Forest Science and Technology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tfst20

Improving the efficiency of forest companies by optimizing the key indicators of sustainable forest management: a case study of the Far East

Pavel Ryabukhin, Ol'ga Kunickaya, Albert Burgonutdinov, Valentin Makuev, Tatiana Sivtseva, Natalia Zadrauskaite, Edward Hertz & Oleg Markov

To cite this article: Pavel Ryabukhin, Ol'ga Kunickaya, Albert Burgonutdinov, Valentin Makuev, Tatiana Sivtseva, Natalia Zadrauskaite, Edward Hertz & Oleg Markov (2022): Improving the efficiency of forest companies by optimizing the key indicators of sustainable forest management: a case study of the Far East, Forest Science and Technology, DOI: 10.1080/21580103.2022.2128900

To link to this article: https://doi.org/10.1080/21580103.2022.2128900

Published online: 19 Oct 2022.

FOREST SCIENCE AND TECHNOLOGY
https://doi.org/10.1080/21580103.2022.2128900

ARTICLE

OPEN ACCESS

Check for updates

Improving the efficiency of forest companies by optimizing the key indicators of sustainable forest management: a case study of the Far East

Pavel Ryabukhin[a], Ol'ga Kunickaya[b], Albert Burgonutdinov[c], Valentin Makuev[d], Tatiana Sivtseva[e], Natalia Zadrauskaite[f], Edward Hertz[g] and Oleg Markov[h]

[a]Department of Technologies of Forestry and Landscape Construction, Pacific National University, Khabarovsk, Russian Federation; [b]Department of Technology and Equipment of Forest Complex, Arctic State Agrotechnological University, Yakutsk, Russian Federation; [c]Department of Roads and Bridges Building, Perm National Research Polytechnic University, Perm, Russian Federation; [d]Department of Technological and Equipment LT 7, Moscow State Technical University N. E. Bauman (Mytishchi Branch), Mytishchi, Russian Federation; [e]Department of Operation of Motor Transport and Auto Repair, North-Eastern Federal University named after M.K. Ammosov, Yakutsk, Russian Federation; [f]Department of Timber Industry and Materials Processing, Northern Arctic Federal University, Arkhangelsk, Russian Federation; [g]Department of Technologies and Equipment of Timber Industry, Ural State Forest Engineering University, Yekaterinburg, Russian Federation; [h]Department of Transport and Production Machines and Equipment, Petrozavodsk State University, Petrozavodsk, Russian Federation

ABSTRACT

Forest plantations provide a wide range of products. Therefore, it is vital to ensure the sustainable growth and adequate management of forest resources. This study aims to examine the current challenges facing the forest industry, such as the depletion of forest resources, the increasing cost of wood processing products, and intensifying competition in the timber market (caused by the tropical wood supply). These challenges force the world's leading forest countries to intensify forest cultivation, to consult forest industries in the Far East and to optimize the sustainable use of forest resources. It was found that current distribution of cutting practices threatens the forest ecosystem. The study suggests a scheme where 10–30% of forest area is clear-cut, 70–90% is selectively logged, and 20–35% is exposed to gradual felling. Factors, such as harvesting time, exhaust emissions, the loss of young trees, topsoil degradation, load on the soil surface, and the slope angle are essential for building mathematical models of forest sustainability. The intensity of wood transportation is also a critical factor influencing the above indicators. The study proposes a model for reorganizing regional wood harvesting companies to improve their profitability. The theoretical model is adapted to the Far Eastern context, but is suitable for use in other parts of the world.

ARTICLE HISTORY
Received 15 June 2022
Accepted 21 September 2022

KEYWORDS
Forest management; logging; mathematical modeling; wood processing

Introduction

Over the years, forest plantations were seen as a source of unlimited resources. Forests indeed provide valuable products for free. Today, however, people began to understand the true significance of the forest biotope. The continuous increase in mass timber consumption which followed the intensive timber production in the 19th century creates the need for better forest management (Angelstam et al. 2016). That would require a rational approach to resource exploitation, a technology to boost accuracy, and modern regulations (Salimova et al. 2018). The concept of sustainable forestry is not new and emerged more than 300 years ago, but it was not widely accepted until recently. As this practice became more widespread, several criteria for sustainable forest management have been developed to ensure regulation at a national or supranational level. Those include, but are not limited to, socio-economic benefits, policies and legal-institutional frameworks, conservation, forest biodiversity, biomass productivity, tree health and vitality, contribution to global carbon cycle, and the extent of logging (Linser et al. 2018). Based on these criteria, certification systems have been designed that ensure compliance with ethical standards (Ezquerro et al. 2019).

During the last century, the boreal forests growing in the northwestern part of Russia were exposed to extensive logging, which continues to this day without the principle of sustainability being adopted. Some progress has been made in recent years though, as the Russian forestry began to incorporate sustainable forest management into the long-term timber production process (Angelstam et al. 2016).

This study is concerned with the intensive reduction of commercial forest plantations, particularly in the Far East. The said problem can only be addressed by enhancing the efficiency of forest management through implementing modern technologies.

CONTACT Pavel Ryabukhin paryabukhin@rambler.ru Department of Technologies of Forestry and Landscape Construction, Pacific National University, Khabarovsk, Russian Federation

Another major issue is the reducing diversity of forest species exposed to destructive anthropogenic influences. To counter this problem, forest companies have to adopt scientific approaches to the organization of processes and machinery exploitation while also considering the regional social and economic aspects. Since the Far Eastern forests have high forest species diversity, they require increased attention and additional efforts to minimize the harmful effects of timber production (Grigoriev et al. 2016; Rudov et al. 2021).

At the current stage of timber production and forestry development, companies generally utilize the latest state-of-the-art forest machinery, but the biological characteristics of the felling sites are mostly ignored (Abuzov and Grigorev 2020; Tambi and Grigoriev 2020). Therefore, it is necessary to identify indicators for forest vehicle selection and optimal operating parameters based on environmental conditions. With this information, companies will be able to enhance forest management efficiency from economic, social, and ecological perspectives (Voronov et al. 2019; Dobretsov et al. 2021; Grigoriev et al. 2021).

This study aims to examine the current challenges related to sustainable forest management in the Far East and to identify optimization potential. The objectives of the study are (1) to determine which of the current modes of felling (clear-cutting, selective cutting, and gradual felling) used in the Far Eastern Federal District (FEFD) is the most optimal; (2) to construct a mathematical model of the logging process and empirically verify its feasibility; (3) to evaluate the profitability of the wood harvesting business and to find avenues for improvement.

Research on forest processes in eastern Russia provides evidence for higher efficiency in regions where machines completely replaced humans due to harsh working conditions. The mechanization initiative, however, created the need for the alternative methods of forest management (Naumov et al. 2016). The variability of forest species and growing sites constitutes another factor that necessitates the development of novel logging practices and other forestry operations (Tambi et al. 2021).

