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REGRESSION MODELS FOR DETERMINING THE OPERATING COSTS OF FORESTRY MILLING MACHINES FOR COMPLETE SOIL PREPARATION FOR REFORESTATION OF POPLAR CLEARINGS

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ABSTRACT

This paper presents the results of an experimental study conducted with a self-propelled milling unit PT-400 with a multifunctional forestry milling machine FAE 300/S-225 for complete soil preparation for reforestation of poplar clearings. Regression models were developed to determine the relative fuel consumption and time consumption for complete soil preparation of poplar clearings. Based on the obtained results, the influence of the speed parameters of the forestry cutters and the working conditions in the fellings on the size of the operating costs was determined. Of all the factors that express the conditions of work, the diameter and density of the stumps have the greatest weight and dominance on the cost indicators. The amount of shredded shoots, bushes and wood waste ranks third, and the mechanical composition of the soil has the least influence. To mitigate the impact of more severe working conditions, it is best to use the cutter's "rotational frequency" factor. Regardless of the type of technological operation performed, lower operating costs are obtained at a higher frequency of rotation of the cutter. Given that this factor can be managed within wider limits, it is recommended that forestry cutters for shredding stumps and roots and mulching wood waste, shoots and bushes, operate at a higher frequency of rotation of the rotor – over 500 min^{-1}.

Key words: relative fuel consumption and time, stump diameter and density, speed.

INTRODUCTION

Forestry cutters are increasingly used in modern technologies for complete site and soil preparation for afforestation of forest areas and clearings. Compared to other machines with plow and disc working bodies used for soil preparation of forestry clearings and areas occupied by wood waste, shoots and bushes, forestry cutters with active rotary working elements have a number of advantages [Hansen et al., 1984; Keča and Pajić, 2015; Marinov and Kostov, 2022]. They more effectively remove woody debris and competing vegetation in new plantings and limit fire hazards in clearings (Hallbrook, 2006; Huggett et al., 2008; Battaglia et al. 2010; Marinov, Kostov and Peev, 2023). According to their purpose, forestry milling machines can be used as brush cutters (mulchers) for removing shoots and bushes, as machines for grinding wood waste from felling, stumps and roots (shredders), as machines for deep primary tilling (rotavators) or as multi-purpose milling machines. The multi-purpose forestry milling machines can perform various technological operations, which reduces the number of machines used and shortens the time for complete soil preparation of the clearings. (Marinov et al., 2017).

Over the past ten years, various forestry cutters have been put into operation in our country, including forest mulchers, rotovators, stump grinders and multi-functional forestry cutters. For complete site and soil preparation for refforestation of poplar clearings, a self-propelled milling unit PT-400 with a multi-purpose forestry milling machine FAE 300/S-225 was implemented in the Vratsa Northwest State Forestry Enterprise. The research carried out so far with this machine has confirmed the high technological properties of the forestry cutters (Glushkov et al., 2021;

Marinov and Jordanova, 2015 and 2017), but also raised a number of questions related to their higher energy intensity and fuel consumption (Marinov, 2019). In order to answer some of these questions, in the present work, experimental studies were carried out to establish the influence of the main production factors on the fuel consumption (energy intensity) and time consumption of forest cutters for complete soil preparation of poplar fellings.

MATERIALS AND METHODS

The subject of research is a PT-400 self-propelled unit with a FAE 300/S multi-purpose forestry cutter for complete site and soil preparation for reforestation of poplar clearings (Figure 1).

Figure 1: Self-propelled milling unit PT-400 with multi-purpose forestry milling machine FAE 300/S for complete soil preparation of poplar fellings (Photo K. Marinov).

The experimental studies were carried out in poplar fellings along the Danube River, where full regeneration felling was carried out. For this purpose, experimental sites were used in different poplar clearings, intended for site and soil preparation for the poplar plantations establishing. These areas are distinguished by a different concentration of wood mass, consisting of wood waste from felling, shoots and bushes, and different density and diameters of the stumps. From the tax descriptions of the plantations in the forestry plans, it is established that these areas are located in typical poplar habitats. The areas are partially floodplain, the soil is alluvial, deep, non-stony, sandy to clayey, superficially compacted, fresh to moist. The terrains are flat, with a slight slope of 2-3° and an altitude of 25÷30 m. To determine the amount of shredded wood mass in the fellings, the method of experimental areas and test plots was used. The research was conducted in experimental areas with different concentrations of wood mass, with different diameter and density of stumps, and with different mechanical composition of the soil.

