Study of the work of a self-propelled mulcher in the preparation of forest soils for planting poplar in the conditions of Bulgaria

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Abstract. The article describes the use of mulcher technology in forestry for the care of forest crops, removal of overgrowth under power lines, in the right-of-way of gas and oil pipelines, railways and highways. With the help of mulchers, they create fire strips in the forest, make clearings. Mulchers clean up fallen trees after fires, floods and hurricanes. They are involved in landscaping and agricultural work. The article examines the work of the PT-400 self-propelled tillage mulcher for the surface crushing of logging waste on the utilized poplar plantations of the Oryakhovsky state forestry in Bulgaria. The work of the Rotor Ferri S stump grinder was studied when crushing poplar stumps with a diameter of up to 50 cm. The hourly productivity of these machines at various operations was determined, and also the process of crushing stumps and felling residues by fractional composition was studied. The work of the mulcher was compared with the bulldozer technology and the mounted tractor stump grinder Rotor Ferri S. It was concluded that the mounted stump grinder Rotor Ferri S is the most suitable machine for grinding poplar stumps of any diameter, since its productivity significantly exceeds that of the PT-400 mulcher/tiller. The load on the tractor is minimal, which saves energy. At the same time, mulching technology is very effective and in demand.

1. Introduction

In modern forestry, mulcher technology is used to care for forest crops [1], remove overgrowth under power lines, in the right-of-way of gas and oil pipelines, railways and highways. With the help of mulchers, they create fire strips in the forest, make clearings. Mulchers clean up fallen trees after fires, floods and hurricanes [2]. They are involved in landscape and agricultural work [3, 4].

After felling poplar trees, stump removal is the last operation before tillage and planting. Poplar is characterized by a central-conical root with a highly developed horizontal root system [5]. In fact, there are three methods for removing poplar stumps: uprooting, extracting and chopping, working bodies for removing stumps are shown in figure 1.

Uprooting is the traditional, most widespread technology in our countries. As you know, uprooting is carried out due to the tractive effort of a caterpillar tractor, in which a bulldozer blade is attached to its front pushing frame with constant or changing angular parameters during operation or loosening teeth. In this case, stumps with a central root are brought to the surface by "rejection" of a horizontal skeletal and thin vertical root. In European countries, the technology of uprooting by an excavator has...
been adopted [6], when a reinforced “toothed grip” Pillari is attached to its boom (figure 1a).

![Figure 1](image)

**Figure 1.** Working bodies for uprooting stumps of "toothed grip" Pillari, fixed on the boom of excavator (a), drill pipe (b), and mounted stump grinder (c).

Central root removal is a technology created in Italy in the middle of the last century. The working body is a pipe with a diameter of 350 or 500 mm, in the lower part there are vertical cutting carbide teeth, and two-way screws are welded on the outer surface (figure 1b). The pipe is driven by a bevel gearbox at a low speed of 35 rev/min, driven by the PTO shaft of a wheeled tractor. After drilling the drill pipe to a depth of 1 m, the drill is removed to the surface, and along with it comes a stump with a central root. Using a hydraulic cylinder, the root removed from the soil is pushed out. This technology was used until the 1980s when the energy crisis began. Currently, the wood of coniferous stumps for energy purposes is harvested in Scandinavian countries, and in Spain - deciduous ones from eucalyptus crops [7]. By removing almost the entire stump from the ground, *Hylobius abietis* is prevented from settling in it [8].

The stump and the central root of the poplar are milled in Italy with a mounted drill, while the milling body is a dense cylinder with a diameter of 180 mm, fixed in place of the tubular drill (figure 1c). A conical screw is installed in its lower part, above which two horizontal cutting knives are diametrically welded, which cut and grind the stump perpendicular to the wood fibers. This technology is used in almost all European countries, followed by deep loosening to a depth of 70 cm. It is this two-stage technology that requires the introduction of mulchers, which simultaneously chop up forest residues and stumps, performing the main and additional tillage.

In Russia, a technology is known for removing the aboveground part of stumps in clearings using a MUP-4 machine based on a forestry tractor LKhT-55 with a mechanical drive of a conical cutter. For hardwoods, a working body with a hydraulic drive and a new arrangement of knife complexes was proposed (figure 2a-b) [9]. The complex consists of a scoring knife installed relative to the shearing knife with a protrusion in the feed direction at a distance of 2-4 mm, and the pairs of knives are offset relative to each other along a helical line with overlapping. This improves the breakage resistance of the cutter by distributing the load more evenly.