Heavy logging and ineffective utilization of machinery can accelerate soil erosion, cause the root system to degrade, and result in landslides or avalanches happening (Horton et al. 2017; Flores et al. 2020). It is possible to resolve these issues through the effective use of automation and by optimizing the timber harvesting process with modern computer-aided methods for management, regulation, control, and accounting. When creating an effective automation system, the main goal is to construct mathematical process models, algorithms, and methods for optimal design and management of the timber processing process. The automation will help intensify timber production and improve economic efficiency.

It will require experimental procedures to modify timber-processing technologies and transportation methods. The adequate modeling and simulation can potentially help to reduce damage to the forest ecosystem (Grigoriev et al. 2021; Markov et al. 2021).

The cumulative cost models of forest machinery and processes include the total annual expenses and the average cumulative cost of the equipment calculated using the life cycle cost analysis (LCCA) approach. These costs are described in detail by Khitrov et al. (2015).

About 80% of all forest resources in Russia come from three regions: Khabarovsk Krai, Primorsky Krai, and the Amur Region. Other areas have much weaker productive functions. The Republic of Sakha and the Sakhalin Region, for example, represent 5% of the stock each. Sakha is mostly home to deciduous trees, which make more than 85% of species composition. Since only a quarter of these resources are used, this Republic is of interest. In the Kamchatka Krai, where the dominant forest species are also deciduous trees, the forest industry is relatively well developed. In the Magadan Region and the Chukotka Autonomous Okrug, the extent of logging activities is the lowest.

Over the past 40 years, the amount of forest resources has been slowly declining. The forest area has reduced by almost 11 million hectares or more than 2% of the total area. Harvested wood represents only 15.6% of the total annual yield, whereas leased sites provide 62.5%. Yet, Far Eastern companies have recently engaged in intensive logging of coniferous timber with partial treatment for export (Grigoriev 2020; Tambi et al. 2020).

In the forest industry, a promising technological process design would require consideration of the specifics of forest exploitation, as well as forestry and socio-ecological requirements. Otherwise, it will not be possible to create an effective structural scheme of forest usage and preserve the ecosystem functions in the region. An effective implementation of forestry-based logging technologies largely depends on the correct choices of a logging machine system and a technological scheme. That is why it is important to perform a comprehensive ecological assessment of the technological schemes and methods of logging applied with the modern logging equipment. The analysis in point can help identify the most effective solutions that will fit the natural production conditions of the forest enterprises. The resulting model presented as an array of mathematical formulas with due account for environmental, production, and regulatory factors will enable the ranking of the existing technological processes and logging systems under environmental, economic, and social criteria.

Materials and methods

Sampling and data collection procedures

Data used to assess the current state of forest stands and their development were taken from the State Report on Forest Usage (Order No. 451 of the Ministry of Natural Resources and Ecology of the Russian Federation dated 08.21.2017). To determine

Figure 1. Approximate map of study area.

Table 1. Static and dynamic indicators charactering the impact of logging systems on the forest ecosystem.

Criteria	Extent of damage to surrounding trees
	Extent of logging (the amount of trees cut down) and blockage (the amount of trees lying on the forest ground)
	Extent of damage to the undergrowth
	Extent of soil damage
	The amount of gas emissions

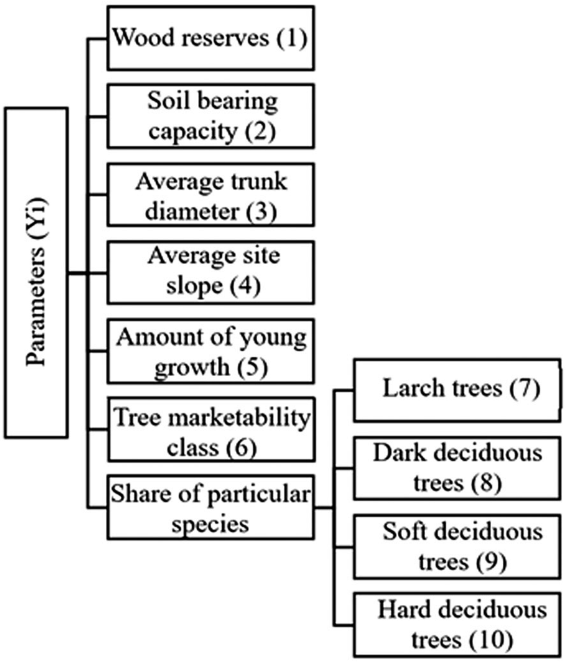

Figure 2. Indicators characterizing the forest stand.

the impact of forest operations on the forest ecosystem, 45 experimental plots were planted in larch and spruce plantations across FEFD forest lands with a total area of 0.496 billion hectares and a total timber stock of approximately 20.2 billion m.[3] A link to a georeferenced map: https://bit.ly/3QMZLWj (Figure 1).

The approximate volume of the total timber stock (M) was determined through calculation. The formula is:

$$M = G \cdot H \cdot F \tag{1}$$

where G is the sum of the cross-sectional areas of forest trees at a height of 1.3 m, $m^2 \cdot ha^{-1}$; H is the average forest tree stand height, m; and F is the average number of tree trunk species.Static and dynamic variables were evaluated based on the criteria presented in Table 1.

Indicators characterizing the forest stand are depicted in Figure 2. These indicators enable a systematic assessment of conditions upon which the exploitation process takes place.

Modeling of characteristics

The pattern recognition theory simplifies the identification of distribution patterns among forest stand exploitation conditions across different plots. Pattern recognition is the process of recognizing patterns on data sets using specific algorithms. In most cases, pattern recognition algorithms are applied to multi-zone or multi-layer raster images of the Earth's surface.

Hypothetically, all of the above factors (Y_{ij}) that influence the forest stand exploitation process can be in place. Therefore, the study came up with the following taxonomic classification algorithm for determining the minimum possible area (S) of the crossing section (an extensional description of taxonomy consists of selecting special subsets (taxa) and determining the set-relations, such as inclusion, empty and non-empty intersection):

$$\begin{gathered} S(\upsilon_{ij}, Y_{im}) \forall i, j \in 1, 2, 3, \ldots n; m \in 1, 2, 3, \ldots, r; \\ \sum_{j=1}^{n} \upsilon_{ij}\upsilon_{kj} - \sum_{j=1}^{n} \upsilon_{ji}\upsilon_{jk} = 0; \;\; 0.0 \le \upsilon_{ij} \le 1.0, \end{gathered} \tag{2}$$

where r is the number of felling sites; n is the number of influencing factors; Y_{im} is the value of the factor i at the felling site m; υ_{ij} are components of the direction cosine matrix.