- Experimental site No 1. Poplar clearing 1st category in "Vidin" State Forestry, division "377-b" and "377-e", in the area of the village of Archar. The average concentration of wood mass is $k_{дм}$ = 19.79 t/ha, that of wood waste from felling is $k_{дм}$ = 12.29 t/ha, and on the bushes and shoots – $k_{дм}$ = 7.50 t/ha.
- Experimental site No 2. Poplar clearing 2nd category in „Oryakhovo“ State Forestry, division „52-a“, located in the area of the island of "Masata". The average concentration of wood mass is $k_{дм}$ = 42.38 t/ha, that of wood waste from felling is $k_{дм}$ = 27.18 t/ha, and on the bushes and shoots is $k_{дм}$ = 15.20 t/ha.
- Experimental site No 3. Poplar clearing 3rd category in „Vidin“ State Forestry, division „250-м“, in the area of the town of Dunavtsi. The average concentration of wood mass is $k_{дм}$ = 74.64 t/ha, that of wood waste from felling is $k_{дм}$ = 58.25 t/ha, and on the bushes and shoots – $k_{дм}$ = 16.39 t/ha.
- Experimental site No 4. Poplar clearing 4th category in „Oryakhovo“ State Forestry, in the area of the town of Kozlodui, division „13-e“. The average concentration of wood mass is $k_{дм}$ = 88.98 t/ha, that of wood waste from felling is $k_{дм}$ = 65.82 t/ha, and on the bushes and shoots – $k_{дм}$ = 23.16 t/ha.
- Experimental site No5. Poplar clearing 5th category in „Oryakhovo“ State Forestry, in the area of the town of Kozlodui,, division „14-e“. The average concentration of wood mass is $k_{дм}$ = 111.26 t/ha, that of wood waste from felling is $k_{дм}$ = 85.31 t/ha, and on the bushes and shoots – $k_{дм}$ = 25.95 t/ha.

In the first experimental site, two trial sites are designated, located in two adjacent subdivisions – 377-б и 377-e. The soil is sandy with a light mechanical composition, but the surface layer is more compacted. The applied logging system is the same as for the rest of the fellings – extraction of assortments in the clearing (CTL), but the felling, pruning and cutting operations of the wooden materials are carried out with a harvester. One test site is 2.1 ha and the other is 5.9 ha. The poplar plantation is reforested with a hybrid variety – P x eur. cv I-214. The soil moisture during the experiments was W = 24÷28%.

The plantation in the second experimental area is of a hybrid poplar variety P x eur. cv. BL. Here there is a relatively small amount of woody debris, but more shrubs, amorphous and shoots. “Cut-to-Length” (CTL) a logging system is used for felling and primary processing of timber – extracting assortments in the clearing with chainsaws and transporting the materials to a temporary warehouse with a wheeled tractor with an assortment trailer. The measured soil moisture during the experiment was W = 31.5%.

The third trial area is 6.6 ha, with an altitude of 30 m and a slope 2^{o}. The plantation is a poplar variety P x eur. cv. I-214. A logging system “Cut-to-Length” (CTL) is used for felling and primary processing of timber. The soil is sandy, slightly stony and not very compacted. The soil moisture during the experiments was W = 23.5%.

The fourth and fifth experimental areas are located in the area of the city of Kozloduy on the territory of the Oryahovo State Forestry. The soil is clay-sandy, medium-heavy to heavy, the humidity is W= 28-30 %. These areas fall into subdivisions “13-e” и “14-e”. The first subdivision, with an area of 9.5 ha, was forested with a hybrid variety of poplar P x eur. cv. BL, and the second with an area of 3.5 ha – with P x eur. cv I-214. “Cut-to-Length” (CTL) logging system was used in these fellings. Significant amounts of wood waste were found in both clearings.

