Modeling of multiple forest use under different management scenarios

S Chumachenko¹, V Kiseleva*, A Kolycheva¹,² and E Mitrofanov¹

¹Mytishchi Branch, Bauman Moscow State Technological University, 1 Institutskaya Street, Mytishchi, 141500 Moscow Region, Russian Federation
²Center for Forest Ecology and Productivity, Russian Academy of Sciences, 84/32 bldg. 14 Profsoyuznaya Street, 117997 Moscow, Russian Federation

*Corresponding email: vvkisel@mail.ru

Abstract. The concept of multiple forest use envisages the implementation of several types of forest use considering ecological and social aspects. The question arises about the compatibility of harvesting timber, non-wood resources, and getting ecosystem services provided by forests. This question can be answered by means of computer modeling of forest dynamics at different patterns of silvicultural activities. The paper presents the ecologo-physiological simulation model FORRUS designed for the forecast and analysis of forest stand dynamics, including the logging-induced one, and complemented by special blocks for the computation of non-wood resources and recreational potential. The model was run for three scenarios: natural development, selective cutting, and intensive forest use, and applied to three objects in two natural zones of Russia. The scenario envisaging selective form of logging is the most convenient for multiple forest use. Intensive pattern of forest management is partially compatible with food resources and conflicts with the recreational potential of a territory. The model can be applied for both the research properties (finding correlations between stand characteristics and intensity of forest use) and the selection of optimal pattern of forest management for a concrete economic entity.

1. Introduction

Multifunctional character is generally intrinsic to forest ecosystems. They should provide food, bioenergy, retain carbon, preserve biodiversity, and withstand catastrophic events [1].

Based on the concept of multifunctionality, several theories emerged, such as the large-scale segregation theory, envisaging the selection of one dominant forest function and the subordination of all other functions and values to the main one; complete integration theory, envisaging a simultaneous multiple use of the whole forest area, and an intermediate small-scale segregation theory, combining the elements of the two first ones [2].

Different types of forest use can be either compatible or conflicting. Increasing demands in biomass force to resolve the problems related to the conflicts among timber logging, ecosystem services supply (food, raw materials, recreation, carbon retention), and biodiversity conservation [3].

Forest management approaches are essentially defined by coherent sets of forest operation processes at a stand level. It is also possible to group the patterns of forest use by its intensity from passive (unmanaged forest nature reserve) to high (intensive even-aged forestry) and intensive (short-rotation forestry, plantations) [4, 5]. Forest stand management can manipulate tree species diversity,
which in turn affects stand structure and finally leads to the changes in forest functions and services [6].

Mathematical modeling of the processes of forest growth and development makes it possible to calculate the changes of forest assessment characteristics for the period equal to the age of maturity of the majority of tree species and thus forecast the feasibility of these or those types of forest use.

In this paper, we regard the compatibility of three types of forest use – timber harvesting, food resources harvesting, and recreation.

2. Methods and Materials

2.1. Model structure and calculation principles

The modeling was carried out using the simulation model FORRUS-S (FOREsts of RUSSia – Stands), programme package for simulation modeling and analysis of forest stand dynamics. It simulates tree growth, increment, natural mortality and undergrowth recruitment, by tree cohorts; models multispecies and uneven-aged stands; models natural stand development, and allows to simulate various silvicultural activities and effect of climate changes [7-9]. The model belongs to the ecologo-physiological class, i.e. it imitates the processes of birth, development, and death of specimens [10].

The model consists of the blocks: Input data and model parameters, Service programmes, Modeling, and Output data. Model input data comprise standard forest site descriptions, forest maps, databases of bioecological data, local climatic conditions, site latitude and other reference information. Modeling block initially consisted of two models: Natural development and Exogenic effects. The natural development model includes four sub-models: Light, Increment, Thinning, and Regeneration (figure 1).

![Figure 1. Structure of the FORRUS-S model.](image)

Each modeling step begins with the calculation of light conditions of plant growth. The Light sub-model calculates the available photosynthetically active solar radiation (PAR) for each modeled forest element. Unlike gap-models [11-13], to calculate the light conditions, the model uses the information about the environment at the distance up to 60 m and considers both direct and scattered solar energy, taking into account actual Sun position.