Each point, or test plot, generates a random sample of characteristics, or factors influencing the forest stand exploitation process. Therefore, it is necessary to consider a differential sorting probability law to link a felling site with a particular taxonomic unit, which is mapped as a polymodal normal distribution. The formula is:

$$\begin{gathered} \phi(Y_j) = \sum_{i=1}^{n} \left\{ \left(\frac{1.0}{2\pi\delta_{5i}^2\delta_{9i}^2} \right) \left(\exp\left(- \left[\frac{\left(F_5 - \sum_{j=1}^{k} a_i \overline{y_{ji}} \right)^2}{2\delta_{5i}^2} + \frac{\left(F_9 - \sum_{j=1}^{k} b_i \overline{y_{ji}} \right)^2}{2\delta_{9i}^2} \right] \right) \right) \right\} \forall \\ F_5 = \sum_{j=1}^{k} a_j \overline{y_j}; \;\; F_9 = \sum_{j=1}^{k} b_j \overline{y_j}, \end{gathered} \tag{3}$$

where k is the number of variables, n is the number of modes; F_i is convolutions of variables in linear form; y_{ji}, $\overline{y_{ij}}$, and δ_{ij}^2 are distribution law parameters; a_j and b_j are the extent of each factor's contribution.

Felling site topography modeling

The following indicators were introduced for simplification:

$$B = H(X) + \xi(X) \tag{4}$$

where B is the felling site topography profile; $H(X)$ is the macro profile; and $\xi(X)$ is the micro profile.

A priori preliminary conclusions about the stationarity of the relationship between micro-profile characteristics and the slope angle of the macro profile can be made after the analysis. The felling site macro profiles for the FEFD with a slope range of 8–30° were examined using a tachograph survey. The primary mathematical model for estimating micro profiles was developed using information about the Earth's surface topography. The optimal way to obtain an accurate description of the felling site micro profile is to consider it as a random static process.

A study of the micro profile involves analyzing the spectral density of its change (ξ_i) using statistical data processing software. The results indicated stationarity. The absence of changes allows modeling the expected variability of $K(\tau)$ and $S(\omega)$ using asymptotically periodic and fractional-periodic functions, respectively. The formulas are:

$$K(\tau) = \sigma_\xi^2 e^{-a|\tau|}\left(\cos\beta\tau + \frac{\alpha}{\beta}\sin\beta\middle|\tau\right| \tag{5}$$

and

$$S(\omega) = \frac{\sigma_\xi^2 2\alpha\left(\alpha^2+\beta^2\right)}{\left(\pi\left(\left(\omega^2-\beta^2-\alpha^2\right)^2+4\alpha^2\omega^2\right)\right)} \tag{6}$$

where σ_ξ^2 is the micro profile variance; α, β are coefficients; and τ, ω represent the lag and the frequency.

Modeling the effects of machinery on the Forest ecosystem

To assess the impact of the logging machine and equipment on the forest ecosystem, a description of the route network was used. The existing schemes were evaluated using the following indicators:

$$K_i = \frac{S_s}{S_{\text{tot}}} \tag{7}$$

$$K_p = \frac{S_i}{S_d} \tag{8}$$

$$K_f = \frac{c}{d} \tag{9}$$

$$K_z = \varphi(K_i, K_p, K_f) \tag{10}$$

where K_i is the tree cutting intensity; K_p is the area blocked by trees that were cut down and tied together in bundles; K_f is the effect of the geometric plantation mapping; K_z is the number of possible sampling locations; S_{tot} is a total felling area; S_s is a total area of harvest plots; S_d is the area of the single site i; c and d are the site mapping criteria.

By using the above indicators, the following parameters can be determined, which characterize the efficacy of the above schemes:

$$Az = \sum_{j=1}^{n}\left(\sum_{i-1}^{m_j} L_i \frac{1}{m_j}\sum_{l-j}^{n} z_l K_i\right) \tag{11}$$

$$L_E = \sum_{j=1}^{n}\left(\sum_{i=1}^{m_j} L_i\right)K_i \tag{12}$$

and the average length ($\overline{L}_{mp}$) of the skid road:

$$\overline{L}_{mp} = \frac{\left(\sum_{j-1}^{n}\frac{1}{m}\sum_{i=j}^{n} K_i z_l \sum_{i=1}^{m_j} L_i\right)}{\left(\sum_{j=1}^{n}\sum_{i=1}^{m_j} L_i\right)} \tag{13}$$

where Az is the skidding distance for a single plot z; L_E is a total length of the skid road; Z_j is a separate area j; j = from 1 to n; L_i is the length of the plot i within the area j; i = from *1* to m_j.

In addition, experiments were held to investigate the effect of using forestry machinery on the preservation of undergrowth. The probability of machine contact with undergrowth when operating a feller-buncher was estimated using the following equation:

$$\sum P = \frac{(S_r + S_x + S_n)}{(0.25\cdot\pi\cdot R - h)\cdot R} = \left. \left[\begin{array}{c} \left[(1/4\cdot\pi\cdot R^2 - R\cdot h)^{-1}\cdot \left\{ \begin{array}{c} \frac{1}{3}\cdot\left(R^3 - \frac{h^3}{8}\right)\cdot(\alpha_B - \alpha_0) - \frac{1}{2}\cdot(R^2 - h^2)\cdot h\cdot \\ \cdot\ln tg\left[{}^{(\pi/4+\alpha_B/2)}\middle/{}_{tg(\pi/4+\alpha_0/2)}\right] \end{array} \right\} \cdot b\cdot\lambda\cdot R \right] + \\ \left[\left((1/4\cdot\pi\cdot R^2 - R\cdot h)^{-1}\cdot \left\{ \begin{array}{c} (\alpha_B - \alpha_0)\cdot\lambda^{-3}\cdot\left[\begin{array}{c} (\lambda^3\cdot h^3 + 3\cdot\lambda^2\cdot h^2 + 6\cdot\lambda\cdot h + 6)\cdot\exp(-\lambda\cdot h) - \\ -(\lambda^3\cdot R^3 + 3\cdot\lambda^2\cdot R^2 + 6\cdot\lambda\cdot R + 6)\cdot\exp(-\lambda\cdot R) \end{array} \right] + \\ +h\cdot\lambda^{-2}\cdot\left[\begin{array}{c} (\lambda^2\cdot h^2 + 2\cdot\lambda\cdot h + 2)\cdot\exp(-\lambda\cdot h) - \\ -\left(\lambda^2\cdot h^2 + 2\cdot\lambda\cdot h + 2\right)\cdot\exp(-\lambda\cdot R) \end{array} \right] \end{array} \right\} \right) \cdot b\cdot N \right] + \\ \left[\pi R^2 - \frac{\pi R^2\cdot\alpha}{180^\circ} - (R - 0.5h)\cdot\sqrt{R^2 - (R - 0.5h)^2}\cdot 0.25\cdot N\cdot\xi_1\cdot\xi_2\cdot H_{cr}\cdot D_{cr}\beta \right] \end{array} \right] \middle/ {}_{(0.25\cdot\pi\cdot R - h)\cdot R} \right. \tag{14}$$

