Search for reserves to improve the efficiency of forest soil preparation technology and land clearing during reforestation by reducing the energy intensity of the process

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Abstract. The intensive development of forest areas in the Russian Federation leads to the need for a significant amount of work related to reforestation. High-quality soil preparation is the key to successful survival of forest planting material of economically valuable species. Traditional technologies of forest soil preparation by dump plowing are outdated today and do not allow to radically increase the level of labor productivity. In the work, calculations were made of the power costs required for soil preparation in the process of mineralization by a forest plow of the PLP-70 type. It has been established that a standard tractor of the Onezhets-300 series, when moving with a plow in a cutting area with simultaneous cutting of shrubs and small forests, allows for confident processing at a speed of no more than 0.3 m/s. This ensures productivity up to 1.5 hectares per shift. To ensure the growth of shift output up to 3.5...4 ha per shift, the required tractor power is at least 250 kW. Domestic serial forestry tractors cannot provide productivity growth, since they have an internal combustion engine power less than required.

1 Introduction

The strategy for the development of the forest complex of the Russian Federation until 2030 calls the insufficient efficiency of reforestation one of the main problems hindering the

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development of the forest complex. Having decreased by almost 2 times over the past 20 years, the annual volume of reforestation today has stabilized at the level of 800 - 900 thousand hectares. Due to the non-compliance with the agrotechnics of growing the created forest crops, their high death is noted in the period before being transferred to the forested area. The need of established forest plantations for agrotechnical care is only half satisfied. The predominant way of reforestation is to promote natural regeneration. Artificially created forest plantations require agrotechnical care. At the same time, the need for agrotechnical care is satisfied only by 60%. Due to non-compliance with the agricultural technology of growing the created forest crops, their death is noted in the period before being transferred to the area covered with forest [1]. One of the reasons can be considered insufficient quality soil preparation, its mineralization. The predominant part of Russia's forests grows on soils subject to severe sodding, where reforestation measures do not bring success without effective preparation. Insufficient tillage is one of those significant problems caused partly by the lack of suitable machinery and partly by the lack of necessary funding. The wide range of different types of equipment for tillage developed in Russia, apparently, is not used in full.

2 Purpose and tasks of the work

The purpose of the work: Improving the efficiency of the process of soil preparation for reforestation by reducing the energy intensity of the process.

Tasks:

1. Determine the required amount of reforestation work, the types of equipment used.
2. Calculate the power costs in the preparation of forest soil by moldboard plowing with forest plows.
3. To analyze the traction and power balance of serial forest tractors in terms of the possibility of increasing the efficiency of forest soil cultivation during reforestation.

3 Problem statement

Annually in Russia, clear cuttings of forests are carried out on an area of more than 1.1 million hectares. In addition to logging, up to 0.2 million hectares die from the action of forest fires, pests, and adverse climatic factors. Over the past five years, the area of forests in Russia has decreased and amount to 765.9 million hectares in 2021. The total area of non-restored forests reached 3.1% of the total area of the forest fund. The results of audit control show that the areas of disposal of the forest fund exceed the areas of reforestation (Figure 1) [2].

Only in the taiga zone of the Russian Federation, about 500 thousand hectares are annually cut down, and the area of forest land requiring clearing is up to 250 - 280 thousand hectares. The total amount of forest areas requiring reforestation and, accordingly, soil preparation is at least 1 million hectares. Therefore, special equipment is required to prepare the soil of cutting areas for reforestation.

