Systematization and mathematical modeling of classification features of forest rakes

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Abstract. With proper maintenance of many territories a technological operation of collecting and raking up chopped residues of undesirable tree and shrub vegetation is often performed. At the same time, despite the variety of mechanization tools used, their classification is currently difficult. The purpose of the research was to develop a classification of technical means for collecting and raking chopped residues with the justification of their name and rational definition. Based on the analysis of more than 500 models the authors of the research recommended to designate the considered technical means as “Forest Rake” and a corresponding definition has been formulated. The authors of the carried out the classification of forest rakes, a system of equations has been developed that describes the position of the boundaries of the characteristic zones of the distribution of the working width of the forest rake, the boundary values of a number of parameters are shown, the criteria for the density of the teeth and the specific width of the rake are proposed, the values of these criteria are given. The results of the work can be used by manufacturing enterprises engaged in the maintenance and operation of transport infrastructure facilities.

1. Introduction
With the current maintenance of a number of infrastructure facilities (for example, right-of-way of railways and highways, gas pipelines, oil pipelines, high-voltage power lines [1-3]), as well as other territories (for example, water intakes and airports), work is often carried out to remove unwanted tree and shrub vegetation from these areas [4-5]. One of the technological operations of the technological process of removing unwanted tree and shrub vegetation from the territory of the above objects [6, 7] is the operation of collecting and raking up chopped residues of this vegetation [8-11]. The specified operation, if it is performed mechanically, is carried out using a specialized technical tool designed to collect and / or rake up uncrushed chopped residues and hung on the front or rear hitch of a tractor or on the end of the manipulator arm of a multifunctional machine (figure 1).

Our study of modern technical means for collecting and raking chopped residues revealed a variety of appropriate means of mechanization used, differing in a whole range of parameters [12, 13]. However, at the same time, we found that, despite the widespread use of the considered technical means in world practice, to date, their classification has not actually been developed, and there is no generally accepted name and definition, which indicates the relevance of our research.
At the same time, we also found that, despite the large number of commercial offers from the manufacturers of the technical means considered in this work and their widespread use in world practice, the systematization of the means of mechanizing the collection and raking of chopped residues is currently difficult due to the actual absence in scientific and reference literature of the relevant classification features. In addition, we revealed the absence of a generally accepted name and definition of the considered technical means, which undoubtedly indicates the relevance of our research.

Taking into account the foregoing, the purpose of the research was to develop a classification of technical means for collecting and raking chopped residues with the justification of their name and rational definition.

2. Methods and materials
The object of the research was the process of functioning of the system for the proper maintenance of a number of infrastructure facilities (right-of-way of railways and highways, gas pipelines, oil pipelines, high-voltage power lines) and other territories. The subject of the study was the technological processes of removing unwanted tree and shrub vegetation from the territories of a number of infrastructure facilities and the means of mechanization used in the performance of the corresponding technological operations.

The research materials were scientific and technical information that was relevant at the time of the work, in particular, catalogs of technical means for collecting and raking unwanted vegetation, posted on the official websites of the manufacturers of this equipment. When performing the work, the methods of systemic and logical analysis, as well as mathematical statistics were used. To achieve this purpose, we analyzed more than 500 models of means of mechanization of collection and raking of chopped residues from various manufacturers representing the countries of Europe, Asia, Africa and North America.

3. Results and discussion
To register the main constructive parameters of modern technical means for collecting and raking chopped residues, including information about their manufacturer and the base vehicle, we have developed a map, an example of filling which is shown in figure 2.

Analysis of the names of the technical means considered in this work allowed us to identify the predominant presence of the word “Rake” (74.4%) with widely represented such characteristics as “Forest”, “Brush”, “Root”, “Dozer”, “Excavator”, “Grapple” etc.
Figure 2. Registration card of the main design parameters of technical means for collecting and raking chopped residues.

Taking this into account, in view of the prevalence of the name of technical means for the collection and raking of chopped residues, as ‘Rake’ and characterizing their non-procedural sign associated with the forest (‘Forest’), we think it expedient to recommend (for the introduction into the practice of organizing work to remove unwanted vegetation in the territories of various infrastructure facilities) to designate the above mentioned technical means as “Forest Rake”.

Despite the actual prevalence in mechanical engineering of means of mechanizing the collection and raking of unwanted vegetation (including its remnants) with the above recommended name, we carried out an information search through numerous dictionaries and encyclopedias (explanatory, forestry, etc.; for example, [14, 15]), as well as technical literature, it was revealed that there is no definition of what exactly should be considered a technical device with the name “Forest Rake”. In our opinion, the definition of a given technical means should reflect its characteristics as equipment intended for the performance of special purposes (with indication these purposes), as well as information about the territories of the preferential use of these technical means.

