The use of forest ecosystem model EFIMOD for research and practical implementation at forest stand, local and regional levels

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\textbf{Abstract}

The idea of the application of one basic type of forest ecosystem model for different scales is proposed and discussed. The individual-based spatially explicit simulation model of tree/soil system EFIMOD is used for the demonstration of its applicability on forest stand, local (forest unit or landscape) and regional levels. At stand level, the model was implemented for theoretical analysis of the effects of environmental changes on forest ecosystems in West Europe and for the quantification of the efficiency of different types of forest thinning. At local level, the EFIMOD model was applied for the long-term simulation to quantify the difference of various silvicultural regimes at the forest lot with 108 individual stands in Central European Russia. At regional level, the model was implemented for a determination of the role of forest soils in carbon balance at the large territory of Leningrad administrative district in Russia.

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\textbf{1. Introduction}

Simulation modelling of forest ecosystems becomes an effective instrument for theoretical analysis of forest dynamics and practical tool for the prediction of stand growth, soil development or degradation and water balance in sustainable forest management in changing natural and economical environment of 21st century. Recently, the idea on the necessity to have a cascade of models with a different spatial resolution was dominant in the terrestrial ecosystem modelling (Acevedo et al., 1995; Chertov et al., 1999a). The main argument was to have a set of various specific models for a single ecosystem, landscape and regional levels. The use of Markov chain models for landscape and regional scales was mostly the essential point of this approach. Correspondingly, the reduction of output parameters from individual stand to regional models was also postulated.

However, the use of stand models for landscape and regional levels is conceptually possible due to a functional similarity of ecosystem models of different scales. Moreover, the development of fast computers gives a technical opportunity for the use of one basic stand model type at any spatial level without reduction of information obtained at the stand level. Here, we discuss some results of and prospects for the implementation of one basic model type to cover different spatial scales in forest ecosystem modelling.

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2. The model

To demonstrate a multi-scale application of one model type, we used a model EFIMOD (model of European Forest Institute) for the description of a tree growth, soil dynamics and biological cycle of C and N in boreal and temperate forest ecosystems. Previously, the model was described in details (Chertov and Komarov, 1997a; Chertov et al., 1999b; Komarov et al., 2003).

It is spatially explicit individual-based simulator for several tree species on different forest soils under European boreal and temperate climatic conditions. Biomass growth of every tree in a stand is modelled in dependence on the tree’s ecological parameters (silvics), tree’s position within the stand and local light and available soil nitrogen. The main tree’s silvics are: (a) maximal biological productivity of leaves/needles (kilogram of biomass increment per kilogram of leaf mass annually) reflecting potential net primary production (NPP) of tree species and (b) specific consumption of nitrogen (kilogram of N per kilogram of biomass increment annually). The soil submodel (Chertov and Komarov, 1997b; Chertov et al., 2001) is used to estimate organic matter dynamics and available nitrogen for tree growth. The soil processes governed by tree litter fall and environmental factors are main driving variables in this model. A distribution of available nitrogen between the trees is calculated taking into account fine root mass and overlapping of the trees’ area of nutrition. The explicit balance of carbon and nitrogen in forest ecosystem is computed in the EFIMOD. The model has annual time step. The input data include standard parameters of forest stands used in practical forestry, climatic and soil hydrological characteristics, and initial pools of soil organic matter (SOM) and nitrogen in organic layer and mineral topsoil. The model outputs represents also standard parameters of forest stand, forest biomass data, net primary production (NPP), pools of SOM and N in the soil, gross emission of carbon dioxide from the soil and production of available nitrogen. The tree output parameters represent the map of the stand, the stand mean values per hectare specified for different tree species and age classes, and also the dendrometric and biomass parameters of every tree in the stand.

3. Material and method

Standard EFIMOD simulations of trees’ growth in a stand and soil change were performed for the model use at different spatial scales.

