Forest fire extinguishing: theoretical study of the screw drum parameter influence on the efficiency of a forest fire soil-sweeping machine

I M Bartenev1, S V Malyukov1,2* and M A Malyukova2

1Forestry Mechanization and Machine Design Department, Voronezh State University of Forestry and Technologies named after G.F. Morozov, 8 Timiryazev street, 394087 Voronezh, Russian Federation
2Department of Production, Repair and Operation of machines, Voronezh State University of Forestry and Technologies named after G.F. Morozov, 8 Timiryazev street, 394087 Voronezh, Russian Federation

*E-mail: mf_malyukov@vgltu.ru

Abstract. Forest fires are studied and developed in all countries with forest resources. However, despite large number of studies, the problem is still far from being resolved and fires still cause great damage to forests. The article deals with research on the influence of the screw drum parameters on the quality of removing the surface soil layer from combustible materials and on the performance of the forest fires soil-sweeping machine. The geometric parameters of the screw drum of the forest fires soil-sweeping machine were optimized. As a result of optimization, the optimal values of the screw channel depth in the range of 7.5-8.7 cm and the screw pitch of 23-40 cm were obtained. At these optimal values, the ground cover content in the thrown soil stream will be less than 15 %, the productivity of the forest fires soil-sweeping machine will be more than 40 kg/s, and the power consumption will be less than 12 kW.

1. Introduction

The problem of fighting forest fires is one of the oldest in human life. According to forest fire statistics more than 300,000 forest fires occur annually on the globe. Only in the last decade, the number of fires has increased by 1.5 times. This happened for two reasons, due to the development of new areas and as a result of more intensive human visits to the forest [1].

The article [2] provides information that forests play a very important role in preserving the environment. At the same time, fires are the main danger. This article presents methods for detecting and extinguishing forest fires. The authors suggest detecting a fire using special temperature sensors. The authors of the article [3] say that the process of spreading a forest fire is influenced by many factors. They managed to create a three-dimensional model of the fire propagation process. This model was tested in real conditions. In the article [4], the authors talk about various difficulties that arise while extinguishing forest fires. They developed tactics to extinguish forest fires. We optimized the number of people and fire engines involved in fire suppression.

In the article [5], the authors presented various technical solutions aimed at improving the effectiveness of forest fire control. In the article [6], the authors assess the risk of forest fires caused by
lightning. The results of their research are of interest to the scientific community and help prevent the spread of forest fires. A large number of annual forest fires have a significant impact on the state and functioning of forests. Forest fires cause enormous damage to nature and the economy. Unfortunately, not only plants and animals, but also people often die in the fire. Forest fires are a problem for all of humanity. Forest fires have a particularly destructive effect on those countries, most of which are covered with forest. In these countries, a forest fire becomes a national tragedy, as it has a significant impact on the country's economy [7].

While conducting a detailed analysis of modern serial technical means for creating mineralized, barrier strips, as well as for extinguishing forest fires, we see that the existing machines do not fully meet the requirements for it. This circumstance has become the reason for creating new multifunctional technical means. These tools would have absorbed all the positive qualities of the units and machines produced today. The scope of its application would be much broader. It would be devoid of serious drawbacks. Thus, the justification of the parameters of the working bodies of a forest fire soil-sweeping machine intended for the elimination of forest fires, as well as the creation of firefighting lanes, is relevant and in demand.

The purpose of this work was to study the influence of the depth of the screw channel and the pitch of the screw drum on the degree of cleaning of the surface soil layer from combustible materials (leaves, branches), the productivity of the ground-sweeping machine and power consumption.

2. Experimental part

In the publications of the authors [8-10], the method of extinguishing forest fires using soil was considered. To do this, they used a ground-sweeping machine. They also used this machine to prevent forest fires. It was used to create fire-fighting mineralized strips.

Previously, the authors published an article [11], which examined the mathematical model. It allowed us to simulate the process of extinguishing a fire with soil. A computer program was created based on this mathematical model. The computer program made it possible to visually track the operation of the ground-sweeping machine. Using a computer program, the geometric parameters of the working bodies of the ground-sweeping machine were set, as well as various types of soil were simulated (figure 1a-c).

