

Long-term forecast of forest ecosystem services under different forest use scenarios

S Chumachenko¹, V Kiseleva^{1,*}, A Kolycheva^{1,2} and V Karminov^{1,2}

¹Department of Forest Assessment, Forest Management, and Geoinformational Systems, Mytishchi Branch, *Bauman Moscow State Technological University*, 1 Institutskaya Street, 141005, Mytishchi, Moscow Region, Russian Federation

²Laboratory of Structural and Functional Organization and Resilience of Forest Ecosystems, *Center for Forest Ecology and Productivity of the Russian Academy of Sciences*, 84/32 bldg. 14 Profsoyuznaya Street, 117997, Moscow, Russian Federation

*Email: vvkiseleva@bmstu.ru

Abstract. Sustainable forest management presupposes a long-term strategic planning of status and use of all forest resources and ecosystem services. The results of long-term scenario modelling can form the basis for decision-making. The paper contains the discussion of the results of scenario modelling run with the FORRUS-S imitational model for the period of 125 years and the rent forest plot with the area of 19,800 ha. Three scenarios of management activities differing in volumes of harvested timber, reforestation, and thinning were implemented. The effect of forest use scenarios on tree species composition, structural indices of forest ecosystems, volumes of food resources, and recreational potential was examined. The scenario envisaging a complete use of permissible harvesting volume and reforestation with no thinnings proved to be the most disastrous for aforementioned ecosystem services, including timber harvesting. The intensive forest use scenario envisaging artificial reforestation and complete cycle of thinnings causes the least negative effect on the volumes of food resources and even increases their diversity. Recreational ecosystem services degrade with increasing intensity of forest use. As a result, the forest user receives several scenarios; the choice of the optimal one for the user depends on the demand for concrete resources or ecosystem services.

1. Introduction

Sustainable forest management presupposes a long-term strategic planning. In a risk-resistant forest management, a harmonised evaluation of multiple market and non-market ecosystem services (ES) is indispensable. Various models can be regarded as the main methodical instrument of long-term planning of activities in the forest [1].

From the viewpoint of regional development, the evaluation and forecasting of ecosystem services is of a special importance. Expert estimations indicate that several Russian regions experience a total use or even deficiency of the most urgent life-supporting ecosystem services [2].

Modern technical tools make it possible to create complicated models in order to evaluate forest functions, their dynamics, relationships, and make long-term forecasts. Scenario modelling develops to support the choice of optimal management and territorial planning strategies [3-5]. Estimation and forecast instruments indicate that providing ecosystem services, which are of the primary interest for forest users and have a money value, are in conflict with other ecosystem services and characteristics of structural diversity of forest ecosystems [3,4]. Some data demonstrate that ignoring of non-market



ecosystem services (ES) can lead to a lost revenue, which might exceed the benefit from market ES [6].

Long-term scenario modelling is applied to generate the strategy and choice of optimal scenarios of forest management. Model experiments demonstrate that no scenario is able to maximise the provision of all ecosystem services [5]. Nevertheless, management strategies are aimed at the search of the most profitable compromise solutions [7]. In particular, the application of combined patterns of forest management is possible to alleviate the negative effects of increasing harvesting to biodiversity and non-wood ecosystem services [8]. A concept of transition from a unilateral timber-oriented forest management to a combined one, involving a stable usage of timber and non-wood forest resources, was suggested [9].

In this work, we present a long-term forecast of providing (timber and food resources) and cultural (recreation) ES as affected by different scenarios of logging and reforestation, via the effect on biological (structural) diversity. In the process of forest management optimization, the target function is the maximization of tenant's benefit. Ecosystem services, both market and non-market ones, form the system of limitations for the target function and are used for the control of acceptability of management scenarios. If a forest use scenario brings a substantial income but leads to a marked degradation of ecosystem services (including non-wood resources), this scenario must be rejected.

2. Materials and methods

2.1. Model description

FORRUS-S (FORest of RUSSia – Stands) is the complex of programmes for the simulation of forest massif dynamics in the boreal and subboreal zones. It is based on the imitation of natural regularities of forest dynamics and describes the processes of stand formation, growth, mortality, and reforestation. The model considers climatic and site characteristics by setting a matrix of potential site index classes for each species and site type. Within a concrete site, the illumination level at all storeys is a leading structure-forming factor.

