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**Results of simulation modeling and optimization
of design parameters of forest rake**

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Abstract

Background. Forest rakes for collecting or raking logging residues are widely used in forestry operations worldwide. The authors' review highlighted the relevance of research aimed at optimizing the design parameters of forest rakes.

The **purpose** is to improve the design elements of forest rakes to increase the efficiency of their use and the quality of work performed.

Materials and methods. The study object was a forest rake with a broken profile of the working elements (teeth). The subject of the study was a mathematical model of the formation of a logging residue pile using a forest rake, taking into account the characteristics of the forest rake and the raked biomass. To identify the optimal design characteristics of a forest rake, a calculation scheme was developed for the formation of a drag pile of logging residue using a forest rake.

Results. Mathematical modeling of the aforementioned drag pile allowed us to identify expressions for determining the optimal height, length, and tilt angles of the upper and lower parts of forest rake teeth. It was established that for the most probable range of internal friction angle variation of 44...46° and expected logging residue lengths of 0.7...1.2 m, the optimal height of a forest rake varies within the range of 840...1800 mm. For lower tooth inclination angles of 32...40°, the optimal length of the upper tooth of a forest rake varies within the range of 840...1100 mm. For upper tooth inclination angles

of 5...11°, the optimal length of the lower tooth of a forest rake varies within the range of 620...790 mm. The need for continued research into the design parameters of forest rakes in the direction of their multifactor optimization to substantiate the optimal performance of forest rakes is substantiated.

Keywords: logging residues; raking; forest rakes; dependence; simulation modeling; optimal characteristics

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Результаты имитационного моделирования и оптимизации конструктивных параметров лесных граблей

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Аннотация

Обоснование. В мировой практике выполнения лесохозяйственных работ широко распространены лесные грабли, осуществляющие сбор или сгребание порубочных остатков. Выполненный авторами статьи обзор позволил выявить актуальность проведения исследований, направленных на оптимизацию конструктивных параметров лесных граблей.

Цель – совершенствование конструктивных элементов лесных граблей для повышения эффективности их применения и качества выполняемых работ.

Материалы и методы. Объект исследования представлял собой лесные грабли с ломаным профилем рабочих элементов (зубьев). Предмет исследования представлял собой математическую модель формирования посредством лесных граблей объема вороха порубочных остатков с учётом характеристик лесных граблей и сгребаемой биомассы. Для выявления оптимальных конструктивных характеристик лесных граблей была составлена расчётная схема формируемого при помощи лесных граблей вороха волочения порубочных остатков.

Результаты. Математическое моделирование указанного вороха волочения позволило выявить выражения для определения оптимальных величин высоты, длин и углов наклона верхней и нижней частей зуба лесных граблей. Установлено, что для наиболее вероятного диапазона изменения угла внутреннего трения 44...46° и ожидаемых размеров длины порубочных остатков 0,7...1,2 м оптимальная ве-

личина высоты лесных граблей варьируется в диапазоне 840...1800 мм. При величинах углов наклона нижней части зуба 32...40° оптимальная величина длины верхней части зуба лесных граблей варьируется в диапазоне 840...1100 мм. При величинах углов наклона верхней части зуба 5...11° оптимальная величина длины нижней части зуба лесных граблей варьируется в диапазоне 620...790 мм. Обоснована необходимость продолжения исследований конструктивных параметров лесных граблей в направлении их многофакторной оптимизации для обоснования оптимальной производительности работы лесных граблей.

Ключевые слова: порубочные остатки; сгребание; лесные грабли; зависимость; имитационное моделирование; оптимальные характеристики

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Introduction

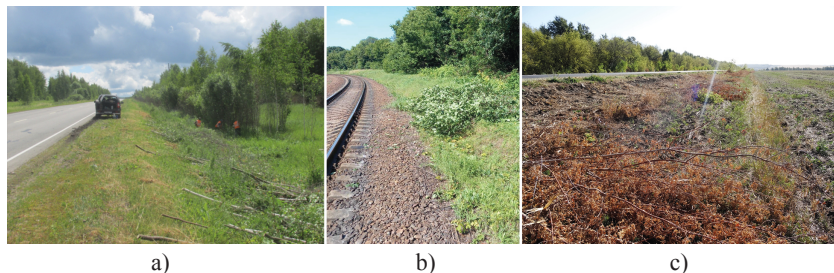
In today's world, the growing process of “greening” production is becoming increasingly important in addressing the challenges of sustainable use of natural resources, particularly in waste management. Incorporating some of the inevitably generated waste into new production as secondary materials is a key environmental and economic objective for many enterprises, including those in the forestry sector.