where $S_f(f = r, x, n)$ is the plantation area where tree damages were recorded; $\lambda = b \cdot N$, where b is the width of the craw-like felling device that faces N trees; M is the crown projection area on the plane in the vertical position: $M = \xi_1 \cdot \xi_2 \cdot H_{cr} \cdot D_{cr}$, where ξ_1 is the index of the geometric crown shape mapping, ξ_2 is the branch density factor in the crown; H_{cr} is the crown height, D_{cr} is the median crown diameter; R is the maximum reach of the boom; h is the skid trail width; β is the coefficient of area blockage (< 1); a_b is the center angle of the area where the feller-buncher operates, degrees.

Forestry equipment can cause significantly damage to the undergrowth, and the above method helps to effectively model that impact as a crucial aspect of undergrowth conservation. The ability to preserve the undergrowth and thin-sized trees in the felling area is among the main criteria for evaluating logging technologies (Kazakov and Ryabukhin 2017).

The technological process modeling has to include multiple factors, including, but not limited to, the harvesting time, air pollution, energy intensity, timber quality loss, and topsoil degradation. In addition, the evaluation process should be comprehensive in order to reach high accuracy.

The accuracy of the proposed model was verified experimentally by performing logging operations at various locations across the FEFD district. The analysis was based on the following two criteria: the portion of trees with no damage and the extent of soil preservation.

Besides causing changes to bioresources and soil, forest machinery release a considerable amount of exhaust emissions, particularly CO_2, while operating. The gross emission of pollutants (gases) B_i was calculated seasonally. The formula is:

$$B_i = \sum_{k=1}^{k} \left(M_{idik} \cdot t'_{mv} + 1.3 M_{idik} \cdot t'_{\text{load}} + M_{mvik} \cdot t'_{id} \right) \cdot D_f \cdot 10^{-6} \tag{15}$$

where M_{idik} is specific gas emission at idling; M_{idik} is specific gas emission under load; t'_{mv}, t'_{load}, and t'_{id} represent the movement time under no load, under load, and at idling, respectively; k is the number of forest machine types used; D_f is the number of operating days.

Damage to the ground-level atmosphere was calculated using the following formula:

$$Y_j^a = \gamma_j^a \cdot L_j^a \cdot O_j \tag{16}$$

where γ_j^a is the specific damage from atmospheric air pollution; L_j^a is the hazard constant; O_j is the atmospheric pollution hazard.

The energy intensity of logging machines and equipment was determined as follows:

$$W - \frac{N * K_N * K_t}{C_h} \tag{17}$$

where N is the rated power value of the engine; K_N is the engine load factor; K_t is the efficiency factor; C_h is the machine capacity per hour.

The above formula allowed obtaining values of specific energy intensity (SEI) for all operations. The technological parameters of logging machines were assessed with respect to cycle time:

$$T_O = T_P + T_{id} + T_{\text{tree}} + T_l \tag{18}$$

where T_O represents operating time of the machine at the experimental plot; T_{id} is the idle time, sec; T_{tree} is the time for processing all trees at the same plot; T_l is the driving time between the felling site and the parking lot.

The average boom path received closer attention. The formula is:

$$L_{pt}^{cc} = \frac{\Delta I_B \cdot L_{pt.cc} R_{cc} + I_B \cdot L_{pt.sl} \cdot F_{sl}}{\Delta I_B \cdot F_{cc} + I_B \cdot F_{sl}} \tag{19}$$

where ΔI_B is excessive logging intensity; $L_{pt.cc}$ and $L_{pt.sl}$ represent the average boom path during clear-cutting and selective cutting, respectively, m.

$$L_{pt} = \sqrt{(x_c - R \cdot \xi + r)^2 + {y_c}^2} - r,$$

where x_c and y_c are coordinates of the centers of gravity at the felling site, m;$\cdot F_{cc}$ and F_{sl} represent the total area of clear-cut and selectively logged plots, respectively, m^2.

Timber use modeling

The model developed in this study considers all woodworking processes, including the application and sale of low-quality wood (LQW). Therefore, the framework for comparative process analysis has an economic component and allows identifying the economic feasibility of using LQW resources.

The final profit can be calculated as:

$$P_p = (\alpha \times \gamma \times V_{tot} \times P_e) + (\beta \times \gamma \times P_v) + (\delta \times V_{tot} \times V_n) + (\Theta \times V_{tot} \times P_{res}) - 3 \tag{20}$$

where α, β, γ, δ, and Θ are the coefficients of the wood share for export, for sales domestically, unmarketable wood, firewood, and residuals from commercial wood, respectively; V_{tot} is the total amount of wood; P_{res} is the sales price of residuals.

Model of j process efficiency is as follows:

$$P_C = \sum SP - \sum PC \rightarrow \max \tag{21}$$

where R_v, SP, and PC stand for revenue, sales profit, and production costs, respectively;

$$\sum PC = \sum_{s=1}^{s} \sum_{f=0}^{f} V_{\text{s, f}}^{t_{FB}} \times P_{s,f} \tag{22}$$

s, f is the number of round wood products, low-grade wood, and trunk residues, $V_{\text{s, f}}^{t_{FB}}$, $P_{s,f}$ – the sales volume and price of products in stock, respectively, over some time, t.

$$\sum 3 = \sum\nolimits_{i=1}^{3} \sum\nolimits_{j=1}^{3} \sum\nolimits_{k=1}^{k} \sum\nolimits_{s=1}^{s} \sum\nolimits_{f=1}^{\text{f}} C_{ij} \times V_{ijksf} \Rightarrow \min \tag{23}$$

where C_{ij} is the production cost of the jth operation at the ith stage; V_{ijksf} is the volume of the sth and fth products that underwent every ith stage of the jth operation using the kth forest machine or equipment; i is the production stage, $i = 1–3$; j are types of operations, $j = 1–5$.

The predominantly brown soils of the taiga mountain are relatively stable, but vulnerable to logging. The results may be interpreted as follows:

$$M_n = 0.839t_1 + 0.772t_2 + 0.0048t_3t_4 \quad (24)$$

where t_1 is the type of transported items, t_2 is the logging mode, t_3 is the intensity of logging by stock, and t_4 is the forest machinery used.

Natural studies can also be interpreted as:

$$D = -0.132 + 0.241q_0(1.031 + 0.082K + 0.043t_4) \quad (25)$$

where q_0 is the forest reserve per hectare, K is the plantation marketability class.