With this in mind, we propose to introduce into the practice of organizing work to remove unwanted vegetation on the territories of various infrastructure facilities the following definition of a technical means for the collection and raking of chopped residues: “Forest Rake is specialized equipment designed to collect and/or rake uncrushed chopped residues in areas to be cleared of unwanted tree and shrub vegetation”.

At the same time, it should be clarified that the definition proposed by us, inherent in all technical means of mechanical removal of chopped residues considered in this work, requires expansion, if necessary and/or the desire of the corresponding manufacturer, to convey to the end consumer more information about the features of the forest rakes he produces, including taking into account the information given in ISO 6814: 2009 “Machinery for forestry - Mobile and self-propelled machinery - Terms, definitions and classification”, as well as the classification of these technical devices developed by us.

The classification of specialized equipment designed for collecting and/or raking up uncrushed chopped residues was developed by us as a result of analysis, generalization and systematization of the data obtained from the study on forest rakes. At the same time, we identified a number of classification features related to the purpose, scope, types and methods of aggregation with the base vehicle, as well as constructive features of the considered technical means (figure 3).

Taking into account the research carried out by us, the technical means of collecting and raking the chopped residues are classified as follows:

- by destination – general purpose and special purpose;
- by type of aggregation – with multifunctional machine and with a tractor;
- by direction impact – direct, reverse and universal;
- by aggregation method – hinged and trailed;
- by fixing – stationary and superimposed;
- by placement - avant-garde and rearguard;
Figure 3. Classification of technical means of collection and raking of chopped residues.

- by drive type – mechanical, hydraulic, electrical and combined;
- by working width – extra-width, width, medium-width, normal, narrow and extra-narrow;
- by density – extra-bushy, bushy, normal, rare and extra-rare;
- by the profile of the surface of the teeth – arc, orthogonal, broken lines and other;
- by cross-section of the surface of the teeth – unchanging and variables;
- by clamping devices – in stock or absent;
- by protective devices – in stock or absent;
- by safety devices – in stock or absent.

The proposed classification of forest rakes makes it possible to systematize the currently produced (as well as previously produced and planned for production) technical means for collecting and raking chopped residues according to a number of parameters related to both the parameters of the considered technical means and the parameters of the basic vehicles, and also the environment. On the basis of the developed classification of forest rakes, it is possible to create both a database of available design solutions for technical means of collecting and raking chopped residues, as well as developments and mathematical models of the corresponding work processes for removing unwanted tree and shrub vegetation from the territories of infrastructure facilities.

When working on the resulting classification, we paid special attention to such classification features of forest rakes as "By working width" and "By density". To obtain adequate classification series of these features, we carried out an additional study of the obtained data sample on such basic constructive parameters of forest rakes as the working width (designated by us $R_B$, mm), the width of one tooth ($Z_B$, mm) and the number of teeth $Z$. Previously, we introduced the following boundary criteria for these parameters: $Z \geq 2$, $500 \leq B \leq 4000$, $12 \leq B \leq 100$, while a detailed explanation of the values of the boundary criteria adopted by us is not included in the goals and objectives of this research.

The results of the research made it possible to confirm the hypothesis about the possibility of dividing the general population into three parts with obtaining the corresponding dependencies: $R_B = f(Z_B)$: $R_B^{(1)}$, $R_B^{(II)}$ and $R_B^{(III)}$ (figure 4), and also to identify the basic system of equations...
describing the position of the boundaries of the characteristic zones of distribution of the working width of the forest rake from the number of their teeth:

\[
\begin{align*}
B_{R}^{(O-I)} &= -1.222 \cdot B_{Z}^2 + 149.357 \cdot B_{Z} - 338.836 \\
B_{R}^{(I-II)} &= -0.674 \cdot B_{Z}^2 + 92.853 \cdot B_{Z} - 678.523 \\
B_{R}^{(II-III)} &= -0.0957 \cdot B_{Z}^2 + 24.994 \cdot B_{Z} + 100.076 \\
B_{R}^{(III-O)} &= -0.0112 \cdot B_{Z}^2 + 6.324 \cdot B_{Z} + 264.62
\end{align*}
\]  

where \( B_{R}^{I}, B_{R}^{II}, \) and \( B_{R}^{III} \) – preliminary dependences of the width of the forest rake on the width of one tooth, respectively, for wide, normal and narrow forest rakes.