The Increment sub-model calculates current increment in diameter and height for each forest element as depending on the quantity of PAR available.
The *Thinning* sub-model calculates the changes in the quantity of specimens of different species in a stand, imitating the mortality in case of PAR deficiency and competition for life space.

The *Regeneration* sub-model evaluates the quantity of natural seminal and vegetative regeneration for each species. The sub-model considers the distance from the nearest sites with generative (seed-bearing) trees, regularity of seed yields, vegetative activity, side conditions, and illuminance under forest canopy.

Modeling step equal to 5 years was selected considering the data of population biology about the time needed for noticeable changes in growth rates, development and light demands of young trees.

At the terminal stage of each step, a set of characteristics is calculated for each forest element within a site: number of trees, age, ontogenetic status, average height, average height of crown beginning, average diameter, area of crown projection and crown form, site index class, biomass of stems, branches, roots, and deadwood volume. The stock volume and relative density are calculated for the site as a whole.

Changing the conditions in the model *Exogenic effects*, it is possible to simulate various regimes of forest management (for example, regimes of logging) and their influence on stand structure.

The model does not take into account natural disturbances and catastrophic phenomena, which are hardly predictable.

Special block *Recreation* was designed in order to evaluate and simulate the dynamics of possible recreational use of forests. Each site is evaluated by two complex indices: recreational attractiveness (the quality of recreational ecosystem services) and resilience to recreation. Initial data for this block are available from forest assessment materials.

The attractiveness implies aesthetic features of the territory and its emotional effect working via the sense of comfort, safety, microclimate, etc., which, in their turn, are determined by stand composition and structure. The resilience reflects the capacity of all ecosystem components to withstand recreational loads; it is determined by species composition, stand age, subcanopy vegetation, forbs composition, soil and moisture conditions, and slope steepness.

We preserved the traditional semi-quantitative (grade) estimation used in recreation studies in Russia [14]. However, the scales used were revised substantially. The recreational potential of each site is characterised by the indices of attractiveness and resilience expressed in decimals as a share of maximum possible value.

The model block *Food resources* was designed to evaluate the yields of the most common berries: blueberry (*Vaccinium myrtillus* L.), raspberry (*Rubus idaeus* L.), and red bilberry (*Vaccinium vitis-idaea* L.), and mushrooms, with input data available from forest assessment materials.

Ecological optima of berries and mushrooms growth and fruiting were set as affected by predominating tree species, site conditions, stand age, and relative density. The values of productivity were obtained from the national reference guide *Russian forest resources inventory reference book* (excluding timber) [15]. Stand density is one of the factors limiting berries’ productivity; however, the guide disregards undergrowth recruitment, which reduces the amount of solar radiation reaching soil surface and decreases the productivity. Thus, the density was replaced by the illuminance at soil level, which is calculated from light transmittance by all vegetation layers [16].

2.2. Objects and scenarios

The model was applied for three objects situated in different regions of Russia and differing by the strategies of forest management: Manga catchment (Karelia Republic, middle taiga), total 16824 ha, Danki Forestry (Moscow Region, coniferous-broadleaved forests), total 6840 ha, and rent plot Grey Horse (Nizhny Novgorod Region, coniferous-broadleaved forests), total 8170 ha.

The main type of current forest use in Danki Forestry is stochastic recreation; timber is yielded only from sanitary cuts and thinnings; food resources are harvested irregularly by local residents and summer residents. In Karelia (Manga Catchment), logging is the dominant type of forest use; harvesting of food resources is important for local population; recreation is not developed despite a
relatively high natural potential. The Grey Horse rent plot is used for logging, recreation, harvesting of food resources, and farming.

Three basic scenarios were run for the model territories: (1) total non-interference in natural forest dynamics (natural development); (2) selective cuts of mature stands and thinnings with following natural reforestation (simplified pattern of forest management in protective forests), and (3) complete set of silvicultural activities: cross-cuts of mature stands, all stages of thinnings, and artificial reforestation with coniferous as target species (simplified pattern of intensive forest use).

In addition, the models allow to divide studied forestries into several zones by landscape characteristics or management regimes set in regulations, to set an individual regime of forest management for each zone, and to simulate separately the dynamics of stand characteristics and related indices of recreational potential and productivity of food resources.