The effect of logging operations is evaluated by Equations (14), (15), (24), and (25).

The search for optimal technological schemes and logging systems can be represented as a minimization of the vector criterion (I):

$$\mathsf{H} = \varphi(W, T, D, M, P, B) \quad (26)$$

where W, T, D, M, P, B are objective functionals of specific criteria (quality indicators).

Finding the most appropriate set of MLS and determining their effectiveness is limited to non-linear vector programming. The criteria analysis revealed contradictions, which led to different results after optimization. Therefore, the vector optimization criterion was integrated, which bases on the first six criteria characterizing the sustainable forest management:

$$\mathsf{H}(X_M, X_R, Y) = [W_E, T_E, P_E, D_E, M_E, B_E] \quad (27)$$

Given that there are many effective points, the above criterion suggests that if one of the indicators improves, it will inevitably cause at least one of the remaining indicators to worsen. For the value of Pareto extremum, a non-linear optimization was performed according to the following criteria:

$$\mathsf{H}(X_M, X_R, Y) = \sum_{\mathrm{i}=1}^{\mathrm{s}} n_{\mathrm{i}}[\hat{L}]\forall n_{\mathrm{i}} \geq 0.0; \sum_{\mathrm{i}=1}^{\mathrm{s}} n_{\mathrm{i}} = 1.0 \quad (28)$$

Consequently, a scalar target function was developed:

$$\mathsf{H}(X_M, X_R, Y) = F\{W_E, T_E, P_E, D_E, M_E, B_E\} \quad (29)$$

The generalized function is:

where $W_\Sigma *, T_\Sigma *, P_\Sigma *, D_\Sigma *, M_\Sigma *, B_\Sigma *$ is the range of permissible values (max-min) of quality indicators.

The wood skidding time under different technological schemes was calculated using the following formula:

$$f(t) = \frac{c_0}{1 + e^{b_0 + b_1 \cdot t + b_2 \cdot t^2}} \quad (31)$$

where c_0, b_0, b_1, b_2 are function parameters, respectively, which are equal to 2.91, 1.29, −0.097, and −0.158 for tree evaluation time and 9.02, 1.69, −0.012, and −0.027 for command execution time; t is the operating time.

Factors represented as nonnegative constraints and conditions imposed on variable predict:

- conditions upon which the round wood is produced:

$$\sum_{s=1}^{s} \sum_{f=0}^{f} V_{s,f}^{FB} \geq P_j^t \cdot j = 0.5 \quad (32)$$

where P_j^t – implementation plan of j-th operation for the time t;

- condition upon which LQW is produced and stockpiling:

$$\sum V_{\mathrm{tot}}^t \times \delta + \sum V_{\mathrm{tot}}^t \times \gamma \times (\alpha + \beta) - V_m^{t,\ FB} \geq 0 \quad (33)$$

where V_{tot}^t, $V_m^{t,\ FB}$ – the volume of marketable wood and LQW accumulated in the warehouse for the time t, respectively.

- the status of wood resource utilization relative to the annual logging capacity:

$$\sum_{s=1}^{s} V_s^{t,\ FB} + \sum_{f=1}^{f} V_f^{t,\ FB} \leq V_{tot}^t \quad (34)$$

The software program runs on algorithms and theoretical models considered in this article. They were interpreted using the unified modeling language (UML). The final stage of the modeling process was the physical representation of the results.

The next step involves working with the MathCAD version 11.0 PRO software, Yakuts, Russia and creating calculation files using standard techniques. Once the files were ready, the database programming began. For this, the Visual Basic version 6.0 software was used. The resulting reports made it possible to analyze the consequences of using logging machines.

$$\Xi = \left[\begin{array}{c} \dfrac{W_\Sigma(X_M, X_T, Y) - W_\Sigma^*}{W_\Sigma^*} - \dfrac{T_\Sigma(X_M, X_T, Y) - T_\Sigma^*}{T_\Sigma^*} - \dfrac{P_\Sigma(X_M, X_T, Y) - P_\Sigma^*}{P_\Sigma^*} - \\ - \dfrac{D_\Sigma(X_M, X_T, Y) - D_\Sigma^*}{D_\Sigma^*} - \dfrac{M_\Sigma(X_M, X_T, Y) - M_\Sigma^*}{M_\Sigma^*} - \dfrac{B_\Sigma(X_M, X_T, Y) - B_\Sigma^*}{B_\Sigma^*} \end{array} \right] \Rightarrow \min \quad (30)$$

Results and discussion

The resulting models allow analyzing the following parameters:

- diameter, m (D – trunk at breast height; D_c – tree crown);
- height and length, m (H – tree height; l_c – crown length; l_{tp} – tree top length; l_{tc} – from the cutting plane to the maximum crown size);
- weights, kg (P_t – tree weight; P_c – crown weight);
- area, m^2 (S_c – crown projection);
- eccentricity (E_c – crown eccentricity);
- moment of inertia, kg·m^2 (M_{in} relative to the pivot axis);
- centers of gravity of the tree (X_t), trunk (X_{tr}), crown (X_c), m;
- the number of tree tops (B_{tp}), pcs;
- the percentage of the bark in the tree volume (V_{br}), %;
- the percentage of branches in the trunk bark volume (V_b), %.

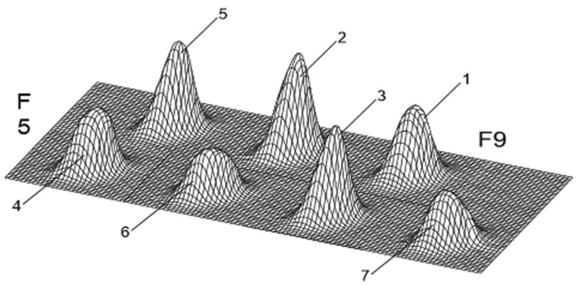

Figure 3. Distribution of taxon (1–7) occurrence frequencies.

Modeling the felling site provides information about the frequency of points in a distribution projection. The graph shows that the densities obtained can be approximated (Figure 3).

As seen, indicators characterizing the felling site can be represented as seven taxa. The main characteristics of trees are a function of these indicators (Table 2). Hence, they can be used to describe them, and these indicators will, in turn, affect the technological process indicators.

Analyzing and applying the results in the context of non-linear equations, the following relief models were obtained:

$$\beta = 0.61461 - 0.01112Y_4 + 0.00015{Y_4}^2 \tag{35}$$

$$\alpha = 0.29084 - 0.01924Y_4 + 0.0004{Y_4}^2 \tag{36}$$

$$\sigma_{\xi}^2 = 0.2505 - 0.0096Y_4 + 0.0001{Y_4}^2 \tag{37}$$

The functions of the micro-profile parameter $K(\tau)$ represent the source material for interpreting stationary processes, which help to model the unevenness of the felling site. This parameter can be obtained through calculating the slope angle Y_4.