![Figure 2](image)

**Figure 2.** Schemes of the working body (a) and fastening of the scoring and shearing knives (b): 1 – upper base, 2 – lower, 3 – beams, 4 – shearing knife, 5 – scoring knife, 6 – hydraulic motor, 7, 8 – wedges, and 9 – bolts.

The analysis of theoretical dependencies showed that when changing the cutting angles of the front cutting edge of the scoring knife within \( \delta p = 30^\circ-60^\circ \), the maximum force \( F_{\text{max}} \) decreases from 1.0 kN to 0.9 kN, and the cutting work from 43 to 41 kJ. With the sharpening angles \( \beta_{\text{sc}} \) of the shearing knife in the range of \( 45^\circ < \beta_{\text{sc}} < 55^\circ \), \( F_{\text{max}} \) and cutting work have maximum values of 1.05…1.1 kN and 43.5 kJ.
When the clearance angle ($\alpha_{sc}$) of the cleaving knife changes from 5º to 40º, the force decreases from 1.05 kN to 0.95 kN, and the cutting work – from 46 to 39 kJ [10].

Due to the fact that mulchers massively entered forestry in our countries, research in this area has expanded [11]. The authors studied the operational properties of mulching technology, comparing it with a bulldozer [12]. A number of studies have been carried out on the hourly productivity of the mulcher in various soil conditions [13]. Particular attention is paid to the consumption of fuels and lubricants [14]. The data obtained from these scientific works are used to determine the norms and wages for machine soil preparation in our countries. In these works, there is no comparison with the work of the mounted stump grinder Rotor Ferri S.

The purpose of this study is to establish the technical, technological and economic parameters of two technologies: mulching and grinding, on the basis of which to determine the area of their application; to study the process of grinding stumps with a large-diameter mulcher.

2. Objects and methods

In 2013, the North-West State Logging Company from Vratsa acquired a PT-400 self-propelled forestry tiller FAE 300/S with a chain drive manufactured by the Italian company FAE Prime Tech S.p.A. The mulcher / tiller has long been known in forestry practice as a machine that works in extremely difficult conditions on rough terrain. The PT-400 is a relatively compact mulcher (6750x2700x3120 mm), curb weight 21 t, equipped with a 6-cylinder Caterpillar C13 Acer turbo diesel engine with 415 h.p. with a certificate of conformity to the environmental standard Euro-3, with a volume of 12.5 L. When the engine is idling, the fuel consumption is 5 L/h, and during intensive operation from 40 to 60 L/h of fuel. The engine power allows the mulcher/ tiller to move at a speed of 2.5-3 km / h in operating mode, depending on the terrain and the density of soil and vegetation (figure 3).

![Figure 3. PT-400 mulcher/tiller (a) and wheeled tractor FIAT 160 - 90 (b) with mounted stump grinder Rotor Ferri S.](image)

In September 2014, on the territory of the Oryakhovsky state forestry enterprise, on a land plot located in the river Danube, with an area of 1.13 ha, laboratory and field tests were carried out. Poplar on the site grew for 16 years, after which it was cut down. The soil is alluvial meadow with a high level of groundwater. After the trees were cut down, the assortments and branches were removed. Shoots up to 2.5 - 3 m high grew from the stumps. The investigated area had a rectangular shape with dimensions: width 31.5 m (7 rows of stumps with a center-to-center distance of 4.5 m) and 36 m long (17 stumps in each). Crop scheme - stumps 4.5 × 4 m. The total number of stumps on the plot is 119. The average diameter of the stumps was determined diagonally in 7 rows, measured by 7 stumps at the beginning, middle and end of the plot. The measurements were carried out in two mutually perpendicular directions - the maximum and minimum diameters were chosen in order to reduce the error due to the uneven shape of the stumps. Average diameter of stumps is $d = 42.25$ cm, maximum diameter of stumps is $d = 56$ cm and minimum diameter of stumps is $d = 30$ cm. Their height ($H$) was also measured relative to the lowest point around them, i.e. average stump height $H = 18$ cm, maximum stump height $H = 22$ cm, minimum stump height $H = 13$ cm. The average diameters of the stumps
were determined in order to establish a mathematical dependence on the time required for their fragmentation.