3. Results and Discussion

3.1. Modeling results

3.1.1. Forest dynamics and use, natural development. The dynamics of indices of recreational potential and food resources yields on the three studied territories is represented on figure 2. To avoid scale disagreement and make the territories comparable, all parameters are represented in a relative scale in percent of their initial values at the zero step.

Here and below, the analysis begins from the second modeling step. This is related to the fact that the data of forest assessment often underestimate the abundance of undergrowth, which leads to illuminance overestimation, which is crucially important for berries yield calculations. The model becomes adjusted and reconstructs a real situation under the canopy by the fifth step.

In case of natural dynamics, the model outputs that the indices of recreational attractivity and resilience are of the medium level (ranging from 0.5 to 0.75) and vary insignificantly with time (figure 2). The only exception is the Danki Forestry (Moscow region) where the stands possess a high resilience to recreation.

The yields of food resources decrease markedly at the first modeling steps at all territories: as soon as all forest management activities are ceased, the subcanopy vegetation develops shadowing soil surface, which becomes critical for all berries and the majority of mushrooms. The second reason is the aforementioned model adjustment, that is, it may be of an artificial origin.

By the middle of the modelled period the yields of both berries and mushrooms increase. The difference in scales and time points of changes is due to the difference in species composition: raspberry, being the most light-demanding resource, plays and important part in Danki forestry, while less light-demanding blueberry is the basic resource of Manga Catchment.

![Figure 2](image-url) **Figure 2.** Dynamics of yields of non-wood resources and indices of recreational potential of the tree studied territories in case of natural forest development, in percent of the values at the zero step. At – recreational attractivity, Re – resilience to recreation, Mu – annual yield of mushrooms, Be – annual yield of berries.
3.1.2. Forest dynamics and use, selective cuts.

Forest use for logging was described in the model by timber harvest volumes, separately for the logging of mature stands and thinnings, by species groups (coniferous, hard-leaved and soft-leaved), and individual species. In this paper, generalised volumes are examined.

In the selective scenario with natural reforestation, big volumes of thinnings are modelled at the first steps in the sites where they should have been but have not been conducted. At the following steps, annual logging volumes become levelled (figure 3).

![Figure 3](https://example.com/fig3.png)

**Figure 3.** Dynamics of yields of non-wood resources and indices of recreational potential of the tree studied territories in case of selective cutting, in percent of the values at the zero step. CAn – annual timber yield, At – recreational attractivity, Re – resilience to recreation, Mu – annual yield of mushrooms, Be – annual yield of berries.

The curves look dentate depending on new stand areas shifted to the next age class and becoming ready for the next stage of thinnings. The model shows the peak of logged volume at the 14-15th step in Danki Forestry (figure 3a) and at the 10-12th step in other objects (figure 3b and 3c).

The indices of recreational potential demonstrate the dynamics, which is similar to the natural scenario, with the exception of the Manga Catchment (Karelia) where both indices decreased slightly (figure 3f).

The yields of mushrooms and berries become higher as compared to the natural scenario. The reaction of mushrooms and berries on the change in stand characteristics differs and generally repeats the natural trends: berries’ yields decrease with time in all cases; in Danki Forestry, this is preceded by a peak at the first modeling steps (figure 3d). The yields of mushrooms increase in Danki and decline in two other objects.

3.1.3. Forest dynamics and use, cross-cuts and plantations. In this scenario, the dynamics of annual timber harvesting is closely related to the readiness of newly created plantation for commercial thinnings and depletion of stock volumes of mature stands of some species (figure 4a-4c).
6

Figure 4. Dynamics of yields of non-wood resources and indices of recreational potential of the tree studied territories in case of intensive management (cross-cutting and plantations), in percent of the values at the zero step. CAn – annual timber yield, At – recreational attractivity, Re – resilience to recreation, Mu – annual yield of mushrooms, Be – annual yield of berries.

The model demonstrates a clear negative interrelation between the harvested timber volume (followed by artificial reforestation with coniferous species) and productivity of food resources and indices of recreational potential. Nevertheless, in Danki and Manga Catchment the yields are still higher than under natural development.

The dynamics of mushroom yields in Danki Forestry (figure 4d) is opposite to the natural one and demonstrates an increasing productivity at the first steps and a gradual decline afterwards. In two other objects, mushroom productivity is higher than under natural conditions but decreases with new cross-cut and artificially reforested areas.