Input data are those of forest survey, including forest maps.

In this way, the multi-species and multi-aged forest ecosystems are modelled with a 5-year step. The forecast period varies from decades to hundreds years; the areas considered vary from dozens hectares (model plots) to thousands square kilometres (forestries or administrative regions). The involvement of external blocks in the model makes it possible to analyse the influence of both climatic effects and forest management activities. To simulate the latter, different regimes can be set, creating the conditions for scenario modelling.

Two special blocks, 'Non-wood resources' and 'Recreation', were created to simulate ecosystem services.

The total yield of food resources (regionally most widespread species of berries and mushrooms) was calculated from National reference tables [10], which contain potential yields depending on site conditions, prevailing species of forest canopy, forest age, and relative density. In the model, the relative density was recalculated into the illuminance at soil level, which is a more adequate characteristic of real conditions of berries and mushrooms growth and fruiting [11].

Recreation forest services are evaluated via complex criteria: indices of recreational attractiveness and resilience and recreational carrying capacity.

The attractiveness reflects emotional effect on visitors; the resilience reflects the capacity of all ecosystem components to sustain recreational loads. Both indices are calculated from the data of forest survey via a system of ranks, which is traditional for Russian landscape survey [12]; however, the system of criteria was revised and developed substantially. The dynamics of recreational capacity of the territory was calculated as the sum of permissible recreational loads determined from forest survey data according to the departmental standard [13].

A more detailed description of model structure is listed in [14,15].

Model outputs are: the characteristic of wood resources (areas, stock volumes, site index classes, diameters, heights, sortiment structure, by species), including their monetary value; non-timber forest resources: physical volumes and economic estimations; characteristics of recreational potential; parameters of soil conditions, dynamics of site conditions.

The attachment of logistic functions of geoinformational systems (GIS) makes it possible to evaluate the transport accessibility of resources for both market harvesting and local population and economic feasibility of logging considering transportation expenses.

In addition, the model allows to make an internal zonation (for example, by harvesting intensity) and provide an individual forecast for each zone.

2.2. Modelling scenarios

Modelling scenarios differ in types and intensity of forest management activities. In particular, we examined: legal and economic restrictions of crosscuts and selective cuts, reforestation, and thinning volumes, including transport accessibility; areas and species composition of artificial reforestation; presence/absence of thinnings and selective cuts in general.

National thinning rules regulate the target forest composition, thinning intensity, periods and number of treatments. These regulated parameters depend on forest region, site index class, initial stand density and composition, and age class. Numeric parameters are gathered in tables; the tables are included in the block or reference information and are addressed by the model at each modelling step. In the region studied, non-commercial thinnings in young stands aimed at the formation of high-quality coniferous forests are recommended twice, at the age of <10 and <20 years, with the intensity of 20-50% depending on site index class and admixture of undesirable species. Following commercial cuts are undertaken at the age of more than 20 years as 2-3 treatments with the intensity of 20-40%.

In this study, we ran 4 basic scenarios, differing in the percent of exploitation of permissible harvesting volumes, reforestation volumes, and thinning types (table 1). These scenarios correspond to the existing (extensive) and expected (intensive) patterns of forest management. We accepted that only really economically accessible sites were logged. The natural development was taken as a reference scenario (S1).

Table 1. Forest management parameters set for the four simulated scenarios.

Management parameters	Scenario indices			
	S1	S2_60_0	S2_95_50	S3_th_95_50
Harvesting, % of total permissible volume	none	60	95	95
Reforestation, % of crosscut area	none	none	50	50
Non-commercial thinnings of young stands, treatments / intensity, % of stock volume	none	none	none	2 / 20-50
Commercial thinnings, treatments / intensity, % of stock volume	none	none	none	2 / 20-40

Three principal limitations are made in the forecast:

- (1) the forecasted dynamics excludes catastrophic events;
- (2) the permissible logging volume remains constant;
- (3) the species composition of cut timber is determined by current market demands: the most requested coniferous species are harvested first, followed by birch and, finally, aspen.

2.3. Site description

The model territory is located in the Leningrad district and is in a long lease for timber harvesting. Its total area is 25,900 ha, including 19,800 ha of forest-covered lands.