**Figure 4.** Zonal and boundary distributions of the dependence of the width of the forest rake on the width of one tooth.

Regarding the consideration of the dependence of the working width of the forest rake capture on the number of their teeth \( B_{R} = f(Z) \), the following should be noted. Despite the fact that we did not identify adequate regression equations for the obtained sample, describing this dependence with a sufficient degree of accuracy, nevertheless it is an obvious fact that with an increase in the number of teeth \( Z \), the width of the forest rake \( B_{R} \) also increases. However, with a stably constant value of \( B_{R} \), an increase in \( Z \) (at \( B_{Z} = \text{const} \)) inevitably leads to a decrease in the interval (distance) between two adjacent teeth \( B_{pr} \) (mm) determined by the dependence:

\[
B_{pr} = \frac{B_{R} - Z \cdot B_{Z}}{Z - 1}
\]

Taking into account the above, we will establish the boundary criteria \( I_{Rz_{\text{min}}} \) and \( I_{Rz_{\text{max}}} \) of the ratio of the width of the teeth \( B_{Z} \) of the forest rake and the interval between two adjacent teeth \( B_{pr} \):
where the achievement of the boundary criterion of the width teeth of the forest rake \( I_{Rz} = 0 \) corresponds to the transition of the forest rake to the category of ‘dumps, buckets’, and \( I_{Rz} = 1 \) – to the category of forest brushes.

As an indicator of the density of the distribution of forest rake teeth, we propose to use a criterion \( D_{Rz} \) defined as the ratio of the interval between two adjacent teeth \( B_{pr} \) and the width \( R \) of the forest rake:

\[
\begin{align*}
\text{at } B_{pr} \to 0: & \quad D_{Rz_{\min}} = \lim_{B_{pr} \to 0} \frac{B_{pr}}{R} \to 0 \\
\text{at } B_{pr} \to B_{R}: & \quad D_{Rz_{\max}} = \lim_{B_{pr} \to B_{R}} \frac{B_{pr}}{R} \to 1
\end{align*}
\]

where the achievement of the criterion of the density of distribution of the teeth of the forest rake as \( D_{Rz_{\min}} = 0 \) and \( D_{Rz_{\max}} = 1 \) corresponds to the transition of the forest rake into the category ‘dumps, buckets’.

It should be noted that despite the similarity of the expressions of the criteria for the width teeth of the forest rake \( I_{Rz} \) and the density of the distribution of the teeth \( D_{Rz} \), there are significant differences between them, which determine that criterion \( I_{Rz} \) characterizes the moment of transition ‘dumps (buckets) \( \leftrightarrow \) forest brushes’, while criterion \( D_{Rz} \) actually shows the degree of remoteness to the specified transition.

Taking into account the above, in order to ensure the possibility of classifying existing and prospective constructions of forest rakes, we propose to introduce the following criteria into practice in scientific and reference literature (as well as at industrial enterprises and when organizing work to remove unwanted tree and shrub vegetation from the territories of various infrastructural objects) the following criteria and their corresponding scales.

To assess the density of the distribution of forest rake teeth along their working width, we propose to use criterion \( D_{Rz} \) (taking into account the ratio of the interval between two adjacent teeth \( B_{pr} \) and the width \( B_{R} \) of the forest rake: \( D_{Rz} = B_{pr} / B_{R} \)) as a classification characteristic, with the following boundary values (table 1):

| Criterion \( D_{Rz} \) | Characteristics of the forest rake |
|-----------------------|----------------------------------|
| 0 \ldots 0.04         | extra-bushy                      |
| 0.04 \ldots 0.09      | bushy                            |
| 0.09 \ldots 0.25      | normal                           |
| 0.25 \ldots 0.5       | rare                             |
| 0.5 \ldots 1.0        | extra-rare                       |

To assess the working width of a forest rake as a classification characteristic, we propose to use the specific width rake criterion \( SW_{R} = f(B_{R}; B_{Z}) \), defined as a function of the ratio of the rake's
working width to the width of one tooth (figure 5). The boundary values of this criterion are set according to the dependencies we have identified (1), taking into account the following corrective trends we have identified:

\[ B_{R_{corr}}^{(O-I)} = -0.1802 \cdot B_Z^2 + 43.665 \cdot B_Z + 1171.994 \]  
(2)

\[ B_{R_{corr}}^{(I-II)} = -0.1802 \cdot B_Z^2 + 43.665 \cdot B_Z + 368.466 \]  
(3)