3.2. Discussion

In the absence of silvicultural activities, the yields of food resources and recreational attractivity depend on a similar set of stand characteristics: both become higher in well-drained sites, with low-to-middle relative density and sparse subcanopy layers. Vice versa, the resilience to recreation increases in the sites with dense undergrowth and decreases at low relative density, which makes the two indices of recreational potential demonstrate an opposite dynamics.

Selective cuttings cause a minor effect on the indices of recreational potential. Annual volumes of timber harvesting demonstrate a positive correlation or no correlation with attractivity but a close negative correlation with the resilience index (R = -0.617 ... -0.943). At the same time, producing gaps in the canopy, they improve the conditions of growth and fruiting of food resources (a noticeable positive correlation or no correlation with annual berries’ yield).

Intensive forest management with the logging of all allowed volume of mature stands, all requested thinnings, and plantations of coniferous species leads to a marked increase in the areas of: coniferous stands, monodominant stands; both mono-layered and complex stands (with subcanopy and undergrowth). Initially small areas of hard-leaved stands recorded in the objects situated in the zone of coniferous-broadleaved forests almost disappear, which negatively affects both biodiversity level and recreational attractivity.
The cross-cuts themselves totally destroy forest environment resulting to the losses in food resources’ productivity for several decades. Total decline of blueberry- and bilberry-bearing sites is reported, their restoration taking more than 35 years [17]. An additional factor decreasing berries’ yields on the cross-cut areas with rich site conditions is the competition with herbs. On the other hand, the crosscuts are followed by coniferous plantations, which form a close canopy drastically reducing the illuminance of soil surface after 2-3 modeling steps.

The expansion of monodominant coniferous plantations, first of all, those of spruce (Picea abies (L.)Karst.) significantly reduces both recreational attractiveness and resilience of forests (the coefficients of correlation between the area of coniferous forests and attractivity range from -0.367 to -0.870 in different objects, and those between the area of coniferous forests and resilience, from -0.708 to -0.975). A clear negative interrelation between food resources’ yields and areas of coniferous species was found (the coefficients of correlation are -0.840 … -0.947 for berries and -0.695 … -0.895 for mushrooms).

Increased areas and stock volumes of coniferous stands coincide in the last scenario with the expanding harvesting of coniferous timber, first of all, from commercial thinnings. This scenario presupposes a significant income from coniferous timber, but the management proves to be narrowly specialised. All other types of forest resources, together with other forest functions, are put into the background, which hardly corresponds to the idea of multiple forest use.

The interrelation between recreation and harvesting of food resources might be ambiguous. On the one hand, the possibility to pick mushrooms and berries increases the recreational attractiveness and even can be treated as an increasing coefficient in the procedure of calculation. On the other hand, in densely populated regions (for example, Moscow Region), high forest attendance is the factor decreasing berries productivity, as blueberries and red bilberries are not tolerant to recreation. In remote areas (for example, in Karelia), harvesting food resources by recreants can produce a conflict with the interests of local population having an additional income from food resources.

4. Conclusion
Model application for the calculation of complex indices in dynamics revealed a systematic shortcoming of forest assessment data – the underestimation of the abundance of undergrowth and understorey, stock volume, and percent of accompanying species. This shortcoming requests an obligatory model adjustment at the first 2-3 steps, which makes the results of the first steps questionable. The model is optimal for the periods close to the logging rotation period (80-100 years) or maximal rent period (49 years).

The FORRUS-S model demonstrates that cross-cuts and recreation are hardly compatible in a long-term perspective, as the indices of recreational attractiveness and resilience decrease gradually as affected by an intensive logging. Therefore, when planning the multiple forest use, these activities should be attached to different territories. The FORRUS-S model has an option of calculation of stand dynamics by zones setting an individual management scenario for each zone.

The regime excluding any silvicultural activities is not optimal for the examined types of forest use, because the maintenance of berries’ productivity requests canopy thinning, while using forests for recreation implies the formation and maintenance of a certain landscape structure.

The scenario prescribing selective cuts seems to be optimal for multiple forest use as it allows to combine maximum types of forest use.

Being based on natural regularities of stand development, the model allows to involve additional types of forest use, in particular, game management. Ground quality for game species can be calculated form forest assessment data.