3.1. Stand level

Here, we represent the analysis of the model run at 22 research plots throughout Europe to study the effects of an increasing of atmospheric nitrogen deposition and air temperature on forest growth. It was 80 years simulation of so-called "managed" even-aged pure Scots pine and Norway spruce stands with regular thinning. The start of simulations was at 1920, 1960 and 2000. The initial tree and soil parameters were identical for these model runs. The simulation started in 1920 reflects situation with a stable climate and increasing nitrogen deposition (from 2·4 to 20-40 kg N ha⁻¹ year⁻¹). The simulation started in 1960 shows the effects of a high nitrogen deposition up to 30 kg N ha⁻¹ year⁻¹ with modest temperature growth. The simulation started in 2000 demonstrates the possible effects of rather high atmospheric nitrogen input (about 15-20 kg N ha⁻¹ year⁻¹) with climate change (annual air temperature increasing about 3 °C for 80 years with about 10% precipitation reduction in Central West Europe and its 20% increasing in North Europe). Additionally, different climatic and nitrogen deposition scenarios were compiled as a combination of low and high nitrogen deposition with a low and high temperature increase. Van Oijen et al. (2004) describe the methods and results of this study in detail. We represent here some additional results on the effects of the environmental changes on SOM pools and total ecosystem carbon pools. The reference level for the comparison of the effects of environmental changes is a simulation started in 1920 with low nitrogen input and no climate change.

At stand level, the EFIMOD was also used for the quantification of the ecological and silvicultural effect of two main types of forest thinning: classical one from below (removal of small oppressed trees) and from above (removal of large trees). The simulation was performed at two German Scots pine and Norway spruce experimental sites (Van Oijen et al., 2004) for 80 years rotation. Four thinning regimes were simulated in pine stands (at 25, 35, 45 and 55 years) and three ones in spruce stands (at 35, 45 and 55 years) with removal 25% of tree biomass at first thinning and 20% at the last one. The other parameters of simulation were identical. The results of simulation were compared with a naturally growing forest without any thinning.

3.2. Local level

At local level, we have used EFIMOD in a case study in Central Russia in combination with geovisualisation software Com- monGIS for spatial exploratory data analysis (Chertov et al., 2002a, in press). A special version EFIMOD PRO was elaborated for the simulation of a big set of individual stands and processing of output parameters. A 300 ha forest lot in experimental forest “Russky Les” South of Moscow, Russia, has been selected for the case study. The model was run in 108 stands of the forest. Each stand (forest inventory compartment, forest patch) has forest inventory characteristics that were used to initialise the model. Every compartment occupies some area that is significantly larger of the simulated plot in the model. In forest inventory, it is postulated that forest has uniform stand and soil parameters at entire area of the compartment. The EFIMOD PRO performs simulation for a small plot (25 m × 25 m) and then recalculates all output data at every time step for the area of forest compartment. Finally, the generalised data for all forest territory was also computed.

Four strategies of silvicultural regimes have been simulated for 200 years time span. A natural development scenario (NAT) is a growth of forest without any silvicultural treatments (thinning, cutting, burning). A selective forest scenario (SC) includes thinning and cutting of old large trees with 30% removing of growing stock every 30 years. A legal Russian forestry according to the Russian forest laws (RL) is a scenario with four thinning and final clear cutting at age from 60 to 90 years in dependence on tree species with burning...
cutting residues and successful forest regeneration. A Rus-

sian illegal forest practice (ILL) represents four intensive thin-

ning from above with taking all best trees, and final clear-

cutting with burning cutting residues and forest regenera-

tion by birch and aspen with low proportion of coniferous

and broad-leaf species. We discuss here the results for main

ecological and silvicultural parameters of all the territory,

however all output parameters for every stand and time step

are also available for the any kind of analysis of the output

data.

3.3. Regional level

We delineate a region as a territory of one contour on a map

having rather complicated diversity of various forests in this

large area. The structure of this diversity can be described

statistically as a set of characteristics of every forest unit cor-

responding to the parameters of individual stand. It gives an

opportunity to use a stand forest model at regional scale.

The possibility of the stand-level model for the regional

application was tested at the evaluation of 50 years soil carbon

balance in forest ecosystems of Leningrad administrative dis-

trict, Northwestern Russia, with a total forested area (without

mire woodlands) of 3.2 million ha. The aim of this application

was to clarify is the forest soils of the region carbon source or

sink. The initial data on groups of forest types, tree species,

stand age classes, dendrometric parameters and the area of

these groups in the region for the simulation at regional level

were compiled using a generalised information of Russian

dendrometric parameters. We compiled the data for the

whole region. It is forest groups with a domination of Scots pine,

Norway spruce or deciduous tree species divided further by

forest types and age classes.

