Forest fire-fighting soil-thrower: improving the efficiency of the work processes

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Abstract. The analysis of the work processes of technical equipment used for forest fire control and preventive activities has revealed that they do not meet the requirements of the process flows. The aim of the work was to increase the efficiency of the work processes of new forest fire-fighting soil-thrower by optimizing the parameters of the milling thrower. The optimization task has been to search for the values of the length and width of the milling thrower blades. These values should provide the highest productivity and smallest supplied power with the average range of soil displacement. Based on the optimization results, the optimal blade length of the milling thrower was revealed in the range of 200-230 mm, and the width of the blade was 150-220 mm. With optimal parameters of the working body, a firefighting machine throws soil into the fire zone at a distance of up to 21 m. It consumes no more than 38 kW of power, and its productivity is 0.22 m³/s on the average.

1. Introduction
Forests are important part of the ecosystem and they play a significant role to preserve and maintain the environment. The main hazard is forest fires because its consequences are terrible in nature. Therefore, there is a need to detect and extinguish fire before it spreads to destroy the resources [1]. Forest fire spreading is a complex process affected by multi-factors. Understanding the relationships between these multi-factors and forest fire spreading trend is vital to predicting the fire spreading promptly and accurately to make the strategy in forest fire extinguishing [2-5].

Effective implementation of preventive and forest fire activities is one of the most urgent and acute problems of forestry.

At the moment, forest plows such as PKL-70, PL-1, PKLN-500A, PLO-400 (manufacturer - LesPromResurs Plant, Russia) are often used for this type of work. Also, more narrowly-targeted equipment is used in the form of PDN-1 series (manufacturer - PA LESAGROMASH LLC, Russia) of field and forest cutters and strip-type PF-1 and ALF-10 mills (manufacturer - Federal budget institution St. Petersburg Research Institute of Forestry), as well as ground sweepers such as GT-3 and others. However, forest plows used to carry out preventive and forest fire activities and trenchers form an insufficiently wide mineralized strip (1-2.5 m). It is far from being effective in the conditions of rapid dynamics of lowland forest fires. Milling slat cutters and ground sweepers are energy-intensive and inefficient, because the tools are aggregated with a creeper gear on tractors, and the cutters have to work in conditions of soddy upper soil layers. It significantly reduces quality and productivity of the process [6].
The analysis of existing serial technical means shows that they insufficiently meet the requirements for the implementation of the work process for creating a protective mineralized strip, localizing and eliminating forest ground fires.

This led to the creation of new technical means that would combine the best qualities of plows and milling tools and expand the range of possible applications. At the same time they should not have the previous shortcomings. So there were tools with the combined working bodies, such as a soil-throwers and strip-laying machine, developed on the basis of the Voronezh State University of Forestry and Technologies named after GF Morozov (Voronezh, Russia). However, these developments do not completely solve the problems of efficiency and quality of preventive and fire-fighting activities, because milling tools (working on a loose soil and ground shaft) are not protected from the roots and stumps. They have large mass and size due to a combination of two types of working bodies in a single design [7-9].

As the experience has shown, it is advisable to use technical means that combine active and passive bodies in their construction for carrying out high-quality preventive and forest fire work. This enables to combine the process of soil pretreatment and the further release of loose soil in a given direction. It also significantly increases the efficiency of the process flows for creating mineralized strips.

The topic of forest fires was practically relevant at all times not only in forest but also agriculture field. Therefore, for a long period the study of process flows of soil-cultivating machines used for preventive and forest fire activities was carried out by many scientists such as A.N. Chukichev, I.M. Bartenev, V.I. Kazakov, M.V. Drapalyuk, P.I. Popikov, P.E. Goncharov, I.S. Fedorchenko, E.I. Maksimov, M.N. Lysych and others.

The analysis of these works shows that the highest efficiency is achieved using the method of creating mineralized strips using machines combining passive working bodies to loosen the soil and active bodies for milling and throwing the resulting soil and earth shaft to the required distance. However, the data obtained from the analysis of the past years is not enough for further improvement of the process flows and creation of more efficient tools.

Currently known theoretical and experimental studies of the process flows do not fully disclose the process of simultaneous interaction of active and passive working bodies with the soil. All this greatly complicates the process of creating a new technology on theoretical and practical levels.

The development and creation of a new design of a forest fire soil-thrower with a hydraulic actuator of the working body requires additional theoretical and experimental studies aimed at a joint work of the shredder-casing (passive working body) and milling-threwer (active working body) with soil during the implementation of process flows of mineralized lanes’ formation, as well as throwing the soil in the direction of the edge of the forest ground fire.

Thus, optimization of the working bodies’ parameters of forest fire-fighting soil-throwers is relevant and in demand [7, 8].