To conduct the research, a multifactorial experiment was conducted with two actively managed factors and four controlled factors. The indicators expressing fuel consumption and time consumption for complete soil preparation were studied. The input parameters (factors) of the study consist of 2 managed factors and 4 unmanaged but controllable factors. The managed factors can be managed and maintained at certain levels during the study. The unmanaged controllable factors express the operating conditions and can be measured and maintained at certain levels during trials.

The input managed parameters (factors) of the study x_i are:

x1 – Speed working gear of the milling unit – [order];

x2 – Frequency of rotation of the cutter, n – [min^{-1}].

The input controlled and maintained factors during the study are:

x3 – Concentration of shredded (mulched) wood mass in fellings (wood waste, shoots and bushes) – $k_{дм}$, [t/ha];

x4 – Average diameter of stumps – $d_п$, [cm];

x5 – Concentration (density) of stumps per unit area – $k_п$, [dka^{-1}];

x6 – Soil mechanical composition [category].

The concentration of mulched wood mass per unit area, including wood waste from felling, shoots and underbrush, was measured and reported in each experimental area. The average diameter and density of the stumps was determined by direct measurements in each experimental area. The mechanical composition, moisture, density and hardness of the soil are established on site and maintained at specified levels in the individual experimental plots. Д The depth of the main tillage is maintained at a constant level of 50 cm. The soil is slightly stony, deep. The mechanical composition of the soil in the different experimental areas varies from light sandy to heavy loam. The examined machine and working organs are in good technical condition. The operators have a good experience of 4.5 years with the same machine. The terrain is flat, with a slight slope of 2÷4°. Test areas and testing grounds are rectangular in shape, which favors productivity.

The outputs parameters of the research Yi are the relative consumption of fuel and time per unit area when operating the PT-400 milling unit with a multi-purpose forestry cutter:

Y_1 – Relative fuel consumption for complete soil preparation per unit area, [l/dka];

Y_2 – Time consumption for complete soil preparation per unit area, [h/dka].

The size of the treated areas and the relative fuel consumed were determined by direct measurements at the end of each trial. The relative fuel consumption Y_1 is defined as the ratio between the amount of fuel consumed and the size of the treated area. To determine the time spent per unit area Y_2, the operations are timed and the processed area is measured.

RESULTS AND DISCUSSION

The obtained results of the conducted experiment are aimed at establishing the influence of the different speed regimes of the forest cutters and the factors of the working environment on the operational indicators of the forestry cutters. The first two input factors x_1 – speed gear of the unit and x_2 – rotation frequency of the cutter are actively managed, and during the experiments they are maintained at three main levels. The other factors characterizing the working conditions in the clearings during the trials are controlled and maintained at certain levels, depending on the working conditions. The factor x_3 – concentration of wood mass in the clearings (wood waste,

shoots and bushes) during the experiments was established and maintained at 5 levels: 1st level – $k_{дм}$ = 19.8 t/ha; 2nd level – $k_{дм}$ = 42.4 t/ha; 3rd level – $k_{дм}$= 74,6 t/ha; 4th level – $k_{дм}$ = 89 t/ha and 5th level – $k_{дм}$ = 111.3 t/ha. The diameter of the crushed stumps was established and studied in the interval from 24 cm to 56 cm, and this x_4 factor in the different trial areas was maintained at 5 levels. The influence of the factor x_5 concentration (density) of stumps is studied in the range of 278 to 667 pieces per 1 ha, being maintained at 4 levels. The sixth factor, soil mechanical composition x_6, is established and maintained at three levels – light sandy soil (-1), medium heavy sandy loam (0) and heavy loam (+1). The levels of input factors in natural and coded form are given in Table 1. The depth of the main tillage is maintained at a constant level of 50 cm, and the humidity is in a state of physical (technological) maturity – 24-32%.

Table 1: Levels of variation of input factors in natural and coded form.