One of the types of waste that represents the most important link in the environmental safety of modern forestry production is wood waste, in particular logging residues.

The established practice of Russian and global logging and forestry enterprises in the overwhelming majority of cases provides for the inevitable formation of so-called «logging residues», while the method of their formation (cutting of growing vegetation, uprooting or tearing out) is not taken into account to indicate the very fact of their occurrence. The logging residues that remain in the forest (or at the site of forestry work) often include the crown and/or root parts of harvested trees, unwanted tree and shrub vegetation (including small-sized undergrowth), fragments of trunks, branches and twigs, etc. (Fig. 1).

As a completely free raw material resource, logging residues (raked logging residues: RLR) can be used to achieve lean production goals such as «minimizing costs» for their formation and the possibility of reuse. However, one of the challenges in ensuring the «reuse» of logging residues is the need to ensure

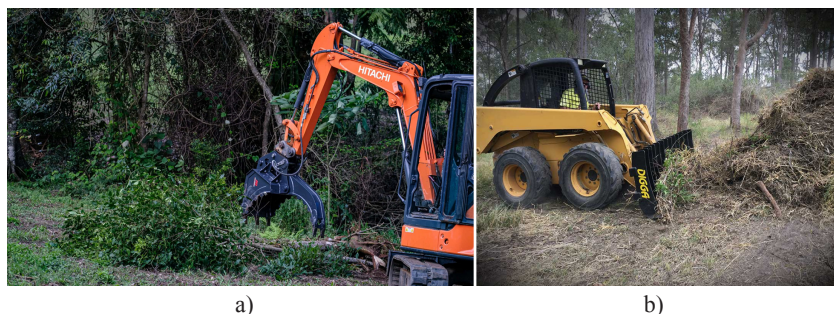
their efficient collection or raking for delivery to the processing site for chips [10] or loading onto vehicles for removal.



a) Cheboksary-Surskoye highway, 2019; b) Lebedi–Saraevka railway section, 2021;
c) Nizhnaya Veduga–Terbuny highway, 2024.

Fig. 1. Formed logging residues

The research of the authors of the article [2] of the world practice of forestry work revealed the widespread use of forest rakes for collecting (Grab Buckets For Excavators; Fig. 2, a) or raking (Digga Stick Rake-2130; Fig. 2, b) logging residues, while in Russia these technological operations have not yet found wide application.



a) b)
Fig. 2. Collection and raking of logging residues with a forest rake

An analysis of the content of global (including Russian) publications devoted to the issue of collecting or raking logging residues has revealed such areas of research as improving existing methods and technologies used for collecting logging waste [12], including substantiating the possibility of applying the concept of «lean production» in logging operations from the point of view of all stages of logging production (logging operations, timber transportation, logging operations, forest restoration operations) [3]; justification of the feasibility of minimizing the

time of collection of the forming biomass between the cycles of its cutting and subsequent processing, especially in continuous technological cycle systems (D. Bergström [7]), ensuring an increase in tractor productivity (N. Kaakkurivaara, A.R. Proto et al. [11; 13; 16]); optimization of the distances of movement of logging residues across the cutting area (M. Aalto, T. Yoshimura, S.A. Borz et al. [5; 8; 17]) taking into account the efficiency of previous and subsequent processes of work on vegetation [15]. The issues of damage to thinned stands remaining after the removal of woody biomass using various mechanization tools were considered in the works of M.-J. Cho, E. Lee et al. [9; 14], the condition of the vegetation cover on strip roads of clearcuts covered with logging residues was assessed in the works of N.I. Tsarev, A.S. Ilintsev et al. [1; 4].