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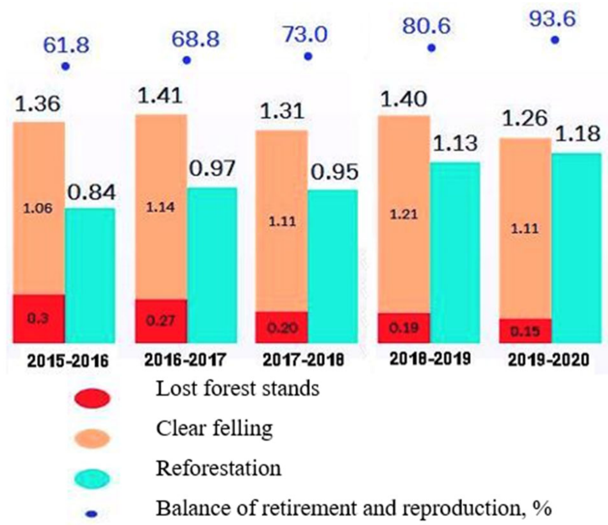

Fig. 1. Forest retirement and reforestation areas, million ha.

In Russia, quite a lot of research is being done on the issues of tillage [3-7]. A special role is played by studies of increasing the patency and energy efficiency of tillage implements operated under the conditions of the need for reforestation in areas that have not been uprooted. A number of studies have established that the use of rippers with disk working bodies in reforestation without uprooting stumps is relevant for meeting environmental requirements, as well as cost-effective [8]. Experiments conducted by Brack Forest indicate a big difference in results depending on where and how to plant seedlings. Experiments show that the depth and location of planting, the type of soil are crucial for the survival and development of the seedling. Milling rippers of the Bracke line are recognized as very effective (Figure 2) [9].

Fig. 2. Milling working body of the Bracke T26 installation and the result of soil milling during reforestation.

Tools with disk working bodies reduce the time of soil preparation, make it possible to work on unprepared sites with local irregularities [10,11]. To work in small areas, the Bracke T21.a disc cultivator is used, which is available in two versions (with a three-point attachment for aggregation with tractors). The design of this machine provides for the possibility of manual adjustment of the disc inclination at nine different angles [12]. To work on difficult, cluttered areas, more powerful rippers Bracke T26.a, Bracke T45.a are used (Figure 3).

Fig. 3. Milling working body of the Bracke T45 installation.

A design feature of the Bracke T26.a ripper is the ability to install manipulators and discs at different widths and at different angles, which allows for varying ground pressure and working body pressure. The Bracke T45.a cultivator is also an effective tool in open clearings, as it provides simultaneous processing of four strips [13]. During reforestation on clearings, promising designs of disc rippers are also used for basic soil preparation. These machines perform simultaneous tillage and partial clearing of the cultivated strips, shifting logging residues with working bodies. Rippers make it possible to provide high-quality tillage in difficult conditions of not uprooted and cluttered clearings [14, 15].

Known machine Bracke T26 (Figure 4), which provides discrete soil preparation and can be used on waterlogged soils.

Fig. 4. Discrete working body of the Bracke T26 installation.

When growing forest crops in clearings, the following methods of stump removal are used:

1. continuous uprooting; strip clearing of clearings;
2. partial uprooting of stumps on strips 2.5 m wide with their displacement to the adjacent backstage; milling the above-ground part of the stumps at the soil level in strips up to 4 m wide;
3. loosening the soil in strips 0.8–1 m wide to a depth of 20 cm with simultaneous milling of stumps up to 20 cm in diameter and logging residues.

Each of these methods is characterized by specific features, has positive and negative sides. Continuous uprooting of stumps during reforestation was implemented very rarely due to the high energy intensity, as well as significant costs. It is used mainly for the preparation of areas for nurseries, industrial crops, plantations and fruit and berry plantations.

The purpose of strip clearing or uprooting is to ensure comprehensive mechanization of reforestation processes in clearings and, despite a slight increase in costs at the beginning, ultimately achieve their reduction due to the creation of better conditions for the passage of forestry units. In the conditions of Siberia and the Far East, where the number of stumps per unit area at the felling age is usually less than in clearing areas of the European part of the Russian Federation, stump uprooting can be omitted, but limited to clearing clearings from logging residues and deadwood with simultaneous cutting of small stumps.

Over the designs of tools for preparing forest soil and clearing territories from low-value forest crops during their reconstruction, as well as strip clearing of clearings in order to improve the quality of the work of forest plows during reforestation work all over the world have been working for more than 90 years.