The scientific novelty of the study lies in the fact that the design parameters of the new machine (protected by patent for invention No. 2616021) and the process of simultaneous interaction with the soil of milling cutter-thrower and casing-ripper of the forest fire soil-thrower are taken into account both in the mathematical models and computer program [10]. New analytical dependences of the average range of soil ejection, machine productivity and power supplied on the implementation of effective workflow on the optimal design parameters of the milling thrower have been identified.

The aim of the work was to increase the efficiency of the process flows of a new forest fire-fighting soil-throwing machine by optimizing the parameters of the milling thrower.

2. Calculations
Among the large number of design and kinematic parameters of a forest fire soil-thrower, the parameters of the milling-thrower blades, such as blade length \( l \) and blade width \( h \), have the most significant effect on the efficiency of the process flows. Since the volume of the soil captured by the milling thrower depends on their values, and the effectiveness of this machine is largely determined by this volume criterion. The design parameters of the milling thrower do not have such an effect on the
overall efficiency of the machine being developed. Optimization should be carried out to determine the optimal indicators of the parameters \( l_f \) and \( h_f \). As a rule, the main criteria for optimization are such parameters as: the performance of the developed structure, the quality of the process flows, and economic efficiency [35]. For a forest soil-thrower, these criteria are \( L_{av} \) – the average distance of soil displacement, m, \( P \) – machine capacity, \( m^3/s \), and \( N \) – supplied power to implement an effective workflow, kW.

The optimization task was to find such values of the parameters \( l_f \) and \( h_f \) at which the average distance of the soil displacement \( L_{av} \) and the productivity of the machine \( P \) would be as large as possible, and the power \( N \) spent by the fire-fighting soil-throwing machine – the smallest one. In our case, the optimization problem was written using the following system of equations:

\[
\begin{align*}
L_{av}(l_f, h_f) & \rightarrow \text{max}; \\
P(l_f, h_f) & \rightarrow \text{max}; \\
N(l_f, h_f) & \rightarrow \text{min}.
\end{align*}
\]

(1)

A series of 16 computer experiments of the developed design was carried out (table 1) to solve the optimization problem and identify the relationship between the necessary criteria and parameters, [6, 7]. In this series, the blade length parameter \( l_f \) was changed at the levels of 170, 200, 230, 260 mm, and the blade width parameter \( h_f \) was changed at the levels of 160, 180, 200, 220 mm.

3. Results and discussion

The approximation of the obtained experimental results was carried out using the mathematical program MathCAD 15 by the method of least squares. After the approximation, the following analytical expressions were obtained:

\[
\begin{align*}
L_{av}(l_f, h_f) &= 0.413l_f + 0.173h_f + 1.2 \cdot 10^{-4}l_f \cdot h_f - 9.375 \cdot 10^{-4}l_f^2 - 3.889 \cdot 10^{-4}h_f^2 - 50.032; \\
P(l_f, h_f) &= -3.715 \cdot 10^{-3}l_f + 3.382 \cdot 10^{-4}h_f + 4.767 \cdot 10^{-4}l_f \cdot h_f + 8.75 \cdot 10^{-6}l_f^2 - 2.222 \cdot 10^{-6}h_f^2 + 0.418; \\
N(l_f, h_f) &= -0.101l_f + 0.072h_f - 7 \cdot 10^{-5}l_f \cdot h_f + 3.437 \cdot 10^{-4}l_f^2 - 9.722 \cdot 10^{-5}h_f^2 + 33.402.
\end{align*}
\]

(2)

where \( l_f \) and \( h_f \) – the length and width of the blade of the milling-thrower, measured in millimeters (mm); \( L_{av} \) – average distance of soil displacement, m; \( P \) – machine productivity, \( m^3/s \); and \( N \) – power consumption, kW.

Table 1. Results of theoretical experiments on the influence of design parameters of a milling working body of a forest fire soil-thrower on its performance indicators.

| \( h_f, m \) | \( l_f, mm \) | \( N, kW \) | \( L_{av}, m \) | \( P, m^3/s \) |
|---|---|---|---|---|
| 160 | 170 | 33.2 | 14.2 | 0.17 |
| 160 | 200 | 34.5 | 14.9 | 0.178 |
| 160 | 230 | 35 | 15.6 | 0.183 |
| 160 | 260 | 35.8 | 16.1 | 0.192 |
| 180 | 170 | 34.2 | 15.2 | 0.176 |
| 180 | 200 | 34.7 | 17.1 | 0.18 |
| 180 | 230 | 34.9 | 17.8 | 0.181 |
| 180 | 260 | 35 | 18.4 | 0.188 |
| 200 | 170 | 34.5 | 17.7 | 0.186 |
| 200 | 200 | 34.8 | 19.7 | 0.199 |
| 200 | 230 | 35 | 20.1 | 0.21 |
| 200 | 260 | 35.4 | 20.5 | 0.212 |
| 220 | 170 | 34.4 | 18 | 0.186 |
| 220 | 200 | 35.3 | 19.8 | 0.22 |
| 220 | 230 | 36.1 | 21.3 | 0.225 |
| 220 | 260 | 36.4 | 20.6 | 0.234 |
F-criterion (Fisher criterion) was used to carry out a statistical assessment of the significance of polynomials’ coefficients [8, 9]. The obtained analytical laws $L_{av}(l_f, h_f)$ (figure 1a), $N(l_f, h_f)$ (figure 1b), $P(l_f, h_f)$ (figure 1c) for convenience, were displayed in the form of graphic images with the help of response surfaces [6].

