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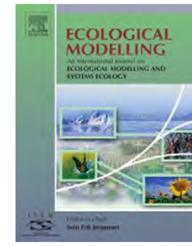

The use of forest ecosystem model EFIMOD for research and practical implementation at forest stand, local and regional levels

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ABSTRACT

The idea of the application of one basic type of forest ecosystem models 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.

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 dominated 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 levels. 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 a 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 represent 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 these 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 CommonGIS 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 Russian illegal forest practice (ILL) represents four intensive thinning from above with taking all best trees, and final clear cutting with burning cutting residues and forest regeneration 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 corresponding 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 district, 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 national forest inventory for Leningrad district. This generalised information represents a matrix of dendrometric characteristics describing a structure of forest stands within the 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. *Calluna* type is mostly with Scots pine stands on dry sandy soils. *Vaccinium* type is forming on well-drained sandy soils with various tree species. *Oxalis* type is representative for an ecological optimum in the region with more productive forests on well-drained loamy soils. *Myrtillus* type is situated on well-drained sandy soils and poor-drained soils of various texture with various tree species. *Politrichum* type occupies poor-drained peat soils. *Herbo-Philipendula* type is forming on a rich wet landforms 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 (m^3 for the entire unit) and stand dendrometric characteristics. The soil and climate initial 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 'representative' pattern of forest ecosystem (stand–soil) that was used for the simulation. The output data of 50 years simulation 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 reflect 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 inflexion 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 analysis 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 environmental factors in this process (Fig. 2 and Table 1). The results of simulation show that high atmospheric nitrogen deposition and growth of temperature in Europe can lead to 4–10% reduction of soil C, but 5–20% increasing of total ecosystem C pool (Fig. 2). Nitrogen deposition has more strong effect on the forest 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 silvicultural effect of two main types of forest thinning demonstrate no strong ecological difference of these types of thinning. The soil organic matter pool differs 3–5%, but the biomass of trees is lowest when removing large trees (thinning from above; Table 2). However, the silvicultural effect of these two types of thinning regimes is very divergent. A signif-

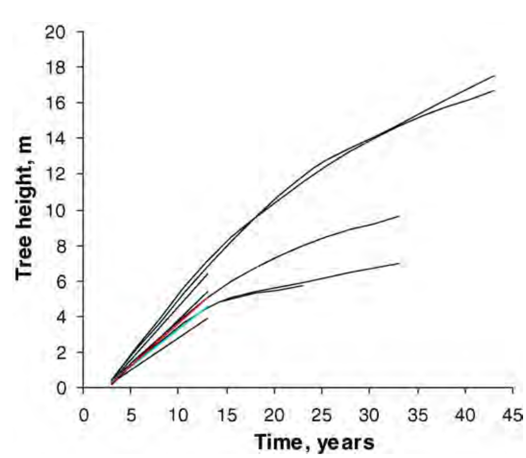

Fig. 1 – Simulated growth of individual trees in a Norway spruce stand. The short curves belong to the trees that dead during the early growth due to competition for light and soil nitrogen.

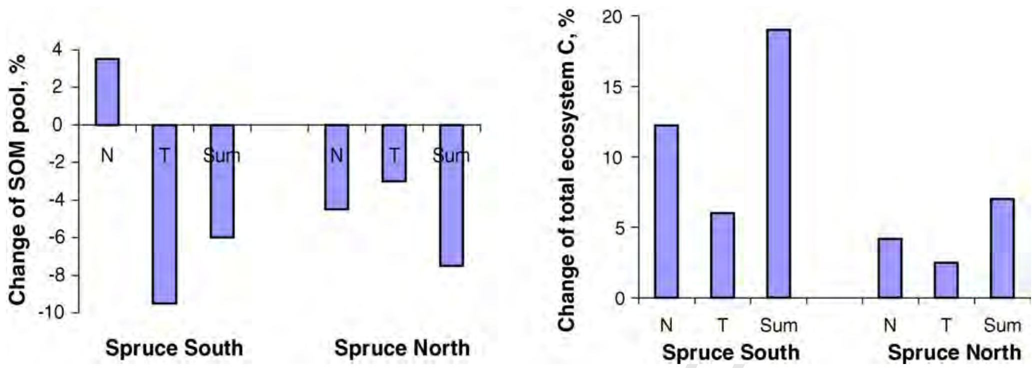

Fig. 2 – The simulated effects of nitrogen deposition and temperature increase on the soil organic matter (SOM), and total ecosystem C pools (kg m^{-2}) in boreal (North) and temperate (South) European Norway spruce forests at the end of 80 years model run, percent to the reference level of stand development without temperature and nitrogen deposition increase. The symbols mean: N, effect of the increasing of nitrogen deposition from 4 to 25 kg N ha^{-1} year^{-1} for 80 years; T, effect of mean annual temperature increasing by 3 °C for the same period; Sum, cumulative effect of nitrogen deposition and temperature for the same period.