The representative review carried out made it possible to establish that at present, world scientific thought in the field of knowledge under consideration is directed towards improving technologies for collecting waste from logging production, including to increase the productivity of tractors and multifunctional machines, and also to reduce the environmental damage caused to nature during the operation of technical equipment that collects or rakes logging residues. However, only a few studies note the need for a thorough study (including simulation modeling methods) of the technical means that deliver the biomass obtained after cutting by dragging to the place of its further transportation by motor vehicles. In particular, S. Ackerman et al. [6] found results indicating a discrepancy between the volume of standing timber, the volume of cut woody vegetation, and the volume of timber delivered to the roadside. Noting the inevitable losses during the dragging of woody biomass, the authors of the study draw attention to the advisability of modeling the performance of biomass raking equipment using data on their optimal characteristics. In this regard, it is important to conduct research on the issue of identifying the optimal design parameters of forest rakes.

The aim of the study is to improve the design elements of forest rakes to increase the efficiency of their use and the quality of work performed.

This objective is achieved by developing an appropriate mathematical model that takes into account the design parameters of forest rakes and the characteristics of the raked logging residues, as well as by performing simulation modeling that allows identifying the optimal design characteristics of forest rakes.

Materials and methods

The study, which is theoretical and based on the synthesis of a number of mathematical expressions with their subsequent numerical solution, was carried out using universal methods of analytical mechanics. The object of the study

was a forest rake with a broken profile of the working elements (teeth), common in Russia and Belarus, attached to the front or rear hitch of a tractor (for example, type Belarus-82.1; Fig. 3).

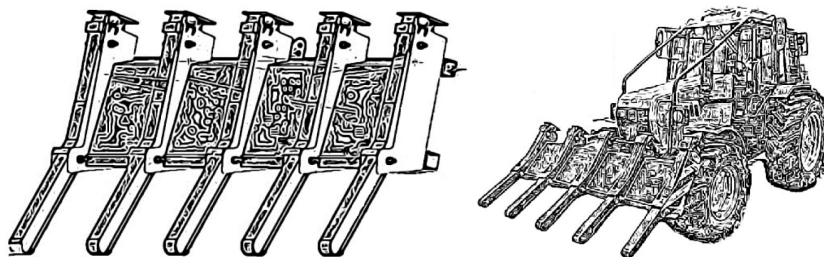


Fig. 3. Models of forest rakes and a tractor with a rake

The subject of the study was a mathematical model of the formation of a pile of logging residues using forest rakes, taking into account the characteristics of the forest rakes and the raked biomass.

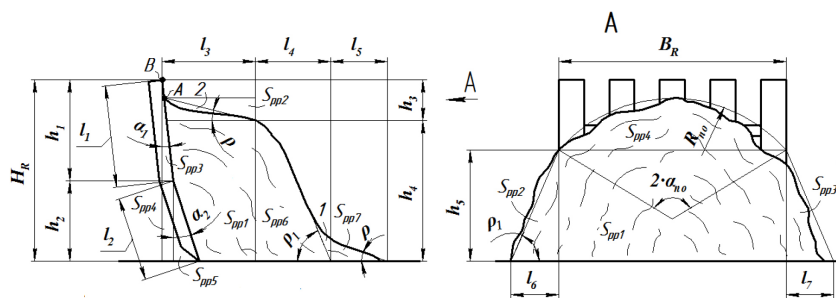


Fig. 4. Calculation scheme for the volume of logging residues generated using a forest rake

To identify the optimal design characteristics of forest rakes, a calculation scheme was drawn up for the formation of a heap of logging residues by means of a forest rake (Fig. 4), the mass, density and volume of which are determined by a combination of the design parameters of the technical means under consideration, in particular, B_R and H_R are the width and height of the forest rake, respectively, m; l_1 and l_2 – the lengths of the upper and lower parts of the forest rake tooth, m; α_1 and α_2 – angles of inclination of the upper and lower parts of the forest rake tooth, degrees. Other key parameters for the interaction of broken-profile forest rakes with logging residues were: ρ – angle of internal friction of freshly cut

wood (logging residues) at rest, deg.; ρ_1 – critical angle of collapse of freshly cut wood (logging residues), deg.; h_3 – the distance from the upper extreme point of the working surface of a forest rake to the point where freshly cut wood (logging residues) begins to fall, m; l_6 (l_7) – width of the raked shaft of logging residues, m. In addition, the volume of the drag pile is influenced by the largest size of the raked logging residues l_{RLR} (m; namely, the length or span of branches at their most distant points from the trunk/trunks of raked logging residues), number of working elements (teeth) Z , width of working elements (teeth) B_z (m).