There are following groups of forest types in the region. Cal-

clena type is mostly with Scots pine stands on dry sandy soils.

Vaccinium type is forming on well-drained sandy soils with var-

ious tree species. Oxalis type is representative for an ecological

optimum in the region with more productive forests on well-

drained sandy soils. Myrtillus type is situated on well-drained

sandy soils and poor-drained soils of various texture with var-

ious tree species. Poltrirum type occupies poor-drained peat

soils. Herb-Philendula type is forming on a rich wet land-

forms of small water flows on fresh, water peat soils. Every

final unit (tree species–forest type and soil–age class) compiled

from the generalised forest inventory data has parameters of

the unit area (ha), growing stock (m³ for the entire unit) and

stand dendrometric characteristics (The soil and climate ini-

tial parameters were also compiled for the every unit using

previously published data [Chertov et al., 2002b]).

These materials were used for an assembling the initial

stand parameters for the EFIMOD runs. We compiled for every

unit of the matrix (tree species–forest type and soil–age class) a ‘repre-

sentative’ pattern of forest ecosystem (stand–soil) that

was used for the simulation. The output data of 50 years sim-

ulation represents an array of all stand and soil parameters for

every unit. Then, the data are generalised in relation to the

total area of the unit, and for a whole region if necessary. No

effects of cutting, forest fire, windstorms and insect attacks

were taken into account. Finally, the contribution of all forests
to soil carbon sequestration was evaluated.

4. Results and discussion

The effectiveness of the EFIMOD for theoretical analysis of

individual tree growth and ecosystem dynamics at stand level

was demonstrated before [Chertov et al., 1999c; Komarov et al.,

2003]. The model allows for the analysis of every tree growth in a

simulated stand. Fig. 1 shows trajectories of individual tree

growth on 25 m transect in a modelled stand. These curves

effect growth as affected by environmental conditions and

the competition for light and soil nitrogen in the stand that

leads to the mortality of the significant part of the trees. Short

curves in Fig. 1 mean that the tree died due to a lack of soil

available nitrogen or to shadowing by the adjoining trees. The

inflation of some curves means the change of growth rate due
to increasing deficit of growth resources by competition. This

application of the model can be used for the theoretical analy-

sis of the spatial patterns of competition for growth resources.

The use of the model at stand level for the quantification
of the factors of forest growth increase in Europe allows for

a conclusion on the relative contribution of the environmen-
tal factors in this process (Fig. 2 and Table 1). The results of

simulation show that high atmospheric nitrogen deposition

growth and temperature in Europe can lead to 4–10% reduc-
tion of soil C, but 5–20% increasing of total ecosystem C pool

(Fig. 2). Nitrogen deposition has more strong effect on the for-

est productivity. Temperature growth is responsible for soil C

reduction. The effect of these environmental factors can lead
to significant increasing of stand height and growing stock in

the forest (Table 1).

The results of the quantification of the ecological and sil-

vicultural effect of two main types of forest thinning demon-

strate no strong ecological difference of these types of thin-

ning. The soil organic matter pool differs 3–5%, but the

biomass of trees is lowest when removing large trees (thin-

ning from above; Table 2). However, the silvicultural effect

of these two types of thinning regimes is very divergent. A signif-

icable increase of tree growth is observed in the group of

thinning from above, and in the group of thinning from

below are small differences. The effect of non-utilising

methods compensates the negative effect of utilising

methods.