The leased plot includes the variety of site condition types and forest types. It encounters pine-predominated forests on coarse soils, alternated by oligotrophic peat bogs, spruce-predominated forests and secondary birch- and aspen-predominated forests. Large wetlands impede territory development but play an important part in water quality control, carbon retention, and food resources provision.

Exploitational forests constitute 48% of the whole plot. Another 52% are protective forests delimited according to national forest legislation and *ecological frame* delimited by the forest user in order to fit the FSC criteria. The frame includes mainly large wetland massifs and some areas of old-growth coniferous forests (key habitats).

Total diversity of food resources is represented by 6 species of berries: cowberry (*Vaccinium vitisidaea* L.), bilberry (*Vaccinium myrtillus* L.), raspberry (*Rubus idaeus* L.), cranberry (*Vaccinium oxycoccos* L.), blueberry (*Vaccinium uliginosum* L.), cloudberry (*Rubus chamaemorus* L.), and 7 species of mushrooms: cep (*Boletus edulis* Bull.), aspen mushroom (*Leccinum* sp.), butter mushroom (*Suillus luteus* (L.) Gray), milk mushroom (*Lactarius necator* (Bull.: Fr.) Pers.), coral milky cap (*Lactarius torminosus* (Schaeff.) Pers.), honey agaric (*Agaricus melleus* L.), and chanterelle (*Cantharellus cibarius* Fr.). In the following discussion, we examine the species with the highest and stable productivity, which can contribute to the income of local population.

The population and infrastructure are concentrated along two rivers; this fact limits seriously the transport accessibility of all resources and some ES.

3. Results and discussion

3.1. Timber harvesting

Timber harvesting is examined as both one of providing ecosystem services and driver of ecosystem service quality via the changes in stand composition and structure [16].

Under the extensive management pattern (the S2 scenarios), the model predicts the depletion of economically available stock volume of coniferous species (figure 1a). The larger the cut areas are, the sharper the depletion is (see the curve for the scenario S2_95_50). Approximately from the tenth modelling step, the deciduous species, birch first, then aspen, constitute the major part of harvested volume (figure 1b). Under the intensive management conditions (scenario S3_th_95_50), the harvesting of coniferous and deciduous timber is comparable in the beginning, with a following noticeable increase in the cut volume of coniferous in the last modelled decades due to reforestation and thinnings. Thinnings provide up to 15% of harvested volume of deciduous and less than 10% of coniferous.

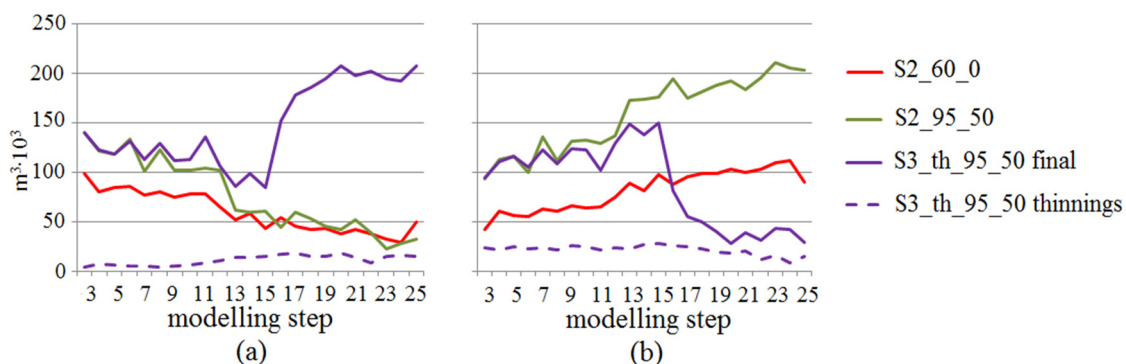


Figure 1. Dynamics of timber harvesting for coniferous (a) and deciduous (b) species from final felling (solid line) and thinnings (dashed line), $m^3 \cdot 10^3$. For scenario denotations, see table 1.

3.2. Harvesting effect on species composition

In case of natural dynamics (scenario S1), the model predicts the increase in the areas under spruce and, in a lesser extent, aspen, with a simultaneous reduction of pine and birch forest areas (figure 2a).