Results and discussion

Mathematical modeling of a heap of logging residues formed by means of a forest rake allowed us to identify an expression for determining the area S_{pp} (m²) of the longitudinal section of the volume of the said heap:

$$\begin{aligned}
 S_{pp} &= S_{pp1} - S_{pp2} - S_{pp3} - S_{pp4} - S_{pp5} + S_{pp6} = \\
 &= \frac{H_R \cdot h_3}{tg \rho} - \frac{h_3^2}{2 \cdot tg \rho} - \frac{l_1^2 \cdot \cos \alpha_1 \cdot \sin \alpha_1}{2} - l_2 \cdot \cos \alpha_2 \cdot l_1 \cdot \sin \alpha_1 - \\
 &\quad - \frac{l_2 \cdot \cos \alpha_2 \cdot l_2 \cdot \sin \alpha_2}{2} + \frac{(H_R - h_3)^2}{2 \cdot tg \rho_1} = \\
 &= \frac{H_R \cdot h_3}{tg \rho} - \frac{h_3^2}{2 \cdot tg \rho} - \frac{l_1^2 \cdot \cos \alpha_1 \cdot \sin \alpha_1}{2} - l_1 \cdot l_2 \cdot \cos \alpha_2 \cdot \sin \alpha_1 - \\
 &\quad - \frac{l_2^2 \cdot \cos \alpha_2 \cdot \sin \alpha_2}{2} + \frac{(H_R - h_3)^2}{2 \cdot tg \rho_1}
 \end{aligned} \tag{1}$$

The established expression (1) is a function of the longitudinal cross-sectional area of logging residues (moving along the cleared surface and interacting with it) depending on the design parameters of the forest rake (namely – H_R , l_1 , l_2 , α_1 and α_2) and taking into account the angles of internal friction ρ and collapse ρ_1 of freshly cut (cut down, torn out with the root system, etc.) vegetation (logging residues).

To identify the optimal values of the design parameters of forest rakes (namely: height H_{Ropt} , length l_{1opt} and l_{2opt} upper and lower parts of the tooth, angles α_{1opt} and α_{2opt} inclination of the upper and lower parts of the tooth) let us differentiate the right-hand side of equation (1) accordingly with respect to H_R (l_1 , l_2 , α_1 and α_2) and obtain the corresponding expressions, including the values of the angles of internal friction ρ and collapse ρ_1 of logging residues:

$$\left\{ \begin{array}{l} H_{R\ opt} = h_3 \cdot \left| 1 - \frac{\operatorname{tg} \rho_1}{\operatorname{tg} \rho} \right|; l_{1\ opt} = \frac{l_2 \cdot \cos \alpha_2}{\cos \alpha_1}; l_{2\ opt} = \frac{l_1 \cdot \sin \alpha_1}{\sin \alpha_2} \\ \alpha_{1\ opt} = \arccos \left(\frac{\sqrt{2} \cdot \sqrt{l_2^2 + 4 \cdot l_1^2 + l_2^2 \cdot \cos(2 \cdot \alpha_2)} - 2 \cdot l_2 \cdot \cos \alpha_2}{4 \cdot l_1} \right) \\ \alpha_{2\ opt} = \arcsin \left(\frac{\sqrt{2} \cdot \sqrt{4 \cdot l_2^2 + l_1^2 - l_1^2 \cdot \cos(2 \cdot \alpha_1)} - 2 \cdot l_1 \cdot \sin \alpha_1}{4 \cdot l_2} \right) \end{array} \right. \quad (2)$$

The design parameters of forest rakes have the greatest impact on their operating efficiency and the overall quality of logging residue removal from the cleared area. Taking this into account, the change in the parameters of the forest rake, the parameters of logging residues, the working conditions and operation of the base vehicle during simulation modeling was carried out within the following limits: $Z = 4 \dots 20$; $B_z = 65 \dots 85$ mm with discreteness 5 mm; $B_R = 2 \dots 2,5$ m with discreteness 0,1 m; $H_R = 1,1 \dots 1,8$ m with discreteness 0,1 m; $l_1 = 0,8 \dots 1,2$ m with discreteness 0,05 m; $l_2 = 0,5 \dots 0,9$ m with discreteness 0,1 m; $\alpha_1 = 2 \dots 25^\circ$ with discreteness 1° ; $\alpha_2 = 25 \dots 50^\circ$ with discreteness 1° ; $\rho = 30 \dots 50^\circ$ with discreteness 1° ; $\rho_1 = 55 \dots 75^\circ$ with discreteness 1° ; $l_{RLR} = 0,5 \dots 1,25$ m with discreteness 0,15 m.

