Evaluation effectiveness of forage harvesters in silage preparation

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Abstract. The indicators of the feed output and, in general, the profitability of animal husbandry rely on the effectiveness of forage harvesters. Models depicting the performance and fuel use of forage harvesters were received resulting from the analysis of the functioning indicators. An effectiveness ratio was suggested for a comparative analysis of their effectiveness. It considers the relationship between performance and fuel use while harvesting grasses of different yields.

Three forage harvesters: Jaguar-840, Jaguar-690 and Maral-125 are analyzed in this article when selecting grass windrows dried to a moisture content of 65%. Comparative analysis of the concerned forage harvesters revealed that the fullest loading of the Jaguar-840 and Jaguar-690 harvesters is achieved with a yield of grass more than 17.5 t/ha, and the Maral-125 combine harvester-with a yield of grass more than 10 t/ha. If the grass yield is up to 7 t/ha, the fuel rate of the harvesters is almost the same. Its changes occurs along a decreasing exponential curve with an increase in the yield of grass. The highest effectiveness ratio, equal to 33.54 (ha / shift)×(t / l), during silage preparation, has a Jaguar-840 forage harvester with a grass yield of 10.0-20.0 t/ha. The lowest effectiveness ratio is 5.63 (ha / shift)×(t / l), has Maral-125 harvester in the grass cutting with a yield of 25.0-30.0 t/ha.

1. Introduction
The costliest phase in the production of grass feed, determining the quality of the feed and the level of preservation of its nutrients, is cutting and storing. Up to 90% of all works associated with feed production are performed during this period. Feed from prewilted grasses like silage and haylage accounts for the greater part of the cattle feed structure. Forage harvester is the major technical device for feed preparation. The forage harvester is the most capital-intensive machine of all the technical devices participating in the grass feed production. Thus, the cost parameters of the received feed and, in general, the profitability of animal husbandry rely on the effectiveness of harvester in the forage link [1, 2]. Owing to the high cost of forage harvesters, all other machines of the forage harvesting link depend on its performance. In other words, the necessary mowing area is provided, a logical chain of transporting feed from the fields to their storage location is built, and storage facilities are accounted to be filled within 4-5 days. [3, 4, 5, 6] With the increase in the energy and fuel costs, the cost of a feed unit will also grow. In this regard, it is significant to analyze the impact of harvesting conditions on the forage harvester's effectiveness [7, 8].
A large amount of data can be processed using a variety of mathematical methods. It has become possible to solve problems of optimizing the use of technical means with the development of data technologies and various mathematical programs allowing to handle a large amount of information using a number of mathematical methods [9, 10, 11]. Approach development in assessing the forage harvester performance will provide an ability to apply it in a formalized form directly, both in existing and developing decision support tools [12, 13]. Both strategic planning at the beginning of the grass harvesting season and in real-life decision-making will contribute to determining the right mix of material and technical resources for the potential of the fields, storage volumes, and the distance between them [9].

2. Materials and methods

The performance of forage harvesters and fuel costs are found to depend significantly on the yield of the cut grass as it is known from the literature [4, 14]. This information is presented in the standard norms of production and fuel consumption [15, 16, 17] in the way of tabular data depending on the grass yield (t/ha), shift performance (ha/cm) and fuel consumption (l/ha). Data from three forage harvesters: Jaguar-840, Jaguar-690 and Maral-125 was analyzed when selecting grass windrows dried to a moisture content of 65%. Tabular information is more convenient for analysis if there are analytical dependencies. For determination of these dependencies, data analysis was fulfilled on the computer. Statistically significant regression equations are received in the form of polynomial dependences for tabular data of performance and fuel consumption. Determination coefficient in all cases outweighed the value of 0.98, which allowed us to use the derived dependences for calculations in the future.

Derived dependencies have the form:
- for output per shift of combine harvesters, ha/cm:
  \[ W(U) = a_1 + b_1 \cdot U + c_1 \cdot U^2 + d_1 \cdot U^3; \]  

- for per-hectare fuel consumption, l/ha:
  \[ T(U) = a_2 + b_2 \cdot U; \]

where \( U \) – grass yield, t/ha (\( U \approx 5.0 - 30.0 \) t/ha).