Upon further quantitative analysis, the resulting response surfaces were represented as level lines. On each response surface and level lines, the factor space $(l_f, h_f)$ was divided into areas: favorable (shaded area, red), in which the necessary optimization criterion shows the maximum or minimum value, and not favorable (purple), in which the optimization parameter we need takes the opposite, negative value.

![Figure 1](image1.png)

**Figure 1.** Private response surfaces when optimizing design parameters $l_f$ and $h_f$: (a)– for an average range of ground release $L_{av}$, m; (b) for power consumption $N$, kW; (c) for productivity $P$, m$^3$/s; where the axis OX is the length of the blade $l_f$, mm, OY is the width of the blade $h_f$, mm, OZ is one of the indicators of efficiency.

To set the boundary values of the necessary criteria, which will divide the favorable and unfavorable areas, the generally accepted rule was used: the favorable area should occupy from 10 to 30% of the factor space. It should not include areas of abrupt changes in function and should be linked to the normative values of each criterion [6, 8, 10].

The boundary between the favorable and unfavorable areas for the function $L_{av}(l_f, h_f)$ was the isoline of 20 m; for $N(l_f, h_f)$ - isoline 35 of kW; for $P(l_f, h_f)$ - the isoline of 20 m$^3$/s. As a result, the obtained optimization cards enabled the design engineer to choose the values of the length and width parameters of the blades of the milling-thrower at which the performance indicators would be in the most optimal range.

When superimposing the favorable areas of the three efficiency criteria, one common graph was obtained showing the general optimal area of all three efficiency criteria (figure 2a, 2b). Analysis of the obtained figure 2a showed that the most optimal combination of design parameters of the length and width of the blade does not have a common optimal zone of all three efficiency parameters. We can notice that the optimal area of expended power $N$ has no intersections with the zone of optimal values of the area $L_{av}$. At the same time, the zone of optimal values of $P$ has intersections with both the region $N$ and the region $L_{av}$. This suggests that the supplied power goes beyond the acceptable values (40 kW for the hydraulic system intended for use) at optimal values of the blade length and width. However, taking into account the desired mass and dimensions of the structure being created, it was decided to expand the optimal values of the efficiency parameters, as well as length and width of the blades.

For visual study, an additional graph of the optimal areas of the three efficiency parameters was constructed. Studying this graph, we can note that when expanding the zone of optimal values of the studied factors $l_f$ and $h_f$, as well as the allowable operating costs of hydraulic power 35-38 kW (figure 2b), the zone of intersection of all 3 areas was obtained.
Figure 2. The overall optimal domain of factor spaces of the parameters $l_f$ and $h_f$, where the axis $OX$ is the length of the blade $l_f$, mm, $OY$ is the width of the blade $h_f$, mm: (a) initial optimal domain of factor spaces; (b) extended optimal domain of factor spaces.

After analyzing the obtained dependencies, we can recommend $l_f = 200-230$ mm, $h_f = 150-220$ mm as the optimal values for the length and width of the blade. Two-factor optimization of the design parameters of a milling working body made it possible to determine their optimal values: blade length $l_f = 200-250$ mm and blade width $h_f = 150-210$ mm. At the same time, the forest fire soil-thrower throws the soil into the fire zone up to 21 m. It consumes no more than 38 kW of power, and its productivity is $0.22$ m$^3$/s on the average.

4. Conclusion

Thus, the scientific novelty of the study lies in the fact that the design parameters of the new machine (protected by patent for invention No. 2616021) and the process of simultaneous interaction with the soil of milling cutter-thrower and casing-ripper of the forest fire soil-thrower are taken into account both in the mathematical models and computer program. New analytical dependences of the average range of soil displacement, machine productivity and power spent on the implementation of an effective workflow on the optimal design parameters of the milling thrower have been identified. Multifactorial optimization of the parameters enabled to determine the most suitable length and width of the working body blades. It subsequently enabled to simplify and optimize the creation of the experimental model of the fire-fighting soil-throwing machine under development. The conducted studies contributed to increasing efficiency of the process flows of forest fire soil-thrower and can be used in the design of new components.

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