Fig. 1 – Simulated growth of individual trees in a Norway

spruce stand. The short curves belong to the trees that
died during the early growth due to competition for light

and soil nitrogen.
The use of EFIMOD at local level shows methodological possibility for the generalisation of a big set of individual stand simulations for the level of forest compartment and then for all the area of forest management unit or landscape. The important aspect of this approach is that it is feasible to have both the data for stand development in details and a generalised data for the territory. The generalised results for the simulated forest lot (Table 3) show that a strategy of natural development is the best alternative from the ecological point of view because it leads to a highest carbon sequestration reflected by the net ecosystem exchange (NEE). The illegal cutting regime is the worst alternative. The Russian legal forestry has lowest output of harvested wood. The selective forest scenario is the best corresponding to the concept of sustainable forestry harmonising forest ecological and silvicultural functions. The results of this case study are described in detail by Chertov et al. (in press). This case study demonstrates a good applicability of forest stand model for the simulation at the local level of forest territory or landscape.

The application of the EFIMOD at regional level also shows a suitability of the stand-level model for a use at this scale. The generalised results described in Table 4. However, the entire simulation results represent a large set of data for every forest unit in the Leningrad region for every time step both for the ‘representative’ stands and for the total area of every unit. It allows for the analysis of the full set of stand-level data for regional synthesis if necessary. In our case, we operated with ecological parameters for the evaluation of the role of soil processes in carbon balance.

In the Leningrad region, the young stands are often a source of carbon due to misbalance between small litter input and the high rate of SOM mineralisation. However, the total balance of

### Table 1 – Effects of the increasing of nitrogen deposition from 4 to 25 kg N ha\(^{-1}\) year\(^{-1}\), temperature increasing by 3 °C for the same period, and cumulative effects of these environmental changes at the end of 80 years simulation, all variants together, percent of changes to values in naturally developed stands without thinning

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Scots pine</th>
<th>Norway spruce</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand height [m]</td>
<td>2.3 (1.71)</td>
<td>3.9 (2.98)</td>
</tr>
<tr>
<td>Growing stock [m(^3) ha(^{-1})]</td>
<td>8.2 (6.43)</td>
<td>12.8 (8.74)</td>
</tr>
<tr>
<td>Soil organic matter pool [kg m(^{-2})]</td>
<td>12.0 (5.33)</td>
<td>5.2 (3.99)</td>
</tr>
<tr>
<td>Soil nitrogen pool [kg m(^{-2})]</td>
<td>1.9 (1.79)</td>
<td>2.9 (3.82)</td>
</tr>
<tr>
<td>Total ecosystem carbon [kg m(^{-2})]</td>
<td>4.4 (4.29)</td>
<td>11.3 (7.32)</td>
</tr>
</tbody>
</table>

### Table 2 – Effect of different regimes of thinning on stand ecological and silvicultural parameters at the end of 80 years simulation, percent of changes to values in naturally developed stands without thinning

<table>
<thead>
<tr>
<th>Stand</th>
<th>Thinning type</th>
<th>Soil C [kg m(^{-2})]</th>
<th>Tree C [kg m(^{-2})]</th>
<th>Harvested wood [m(^3) ha(^{-1})]</th>
<th>Tree number per hectare</th>
<th>Stand parameters at final cutting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
</tr>
<tr>
<td></td>
<td>height [m]</td>
<td>diameter [cm]</td>
<td>basal area [m(^2) ha(^{-1})]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scots pine</td>
<td>Below</td>
<td>-4</td>
<td>-12</td>
<td>24</td>
<td>-65</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Above</td>
<td>4</td>
<td>-34</td>
<td>10</td>
<td>-9</td>
<td>7</td>
</tr>
<tr>
<td>Norway spruce</td>
<td>Below</td>
<td>-3</td>
<td>-1</td>
<td>32</td>
<td>-35</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Above</td>
<td>5</td>
<td>-14</td>
<td>17</td>
<td>-12</td>
<td>8</td>
</tr>
</tbody>
</table>
In our application of the individual-based stand model to local and regional scales we suggested that the units on highest levels (forest compartment at the local scale, and unit of structural matrix at regional level) have uniform stand parameters. This postulate allowed for the extrapolation of the output data of the stand simulation for the entire area of corresponding units of higher levels. Kurz and Apps (1999) also used this approach with a Canadian biomass model CBM-CFS2 for a simulation of a 70 years dynamics of about 12,000 contours for the countrywide Canadian forest stands. However, this methodology cannot applicable in a case of spatial heterogeneity of stand and soil parameters in the modelled unit. In this case, the division of territory by a regular net with a fixed ‘mesh’ size (patch, pixel) is used. An example of this methodology for the application of forest models at local and landscape level can be a work by Chumachenko et al. (2003) for rather big forest territories in Central European Russia. They divided forest area by polygons 16 m × 16 m and run the model for every polygon at the area of few thousand hectares.