On the basis of the data, graphs were built to clearly illustrate the behavior performance and fuel consumption of the studied forage harvesters, depending on the grass mass yield. Also, equations characterizing them were built (see Figure 1).

The calculated coefficients of the approximating equations specified in Figure 1, the performance indicators of the Jaguar-840, Jaguar-690 and Maral-125 forage harvesters when selecting grass windrows, following by laying grass in the trenches, are shown in the table 1.

| Brand     | Performance indicators of forage harvesters |
|-----------|--------------------------------------------|
|           | Performance, ha/shift | Fuel consumption, l/ha |
| Jaguar 840 | ![Graph](#) | ![Graph](#) |
| Jaguar 690 | ![Graph](#) | ![Graph](#) |
| Maral 125  | ![Graph](#) | ![Graph](#) |
Figure 1. Base-line data and approximating equations of performance indicators of Jaguar-840, Jaguar-690 and Maral-125 forage harvesters in the selection of windrows

Table 1. Equation coefficients characterizing the operation of harvesters

| Brand of the harvester | Harvesters’ performance indicators and equation coefficients values | Fuel consumption, l/ha |
|------------------------|-------------------------------------------------|------------------------|
|                        | Performance, ha/shift | Fuel consumption, l/ha | |
|                        | $a_1$   | $b_1$   | $c_1$ | $d_1$ | $a_2$ | $b_2$ | |
| Jaguar-840             | 23,27   | 1,146   | -0,114 | 0,0021 | 3,53  | 0,431 | |
| Jaguar-690             | 18,74   | 1,154   | -0,111 | 0,0021 | 3,55  | 0,358 | |
| Maral-125              | 20,95   | -1,17   | 0,0202 | -     | 2,17  | 0,637 | |

On the basis of the performance indicators presented in Figure 1, it is possible to determine other ones of the forage harvesters, in particular, the shift performance (t/shift), the shift fuel consumption (l/shift), as well as the fuel rate per ton of prepared feed (l/t).

For determining the shift performance of the harvester (t/shift), the expression (1) shall be multiplied by the yield:

$$W_{sh}(U) = a_1 \cdot U + b_1 \cdot U^2 + c_1 \cdot U^3 + d_1 \cdot U^4.$$  \hspace{1cm} (3)

Shift fuel consumption (l/shift) is specified as a result of the product of the expressions (1) and (2):

$$T_{sh}(U) = (a_1 + b_1 \cdot U + c_1 \cdot U^2 + d_1 \cdot U^3) \cdot (a_2 + b_2 \cdot U).$$  \hspace{1cm} (4)

Shift fuel consumption rises with the growth of the input green mass to the chopping rotor. For this reason, with an increase in the grass yield to 15.0 t/ha, the shift fuel consumption rises for the Jaguar-840 and Jaguar-690 harvesters. In the Maral-125 harvester, grass yield does not have such a significant impact on fuel consumption because of the lower throughput capacity of the chopper.

The key indicator of the economic efficiency of harvesting is the fuel rate per unit of output (l/t):
During forage harvesting, the timing of grass cutting is of great significance. Grass should be cut in a short time and in optimum term. To make a comparative analysis of the forage harvester efficiency, the following correlation is proposed (effectiveness ratio):

\[ K_{te}(U) = \frac{W(U) \cdot U}{T(U)} \]  

The relation of this dimension has the form:

\[ \frac{\text{HA-T}}{\text{SHIFT-HA}} \cdot \frac{\text{HA-T}}{\text{L-SHIFT-HA}} = \frac{\text{HA-T}}{\text{L-SHIFT}} \cdot \frac{\text{HA-T}}{\text{L-SHIFT}} \]

The dimension of the relation (6) indicates that the physical meaning of the effectiveness ratio is the product of the performance of the machine (ha/shift) on the amount of feed harvested per unit of fuel consumed. As each of the multipliers shall tend to the maximum, the coefficient itself has a high significance when increasing the efficiency of machine use.