Figure 1. A fragment of a computer program showing the operation of a forest fires soil-sweeping machine in three projections: left (a), top (b), and front (c) views.

The mathematical model was based on Newton's second law. The method of discrete elements (DEM) was used [12, 13]. The working bodies of the ground-sweeping machine were represented in the model by a set of elementary triangles. The screw drum was modeled as a separate geometric figure and was represented as a cylinder. The screw screws were also represented as triangles (figure 1).

The remaining free edges after joining the triangles played the role of cutting edges of the rotor, disk, and screw. The rotor, the drive and the auger drum were rotated with prescribed angular velocities. To set the disk at two spatial angles, two transformations of the coordinates of the vertices of elementary triangles were performed.

During the simulation, the interaction of each soil element with each triangle of working surfaces was constantly checked. After that, the forces of elastic interaction and viscous friction were
calculated.

During the computer experiment, the ground-sweeping machine moved at a constant speed along one of the coordinate axes. During the first two seconds of the model time from the beginning of the computer experiment, the ground-sweeping machine switched to a steady mode of operation and formed a flow of soil moving along a parabolic trajectory.

The numerical integration of differential equations of motion of soil elements was carried out by the second order Runge-Kutta method.

3. Results and discussion

As the main geometric parameters of the screw drum, we considered the depth of the screw channel \( h \) and the pitch of the screw \( s \). During computer experiments, we changed the depth of the screw channel \( h \) in the range from 4 to 16 cm in 4 cm increments (figure 2a-c).

![Figure 2](image)

**Figure 2.** Representation in the model of screw drums with different depth of the screw channel \( h \).

Analyzing the graphs shown in figure 3, we can say that at a shallow depth of the screw channel (4-6 cm), the screw drum does not remove the entire layer of ground cover. In this case, the process of shifting the cover to the side is ineffective. As a result, the share of the ground cover in the flow of the thrown soil is quite high and reaches values of 25-43 % (figure 3a). It leads to the fact that the productivity of the forest fires soil-sweeping machine is relatively low (about 38 kg/s) (figure 3b). However, the power consumption, in this case, is quite small (about 7-9 kW) (figure 3c). Since the screw drum experiences little resistance to rotation from the side of the soil cover layer of small depth (figure 3c).

![Figure 3](image)

**Figure 3.** The effect of the depth of the screw channel of the screw drum \( h \) on the performance indicators of the forest fires soil-sweeping machine: the proportion of \( \rho_p \) of soil cover in the soil flow (a), productivity \( P \) (b) and power consumption \( N \) (c).

With a large depth of the screw channel (12-16 cm) (figure 3a-3c), the screw drum is deeply embedded in the soil, and cleans the working strip not only from the ground cover, but also from the upper soil layer. At the same time, the share of soil cover in the propelled soil is very small (4-9%) (figure 3a), the productivity of the forest fires soil-sweeping machine is relatively high (42-44 kg/s) (figure 3b). However, the power consumed by the forest fires soil-sweeping machine is excessively high (about 16-24 kW) (figure 3c), and the screw drum, which is deeply embedded in the soil cover and soil and is involved in an intensive mechanical process, consumes the bulk of the power.

During numerous experiments, we found that the optimal value for the depth of the screw channel is a range of 8-10 cm (figure 3a-c). In this case, the screw almost completely clears the working strip.
from the ground layer. Another positive point is that the screw is not too deep. Large power losses are not observed. Analyzing figure 3, we see that the share of ground cover in the thrown soil is within 11-15 %, the productivity of the forest fires soil-sweeping machine is about 41 kg/s, the power consumption is quite small 11-13 kW.