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 the reference level of a stand growing with low nitrogen input and no climate change, mean (S.D.)

Parameters	Scots pine (n = 24)	Norway spruce (n = 18)
Stand height [m]	2.3 (1.71)	5.9 (2.98)
Growing stock [m^3 ha^{-1}]	8.2 (6.43)	12.8 (6.74)
Soil organic matter pool [kg m^{-2}]	−4.4 (3.33)	−4.2 (5.99)
Soil nitrogen pool [kg m^{-2}]	−2.0 (1.78)	−2.9 (3.62)
Total ecosystem carbon [kg m^{-2}]	4.4 (4.29)	11.3 (7.32)

icant contrast is in the size and volume of merchantable wood. The removing of small trees at the thinning from below results in a highest volume of harvested wood and formation of large trees at final cutting. Thinning from above forms rather dense stand with smaller trees. The total forest productivity at this type of thinning is lower then at the tinning from below.

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 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

Stand	Thinning type	Soil C [kg m^{-2}]	Tree C [kg m^{-2}]	Harvested wood [m^3 ha^{-1}]	Tree number per hectare	Stand parameters at final cutting		
						Mean height [m]	Mean diameter [cm]	Basal area [m^2 ha^{-1}]
Scots pine	Below	−4	−12	24	−65	35	39	−34
	Above	4	−34	10	−9	−7	−7	−22
Norway spruce	Below	−3	−1	32	−35	14	15	−15
	Above	5	−14	17	12	−8	−8	−6

Table 3 – Simulated carbon budget, mean values for 200 years for all forest area and silvicultural regimes, t C ha^{-1} $year^{-1}$

Parameters of carbon budget	Silvicultural scenarios[a]			
	NAT	SC	LR	ILL
NPP[b]	6.37	5.54	4.75	4.15
C–CO_2 of the emission from soil and coarse woody debris	5.38	4.17	3.48	2.90
Harvested wood	0	1.18	1.04	1.33
Burning cutting residues	0	0	0.23	0.18
Sum of C going away from the ecosystems	5.38	5.35	4.75	4.40
NEE[c]	0.99	0.19	0	−0.25

[a] NAT, natural development without cutting; SC, selective cutting regime; LR, Russian legal clear cut regime; ILL, Russian illegal clear cuttings, explanations in the text.
[b] NPP, net primary production.
[c] NEE = NPP − (sum of C going away), net ecosystem exchange.

soil C is positive. The main contributions to carbon sequestration have soils of two widespread forest types at well-drained soils of different productivity (*Oxalis* and *Myrtillus*). Altogether, the forest soils of the region are sinks of atmospheric carbon. A simulated total soil carbon surplus reaches 8.6 million t at the area of the region for 50 years time span in a case of absence of catastrophic events and heavy clear cutting. This picture of consistent accumulation of soil carbon can be a proof of significant degradation of 'natural' forest soils as a result of forestry practice and heavy disturbances during the last centuries.

We can conclude that the discussed examples of the application of a stand-level forest ecosystem model for local and regional levels prove out the prospects for the use of one basic model type for multi-scale simulation. The previous methodological approach (Acevedo et al., 1995; Chertov et al., 1999a,b,c) postulated that transition from individual stand level to local and regional levels leads obligatory to the reduction of the output parameters. However, the approach discussed allows for a simulation of the ecosystem dynamics at large scales without loss of information on the forest dynamics on stand level because presence of the full output data of the stand model runs. Here, we discussed mostly the generalised ecological parameters of forest ecosystems. However, it is possible a comprehensive representation of all silvicultural and pedological output parameters of stand level at local and regional levels if necessary. The analysis of the results obtained allows for a proposal of the spatial hierarchy to use stand model at different scales with the patterns of output data (Table 5).

Table 4 – Simulated annual changes of soil carbon per total area of the forest type unit in the forests of Leningrad region, 1000 t C $year^{-1}$

Forest site types	Area, 1000 ha	Young stands	Total
Calluna	32.8	1.3	4.0
Vaccinium	294.0	−1.1	8.7
Oxalis	894.9	4.1	97.6
Myrtillus	1373.8	−0.4	70.7
Politrichum	323.3	3.0	18.3
Herbo-Philipendula	301.8	−11.7	−26.3
Total	3220.8	−4.8	173.0

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 km^2. 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 transformed 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 biomass productivity (NPP) and soil processes with their interaction in dependence on environmental factors and available resources has a real privilege over the simulators based on standard growth tables only.