At present, forest plows PKL-70, PLP-70, PLP-135 are the most widely used in Russia (Figure 5). The plows are designed for plowing for sowing and planting forest crops in the forest and forest-steppe zones on not uprooted clearings with up to 600 stumps per 1 ha, as well as for laying mineralized firebreaks. With a large number of stumps, preliminary clearing is necessary.

The plow is a welded structure and consists of a frame that carries the details of the working bodies: a plowshare, dumps, a splitting knife in front, which splits the stumps, cuts the sod, pushes the deadwood and logging waste. The frame represents a spatial form, consisting of two horizontal beams welded at the joint to the riser and closed on both sides with sheets.


Fig. 5. PLP-70 plow and TDT-55A tractor aggregated with a plow.

The plow is aggregated with caterpillar tractors LHT - 4, TLP - 4, TT-4M, Onezhets-300 using a front or rear hitch. Capture width up to 2.5 m. Declared productivity for laying forest belt is 1.9 km/h. During the operation of the plowshare, the undergrowth and small stumps are cut off, and the dumps shift them into the inter-strip space along with logging residues and deadwood [16].

With the positive qualities of the listed tools (simplicity, low cost, minimal maintenance), which solve the problem of complex mechanization of work on preparing the soil in clearings, they also have a number of disadvantages. The disadvantages of such dumps when working on clearing cutting areas for reforestation is the increased energy intensity of the technological process. During the period of creation of the tools mentioned above, with sufficient engine power of the base tractor and extremely low cost of fuel and lubricants, this consideration did not play a significant role. The first place was given to the possibility of their serial production in experimental mechanical workshops on the existing machine park of a rather primitive level [17]. At present, the production of tractors LHT - 4 and TLP - 4 is carried out on a piece-by-piece basis at the Borovlyansky Mechanical Plant in the Altai Territory.

4 Results and discussion

Let us calculate the acting forces during the operation of a classic wedge plow used in clearing cutting areas during reforestation. The general view of the calculated structure is shown in Figure 6.

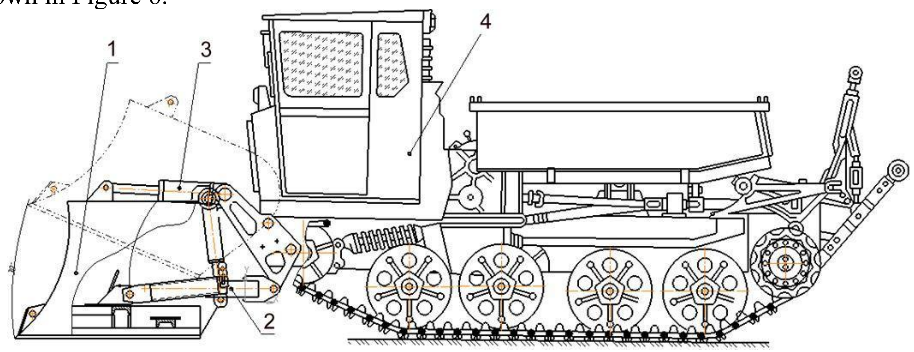

Fig. 6. Strip plowing machine with a wedge-type plow: 1 – wedge plow, 2 – hitch, 3 – hydraulic cylinder, 4 – basic tractor.

The main parameters of the tool in the form of a traditional wedge body are chosen on the basis of the relevant recommendations obtained in the study of such tools. The parameters of the working body are given in Table 1.

Table 1. Main parameters of the gun.

