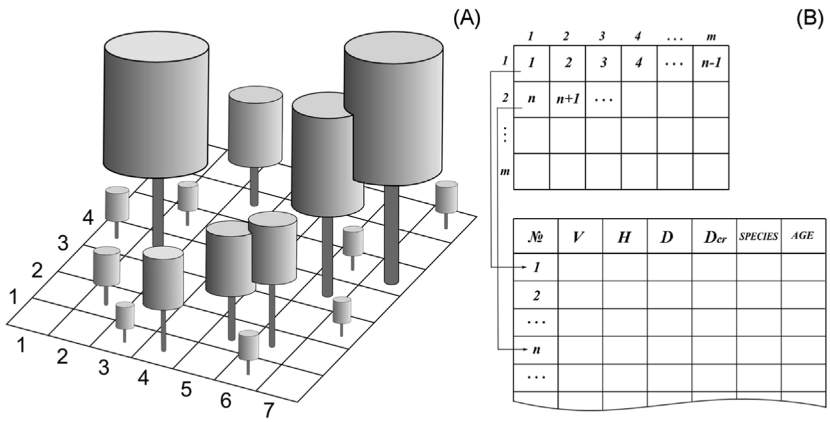

Fig. 1. Tree plotting in spatial grid (A), management of search and storage of modeled stand cell data (B).

The model can also be employed in sustainable forest management to develop and analyze different scenarios of selective cutting.

2. Model description

The model TEMFORM (TEMperate FORests Model) suggested in this work is an individual-based approach widely used in modern forest stand models (Liu and Ashton, 1995; Bugmann, 1996; Chave, 1999; Lexer and Honninger, 2001; Grote and Pretzsch, 2002; Mäkelä and Makinen, 2003; Verzelen et al., 2006; Van der Werf et al., 2007; Kramer et al., 2008). In this approach, forest stand dynamics is modeled by combining descriptions of each tree growth, species characteristics, and locally available resources. Trees are located in the stand with explicit spatial positions and interact with one another because of competition for light. The simulated sample plot is divided into a cell grid with a size of 0.4 m × 0.4 m, which can be correlated to the dimensions of a tree stem. Each cell can contain only one tree at a time. Each tree is not bound to the cell center but is placed there randomly (Fig. 1A). Dividing a continual space improves seed dispersion algorithms and identifies the nearest neighbors. The cell number is set by a user but is limited by the calculating power of the PC. Cell content data are tabulated, as shown in Fig. 1B. To model the tree stand dynamics in a sample plot originates edge effect from the ignorance of interdependences that occur outside the bounded region. To avoid edge effects the simulated plot is folded into a torus when the edges touch.

The tree crown in the model is approximated by a cylinder, and its dimension characteristics are expressed by its diameter (D_{cr}) and length (H_{cr}). To calculate the light regime with the algorithm presented below, the modeled stand is discretized into volume cells (Fig. 3). This step ensures a precise calculation of solar radiation in the tree crown under the shade of neighboring trees.

2.1. Model structure

The structural scheme of the model consists of several program blocks: initial data, intermediate data, forest stand model, and output data (Fig. 2). The arrows indicate the interrelations of these blocks.

The initial data block reads the information stored in the external text files and contains species-specific parameter values that represent different tree characteristics (tree growth equations coefficients, light extinction coefficient, maximum lifespan, age of seed production, etc.), as well as its initial spatial distribution. Initial distribution data can be factual (present actual tree distribution on a plot) or specially selected depending on the research objective.

The tree stand dynamics model consists of several blocks that describe the growth, mortality, reproduction and interrelation processes of the tree. The spatial distribution of trees determines the common light resource distribution that causes tense competitive relations among individuals. Competitive processes affect tree growth and eventually lead to tree degradation and mortality. These events change the spatial structure of the area and establish new competitive relations. All interconnections between spatial distribution and individual growth processes predetermine the tree stand dynamics. Tree growth, endogenous thinning, and natural regeneration are modeled with a step equal to 1 year. Stem volume and diameter increment are calculated depending on the degree of shading by neighboring trees. Tree mortality occurs as a result of competition for light and natural aging, as well as different external factors such as windfall, ungulates that consume saplings, insect outbreaks, fires, and cutting.

As a result of modeling, the researcher obtains various statistics, such as growing stock volume, number of trees, spatial distribution, age structure, and species composition of the stand, which are shown in graphs and tables. To provide a visual presentation of the spatiotemporal dynamics of the modeled forest stand, the program offers a 3D visualization of trees in the spatial grid.

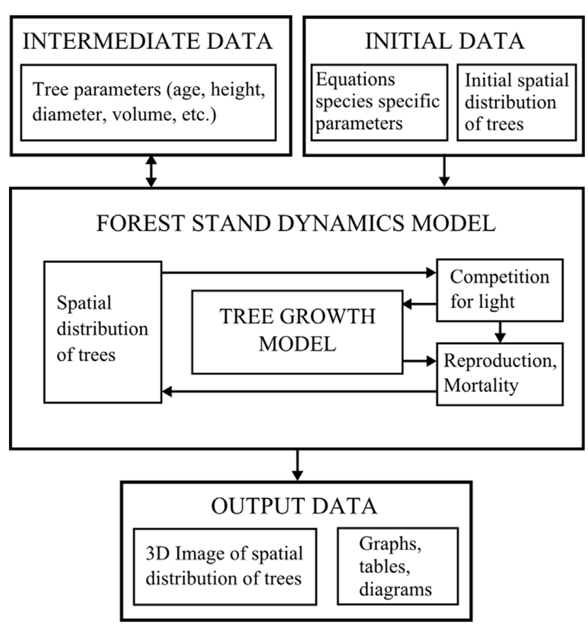

Fig. 2. Structural scheme of the tree stand dynamics model.