Poplar is characterized by a central root reaching a depth of 0.9 - 1.5 m, since its shape is cylindrical, and in the lower part it is conical. In the upper 1/3 of its length, the main roots are located, from which thin secondary roots are directed downward. The process of fragmentation of stumps was studied at the upper and lower levels of the diameters range: \( d_{\text{max}} = 50 - 56 \text{ cm} \) and \( d_{\text{min}} = 30 - 35 \text{ cm} \). Observations were made on the crushing time and trajectory of the machine during operation. Samples were taken from crushed wood at three depth levels: 10, 20, and 30 cm from square plots 1x1 m, and the treated soil was sieved through a sieve. The wood was analyzed by geometric parameters: thickness, width and length. To study the duration of individual technological operations, we used the methodology according to IUFRO S3.04.02 [15], recommended for studying work processes in the forest. The wear of the working knives of the mulcher, located on average 1/3 of the drum length by operating hours (100, 200, 300 and 400), was observed, and the profile change was determined by a curve measuring device.

In 2017, a mounted stump grinder Rotor Ferri S, mounted on a FIAT 160 - 90 tractor and driven from a power take-off shaft, was put into operation on the sites along the Maritsa River in the Plovdiv forestry enterprise (figure 3b). The stumps had an average diameter of \( d = 40.56 \text{ cm} \) and a height of \( H = 25 \text{ cm} \). The scheme of stumps is 4.5x4 m, the same as those crushed with mulcher in the Oryakhovsky forestry enterprise. Their average diameters were similar in size. The phases of the work were as follows: moving the unit in the row of stumps and installing the working body in the center of the stump; grinding, pulling the drill out of the soil; moving to the next stump; at the end of the row, turn to the beginning of the next row of stumps. At the lower end of the cutting blades there are two stops that allow you to adjust the chip thickness from 1 to 10 cm for hard and soft wood, respectively. An economic analysis was carried out to determine the cost of stump milling based on the methodology for estimating the hourly costs of a mulcher and stump grinder. Unproductive times were also taken into account when the operator or machine is not working. It also took into account the cost of transporting cars and profits for the business.

3. Results and discussion

3.1. Study of the effect of the diameter of the stump on the duration of the grinding process using both technologies

Studying the duration of the process of crushing poplar stumps with an PT-400 mulcher and a FIAT tractor with a mounted stump grinder Rotor Ferri S revealed the crushing time of 50 stumps with different average diameters. As a result of processing the experimental data, it was found that the average time for grinding a stump with a mulcher is 168.76 s, and with a chopper - 23.88 s, which is exactly 7 times less than the grinding time. The average hourly productivity of the mulcher was 16.52 stumps and 108.83 - of the stump grinder. The distribution of total working time at various stages of work in absolute terms and in percentage for the two technologies is shown in table 1.

| The quantities | Mulcher PT-400 | Stump grinder Rotor Ferri S |
|---------------|---------------|----------------------------|
| Average time of grinding one stump, s | 168.76 | 23.88 |
| Average travel time between individual stumps, s | 10.50 / 49.10 | 9.20 |
| The total average processing time for one stump, s | 179.26 / 217.86 | 33.08 |
| Average number of crushed stumps per hour, pieces | 20.10 / 16.52 | 108.83 |
| Crushed stumps and cultivated areas, ha/h | 0.211 / 0.175 | 1.977 |

*The data for the PT-400 mulcher refers to the complete milling / mulching of areas between individual trees and spaces between rows to a depth of 50 cm.

From the data in table 1, it can be concluded that the hourly productivity of grinding stumps of a grinder is 5.4 times higher than that of a mulcher. The advantage of mulching technology is that it can perform both primary and secondary treatment of areas between trees and individual rows, which saves...
a lot of money. Of course, the cultivated area is slightly reduced from 0.211 to 0.175 ha/h.

Figure 4. Dependences of the duration of grinding on the diameter of the stumps with a mulcher and a mounted stump grinder.