This network methodology is widely used in recent landscape models, for example, in the LANDIS (He et al., 1999; Mladenoff, 2004) where the area of a landscape is also divided by regular patches with a size from 1 to 100 km². There are also attempts here to integrate stand-level gap models in a structure of large-scale landscape models postulating the forest uniformity in every polygon (He et al., 1999; Garman, 2004).

At the regional level, the proposed use of one basic stand simulator is fully corresponding to the facilities of EFISCEN model (Nabuurs et al., 2003) implemented at a national and Pan-European scale. This model uses silvicultural growth tables to simulate forest growth. Therefore, it calculates tree increment following to the fixed ‘prescribed’ patterns of stand growth. Then, the calculated silvicultural parameters (wood increment and growing stock) are transferred into the stand biomass and other ecological parameters, and then a litter fall for a soil submodel is separately estimated. This model has no feedback from the soil to tree growth and elements’ turnover in the ecosystem. In this relation, we think that the use of the stand model of forest ecosystem that directly accounts for feedback from the soil to tree growth and elements’ turnover in the ecosystem. In this relation, we think that the use of the stand model of forest ecosystem that directly accounts for feedback from the soil to tree growth and elements’ turnover in the ecosystem. In this relation, we think that the use of the stand model of forest ecosystem that directly accounts for feedback from the soil to tree growth and elements’ turnover in the ecosystem. In this relation, we think that the use of the stand model of forest ecosystem that directly accounts for feedback from the soil to tree growth and elements’ turnover in the ecosystem.

Table 3 – Simulated carbon budget, mean values for 200 years for all forest area and silvicultural regimes, t C ha⁻¹ year⁻¹

<table>
<thead>
<tr>
<th>Parameters of carbon budget</th>
<th>Silvicultural scenariosa</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPPb</td>
<td>NAT</td>
</tr>
<tr>
<td>C–CO₂ of the emission from soil and coarse woody debris</td>
<td>6.37</td>
</tr>
<tr>
<td>Harvested wood</td>
<td>5.28</td>
</tr>
<tr>
<td>Burning cutting residues</td>
<td>0</td>
</tr>
<tr>
<td>Sum of C going away from the ecosystems</td>
<td>0</td>
</tr>
</tbody>
</table>
| In our application of the individual-based stand model to local and regional scales we suggested that the units on highest levels (forest compartment at the local scale, and unit of structural matrix at regional level) have uniform stand parameters. This postulate allowed for the extrapolation of the output data of the stand simulation for the entire area of corresponding units of higher levels. Kurz and Apps (1999) also used this approach with a Canadian biomass model CBM-CFS2 for a simulation of a 70 years dynamics of about 12,000 contours for the countrywide Canadian forest stands. However, this methodology cannot applicable in a case of spatial heterogeneity of stand and soil parameters in the modelled unit. In this case, the division of territory by a regular net with a fixed ‘mesh’ size (patch, pixel) is used. An example of this methodology for the application of forest models at local and landscape level can be a work by Chumachenko et al. (2003) for rather big forest territories in Central European Russia. They divided forest area by polygons 16 m × 16 m and run the model for every polygon at the area of few thousand hectares.

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We can conclude that, if a tendency for the use stand models for higher spatial levels will be further developing then the landscape and regional models can be considered as a specific software shell for the adaptation and processing of the stand model runs for large scale. Actually, we also develop an approach in this direction by the integration the EFIMOD with the geovisualization and exploratory spatial data analysis systems 'CommonGIS' (Andrienko et al., 2003; Chertov et al., 2002a, in press).

We suppose that the approach discussed in this work is not in a certain contradiction with the previous methodology (cascade of specific models for different scales). It is the additional methodological option that perhaps will be more effective for practical implementation of the forest modelling. It is of crucial importance for planning and realization of the concept of sustainable forest management. Anyway, the acceptance of the methodology always depends on the aims of the model application.

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