Under the extensive management, a constant decrease of coniferous areas coincides with reduces harvested volume of pine and spruce timber; since the 10th step, the same process is modelled for birch, with a simultaneous expansion of aspen (figures 2b and 2c). This trend is especially apparent in case of complete use of permissible volume (scenario S2_95_50) where the percentage of coniferous falls under 30% (figure 2c). The reforestation with no following thinnings appears to be useless for maintaining the areas of more valuable coniferous species.

If reforestation and thinnings are envisaged, the model demonstrates the stabilisation of coniferous at approximately 50% level and smaller participation of aspen as the latter is first removed in the process of thinnings (figure 2d).

It is evident that harvesting is of crucial importance for stand age structure and thus, areas of key habitats (in particular, old-growth forest) and scenic beauty value.

In case of natural development (scenario S1), the areas of old-aged spruce and pine forests increase during the first 70 and 50 years, respectively, followed by their dieback and replacement by other species.

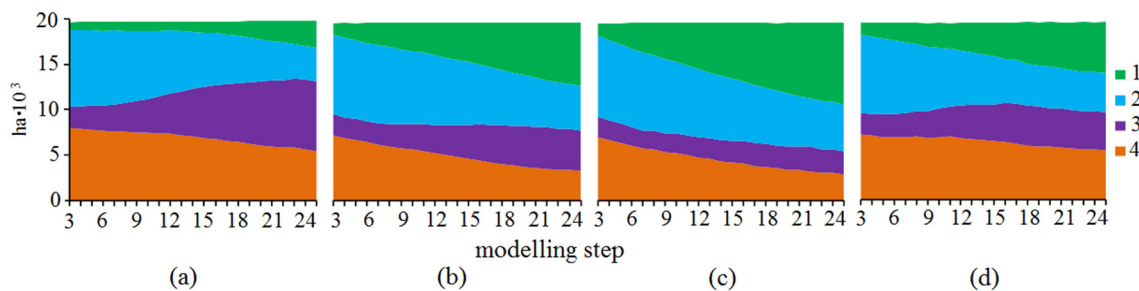


Figure 2. Forecasted dynamics of areas with the predomination of coniferous and deciduous species, $\text{ha} \cdot 10^3$. Modelling scenarios: (a) S1; (b) S2_60_0; (c) S2_95_50; (d) S3_th_95_50; (1) aspen, (2) birch, (3) spruce, and (4) pine.

In case of harvesting, the areas of old-aged coniferous forests decrease proportionally to the percent of use of permissible harvesting volumes. At the first modelling steps, the cut-off is balanced by the ageing of pre-mature forests. Later on, since the 10th-15th steps, the areas of old-aged coniferous begin to decrease markedly. Coniferous plantations are cut as soon as their reach the age of maturity (80-100 years) before their last generative stage. In exploitative forests, the old-aged coniferous are cut off completely.

3.3. Effect of forest use regime on stand structural indices

Gradual complication of stand structure is intrinsic to the natural dynamics. The modelling indicates the reduction of the percent of both monodominant (figure 3a) and single-storey stands (figure 3b). In case of intensive forest usage, the areas of stands with a primitive spatial structure and poor species diversity increase in accordance with harvesting intensity. This may be caused by the formation of single-species sapling stands on cross-cut plots. Regularly thinned forest plantations (scenario S3_th_95_50) evidently further increase the share of single-storey stands (figure 3b).

3.4. Effect of forest use regime on the yield of food resources

The changes in illuminance after final cuts, selective cuts, and thinnings influence markedly the yields of food resources. The reaction of different species can be opposite depending on their association with a certain forest type and light conditions [11].

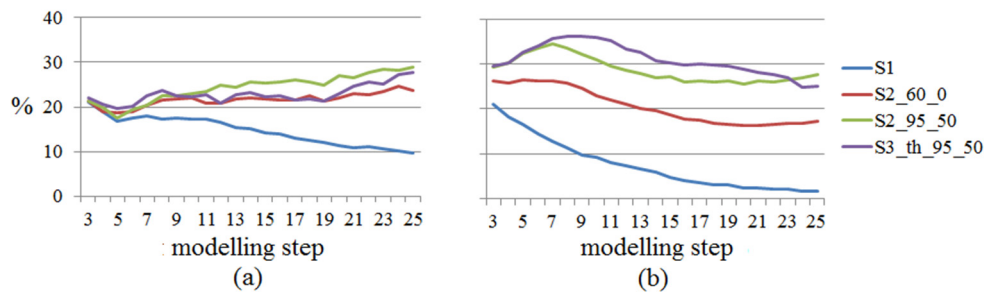


Figure 3. Forecast of the percentage of monodominant (a) and single-storey (b) stands under different scenarios of forest use, % of total forested area.