Speed gear of the milling unit – x_1		**Frequency of rotation of the cutter – x_2**		**Concentration of wood mass in the clearing – X_3**	
Natural form	**Coded form**	**Natural form**	**Coded form д**	**Natural form**	**Coded form**
1-ва предавка	X_1 = -1	250 min^{-1}	X_2 = -1	$k_{дм}$ = 19.8 t/ha	X_1 = -1
1-ра предавка	X_1 = 0	375 min^{-1}	X_2 = 0	$k_{дм}$ = 42.4 t/ha	X_1 =-0.506
3-та предавка	X_1 = 1	500 min^{-1}	X_2 = 1	$k_{дм}$ = 74.6 t/ha	X_1 = 0.197
				$k_{дм}$ = 89.0 t/ha	X_1 = 0.513
				$k_{дм}$ = 111.3 t/ha	X_1 = 1

Diameter of stumps – x_4		**Density of stumps – x_5**		**Mechanical composition of the soil – X_6**	
Natural form	**Coded form**	**Natural form**	**Coded form**	**Natural form**	**Coded form**
d=24 cm	X_1 = -1	$k_п$ = 278 ha^{-1}	X_3 = -1	Light sandy	X_4 = -1
d=32 cm	X_1 = -0.5	$k_п$ = 400 ha^{-1}	X_3 = -0.373	Medium sandy-loam	X_4 = 0
d=40 cm	X_1 = 0	$k_п$ = 500 ha^{-1}	X_3 = 0.141	Heavy loam	X_4 = 1
d=48 cm	X_1 = 0.5	$k_п$ = 667 ha^{-1}	X_3 = 1		
d=56 cm	X_1 = 1				

The obtained experimental results were subjected to processing and statistical analysis, and the specialized calculation program QstatLab-6 was used for the calculation procedures. As a result, regression models were obtained for determining the studied output parameters yi as functions of the response of the studied factors x_i. After conducting a stepwise regression analysis and removing the insignificant regression coefficients b_{ij} и b_{ii}, regression equations of the 2nd degree were obtained to describe the studied process. The significance of the regression coefficients b_i, b_{ij} и b_{ii} was determined at a significance level $\alpha = 0.05$. In models with worse properties, these coefficients are excluded from the equations. After checking the adequacy of the obtained equations, it was found that with a high degree of reliability they describe the studied processes and can be used to predict the studied indicators.

To determine the relative fuel consumption of forestry cutters for complete soil preparation of poplar fellings, the following regression equation was obtained:

$$Y_1 = 132.445 + 44.44x4 + 35.94x5 – 23.23x2 + 26.84x4x4 + 18.65x4x5 + 14.56x3 + 5,59x2x2 + 9.12x6 + 7.34x3x3 -7.26x2x4 + 4,38x4x6 +4.28x1x2 + 3,47x5x6 – 2.61x2x5 + 2.49x1x3 + 2.25x1x6 + 1.99x6x6 + 1.43x1x1 – 1.09x1 + 1.079x5x5 – 1.08x2x6, [l/da] \quad (1)$$

Where x1 is the speed gear [gear order];

x2 – the frequency of rotation of the cutter [min-1];

x3 – the concentration of wood mass in the clearings – wood waste, shoots and bushes – kдм [t/ha];

x4 – the average diameter of the stumps – dп [cm];

x5 – the concentration (density) of stumps per unit area – kп [dka-1];

x6 – the mechanical composition of the soil [category].

The proposed model in equation (1) includes all significant factors in a coded form, influencing the relative fuel consumption of forestry cutters for complete soil preparation of poplar clearings.

To determine the time consumption per unit area for complete site and soil preparation of poplar clarings, the following regression equation was obtained:

$$Y_2 = 1,87 + 0,61x4 + 0,49x5 + 0,36x4x4 + 0,25x4x5 – 0,30x2 + 0,17x3 + +0,15x6 – 0,13x1 – 0,12x2x4 + 0,09x3x3 – 0,06x2x5 + 0,06x1x1 + 0,05x1x2 + 0,05x4x6 + 0,04x5x6 + 0,03x1x6 + 0,03x2x2 +0,02x1x3 – 0,02x2x6 +0,01x6x6 + 0,01x2x3, [h/da] \quad (2)$$

In the proposed model, equation (2) presents all significant factors in a coded form, having a significant impact on the time consumption of an area of 1 decare. Through them, the necessary number of machine hours can be determined for complete soil preparation of poplar fellings for the poplar plantations establishing. On this basis, the time for afforestation of poplar cuttings can also be planned.