Parameter name	Meaning
Width of the wedge at the ends of the knives, m	$2.5^{\pm 0.02}$
Clearing depth, m	up to $0.8^{\pm 0.02}$
Angle of installation of knives in the horizontal plane, deg.	0^0
Knife sharpening angle, deg.	30^0
Angle of installation of knives from the longitudinal-vertical plane, deg.	40
Diameter of cut trees, m	up to 0.1
Working forward speed, V_d, m/s	0.26
Adhesion force, c_0, N/m^2	15000
Cross-sectional area of the cleared route, S, m^2	1.6….2.0
Volumetric gravity, γ_g, N/m^3	6000
Height of drawing prism (cavalier), h_k, m	0.6
Cavalier slope angle to the horizon, α_k, deg.	40^0
Loosening factor, f_p	0.8
Coefficient of external friction f_c	0.6
Angle of external friction, φ_c	31^0
Coefficient of internal friction, f_g	0.1
Angle of internal friction, φ_g	9^0

The working speed of movement of the implement is assumed to be 0.2 - 0.5 m/s, since the crawler tractor Onezhets 300 was chosen as the base tractor, which has a range of working speeds of 0.09 - 1.31 m/s, and a pulling force of up to 40 kN. The calculation of the forces acting on the working bodies (dumps) of the plow is carried out to determine the reactions acting on the plow when clearing the forest planting furrow from woody vegetation, calculating the tractive effort required to complete the clearing process.

The wedge working body is shown in Figure 7.

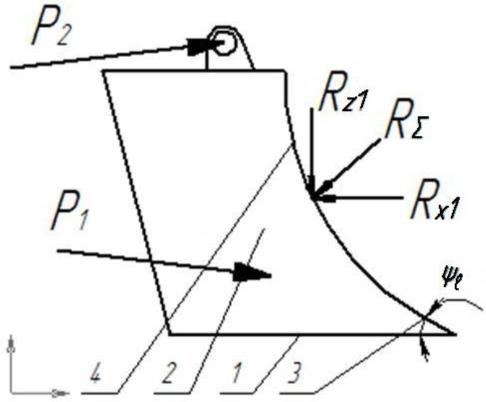

Fig. 7. Schemes of the wedge working body, side view: 1 – plough share; 2 – wing blade; 3 – sock; 4 – chest blade.

Since all elements of the working body are symmetrical with respect to the longitudinal-vertical plane of the unit and the guide curve, the components of the reactions perpendicular to the axis of the drain route are mutually balanced, and when considering the total reactions acting on the wedge, we can assume that they are located in the plane of motion, that is, in the plane of the guide curve. The horizontal ΣR_h and vertical ΣR_v components of the total reaction (kN) are determined by the expression

$$\Sigma R = \sqrt{\left(\Sigma R_{x1}\right)^2 + \left(\Sigma R_{z1}\right)^2}\ , \tag{1}$$

where R_{x1} and R_{z1} are the horizontal and vertical components of the reaction to the lower part of the working body, N.

The components of the reaction R_{x1} and R_{z1}, N, are determined by the following expressions

$$R_{x1} = c \cdot S \cdot B_1 \cdot B_2 + \gamma_g \cdot S \cdot h_k \cdot B_1 \cdot B_3, \tag{2}$$

$$R_{z1} = c_0 \cdot S \cdot B_2 \cdot B_4 + \gamma_g \cdot S \cdot h_k \cdot B_3 \cdot B_4, \tag{3}$$

$$B_1 = \frac{2 \cdot \cos\varphi}{\cos\left[0{,}5\left(\psi_{lu} + \psi_g\right)\right]} \cdot \frac{2 \cdot \cos\varphi}{\left[\sin\varphi_l \cdot \sin\alpha_l + tg\varphi_c \cdot \sqrt{1 - \sin^2\psi_l \sin^2\xi \cdot \left(1 + \cos^2\alpha_l\right) tg^2\left(\psi_l + \varphi_c + \varphi_g\right) 0{,}5}\right]}, \tag{4}$$

$$B_2 = \frac{\cos\varphi_g}{\left\{\sin\alpha_{lu} \cdot \cos\left[0{,}5 \cdot \left(\psi_{lu} + \varphi_g\right)\right]\right\}} \tag{5}$$

$$B_3 = \frac{ctg\xi}{\left(2\sin\alpha_l \cdot \cos\psi_l\right)}, \tag{6}$$

$$B_4 = 2\cos\varphi\left\{\cos\left[0{,}5\left(\psi_{lu} + \varphi_g\right)\right]\right\}^{-1} \cdot \left(\cos\psi_l - tg\varphi_c \cdot \sin\psi_l \cdot \sin\xi\right), \tag{7}$$