The results of simulation modeling of the optimal values $H_{R\ opt}$ (mm) of the height of forest rakes made it possible to establish (Fig. 5), that in the studied range of changes in the angles ρ of internal friction, a 2.5-fold reduction in the length of logging residues leads to a 185% reduction in the optimal height of forest rakes, moreover, within the same angle ρ value, such a reduction reaches 250%. For the most probable range of change in the angle of internal friction $\rho = 44 \dots 46^\circ$ and the expected length of logging residues $l_{RLR} = 0.7 \dots 1.2$ m, the optimal height of the forest rake varies in the range $H_{R\ opt} = 840 \dots 1800$ mm.

The results of simulation modeling of the optimal values $l_{1\ opt}$ (mm) of the length of the upper part of the tooth of a forest rake made it possible to establish (Fig. 6), that in the studied range of angle α_2 changes, a reduction in the length l_2 of the lower part of the forest rake tooth by 1.4 times leads to a decrease in the optimal length $l_{1\ opt}$ by 1.1...1.2 times. In both the region of large and small values of angles α_2 , when changing the length of the lower part of the tooth, the optimal values of the length of the upper part of the tooth of a forest rake differ

moderately ($\Delta l_{opt} = 21...24\%$), as do the optimal values of the heights of forest rakes ($\Delta H_{Ropt} = 28...30\%$). For angles α_2 of $32...40^\circ$, the optimal length l_{opt} of the upper part of the forest rake tooth varies in the range of $840...1100$ mm.

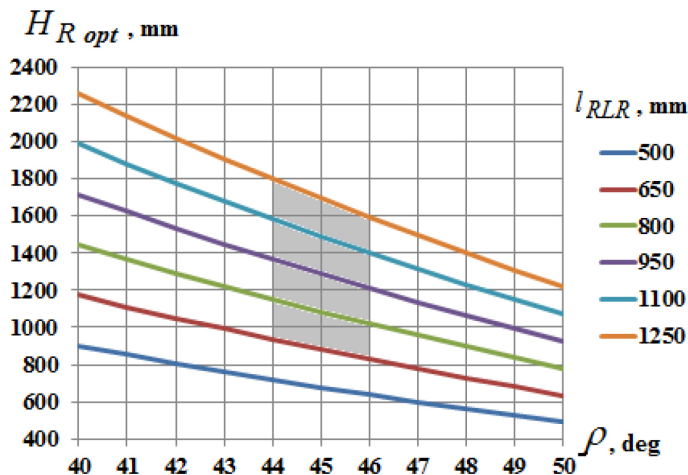


Fig. 5. Results of simulation modeling of optimal values of forest rake height depending on the angle of internal friction and the length of logging residues

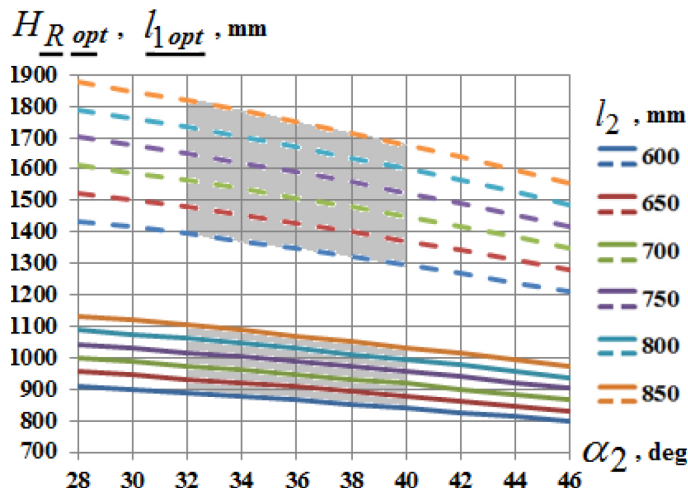


Fig. 6. Results of simulation modeling of optimal values of the length l_{1opt} of the upper part of the tooth and the height H_{Ropt} of the forest rake depending on the angle α_2 of inclination and the length l_2 of the lower part of the tooth