Total yield of berries decreases by 25-40% after crosscuts and the importance of species changes: as compared to natural dynamics (figure 4a), the yields of light-demanding raspberry appearing on crosscut plots become noticeable (figure 4, b and c). They are subjected to fluctuations depending on logged areas and rate of canopy expansion. The maintenance of coniferous through reforestation and regular improvement of light conditions after thinnings envisaged in the ‘intensive’ scenario support the yields of bilberries. In this scenario, the resources of berries are the most diverse (figure 4d).

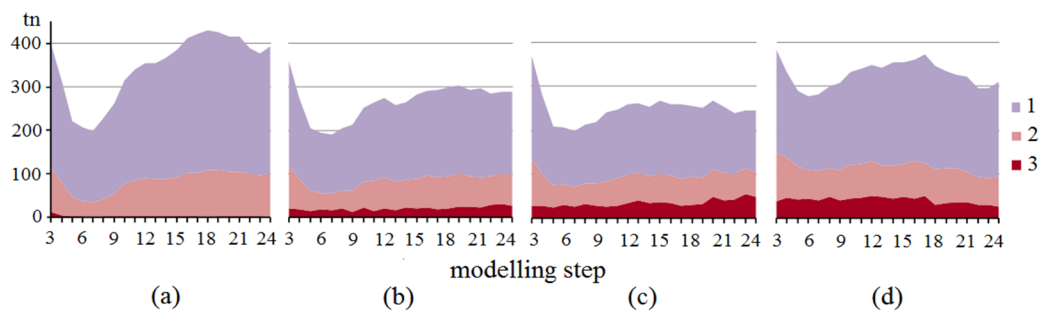


Figure 4. Forecast of berries yields under different scenarios of forest use, tons. Modelling scenarios: (a) S1; (b) S2_60_0; (c) S2_95_50; (d) S3_th_95_50; (1) bilberries (*Vaccinium myrtillus* L.), (2) cowberries (*Vaccinium vitis-idaea* L.), (3) raspberries (*Rubus idaeus* L.).

Total available yield of mushrooms is maximal in the natural scenario (figure 5a) and decreases markedly under forest management activities, especially in the extensive scenario S2_95_50 (figure 5c). In case of less intensive harvesting, the changes are less pronounced (figure 5b). Mushroom species composition proves to depend on the species composition of reforestation: a higher percentage of coniferous in the scenario S3_th_95_50 markedly increases the yields of the most valuable species: ceps (*Boletus edulis* Bull.) and butter mushrooms (*Suillus luteus* (L.) Gray) (figure 5d).

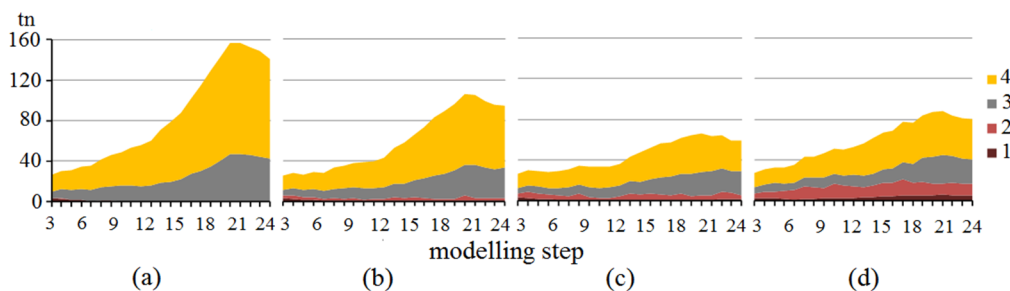


Figure 5. Forecast of mushroom yields under different scenarios of forest use, tons. Modelling scenarios: (a) S1; (b) S2_60_0; (c) S2_95_50; (d) S3_th_95_50; (1) *Boletus edulis* Bull., (2) *Suillus luteus* (L.) Gray, (3) *Lactarius necator* (Bull.: Fr.) Pers., (4) *Cantharellus cibarius* Fr.