At the current stage of studies, we presented refined scenarios used to test model capacities and applicability. The nearest perspective is to run concrete scenarios of forest management, with forestry subdivision into large territorial units (zones) and diversified forest use patterns for each zone; to select optimal scenarios of forest management depending on the priorities of concrete forest plot holder or regional forest management policy.
Acknowledgements
The study was carried out as part of the FP7 ERA – Net Sumforest-POLYFORES project with the financial support of the Ministry of science and higher education of the Russian Federation (project unique identifier RFMEFI61618X0101).

References
[1] Manning P, Taylor G and Hanley M E 2015 Bioenergy, food production and biodiversity – an unlikely alliance? GCB Bioenergy 7 (4) 570
[2] Adamovskv A N 2013 Evolution of approaches to multiple forest use [Evolyutsiya podkhodov k mnogotselevomu lesopol’zovaniyu – in Russian] Forest Technical Bulletin 2 198
[3] Teben’kova D N, Lukina N V, Chumachenko S I, Danilova M A, Kuznetsova A I, Gornov A V, Shevchenko N E, Kataeva A D and Gagarin Yu N 2019 Multifunctionality and biodiversity of forest ecosystems [Mnogofunktional’nost’ i bioraznoobrazie lesnykh ekosistem – in Russian] Russian Journal of Forest Science 5 341
[4] Duncker P S, Raulund-Rasmussen K, Gundersen P, Katzensteiner K, De Jong J, Ravn H, Smith M, Eckmüllner O and Spiecker H 2012 How Forest Management affects Ecosystem Services, including Timber Production and Economic Return: Synergies and Trade-Offs Ecology and Society 17(4) 50.http://dx.doi.org/10.5751/ES-05066-170450
[5] Duncker P S, Barreiro S M, Hengeveld G M, Lind T, Mason W L, Ambroz S and Spiecker H 2012 Classification of Forest Management Approaches: A New Conceptual Framework and Its Applicability to European Forestry Ecology and Society 17(4) 51 DOI 10.5751/ES-05262-170451
[6] Dieler J, Uhl E, Biber P, Müller J, Rötzer T and Pretzsch H 2017 Effect of forest stand management on species composition, structural diversity, and productivity in the temperate zone of Europe European Journal of Forest Research 136 (4) 739
[7] Chumachenko S I 1998 The modeling of dynamic of all-aged multispecies forest coenosis Journal of General Biology [Zhurnal obshchei biologii – in Russian] 59 (4) 375
[8] Chumachenko SI, Korotkov V N, Palenova M M and Politov D V 2003 Simulation modeling of long-term stand dynamics at different scenarios of forest management for conifer-broad-leaved forests Ecol. Modeling 170 345
[9] Chumachenko S I and Smirnova O V 2009 Modeling of successional dynamics of stands [Modelirovanie suktsessionnoi dinamiki nasazhdenny – in Russian] Russian Journal of Forest Science 6 3
[10] Porte A and Bartelink H H 2002 Modeling mixed forest growth: are view of models for forest management Ecol. Modeling 150 141
[11] Botkin D B, Janak J F and Wallis J R 1972 Some ecological consequences of a computer model of forest growth J. Ecol. 60 (3) 849
[12] Shugart H H1984A Theory of Forest Dynamics: the Ecological Implications of Forest Succession Models (New York: Springer) p 278
[13] Bartelink H H 2000 A growth model for mixed forest stands For. Ecol. Manag. 134 (1–3) 29
[14] RysinS L 2003 Recreational potential of forest park landscapes and methods of its studies [Rekreationsnyi potencial lesoparkovykh landshtav i metody ego izucheniya – in Russian] Silvicultural information 1 17
[15] Russian forest resources inventory reference book (excluding timber) 2015 (Pushkino: VNIIILM) p 282
[16] Duliina A A and Chumachenko S I 2019 Review of models of food resources evaluation of the forests of Central Russia Forest Science Issues 2 (2) 1 DOI 10.31509/2658-607x-2019-2-2-1-16
[17] Kivelovich LE, Pankov VB and Kivileva IM 2015 The impact of forestry activities on the state and productivity of food and medicinal plants [Vliyanie lesokhozyaistvenoi deyatelnosti na...
sostoyanie I produktivnost' pishchevykh I lekarstvennykh rastenii – in Russian] Silvicultural information 2 24