According to the results of the analysis, the intensity of timber harvesting activities needs redistribution, as shown in Figure 4.

Changing the ratio between the types of timber harvest will help preserve biodiversity and ecological

Table 2. Characteristics of felling sites in the FEFD.

		Quantitative interpretation of each taxa's value						
Criterion, Y_i	Measurement unit	1	2	3	4	5	6	7
1	$\frac{'i^3}{\tilde{a}'a}$	$\frac{142.7}{60}$	$\frac{171.8}{61.7}$	$\frac{186.7}{61.0}$	$\frac{149.5}{61.2}$	$\frac{175.9}{62.8}$	$\frac{192.6}{58.9}$	$\frac{150.3}{58.1}$
2	$\frac{\hat{e}\tilde{a}}{\tilde{n}'i^2}$	$\frac{3.41}{1.13}$	$\frac{3.41}{1.13}$	$\frac{3.41}{1.13}$	$\frac{2.12}{0.71}$	$\frac{2.12}{0.71}$	$\frac{2.12}{0.71}$	$\frac{0.83}{0.26}$
3	m^3	$\frac{0.41}{0.13}$	$\frac{0.59}{0.19}$	$\frac{0.92}{0.31}$	$\frac{0.41}{0.13}$	$\frac{0.59}{0.19}$	$\frac{0.92}{0.31}$	$\frac{0.41}{0.13}$
4	Degrees	$\frac{12.05}{3.89}$	$\frac{12.08}{3.89}$	$\frac{12.01}{3.87}$	$\frac{11.23}{3.52}$	$\frac{12.16}{3.68}$	$\frac{11.22}{3.51}$	$\frac{20.14}{1.98}$
5	%	$\frac{0.91}{0.25}$	$\frac{0.88}{0.26}$	$\frac{0.87}{0.26}$	$\frac{0.90}{0.26}$	$\frac{0.88}{0.26}$	$\frac{0.86}{0.26}$	$\frac{0.93}{0.25}$
6	%	$\frac{0.62}{1.60}$	$\frac{0.68}{1.73}$	$\frac{1.25}{1.81}$	$\frac{0.42}{1.23}$	$\frac{0.51}{1.51}$	$\frac{1.21}{1.74}$	$\frac{0.27}{1.08}$
7	%	$\frac{1.59}{2.39}$	$\frac{1.98}{2.68}$	$\frac{1.72}{2.61}$	$\frac{1.74}{2.47}$	$\frac{2.28}{2.79}$	$\frac{1.98}{2.72}$	$\frac{2.48}{2.80}$
8	%	$\frac{3.89}{3.62}$	$\frac{3.68}{3.57}$	$\frac{3.46}{3.16}$	$\frac{4.44}{3.89}$	$\frac{4.13}{3.75}$	$\frac{3.38}{3.15}$	$\frac{4.02}{3.74}$
9	%	$\frac{3.06}{2.07}$	$\frac{2.87}{1.79}$	$\frac{2.77}{1.56}$	$\frac{3.06}{2.16}$	$\frac{2.84}{1.99}$	$\frac{2.60}{1.69}$	$\frac{2.77}{1.36}$
10	Shares	$\frac{0.81}{1.34}$	$\frac{0.80}{1.40}$	$\frac{1.23}{1.68}$	$\frac{0.61}{1.03}$	$\frac{0.63}{1.16}$	$\frac{1.03}{1.78}$	$\frac{0.43}{0.82}$

Note: 1–7: seven indicators characterizing the felling area represented as taxa, Y_i-criteria; Criteria: 1 – timber reserves, 2 – soil bearing capacity, 3 – average trunk diameter, 4 –average site slope, 5 – amount of young growth, 6 – the marketability class, 7 – share of larch trees, 8 – dark deciduous trees, 9 – soft deciduous trees, and 10 – hard deciduous trees.
Measurement unit: $\frac{'i^3}{\tilde{a}'a}$ – indicator of timber reserves, $\frac{\hat{e}\tilde{a}}{\tilde{n}'i^2}$ – indicator of soil bearing capacity, m^3 – cubic meters, %: percentage; degrees: degrees of inclination; shares: the proportion of hard deciduous trees.

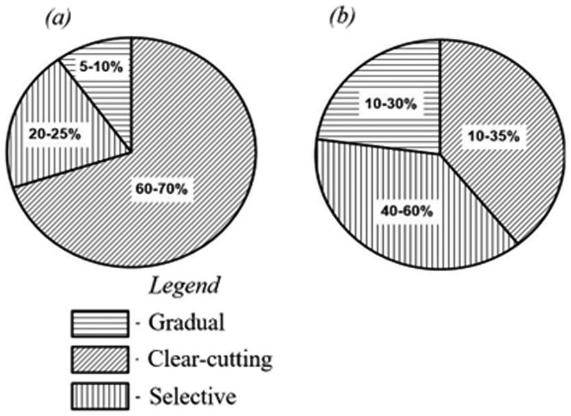

Figure 4. Distribution of logging modes used in the Far Eastern forests: (a) current distribution; (b) recommended intensity. Gradual felling, clear-cutting, and selective cutting.

stability. With other factors influencing the harvesting process, such as air pollution, energy consumption, timber quality loss, topsoil degradation, and the ability of the logging system to preserve the undergrowth, this solution can provide a complex effect on the species richness. In addition, the recommended scheme will support sustainability.

The quantitative values of the process and machinery indicators analyzed are given in Table 3.

As seen, the most optimal strategy is to use a whiplash technology with a SM4-type machine that minimizes the movement of wood by delivering the shaping module straight to the felling site or the timber processing area. It will considerably reduce the negative impact on the atmosphere and the trees.

Data on the impact of emissions are presented in Figure 5.

The models that describe the machinery operation and qualitatively demonstrate the change in the environment are based on the formalization of forestry operations. The criteria for sustainable forest management are listed in Table 4.

The skidding time was also determined analytically for different schemes. It was found to be most influenced by the operator's evaluation of the tree to be felled. The results are approximated using Equation (33) and presented in Figure 6.

Given the biological diversity of forests, the mountainous landscape, and intense anthropogenic activity, there is a need for a comprehensive scientifically based approach to forest exploitation that will take the ecological, economic, and social characteristics of the region into account. Forests in the FFD have high biodiversity; therefore, any wood harvesting company's priority would be to preserve the forest ecosystem or minimize disturbances (Kovalev 2004).

The results of this study are in line with previous opinions that the intensity of logging operations should not be the only factor to underpin forest management strategies. In forestry, it is necessary to minimize the impact of technology to maintain plant diversity, soil quality, and carbon storage. Moreover, forests must be managed as complex adaptive systems (Putz et al. 2008; Weber et al. 2011).