From the graph (figure 4), we can conclude that the mulcher is effective in the range of chopping stumps up to 20 cm and a processing depth of up to 50 cm, while the stump grinder can chop up stumps with a diameter of up to 60 cm at a depth of 1.5 m and a width of 1.2 m. The relationship between grinding time (y) and stump diameter (x) is a power function with a very high correlation coefficient (R²) 0.7945 and 0.9398.

3.2. Studies of the process of crushing stumps using both technologies.

Investigated the process of fragmentation of branches, freely scattered over the surface between the rows of culture, with sizes: diameter from 3 to 10 cm and length up to 3-4 m (figure 5a). Chopping was most efficient when the branches were arranged laterally to the direction of travel of the mulcher. At the same time, the size of the chips ranged from 2 to 7 cm, and with a parallel and inclined arrangement of the branches, it was almost twice as long. The fragmentation of the branch is not all right, since the branches, unlike the stumps, are not anchored. The tillage depth was up to 20 cm, the productivity was from 3.5 to 4 ha/h at an average mulcher speed of 1.6 km/h.

When clearing forests and clearings with the FAE 300 / S-225 mulcher, researchers [13] obtained the following results. The fraction of chopped wood over 5 cm in length makes up 10% of the total mass. It is dominated by fragments up to 30 mm long, which is 72% of the total mass.

When crushing stumps with a small diameter of up to 20 cm, the productivity was up to 0.560 ha/h (figure 5b). For chopping stumps with a diameter of 30-40 cm, which is the most common, the mulcher reversed the movement. As the rotor was raised above the stump, the process of chopping wood fibers decreased. The process was accelerated when splitting occurred in the longitudinal direction along the length of the fibers. For this, a reciprocating movement of the mulcher was necessary, which means that the productivity decreased to 0.360 ha/h (figure 5c). Accordingly, when chopping stumps with a diameter of more than 50 cm, it was also necessary to change the direction of the mulcher three times, and sometimes four times, which reduced productivity lower 0.2 ha/h (figure 5d).

The hourly productivity of the mulcher for tillage (uprooting, main and additional tillage) relative to the diameter of the stumps is shown in figure 6, the equation is a power function with a fairly high correlation coefficient.
Figure 5. Mulcher operation technology for crushing stumps of different diameters for the processes of crushing: branches with diameter of 30 to 100 mm on the soil surface (a), and stumps with diameter up to 200 mm (b), 300-400 mm (c), and more than 500 mm (d).

Figure 6. Hourly productivity of the mulcher depending on the diameter of the stumps.

The chopped stumps were collected from behind in the direction of travel of the mulcher at a depth of 25 to 30 cm. The stumps were crushed into medium-sized chips: large, 230 mm long and 27 mm thick, and small ones 80 mm long and 5 mm thick (figure 7). Large chips were torn off the stump along the grain when the mulcher rotor began to break the stump. The fine one was separated from the upper surface of the stump across the grain of the wood. The shavings “unravel” along the length of the fibers, which allowed the stump to quickly decompose in the soil.

The hourly productivity of the stump grinder (the number of crushed stumps in relation to their diameter) is shown in (figure 8). The graph shows that with an increase in the diameter of the stumps from 20 to 60 cm, the grinding performance decreased by 3 times. This is due to the fact that with a large diameter the stump has a strong root system, which requires additional "drilling" near the stump to be treated 2-3 times more in order to "tear" it.
Figure 7. Large and small chips of crushed stumps with a mulcher.

Figure 8. Hourly output of the stump grinder - the number of crushed stumps by their diameter.

3.3. Determination of the hourly costs of a mulcher and stump grinder for crushing poplar stumps.

Table 2. Determination of technical and economic indicators of mulcher and stump grinder.