Table 5 – Hierarchy of spatial scales for the application of individual-based forest stand model at different spatial levels

Level	Parameters of individual tree growth	Stand/soil parameters in detail	Generalised parameters of any format for forest area
Stand	X	X	–
Local/landscape	X[a]	X	X
Regional	X[b]	X[b]	X

[a] It is possible option in a case of specific response.
[b] It is possible for the 'representative' patterns of the stands.

We can conclude that if a tendency for the use the 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 our approach in this direction by the integration the EFIMOD with the geovisualisation and exploratory spatial data analysis system '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 realisation 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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REFERENCES

Acevedo, M.F., Urban, D.L., Ablan, M., 1995. Landscape scale forest dynamics: GIS, gap and transition models. In: Goodchild, M.F., Stewart, L.T., Parks, B.O., Crane, M.P., Johnston, C.A., Maidment, D.R., Glendidning, S. (Eds.), GIS and Environmental Modelling. Progress and Research Issues. GIS World, Fort Collins, CO, pp. 181–185.

Andrienko, G., Andrienko, N., Voss, H., 2003. GIS for everyone: the CommonGIS project and beyond. In: Peterson, M. (Ed.), Maps and the Internet. Elsevier Science, pp. 131–146.

Chertov, O.G., Komarov, A.S., 1997a. Simulation model of Scots pine, Norway spruce and Silver birch ecosystems. In: Sustainable Development of Boreal Forests. Proceedings of the 7th Annual Conference of IBFRA, St. Petersburg, August 19–23, 1996, pp. 161–167.

Chertov, O.G., Komarov, A.S., 1997b. SOMM—a model of soil organic matter dynamics. Ecol. Modell. 94, 177–189.

Chertov, O.G., Komarov, A.S., Karev, G.P., 1999a. Modern Approaches in Forest Ecosystem Modelling. Brill, Leiden, Boston, Köln, 130 pp.

Chertov, O.G., Komarov, A.S., Tsiplianovsky, A.V., 1999b. A combined simulation model of Scots pine, Norway spruce and Silver birch ecosystems in European boreal zone. Forest Ecol. Manage. 116, 189–206.

Chertov, O.G., Komarov, A.S., Tsiplianovsky, A.V., 1999c. Simulation of soil organic matter and nitrogen accumulation in Scots pine plantations on bare parent material using forest combined model EFIMOD. Plant Soil 213, 31–41.

Chertov, O., Komarov, A., Andrienko, G., Andrienko, N., Gatalsky, P., 2002a. Integrating forest simulation models and spatial-temporal interactive visualisation for decision making at landscape level. Ecol. Modell. 148 (1), 47–65.

Chertov, O.G., Komarov, A.S., Bykhovets, S.S., Kobak, K.I., 2002b. Simulated soil organic matter dynamics in forests of the Leningrad administrative area, northwestern Russia. Forest Ecol. Manage. 169 (1–2), 29–44.

Chertov, O., Komarov, A., Mikhailov, A., Andrienko, G., Andrienko, N., Gatalsky, P. Geovisualisation of forest simulation modelling results: a case study of carbon sequestration and biodiversity. Comp. Electron. Agric., in press.

Chumachenko, S.I., Korotkov, V.N., Palenova, M.M., Politov, D.V., 2003. Simulation modelling of long-term stand dynamics at different scenarios of forest management for conifer—broad-leaved forests. Ecol. Modell. 170, 345–361.

Garman, S.L., 2004. Design and evaluation of a forest landscape change model for western Oregon. Ecol. Modell. 175, 319–337.

He, H.S., Mladenoff, D.J., Crow, T.R., 1999. Linking an ecosystem model and a landscape model to study forest species response to climate warming. Ecol. Modell. 114, 213–233.

Komarov, A., Chertov, O., Zudin, S., Nadporozhskaya, M., Mikhailov, A., Bykhovets, S., Zudina, E., Zoubkova, 2003. EFIMOD 2—a model of growth and elements cycling in boreal forest ecosystems. Ecol. Modell. 170, 373–392.

Kurz, W.A., Apps, M.J., 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. Ecol. Appl. 9 (2), 526–547.

Mladenoff, D.J., 2004. LANDIS and forest landscape models. Ecol. Modell. 180, 7–19.

Nabuurs, G.-J., Päivinen, R., Pussinen, A., Schelhaas, M.-J., 2003. Development of European Forests Until 2050. EFI Research Report 15. Brill, Leiden, Boston, Köln, 242 pp.

Van Oijen, M., Ågren, G.I., Chertov, O.G., Kellomäki, S., Komarov, A., Mobbs, D.C., Murray, M.B., 2004. Evaluation of past and future changes in European forest growth by means of four process-based models. In: Karjalainen, T., Schuck, A. (Eds.), Causes and Consequences of Forest Growth Trends in Europe—Results of the RECOGNTION Project. Brill, Leiden, Boston (Chapter 4.4).