The proposed regression equations for determining the relative fuel consumption and time consumption of forestry cutters for complete soil preparation of poplar clearings are suitable for establishing the influence of the main speed parameters of forest cutters and working conditions. The following more important conclusions and recommendations can be made from the obtained models:

1. The relative fuel consumption and energy intensity of forestry cutters for complete soil preparation of poplar fellings is most strongly influenced by the diameter and density of the stumps. They are followed by the rotation frequency of the cutter and the concentration of the mulched wood mass per unit area. The mechanical composition of the soil and the speed gear of the milling unit have relatively less influence. From equation (1), it can be found that the regressors in front of the linear terms of stump diameter and density are respectively equal to $b_4 = 44.4$ and $b_5 = 35.9$. Also, these factors have the largest values over the quadratic and interaction terms – $b_4^2 = 26.8$ и $b_4.b_5 = 18.7$. These results are indicative of the dominant importance of diameter and stump density on the operating costs of forest cutters.
2. The factors expressing the speed indicators show that the rotation frequency of the FAE 300/S milling machine has a greater weight compared to the operating speed and gearing of the PT-400 drive unit. The regressor in front of the linear term of the "rotating frequency" factor is $b_2 = 23.2$, which is almost 2 times smaller than that of the dominant factor “stump diameter”, and the regressor in front of the gear is $b_1 = 1.1$, which is almost 44 times smaller. It should be noted here that the levels of the gear and the working speed of the milling unit have been studied in a small variation interval, which corresponds to the technical capabilities of the milling unit and which ensures the required processing quality.

3. The concentration of the mulched wood mass and the mechanical composition of the soil have relatively less influence on the fuel consumption per unit area. The regression coefficient before the linear term of the factor "concentration of wood mass" is b_3=14.6, and that before the factor "mechanical composition of the soil" is b_6 = 9.1. These values show that the degree of influence of the amount of shredded wood mass is about 3 times weaker, and the mechanical composition of the soil is about 5 times weaker than that of the diameter and density of stumps.
4. The power of influence of the six investigated factors on time consumption has the same order as on fuel consumption. Here, too, the average diameter and the concentration of stumps have the greatest weight of influence. The regressors for these factors are b_4 = 0.61 and b_5 = 0.49, respectively. In third place, with about 2 times less weight, is the factor "rotation frequency of the cutter", whose regressor is b_2 = 3.31, followed by the factor "concentration of wood mass" with a regressor b_3 = 0.17, which is about 3.5 times less than the influence of dominant factors. In fifth and sixth place are the factors "mechanical composition of the soil" and "speed gear", whose regressors are respectively – b_6 = (+)0.15 and b_1 = (-)0.13, which is nearly 4 times and 5 times weaker from that of the dominant factors.

Of all the factors that express the working conditions, the diameter and density of the stumps have the greatest weight on fuel consumption and time for soil preparation in poplar fellings. In third place is the "concentration of wood mass" factor. The mechanical composition of the soil, compared to other factors, has the least influence.

CONCLUSIONS

From the conducted experimental research with a self-propelled milling unit PT-400 with a multi-purpose forestry milling machine FAE 300/S-225, regression models were derived for determining the relative consumption of fuel and consumption of time for complete soil preparation of poplar cuttings. Based on them, it is possible to determine how the working conditions and speed regimes of the forest cutters influence the operating costs.

The obtained results show that of all the factors that express the working conditions, the diameter and the density of the stumps have the greatest weight and dominance on fuel costs and time for complete soil preparation of poplar cuttings. The amount of shredded shoots, bushes and wood waste ranks third, and the mechanical composition of the soil has the least impact.

To mitigate the influence of the more severe working conditions in the clearings, the frequency of rotation of the cutter and the speed gear, which have negative values in the obtained regression models, can be used. Because the gearing and operating speed of the drive unit have more limited variation, they do not have the qualities of effective countermeasures. The main factor that can be effectively used to reduce the operating costs of forestry cutters under more severe operating conditions is the frequency of rotation of the cutter's rotor. Regardless of the type of technological operation performed, lower operating costs are obtained at a higher rotation frequency of the milling cutter. Given that this factor can be controlled within wider limits, it is recommended that forestry milling machines for shredding stumps and roots and for mulching wood waste, shoots and bushes, operate with a higher rotor speed – over 500 min^{-1}.

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