The assessment of the wood harvesting process includes looking into the operating conditions, cutting intensity, and logging technology and equipment applied. Despite the well-known facts of forest preservation and compliance with scientific recommendations on "eco-friendly" logging, the use of multi-operational forestry machines continues to cause forest degradation in the Far East (Ryabukhin et al. 2010).

To construct mathematical models of all quality indicators that characterize the operation of forestry equipment and the severity of its impact, the logging operations underwent formalization. In other words, a mathematical description of both logging equipment and logging technologies was provided.

According to some researchers, the current advancement of forestry machinery that moves it toward a broader range of functions and higher accuracy accelerates the development of forest industry through informatization and automation (Kovalev 2004; Kazakov and Ryabukhin 2017). This finding coincides with this study. In addition, this research explored the possibility of improving the efficiency of forestry enterprises and its modeling by optimizing the key indicators of sustainable forestry management, the underlying principles of which include data structurization and data unification, among other things. The study provides forest decision makers with solutions for modeling forest resources, logging equipment, and technological processes. Using these models, forest decision makers will be able to quantitatively assess the timber harvesting system performance and choose an optimal technological process scheme and an optimal logging machine.

All exploitation conditions are crucial in describing the production and sale of wood resources by other companies. The proposed model considers all conditions upon which wood resources are used in the current economic reality. It is a complex framework and combines indicators that are determined either analytically or statistically. Such an approach allows determining the optimal structure of the forest business with regard to the selling price of timber.

The proposed methodology can be used to analyze the operating efficiency of the transport systems in forestry enterprises or the technological processes in which they are involved. Great attention was paid to the functional performance of the "machine-human-environment" system. The time operators spend visually examining the tree and then cutting it down was also considered.

These results are similar to those reported by other authors, who argue that adaptation of logging intensities should be accompanied by the maintenance of ecosystem heritage, such as hollow trees that are not valuable to timber production but are crucial to biodiversity (Meijaard et al. 2005). When selecting a felling system (method), one should meet the following principles: constancy of forest coverage, minimization of the gap between felling and reforestation, sustainable natural regeneration, and rational use of logging sites.

Table 3. Summary of analysis results for machinery exploitation and logging operations.

Process operation		Logging machine system	Parameters: Technological		Forest and environmental		Geo-environmental		Economical			Rank
			W, kWh/m^3	T, s/m^3	P, %	M, %	D, m3/ha	B_i, t/year	Δ, degrees	Π, kN/m^2	K, rubles.	
WLT	FB + TLS + TL + WLL + Hl + Ul + Bc + As	SM3	43.24 / 4	838 / 4	59 / 6	20.6 / 8	25.3 / 4	7.81 / 8	28 / 10	49 / 8	1,108 / 4	IV
	FB − T + SMD + LRH + WLH + HL + Ul + BB + As	SM4	33.25 / 10	557 / 10	23 / 10	19.9 / 10	12.6 / 10	6.54 / 10	21 / 8	49 / 8	834 / 10	I
CTL	FB + TLS + TL − Bc + LL + Hl + Ul + As	SM1	41.12 / 6	671 / 8	59 / 6	20.6 / 8	22.4 / 6	11.05 / 6	28 / 10	49 / 8	915 / 8	III
	F − TL − Bc + LT − H + Hl + Ul + As	SM2	38.83 / 8	712 / 6	35 / 8	19.9 / 10	19.6 / 8	11.97 / 4	21 / 8	46 / 10	932 / 6	II

Note: the numerator represents the value and the denominator represents the score (the lower the score, the better the silvicultural and technological indicators): 1st place – 10; 2nd place – 8; 3rd place – 6; 4th place – 4. Symbols "+" and "–" indicate the presence/absence of specific operations at the site.
WLT: whiplash technology; CTL: cut-to-length technology; FB: felling-bunching; TLS: tree length skidding; TL: tree limbing; WLL: whiplash load; Hl: hauling; Ul: unloading; Bc: bucking; As: assorting; T: transportation; SMD: shaping module delivery; LRH: limb removal in the hopper unit; WLH: whiplash handling; BB: bundle bucking; LL: log loading; F: felling; LT: log transportation; H: handling.

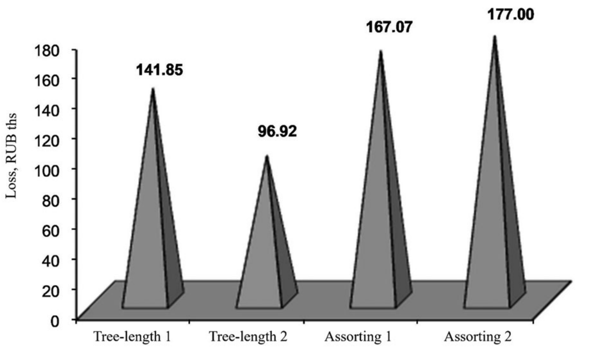

Figure 5. Impact of carbon emissions on the surface atmosphere in monetary terms. Loss, RUB ths; Tree-length, Assorting.

Table 4. Criteria for sustainable forest management.

Criteria	Specific energy intensity of operations (SEI), W, ml/m^3
	Specific time expenditures (STE). T, sec/m^3
	Wood waste (WW). D. m^3/ha
	Soil salinity (SS), M, %
	Damage to surrounding trees, young growth, undergrowth, and thin-sized trees, P, %
	Gross pollutant emission (GPE). Vi, t/year
	Soil pressure (SP), P, kN/m^2
	Cost of 1 m^3 of timber (WC), K rub.

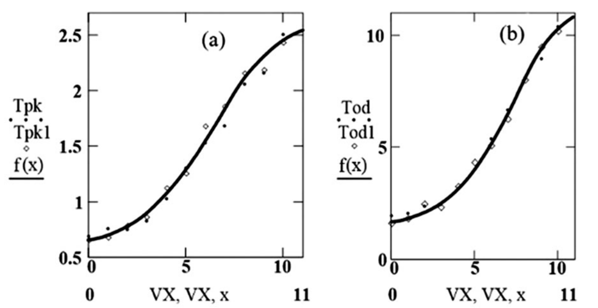

Figure 6. Graphical interpretation of time required to (a) provide a command; (b) evaluate the tree structure.

Profit from sales was accepted as an indicator of economic efficiency. It allows estimating the extent of woody raw material usage among the population. Overall, the proposed framework allows assessing the economic, environmental, and social significance of the logging operation.

Conclusions

This study reports the results of mathematical modeling and hands-on research aimed to improve the quality of sustainable forest management in the Far East. Considering the tree species composition in the FEFD district, stand age and topography, the optimal logging strategy will include 10–30% of clear-cutting, 70–90% of selective logging, and 20–35% of gradual logging. This option will preserve the maximum biological diversity of the regional flora and ensure a continuous cutting process.