Where c_0 – specific adhesion force, N/m^2; c_0 = 15000 N/m^2;
S – cross-sectional area of the cleared route, m^2;
γ_g – volumetric gravity, N/m^3; γ_g = 6000 N/m^3;
h_k – drawing prism height (cavalier);
H_k, b_d – depth and width of the cleared route, m;
α_k – slope angle of the cavalier to the horizon, град, $\alpha_k = 40^0$;
f_p – loosening factor, 0,8;
φ_c, φ_g – respectively, the angles of external and internal friction;
$\varphi_c = arctgc\, f_c$, $\varphi_g = arctg\, f_g$; f_c =0,6, f_g = 0,1;

ψ_l and α_l – cutting and gripping angles of the plowshare (30^0 and 40^0 respectively);
ξ – angle between the relative trajectory of movement along the share and its blade, $\xi = \alpha_l$;
α_{lu}, ψ_{lu} – respectively, the installation angles of the ideal wedge, degrees

$$\psi_{lu} = \arccos \cdot \left[\left[F \pm \cos\beta' \cdot \sqrt{\cos^2\beta' + \cos^2\psi_l \cdot \cos^2(\beta + \varphi_c) - F^2}\right]\right] \cdot \left(\cos^2\beta' + \cos^2\psi_l\right)^{-1}, \quad (8)$$

$$\cos(\alpha_{lu} - \alpha_l) = (\cos\varphi_c - \cos\psi_l \cos\psi_{lu}) \cdot (\sin\psi_l \cdot \sin\psi_{lu})^{-1}, \quad (9)$$

$$F = [\cos\varphi_c - \sin(\beta + \varphi_c) \cdot \sin\psi_l \sin\beta'] \cdot \cos\psi_l, \quad (10)$$

$$\beta = arctg(tg\psi_l \cdot \sin\xi), \quad (11)$$

$$\beta' = arctg \cdot \left(tg\xi \cdot \cos^{-1}\psi_l\right), \quad (12)$$

Slope (deg.) of the resultant ΣR reaction

$$\theta_R = arctg \cdot \left(\frac{\sum R_{x1}}{\sum R_{z1}}\right), \quad (13)$$

Vertical coordinate, m of the point O' of application of the reaction $h_z = (0.4\ldots0.5)\ H_k$. Substituting the numerical values in the above formulas, we determine the resistance to the movement of the plow

$$F = \left[\cos 9^0 - \sin(20^0 + 9^0) \cdot \sin 30^0 \cdot \sin 41^0\right] \cdot \cos 30^0 = 0,72$$

$$\psi_{lu} = \arccos \cdot \left[\left[0,72 \pm \cos 41^0 \cdot \sqrt{\cos^2 41^0 + \cos^2 30^0 \cdot \cos^2(20^0 + 9^0) - 0,72^2}\right]\right] \cdot \left(\cos^2 41^0 + \cos^2 30^0\right)^{-1} = 37^0,$$

$$B_1 = \frac{2 \cdot \cos 9^0}{\cos[0,5(45^0 + 31^0)]} \cdot \frac{2 \cdot \cos 9^0}{\left[\sin 30^0 \cdot \sin 41^0 + tg 9^0 \cdot \sqrt{1 - \sin^2 30^0 \cdot \sin^2 40^0 \cdot (1 + \cos^2 30^0) tg^2 (30^0 + 9^0 + 31^0) 0,5}\right]} = 0,13$$

$$B_2 = \frac{\cos 31^0}{\{\sin 40^0 \cdot \cos[0,5 \cdot (37 \quad + 31^0)]\}} = 1,67$$