| Consumption type                        | PT 400  | FIAT 160 - 90 | Rotor Ferri S |
|-----------------------------------------|---------|---------------|--------------|
| **Basic data**                          |         |               |              |
| Machine price, (€)                      | 500 000 | 120 000       | 40 000       |
| Amortization period, (years)            | 10      | 10            | 10           |
| Annual workload, (h)                    | 800     | 1000          | 300          |
| Rated power, (kW)                       | 288     | 176           | -            |
| Interest rate, (%)                      | 5       | 5             | 5            |
| **Constant costs**                      |         |               |              |
| Depreciation deductions, (€)            | 50 000  | 12 000        | 4 000        |
| Annual interest, (€)                    | 12 500  | 3 000         | 1 000        |
| Repair factor                           | 1.0     | 0.8           | 0.5          |
| Repair quota, (€)                       | 50 000  | 10 308        | 2 147        |
| Annual insurance, (€)                   | 250     | 120           | -            |
| Storage area, (m²)                      | 30      | 25            | 6            |
| Annual security costs, (€)              | 600     | 500           | 120          |
| Liquidation value, (€)                  | 48 750  | 11 700        | 4 000        |
| Fixed annual expenses, (€)              | 108 475 | 24 758        | 6 867        |
| Fixed working costs of the machine, (€) | 136     | 25            | 23           |
| **Variable costs**                      |         |               |              |
| Machine operator costs, (€ / h)         | 10.5    | 10.5          | -            |
| Fuel costs, (€/ h)                      | 15      | 7             | -            |
| Oil costs, (€/ h)                       | 3       | 0.4           | 0.2          |
| Fuel cost, (€/ l)                       | 1.2     | 1.2           | -            |
| Tire costs, (€/ h)                      | -       | 2             | -            |
| Cutter costs per working hour, (€/ h)   | 14.0    | -             | 1.3          |
| Charge of variable costs, (€/ h)        | 42.5    | 19.9          | 1.5          |
| Total costs per machine hours, (€/ h)   | 178.5   | 44.9          | 24.5         |
| **Final system costs, (€/ h)**          | 178.5   | 69.4          |              |
Hourly costs of both machines are based on a standard schedule. Economic parameters determine the effectiveness of the technology. As an example, we can point out that on one machine, the quality of operations is performed at a high level, but it has a very high shipping cost. It also requires large expenditures for consumables, repairs and wages of maintenance personnel. In this case, machine can perform these operations for a short time, and machine is not profitable for continuous operation. Machines and technologies must be versatile to perform various operations (for example, they must crush stumps with a diameter of up to 50 cm and more). In this case, loading of the machine is ensured throughout the year. Cost of the cars should be low. In this case, we are comparing new mulching technology with traditional shredding, which has a high degree of versatility. Tractor can be used for agricultural work, including in winter for clearing snow from roads. Economic analysis was carried out on the basis of the annual load of both technologies - a mulcher for 800 h, a tractor for 1000 h and stump grinder for 300 h. After ten years of operation, we should have the money to buy a new car. We will be able to sell old amortized machine at a salvage value of € 48,750 - mulcher, tractor € 11,700 and stump grinder € 6,867.

From the table 2, it can be concluded that the final cost of the mulcher system is 2.57 times higher, but it is to some extent compensated by the fact that the mulcher performs both basic and additional tillage, which cannot be done with a stump grinder.

4. Conclusions and recommendations
The main field of application of the PT-400 tiller is soil preparation in afforestation areas, where it is necessary to destroy shrubby vegetation, chop small stumps up to 20-25 cm and residues after harvesting wood. The depth of tillage should not exceed 30-35 cm, which allows planting small two-year-old seedlings. Mulching technology is a modern alternative to a bulldozer and an effective method of cleaning areas from trees and shrubs. When chopping stumps with a diameter of more than 20 cm, the mulcher's productivity is significantly reduced, and the wear of the cutters increases. The machine cannot be used for crushing large stumps, as the shape of the knives is not suitable for this operation, and the working depth of processing increases to 50 cm.

The Rotor Ferri S mounted stump grinder is the most suitable machine for crushing poplar stumps of any diameter, as its performance significantly exceeds that of the PT-400 mulcher. Tractor load is minimal, which saves resources. The question may arise: can the shredder and mulchers work in the same system? We believe that this is not economically feasible, since a stump grinder that sinks into the ground to a depth of 50 cm is many times cheaper than a mulcher.

In the future, mulchers will find more and more widespread use in forestry work in our countries, which will greatly stimulate the subsequent natural or artificial reforestation. The mulching process is carried out quickly, efficiently and with the least damage to the environment, as well as with minimal costs. This requires the expansion of the use of mulching technology in the future, since it causes minimal damage to the remaining plantations and meets the requirements of logging, forestry and fire safety. Mulchers are machines that do not reduce the productivity of the stand and its ability to regenerate, where at this stage of the development of forestry equipment, mulching technology is the most effective.

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