One way for timber harvesting companies to improve profitability is to move toward completeness. In other words, companies have to collect residues from the cutting and timber processing operations and use this waste in pulp and paper production.

The present conclusions are supported by a large database of long-term empirical evidence collected in previous years in felling sites, stationary facilities, and research plots. In addition, the experimental analysis of the mathematical models shows that reducing the amount of wood transportation decreases the SEI of the process by 18.3%, the harvesting time by more than 35%, young tree damage by 2 times, and exhaust emissions by 35%. These effects were likely due to the presence of a shaping module at the cutting and timber processing area. Reduced time for tree evaluation was also a contributory factor. Models describing the operation of equipment and qualitatively demonstrate changes in the external environment are based on the formalization of forestry operations. Because of that, it can significantly reduce the negative environmental footprint.

The proposed model for logging operations in the Far East Federal District has been proven socio-economically and environmentally feasible. It also allows for optimization in other regions or countries.

Acknowledgments

The work was carried out within the confines of the scientific school “Advances in lumber industry and forestry”.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The underlying content of this article was supported by the grant of the Russian Science Foundation [No. 22-26-00009], https://rscf.ru/project/22-26-00009/.

Data availability statement

Data will be available on request.

References

Abuzov A, Grigorev I. 2020. Design features of cable forestry systems on soft pneumatic supports. Lesotekhnicheskiy Zhurnal. 10(1):86–95.

Angelstam P, Naumov V, Elbakidze M. 2016. Transitioning from Soviet wood mining to sustainable forest management by intensification: are tree growth rates different in northwest Russia and Sweden? For Int J For Res. 90(2):292–303.

Dobretsov R, Grigorev I, Tikhonov E, Mikheev A, Khakhina A, Storodubtseva T, Shiryaev S, Burgonutdinov A. 2021. Impulse control technology for improving steering control systems of the tracked vehicles. IREACO. 14(3):172–178.

Ezquerro M, Pardos M, Diaz-Balteiro L. 2019. Sustainability in forest management revisited using multi-criteria decision-making techniques. Sustainability. 11(13):3645.

Flores BM, Staal A, Jakovac CC, Hirota M, Holmgren M, Oliveira RS. 2020. Soil erosion as a resilience drain in disturbed tropical forests. Plant Soil. 450(1–2):11–25.

Grigoreva O, Runova E, Alyabyev A, Hertz E, Voronova A, Ivanov V, Shadrina S, Grigorev I. 2021. Influence of different forest management techniques on the quality of wood. J Renew Mater. 9(12):2175–2188.

Grigoriev VI. 2020. Opportunities for the development of the Russian solid biofuel imports. Increasing the efficiency of the forestry complex. Materials of the Sixth All-Russian National Scientific and Practical Conference with International Participation; Petrozavodsk. p. 44–45.

Grigoriev IV, Gazizov AM, Grigorieva OI. 2016. New technological processes of logging operations. Bull Bashkir State Agrarian Univ. 2(38):97–102.

Grigoriev IV, Zorin MV, Grigoriev GV, Rudov SE, Shvetsova VV, Kalita GA. 2021. Analysis of methods for strengthening temporary transport tracks for wood skidding and hauling. Woodwork Ind. 2:10–29.

Horton AJ, Constantine JA, Hales TC, Goossens B, Bruford MW, Lazarus ED. 2017. Modification of river meandering by tropical deforestation. Geology. 45(6):511–514.

Kazakov NV, Ryabukhin PB. 2017. Modeling of logging operations: a monograph. Khabarovsk, Russia: The Pacific State University.

Khitrov EG, Grigoriev IV, Khakhina AM. 2015. Increase of skidding efficiency by substantiating forest machine KPIs during operational control of soil properties. Saint-Petersburg, Russia: Scientific Publication.

Kovalev AP. 2004. Silvicultural and ecological foundations of sustainable forest management in the Far East [dissertation]. Primorsky Krai, Russia: Primorsky State Agricultural Academy.

Linser S, Wolfslehner B, Asmar F, Bridge SR, Gritten D, Guadalupe V, Jafari M, Johnson S, Laclau P, Robertson G. 2018. 25 Years of criteria and indicators for sustainable forest management: why some intergovernmental C&I processes flourished while others faded. Forests. 9(9):515.

Markov OB, Voronov RV, Davtyan AB, Grigoriev IV, Kalita GA. 2021. Mathematical model for selecting a system of machines for developing and operating forest plantations. Woodwork Ind. 1:16–26.

Meijaard E, Sheil D, Nasi R, Augeri D, Rosenbaum B, Iskandar D, Setyawati T, Lammertink M, Rachmatika I, Wong A. 2005. Life after logging. 1st ed. Jakarta: Center for International Forestry Research.

Naumov V, Angelstam P, Elbakidze M. 2016. Barriers and bridges for intensified wood production in Russia: insights from the environmental history of a regional logging frontier. Forest Policy Econ. 66:1–10.

Putz FE, Sist P, Fredericksen T, Dykstra D. 2008. Reduced-impact logging: challenges and opportunities. For Ecol Manage. 256(7):1427–1433.

Rudov SE, Kunitskaya OA, Grigoriev IV, Grigorieva OI, Kalyashov VA, Nguyen TN. 2021. Modern machinery systems for the development of forests on slopes. Repair Restorat Moderniz. 1:35–42.

Ryabukhin PB, Kovalev AP, Kazakov NV, Lutsenko EV. 2010. Logging in the Far East: state and prospects. Khabarovsk, Russia: Far East Forestry Research Institute.

Salimova T, Biryukova L, Vukovich N. 2018. Quality management and certification in sustainable forest management (SFM): the case study of Russia. Int Rev. (3–4):105–122.

Tambi AA, Grigoriev IV. 2020. Improvement of harvester efficiency by eliminating the loss of time for the preparation of cutting tools. Repair Restorat Moderniz. 4:12–16.

Tambi AA, Grigoriev IV, Davtyan AB, Pomiguev AV, Kalita ON, Grigoriev VI. 2021. Technological integration of woodprocessing companies. Woodwork Ind. 1:26–37.

Tambi A, Morkovina S, Grigorev I, Grigor'ev V. 2020. Development of circular economy in Russia: biofuel market. Forestry. 9(4):173–185.

Voronov RV, Markov OB, Grigoriev IV, Davtyan AB. 2019. Mathematical model of the modular principle in selecting machinery system for creating and operating forest plantations. Proceedings of higher educational institutions. Forest J. 5(371):125–134.

Weber M, Stimm B, Mosandl R. 2011. New aspects in tropical silviculture (review). Silviculture in the tropics. New York (NY): Springer Verlag; p. 63–89.