$$B_3 = \frac{ctg 40^0}{(2 \sin 40^0 \cdot \cos 30^0)} = 1,07$$

$$B_4 = 2\cos 31^0 \cdot \{\cos[0,5(30^0 + 31^0)]\}^{-1} \cdot \left(\cos 30^0 - tg 31^0 \cdot \sin 30^0 \cdot \sin 40^0\right) = 0,37$$

$$\beta = arctg(tg 30^0 \cdot \sin 40^0) = 20^0$$

$$\beta' = arctg \cdot \left(tg 40^0 \cdot \cos^{-1} 30^0\right) = 41^0$$

Vertical coordinate, m of the point O' of application of the reaction $h_z = (0.4\ldots0.5)\ H_k$.

$$R_{x1} = 15000 \cdot 2 \cdot 0,13 \cdot 1,67 + 6000 \cdot 2 \cdot 0,6 \cdot 0,13 \cdot 1,07 = 7514{,}52H$$

$$R_{z1} = 15000 \cdot 2 \cdot 1,67 \cdot 0,37 + 6000 \cdot 2 \cdot 0,6 \cdot 1,07 \cdot 0,37 = 21387{,}48H$$

$$\Sigma R = \sqrt{7514{,}52^2 + 21387{,}48^2} = 22669{,}02H \approx 22{,}7\kappa H$$

For calculations of a unit with a plow, it is necessary to know its traction resistance F_{tk} and the vertical component F_{vk} of the forces acting on the structure. Traction resistance and the vertical component are determined by the expression

$$F_{tk} = 2 \cdot R_{x1} \cdot \sin\alpha, \quad (14)$$

where α is the angle of deviation of the resistance force from the longitudinal axis of the working body, deg. $\alpha = 40^0$.

$$F_{vk} = 2 \cdot R_{z1}, \tag{15}$$

$$F_{tk} = 2 \cdot 7514{,}52 \cdot 0{,}6428 = 9660{,}67H = 9{,}66H$$

$$F_{vk} = 2 \cdot 21387{,}48 = 42744{,}96H = 42{,}74\kappa H$$

The traction resistance of the plow F_{tyg} is made up of the forces of resistance and friction on the ground of the support ski installed under the plow to regulate its depth. From the weight of the plow 8 kN and the vertical component of the cutting forces 21.3 kN is determined by the expression

$$F_{tyg} = F_v \cdot f_{tr}, \tag{16}$$

$$F_{tyg} = (8 + 21{,}3) \cdot 0{,}5 = 14{,}65\kappa H$$

The power consumption N_{dv} for clearing when performing the technological process for gears at the speed V_d is determined by the formula

$$N_{\text{dv}} = \frac{\left(F' + G_m \cdot f_k\right) \cdot V}{\eta_x} \kappa H, \tag{17}$$

Where F' – total traction resistance of the wedge, $F' = F_{tyg} + F_{tk}$, kN;
G_m – tractor weight force, kN;
η_x – efficiency of undercarriage mechanisms, η_x =0,8;
V – movement speed, m/s, we accept 0.26 m/s (first gear of the gearbox);
f_k – track rolling resistance coefficient

Substituting the numerical values, we determine the power costs for the movement of the unit (in 1st gear of the tractor gearbox)

$$N_{dv0,26} = \frac{\left(14{,}65 + 9{,}66 + 90 \cdot 0{,}2\right) \cdot 0{,}26}{0.80} = 14kWt$$

When clearing the tracks from shrubs and undergrowth, the traction resistance of the wedge R, kN is determined by the expression

$$R_g = G_o \cdot \left((f_{tr} + \sin\alpha\right) + m \cdot n \cdot (\pi d^2 / 4) \cdot k_p \tag{18}$$

Where G_o – plow weight force, N;
f_{tr} – coefficient of friction;
α – terrain slope angle, deg.;
m – tree cutting factor, m = 0,7;
n – number of trees cut at the same time, n = 2;
d – diameter of cut trees, cm, d = 10 cm;
k_p – wood shear resistance coefficient, k_p = 1500 N/cm^2