3.5. Effect of forest use regime on the recreational potential

The indices of recreational potential depend on multiple single and structural characteristics varying with time both with and without silvicultural activities.

The index of attractiveness improves with stand age, illuminance under forest canopy, and complication of species composition and structure. An opposite trend emerges with the expansion of close-canopy monodominant young stands, single-species cultures with a simple vertical structure, and high density of lower layers. A low attractiveness is inherent to spruce forests because of unfavourable microclimate and light deficiency. Hence, the decrease of recreational attractiveness in the scenario S3_th_95_50 is quite expected (figure 6a). However, the effect is not very pronounced, the largest deviations from the natural dynamics do not exceed 10%.

The effect of forest management scenarios on stand resilience to recreation is more substantial. The index of resilience experiences a negative effect of logging of old-aged forests replaced by the young ones and formation of single-storey stands, which happen under all management scenarios (figure 6b). Minimal values under the intensive scenario are related to artificial maintenance of spruce stands as spruce with its surface root system is referred to as the least recreation-resistant tree species. In the process of simulation, the resilience index increases as affected by increasing age, development of subcanopy layers, and species shift from spruce to deciduous.

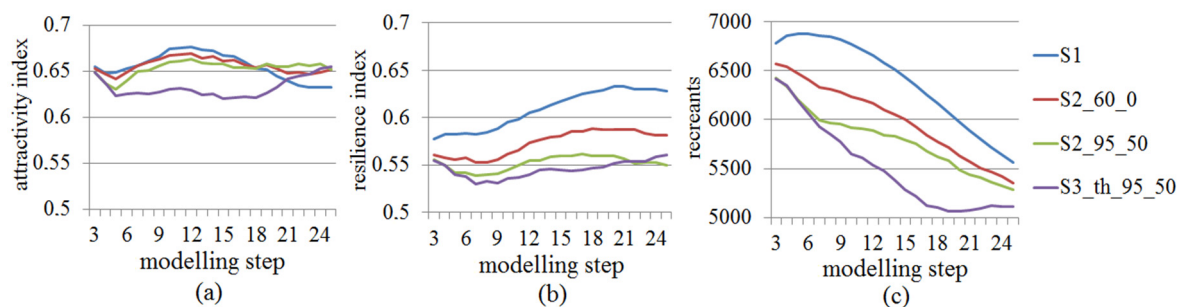


Figure 6. Forecasted dynamics of complex indices of recreational potential of rented plot under different scenarios of forest management: (a) recreational attractiveness; (b) resilience to recreation; (c) recreational carrying capacity.

The recreational carrying capacity calculated as the sum of critical loads of all sites decreases under all scenarios but due to different reasons. In unmanaged forests (S1), this is related to the replacement of more resistant pine and birch by less resistant spruce. In case of logging, the carrying capacity depends on the areas of young stands and their species composition. In intensively managed forests (S3), the recreational carrying capacity is minimal but remains steady reaching a kind of equilibrium with a silvicultural system (figure 6c).

4. Conclusion

The paper represents an attempt to pass from theoretical modelling to practical decision-making. Using the capacities of FORRUS-S imitation model, we made a forecast of dynamics of quantitative characteristics of timber yields, stand structural diversity, non-timber products, and recreational resources.

Logging led to shifts in a relative importance of tree species, simplification of composition and vertical structure, and extinction of old-aged climax forests. This affected directly forest ability to provide ecosystem services.

The calculations demonstrated an absolute irrelevance of artificial reforestation without following thinnings. This scenario caused the most pronounced negative consequences for all ecosystem services.

The intensive model of forest management proves to be efficient in a long perspective, as it allows the user to maintain a stable percentage of coniferous within the rent plot and markedly improve the

harvesting of coniferous timber in the second part of the modelling period. This scenario produces the least negative effect on the yields of non-timber resources and even increases their diversity. However, the quality of recreational ecosystem services becomes definitely reduced, first of all, due to the changes of parameters determining forest resilience to recreation.

The intensive scenario proves to be the most appropriate for a long-term maintenance of market (monetisable) ecosystem services. Considering the remoteness of the studied plot from urban areas and related low demand in recreation services, this scenario can be regarded as a basic one for the forest user. Economic aspects and spatial distribution of quality of ecosystem services should be examined separately.