To obtain reliable data on the effect of the second geometrical parameter of the screw drum – the pitch of the screw \( s \) on the operation of the forest fires soil-throwing machine, we studied it together with the influence of the screw channel depth \( h \). Further, in the experiment, we set the goal of two-factor optimization of geometrical parameters of the screw drum. Analytically, this optimization problem was written as follows:

\[
\begin{align*}
 p_p(h,s) & \to \min; \\
 P(h,s) & \to \max; \quad \Rightarrow h^{optimal}, \ s^{optimal}; \\
 N(h,s) & \to \min;
\end{align*}
\]  

(1)

The solution to the optimization problem was to find a region of changes in factors \( h \) and \( s \), in which the share of ground cover in the soil flow \( p_p \) and the power consumed by the forest fires soil-sweeping machine \( N \) will be minimal at the same time, as well as the maximum productivity of the forest fires soil-sweeping machine \( P \).

\[
\begin{align*}
 p_p(h,s) & = 0.667 h^2 + 5.767 \cdot 10^{-4} s^2 - 0.040 h \cdot s - 13.75 h + 0.531 s + 74.75; \\
 P(h,s) & = -0.115 h^2 - 0.018 s^2 - 3.676 \cdot 10^{-3} h \cdot s + 3.496 h + 1.287 s - 0.473; \\
 N(h,s) & = 0.083 h^2 + 8.074 \cdot 10^{-3} s^2 + 2.941 \cdot 10^{-3} h \cdot s - 0.064 h - 0.539 s + 14.03;
\end{align*}
\]  

(2)\(\) \(\) \(\)  

(3)\(\) \(\) \(\)

where \( h \) and \( s \) measured in centimeters, \( p_p \) - in percent, \( P \) - in kilograms per second; \( N \) - in kilowatts.

Figure 4. Representation in the model of screw drums with different screw pitch \( s \).

To solve the two-factor optimization problem, nine computer experiments were carried out in which the screw depth of the screw channel \( h \) was changed at the levels of 4, 8, 12 cm while changing the screw pitch \( s \) at the levels of 16, 33, 66 cm. The external view of the screw drum at various screw steps is shown in figure 4a-c. To ensure the condition of continuity of the shift of the ground cover, the rotational speed of the screw drum \( \omega_d \) changed inversely with the screw pitch and was 7.2 rot/s for \( s = 16 \) cm (figure 4a), 3.5 rot/s for \( s = 33 \) cm (figure 4b), 1.8 rot/s for \( s = 66 \) cm (figure 4c).

Based on the data set obtained as a result of nine optimization computer experiments, as well as on the results of the approximation, the analytical formulas for the performance indicators of the forest fires soil-sweeping machine are obtained:

\[
\begin{align*}
 p_p(h,s) & = 0.667 h^2 + 5.767 \cdot 10^{-4} s^2 - 0.040 h \cdot s - 13.75 h + 0.531 s + 74.75; \\
 P(h,s) & = -0.115 h^2 - 0.018 s^2 - 3.676 \cdot 10^{-3} h \cdot s + 3.496 h + 1.287 s - 0.473; \\
 N(h,s) & = 0.083 h^2 + 8.074 \cdot 10^{-3} s^2 + 2.941 \cdot 10^{-3} h \cdot s - 0.064 h - 0.539 s + 14.03;
\end{align*}
\]  

(2)\(\) \(\) \(\)

(3)\(\) \(\) \(\)

(4)

where \( h \) and \( s \) measured in centimeters, \( p_p \) - in percent, \( P \) - in kilograms per second; \( N \) - in kilowatts.

Using these formulas, we can quickly evaluate the performance of the forest fires soil-sweeping machine. The scientific novelty of the article consists in obtaining data of analytical dependencies. In this case, it isn’t necessary to conduct real or computer experiments. Just change the values of the geometric parameters of the screw drum.

For further analysis, the functions \( p_p(h,s) \), \( P(h,s) \) and \( N(h,s) \) are presented in the form of graphs (figure 5) and cartograms (figure 6). The graphs allow you to visually analyze the nature of the influence of the depth of the screw channel and pitch of the screw of the screw drum on the performance indicators of the forest fires soil-sweeping machine. Cartograms are intended for
The graphs (figure 5a-c) represent the response surfaces. It is painted in different colors. The red color on the chart indicates a favorable area. In this area, the proportion of ground cover in the soil flow of \( p_p \) (figure 5a) and the power consumed by the ground-sweeping machine \( N \) (figure 5c) take minimum values. In this case, the productivity of the ground-sweeping machine \( P \) (figure 5b) takes the maximum value. The purple color on the chart means not a favorable area. In this area, the optimization parameters listed above take on a negative value. Other colors indicate a smooth transition from a favorable area to a non-favorable area.