Substituting numerical values, we get

$$R_g = 8000 \cdot \left(0{,}5 + \sin 15^0\right) + 0{,}7 \cdot 2 \cdot \left(\frac{3{,}14 \cdot 10^2}{4}\right) \cdot 10 \cdot 1500 = 170\kappa H$$

With engine power N_e = 88 kW, the unit can only be operated in first gear. At the same time, the operation of the machine with engine power consumption up to 86% of the maximum will be accompanied by high fuel consumption and a decrease in resource. Figure 8 shows a graph of changes in the required engine power (kW) of the tractor and productivity for the preparation of forest belts for planting (ap/shift) depending on the speed of the machine.

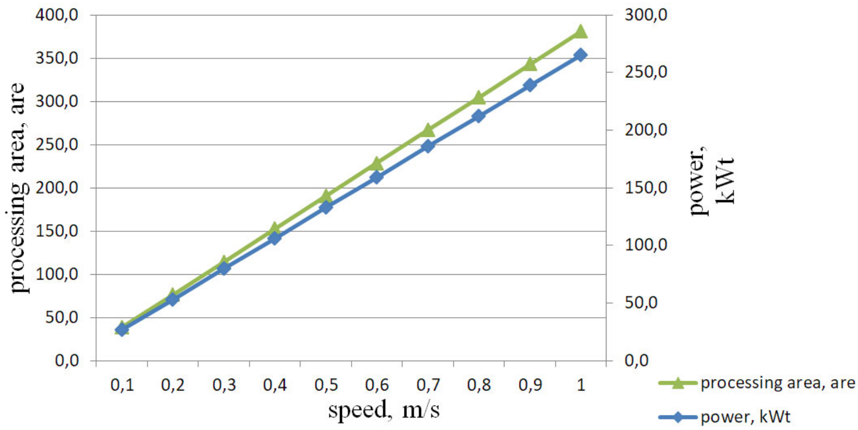

Fig. 8. Dependence of power and performance on processing speed.

It can be seen from the graph that in order to achieve an acceptable shift productivity comparable to that of forest cultivators, for example, Bracke Forest, (i.e. at least 4 hectares per shift), a machine speed of about 1 m/s (or 3.6 km/h), then an engine power of at least 250 ... 300 kW is required. This is a very high figure and it is not provided by the existing domestic serial forest tractors. Such high indicators of the required power are due to the significant size of the formed furrow. However, when implementing the reforestation technology, there is no practical need to form a mineralized furrow with a cross section of up to 1.8 m^2. The experience of using Bracke Forest machines says that when planting seedlings, it is possible to reduce the area of mineralization to a value of 0.3 ... 0.5 m^2 per seedling. It is on this principle of minimizing the areas of power cutting of the soil that the Bracke Forest M24 machine works.

With a decrease in the area of mineralized forest soil, power costs will proportionally decrease and the speed of work or the number of simultaneously formed planting holes will increase. Modern equipment for reforestation, due to sanctions and the withdrawal of many manufacturers from the market, is currently limitedly available to forest users. Bracke Forest equipment was no exception. Therefore, it is necessary to independently develop designs using reverse engineering methods and domestic basic machines, within the framework of existing regulations, concepts and strategies.

5 Conclusions

The forest areas of Russia are in need of reforestation. The volume of forest land requiring reforestation is at least 1 million hectares per year.

The power required to drive the traction means during plowing is directly proportional to the required tillage speed. To ensure a significant increase in labor productivity in the implementation of traditional moldboard plowing in the process of mineralization of forest soil, up to 250 kW of power is required.

The existing serial forest tractors of domestic production do not provide the possibility of implementing an increase in output during plowing on the territory of the cutting area. To increase the efficiency of work, it is required to reduce the energy intensity of the processing process, i.e. transition from mouldboard plowing to milling or to strip processing.

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