Replacing the relations (1) and (2) in expression (6), we get an equation for calculating the comparative effectiveness of forage harvesters:

\[ K_{te}(U) = \frac{(a_1 + b_1 \cdot U + c_1 \cdot U^2 + d_1 \cdot U) \cdot U}{a_2 + b_2 \cdot U} \]

3. Results and Discussion
For a comparative analysis of the performance indicators (shift performance and fuel consumption) of the Jaguar-840 (J8), Jaguar-690 (J6) and Maral-125 (M1) forage harvesters, we introduce them in a graphical interpretation in Figure 2 a, b on the same coordinate axes – depending on the yield of the grass density (x).

Analysis of Figure 2 indicates that in terms of performance (ha/cm), Jaguar-840 is the leader, and in terms of fuel consumption (l/ha) - Maral – 125. All curves have a downward nature. Harvesters have the highest performance with a grass yield of more than 5.0-10.0 t/ha. Per-hectare fuel consumption grows with the increase in the grass yield for all harvesters. Maral-125 has the most intensive rise in fuel consumption.

Calculation made according to formulas (3) and (4) are presented in Figure 3. Findings obtained suggest that the stable performance of Jaguar-840 (J8) and Jaguar-690 (J6) harvesters is achieved with a yield of more than 15 t/ha. 350 and 280 t/shift, respectively. Stable performance of Maral-125 (M1) starts with a yield of more than 10 t/ha and is 100 t/shift.
Performance, ha/shiftFuel consumption, l/ha

Figure 2. Comparing the performance and fuel consumption of forage harvesters: a-performance, ha / shift; b-fuel consumption, l / ha

Performance, ha/shiftFuel consumption, l/ha

Figure 3. Comparative indicators of performance (t / shift) and fuel consumption (l/shift) by forage harvesters per shift, depending on the grass yield: a-performance, t / shift; b-fuel consumption, l / shift

Calculations made by the formula (5) of fuel rate of the harvesters under consideration are given in the Figure 4.

Fuel rate, l/t
Findings obtained indicate that depending on the grass yield, the fuel rate changes almost threefold, from 1.15 l/t with a yield of 5 t/ha, to 0.45 l/t with a yield of more than 25.0 t/ha for Jaguar-690. Maral-125 has a fuel rate with a grass yield of up to 7.0 t/ha, roughly the same as that of Jaguar-840 and Jaguar-690. At high grass yields, the fuel rate of Maral-125 is 1.5-2.0 times higher than in Jaguar-840 and Jaguar-690.

The performed calculations using formula (7) for Jaguar-840 (J8), Jaguar-690 (J6) and Maral-125 (M1) forage harvesters, depending on the grass yield (x), are given in Figure 5.

Data obtained show that Jaguar-840 and Jaguar-690 forage harvesters have the highest effectiveness in choosing the dried mass from the windrows and loading it in milled form into the vehicle in comparison with the Maral-125. In case of low yield (5 t/ha) of forage land, they are effective by about 1.5 times, and in case of high yield (more than 25 t/ha) - about 3.5 times. The greatest variation in the effectiveness of Jaguar forage harvesters over the Maral-125 is reached at a yield of 13 t/ha.

4. Conclusions
1. The fullest loading of Jaguar-840 and Jaguar-690 forage harvesters is reached with a grass yield of more than 17.5 t/ha, and Maral-125 harvester-with a yield of more than 10 t/ha.
2. If the grass yield is up to 7 t/ha, the fuel rate of the considered harvesters of different types is practically the same. Its changes occurs along a decreasing exponential curve with an increase in the yield of grass.
3. Expression developed for calculating the comparative effectiveness of forage harvesters (7) enables us to estimate their effectiveness in production conditions, accounting for the grass yield. The highest effectiveness ratio, equal to 33.54 (ha/cm) ×(t/l), in the preparation of silage has a Jaguar-840 and Jaguar-690 with a grass yield of 10.0-20.0 t/ha. The lowest effectiveness ratio, equal to 5.63 (ha/cm) ×(t/l), is of Maral-125 in the cutting of grasses with a yield of 25.0-30.0 t/ha. But its highest effectiveness is fulfilled in the cutting of grasses with a yield of 5.0-10 t/ha.

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