Note that for the corrective trend (2) we have identified the boundary point of its beginning \( B_{Z_{corr}}^{O-I} = 84.2351 \) mm (figure 4), and for the corrective trend (3) the boundary point of its beginning \( B_{Z_{corr}}^{I-II} = 68.7878 \) mm. In addition, to assess the width of the forest rake, we determined the lower limit of the distribution of extra-wide forest rake \( B_{R_{c\ min}}^{V-I V} = 4224.892 \) mm and the lower limit of the distribution of the extra-narrow forest rake \( B_{R_{\ c\ min}} = 3 \cdot B_Z \), mm.

\[ S W_R \]

**Figure 5.** Classification distribution of forest rakes according to the criterion of specific width \( SW_R \).

In figure 6a shows the distribution of the forest rake models adopted by us in the analysis by the criterion of the density of the distribution of teeth \( D_{R_z} \). In figure 6b shows the distribution of the forest rake models adopted by us in the analysis according to the criterion of specific width \( SW_R \). It should be noted that, in accordance with our proposed classification, about 9% of forest rakes are extra-bushy (with a predominant number of teeth \( Z \geq 20 \) and a medium-wide or normal working width), while there are practically no extra-rare forest rakes (with a number of teeth \( Z = 2 \)).
Figure 6. Distribution of forest rake models: (a) by the criterion of tooth density $D_{rz}$; (b) by the criterion of specific width $SW_k$.

Also in accordance with our proposed classification the most common (about 43%) are forest rakes of normal width, at the same time, we revealed a comparable total number of medium-wide (about 37%) and wide (about 5%) forest rake. Rarely are extra-wide rakes with a working width of more than 4200 mm (about 1.5%) and virtually absent – extra-narrow forest rakes, which were included by us in the above classification only taking into account a small share of the probability of appearance on the market of forest rakes of technical means with constructive parameters corresponding to extra-narrow rakes.

As an example, let us classify some modern models of forest rakes (figure 7):

Figure 7. Visualization of classified forest rake models: (a) Norm Engineering Stick Rakes; (b) Digga Stick Rake; (c) Bedrock BDR 14 Rake; (d) ZPI.

- Norm Engineering Stick Rakes – hinged, stationary, avant-garde in placement, medium-wide, extra-bushy general-purpose forest rakes, aggregated with a multifunctional machine, hydraulic drive, direct impact, with a broken lines profile of a unchanging cross-section of the tooth surface (figure 7a).
- Digga Stick Rake – hinged, stationary, medium-wide, bushy forest rakes for general purposes, aggregated with a multifunctional machine, hydraulic drive, universal impact, with an arc profile of a unchanging cross-section of the tooth surface (figure 7b).
- Bedrock BDR 14 Rake – hinged, superimposed, avant-garde in placement, medium-wide, bushy forest rakes of general purpose, aggregated with a bulldozer, mechanical drive, direct impact, with a straight profile of unchanging cross-section of the tooth surface (figure 7c).
- ZPI – hinged, stationary, rearguard in placement, normal in width and density, general purpose forest rakes, aggregated with a tractor, hydraulic drive, direct impact, with a broken lines profile of unchanging cross-section of the tooth surface and the presence of protective devices (figure 7d).
4. Conclusion
As a result of the analysis, generalization and systematization of scientific and technical information obtained in the course of research on technical means of collecting and raking up unwanted vegetation (including its chopped residues), for the introduction into the practice of organizing work to remove unwanted vegetation in the territories of various infrastructure facilities:

1. It is recommended to designate technical means for collection and raking of chopped residues as “Forest Rake”.
2. The following definition of a technical means for the collection and raking of chopped residues has been formulated: “Forest Rake is specialized equipment designed to collect and/or rake uncrushed chopped residues in areas to be cleared of unwanted tree and shrub vegetation”.
3. A number of classification features were identified and the classification of technical means for the collection and raking of chopped residues was performed.
4. A system of equations has been developed that describes the position of the boundaries of the characteristic zones of the distribution of the working width of the forest rake from the number of their teeth, the boundary values of a number of parameters are shown.
5. To assess the density of the distribution of forest rake teeth along the width of their capture, the criterion of the density of the teeth $D_{R_{Z}}$ is proposed as a classification characteristic, the values of this criterion are given.
6. To assess the working width of the forest rake, the criterion of the specific width of the rake $SW_{R}$ is proposed as a classification characteristic, and the graph of the classification distribution of the forest rake according to this criterion is given.
7. On the basis of the developed classification of forest rakes, it is possible to create both a database of available design solutions for technical means of collecting and raking chopped residues, as well as developments and mathematical models of the corresponding work processes for removing unwanted tree and shrub vegetation from the territories of infrastructure facilities.

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