An example of the use of cartograms is shown in figure 6a. If the depth of the screw channel is 6 cm (point \( A \)) and the screw pitch is 30 cm (point \( B \)), then the corresponding point of the factor space \( C \) falls next to the level line \( p_p = 25\% \) (figure 6a). That is, the share of soil cover in the soil flow will be 26%.

The areas of favorable (minimum or maximum) indicator values are highlighted in green on cartograms. The favorable and unfavorable areas are separated from each other by values equal to \( p_p = 15\% \) (figure 6a), \( P = 40 \text{ kg/s} \) (figure 6b) and \( N = 12 \text{ kW} \) (figure 6c). The choice was made based on the conditions that the favorable area will occupy a significant share of the factor space, include the smallest or largest (depending on the meaning) values of the criterion, and the border of the area will be a level line on the cartogram.

![Figure 5](image-url)

**Figure 5.** Graphs of the influence of the depth of the screw channel \( h \) and the screw pitch \( s \) of the screw drum on the share of the ground cover in the soil flow \( p_p \) (a), the productivity of the forest fires soil-sweeping machine \( P \) (b) and the power \( N \) consumed by the forest fires soil-sweeping machine.

![Figure 6](image-url)

**Figure 6.** Cartograms for optimizing the geometric parameters of the screw drum of a forest fires soil-sweeping machine. The favorable areas of the factor space are highlighted in green. The overall optimal area is highlighted in black.

The optimal area (figure 6d) is obtained by overlapping favorable areas. The optimal area
simultaneously takes into account the requirements of a low ground cover content in the soil flow, a high productivity value and a low power consumption of the forest fires soil-sweeping machine.

According to the optimal location in the factor space (figure 6d), we can draw the following conclusion. The optimum depth of the screw channel is 7.5-8.7 cm, the optimal pitch of the screw is 23-40 cm. In this case, the content of soil cover in the throwable soil stream will be less than 15%, the productivity of the forest fires soil-sweeping machine will be more than 40 kg/s, and the power consumption will be less than 12 kW.

The scientific originality of the article lies in the fact that the auger clears the upper fire-dangerous soil layer. The leaves and branches do not fall into the fire, while increasing the productivity of the ground-sweeping machine. In the article [12], the authors modeled the operation of a screw conveyor using the discrete element method (DEM). They determined the relationship between the speed of rotation of the screw and the nature of the particle flow. Their simulation results are consistent with experimental data. In the work [13], the authors studied the particle flow in screw feeders. They investigated the effect of the screw length on energy consumption and solid consumption. We also studied the forces of coupling of particles with each other. In the article [14], the geometric parameters of the screw were determined. The theoretical calculations were confirmed by experiments. As in our article, the authors [15] used the method of discrete elements (DEM) while conducting research. They studied the influence of various geometric parameters of the auger on energy consumption, particle consumption, and wear of the auger.

The optimal parameters of the screw drum obtained in this article can be taken into account when developing ground-sweeping machines. These machines will allow you to quickly extinguish a forest grassroots fire. Due to the fact that the surface layer of the soil is cleared of combustible materials, leaves and dry branches do not fall into the fire. The fire is extinguished with soil without combustible materials.

4. Conclusion

The influence of the depth of the screw channel and the pitch of the screw of the screw drum on the quality of soil cleaning from the ground cover, productivity and power consumption of the ground-sweeping machine is studied. Scientific originality consists in the fact that the installation of the screw allowed to prevent the release of the upper fire-dangerous layer of soil into the fire, to increase the productivity of the ground-sweeping machine. The scientific novelty lies in the fact that new analytical dependences of the proportion of ground cover in the soil flow, the productivity of the ground-sweeping machine and power consumption on the optimal geometric parameters of the screw drum were revealed. The two-factor optimization allowed us to obtain optimal values of the depth of the screw channel and the pitch of the screw. On the basis of the data obtained in this article the design of forest fires soil-throwing machines developed in the future will make it possible to cope more effectively with fire to more quickly localize the combustion zone. These ground-sweeping machines can be used to extinguish forest fires in various countries.

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