The results of simulation modeling of the optimal values (mm) of the length of the lower part of the tooth of a forest rake made it possible to establish (Fig. 7), that in the studied range of angle α_1 changes, a reduction in the length l_1 of the upper part of the forest rake tooth by 1.2 times leads to an increase in the optimal length l_{2opt} by 1.6...1.7 times. In the region of small angle values $\alpha_1 = 2...4^\circ$, when changing the length of the upper part of the tooth, the optimal values of the length of the lower part of the tooth of a forest rake differ insignificantly ($\Delta l_{2opt} = 2.5...3.5\%$), while for large angle values $\alpha_1 = 18...20^\circ$ the differences in the studied length reach $\Delta l_{2opt} = 11\%$ or more. For angles α_1 of $5...11^\circ$, the optimal length l_{2opt} of the lower part of the forest rake tooth varies in the range of 620...790 mm.

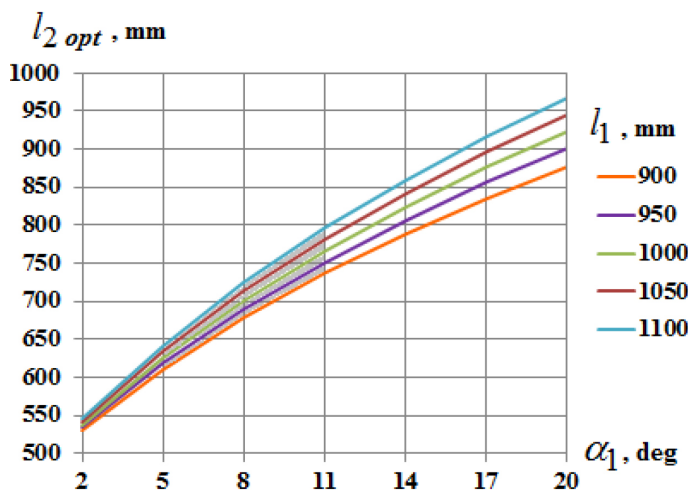


Fig. 7. Results of simulation modeling of optimal values of the length l_{2opt} of the lower part of the tooth of a forest rake depending on the angle α_1 of inclination and the length l_1 of the upper part of the tooth

The design, manufacture and practical application of forest rakes based on the identified optimal values of their design parameters will make it possible to solve a whole range of forestry problems by aggregating the technical means in question on tractors of varying power. At the same time, it should be noted that it is necessary to continue research in the direction of multi-factor optimization of the design parameters of forest rakes in order to ensure the possibility of visualization and description of the indicators of the influence of the design parameters of forest rakes on the efficiency (in particular, productivity) of their work.

Conclusion

1. It has been established that despite the widespread use of forest rakes in global forestry practice, there are no studies devoted to determining the optimal characteristics of technical means for collecting and raking logging residues.

2. It is shown that for the most probable range of change in the angle of internal friction of logging residues of $44...46^\circ$ and the expected dimensions of their length of $0.7...1.2$ m, the optimal value of the height of a forest rake varies in the range $H_{\text{Ropt}} = 840...1800$ mm. With the inclination angles of the lower part of the tooth of $32...40^\circ$, the optimal length of the upper part of the forest rake tooth varies in the range $l_{\text{1opt}} = 840...1100$ mm. With the angles of inclination of the upper part of the tooth of $5...11^\circ$, the optimal length of the lower part of the tooth of a forest rake varies in the range $l_{\text{2opt}} = 620...790$ mm.

3. The necessity of continuing the research of design parameters of forest rakes in the direction of their multifactor optimization to substantiate the optimal performance of forest rakes is substantiated.

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Alexey A. Platonov: general guidance of the research direction, critical revision of the article text with the introduction of valuable intellectual content.

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Maxim A. Popov: selection and analysis of scientific literature on the topic of the article, writing the text of the article.

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