Acknowledgments

The authors thank the IKEA Company for the financial support and provided actual data.

References

- [1] Shvidenko A, Schepaschenko D, Kraxner F and Onuchin A 2017 Transition to sustainable forest management in Russia: theoretical and methodological backgrounds. *Sib. J. For. Sci.* **6** 3 doi: org/10.15372/SJFS20170601 [In Russian]
- [2] Bukvareva E, Zamolodchikov D and Grünwald K 2019 National assessment of ecosystem services in Russia: methodology and main problems. *Sci. Total. Environ.* **655** 1181 doi: org/10.1016/j.scitotenv.2018.11.286
- [3] Pang X, Nordström E-M, Böttcher H, Trubins R and Mörtberg U 2017 Trade-offs and synergies among ecosystem services under different forest management scenarios – The LEcA tool. *Ecosyst. Serv.* **28** 67 doi: org/10.1016/j.ecoser.2017.10.006
- [4] Schwaiger F, Poschenrieder W, Biber P and Pretzsch H 2019 Ecosystem service trade-offs for adaptive forest management. *Ecosyst. Serv.* **39** 100993 doi: org/10.1016/j.ecoser.2019.100993
- [5] Morán-Ordóñez A, Ameztegui A, De Cáceres M, de-Miguel S, Lefèvre F, Brotons L, Coll L 2020 Future trade-offs and synergies among ecosystem services in Mediterranean forests under global change scenarios. *Ecosyst. Serv.* **45** 101174 doi: org/10.1016/j.ecoser.2020.101174
- [6] Niemi E 2020 Forests and Ecosystem Services *Encyclopedia of the World's Biomes* ed M I Goldstein, D A DellaSala (Amsterdam: Elsevier) volume 3 pp 160–167
- [7] Teben'kova D N, Lukina N V, Danilova M A, Kuznetsova A I, Gornov A V, Shevchenko N E, Kataev A D, Gagarin Y N and Chumachenko S I 2020 Multifunctionality and biodiversity of forest ecosystems. *Contemporary problems of ecology* **13**(7) 709 doi: org/10.1134/S1995425520070136
- [8] Eyvindson K, Repo A and Mönkkönen M 2018 Mitigating forest biodiversity and ecosystem service losses in the era of bio-based economy. *Forest Policy Econ.* **92** 119 doi: 10.1016/j.forpol.2018.04.009
- [9] Sheppard J P, Chamberlain J, Agundez D, Bhattacharya P, Chirwa P W, Gontcharov A, Sagona W G, Shen H, Tadesse W and Mutke S 2020 Sustainable forest management beyond the timber-oriented status quo: transitioning to co-production of timber and non-wood forest products – a global perspective. *Current Forestry Reports* **6** 26 doi: org/10.1007/s40725-019-00107-1
- [10] *Russian Forest Resources Inventory Reference Book (Excluding Timber)* 2015 (Pushkino: VNIILM) p 282
- [11] Dulina 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: org/10.31509/2658-607x-2019-2-2-1-16 [In Russian]
- [12] Rysin S L 2003 Recreational potential of forest park landscapes and methods of its studies. *Sylvicultural Information* **1** 17 [In Russian]

- [13] *Provisional Methods of Calculation of Recreational Loads on Natural Complexes for The Organisation of Tourism, Guided Tours and Mass Everyday Recreation and Provisional Standards of These Loads* 1987 (Moscow: State Committee of Forestry) p 33
- [14] Chumachenko S I, 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. Model.* **170**(2) 345 doi: org/10.1016/S0304-3800(03)00238-2
- [15] Chumachenko S I, Kiseleva V V, Kolycheva A A and Mitrofanov E M 2020 Modeling of multiple forest use under different management scenario. *IOP Conf. Ser.: Earth Environ. Sci.* **574** 012011 doi: org/10.1088/1755-1315/574/1/012011
- [16] Huuskonen S et al. 2021 What is the potential for replacing monocultures with mixed-species stands to enhance ecosystem services in boreal forests in Fennoscandia? *Forest Ecol. Manag.* **479** 118558 doi: org/10.1016/j.foreco.2020.118558

Reproduced with permission of copyright owner. Further reproduction prohibited without permission.