Statistical models expressing relations between soil moisture, aggregate speed, and tillage depth at plowing and cultivation

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Abstract. The study is based on a one-year field experiment (2019) in the land of the Chirpan region located in central Bulgaria. The agrotechnical operations of plowing and cultivation, applied in technology for the production of sunflower, are studied. Four models (Linear, Exponential, Logarithmic, and Quadratic) were compared at p < 0.05, defining the relation between soil moisture, aggregate speed, and the uniformity of the soil index Tillage depth during plowing and cultivation. It was found that in plowing at a speed of 4 km/h the Quadratic model described the relation between soil moisture and tillage depth with the highest coefficient of determination ($R^2 = 0.682$). Relating to plowing at a speed of 4.5 km/h the most suitable is the Exponential model ($R^2 = 0.729$), i.e. about 68.2% and 72.9% of the variations in tillage depth are due to the influence of the moisture of the soil. The coefficients of determination, calculated when cultivating at speeds of 8 km/h ($R^2 = 0.526$) and 9 km/h ($R^2 = 0.557$), show that the Quadratic model most strongly (52.6% and 55.7%) determines the relation between soil moisture and tillage depth. The developed models could be used to optimize the control systems of agricultural machinery.

1. Introduction
To meet the agro-technical requirements necessary for the production of trench crops, it is not enough to apply only single tillage. Depending on the soil and climatic conditions, it is necessary to carry out several successive treatments differing in time and method of implementation. Long-term research on the application of agrotechnical practices shows the possibility of the approach in choosing a given agro-technical solution [1, 2, 3]. Plowing and cultivation are part of the soil preparation involved in the technology of sunflower production. Depending on the type of soil, during plowing, the machine-tractor unit turns the soil layer to a depth of 25-40 cm. When cultivating, the soil is loosened, mixed, and saturated to a depth of 15 cm. The uniformity of the depth of cultivation is important for restoring the compaction of the soil, improving the penetration of water into the lower layers, changing the distribution of soil aggregates, has a beneficial effect on the growth and development of plants, providing an even sowing bed [4, 5].

Several authors have developed mathematical models, by studying how the depth of tillage influences the growth, development, and productivity of different crops, as well as how affects the physical properties of the soil, its structure, porosity, etc. [1, 4, 6, 7, 8, 9]. Baoyi Ji et al. [10] applied...
ANOVA and Duncan’s test, finding statistically significant differences between several tillage systems at different depths and tracking the activity of soil enzymes. Panasiewicz et al. [11] evaluated the effect of three tillage systems on the productivity of different crops by using ANOVA, Tukey’s, LSD Multiple Range test. The relationship between the parameters was determined with the Pearson correlation coefficient. Ahmad et al. [12] also analysed the effect of deep tillage on soil properties and wheat yield using the General Linear Model procedure. Frink et al. [13], Dallev and Ivanov [4] compile linear and nonlinear models that could be used as a basis for developing systems for optimizing tillage machines.

The information from the available literature on the uniformity of the depth of cultivation in the technological operations of plowing and cultivation depending on the soil moisture is scarce; therefore the expansion of the studies in this direction is justified.

The purpose of this article is to monitor the stability of the machine-tractor unit in terms of depth of tillage and cultivation and to compile statistical models expressing the relations between soil moisture, speed of the aggregate, and tillage depth. These models could be used to optimize the management systems of agricultural machinery.

2. Materials and methods

2.1. Experimental design
The experiments were carried out in the 2019-2020 agricultural year on a field, prepared for sowing sunflowers. The field is located in the Chirpan region in the central part of the Republic of Bulgaria. The area over which the research was conducted is 42 400 m² (Figure 1). In the studied area, several types of soils are located unevenly. Humus-carbonate soils predominate for the most part, but there are also traces of resins (leached, typically clayey) and resins (leached, cinnamon, and slightly clayey).

The field on which the experiments were conducted has been divided into two equal sections both with dimensions of 530 m long and 40 m wide (Figure 1). The plowing is done with a five-body reversible plow aggregated to a tractor with 200 hp. at a speed of 4 km/h in the first section, and 4.5 km/h at the second. When cultivating, the machine-tractor unit consisted of a tractor (220 hp.) and a nine-meter cultivator operating at speeds of 8 km/h and 9 km/h accordingly in the first and the second field.

![Figure 1. Experimental sections, Chirpan region, Bulgaria (in red squares).](image)

Table 1 presents the period of execution and the depth of processing of the considered technological operations of plowing and cultivation. The depth of processing for the individual operations at the respective speeds of each field is measured with a linear meter, as follows: length - 10 measurements every 50 m; in width - 5 measurements every 8 m. Data on soil moisture has been taken with AM-128 SOIL-soil moisture meter at the respective points of the two sections.
Table 1. Period of execution and depth of processing of the technological operations applied in sunflower production.

| Technological operation | Date of performance | Tillage depth (cm) |
|-------------------------|---------------------|--------------------|
| Plowing                 | 14.12.2019          | 28-32              |
| Cultivation             | 28.01.2020          | 14-16              |

2.2. *Statistical data analysis*

The effect of soil moisture on the depth of tillage for the agrotechnical operations plowing and cultivation at different speeds of the aggregate was analysed using Two-way analysis of variance (ANOVA) and Regression analysis. The aim was to compile predictive models defining the relations between the observed parameters. Level of significance $p < 0.05$ was considered statistically significant. Levine’s test of equality of error variances was applied to check the homogeneity of the samples.

Four different regression models - Linear (1), Logarithmic (2), Quadratic (3), and Exponential (4) were compared, given as:

1. $a = \text{const.} \cdot x + b$
2. $a = \text{const.} \cdot b \log(x)$
3. $a = \text{const.} \cdot b_1x + b_2x^2$
4. $a = \text{const.} \cdot e^{bx}$

where $a$ is the observed parameter tillage depth for agrotechnical operations plowing and cultivation at different speeds, $x$ is the fixed factor soil moisture, and $\text{const.}; b; b_1; b_2$ are the model coefficients. The results were calculated with SPSS 26.0.0.1 (IBM© SPSS Statistics, 2019).

3. Results and discussion

The uniformity of the depth of the cultivations (plowing and cultivation) according to the instantaneous soil moisture during the movement of the machine - tractor unit at two speeds is traced and regression models are developed expressing the connection between them.

3.1. *Basic statistics and Correlation analysis*

Table 2 presents the results of the bivariate correlation method for the observed parameters depth of plowing, speed of the aggregate, and soil moisture at a level of significance $p < 0.05$. The Pearson correlation coefficient ($r$) reveal that there is a very weak correlation between the factors speed of the aggregate and soil moisture ($r = 0.081$), i.e. their influence on the studied parameter depth of plowing can be analyzed separately. The relation between the depth of plowing and speed of the aggregate is very weak ($r = 0.082$). The relationship between the parameters depth of plowing and soil moisture ($r = 0.836$) is strong and positive, which is a prerequisite for the creation of different regression models and the analysis of the influence of soil moisture on the depth of plowing.

The calculated correlation coefficients of the studied parameters depth of cultivation, speed of the aggregate, and soil moisture at a significance level $p < 0.05$ are presented in Table 3. Similar to the previous results (Table 2), there is a very weak correlation between the factors speed of the aggregate and soil moisture ($r = 0.010$), i.e. their influence on the studied parameter depth of cultivation can also be examined separately. Regarding the parameters depth of cultivation and speed of the aggregate, a very weak and negative correlation has been registered ($r = -0.033$). A strong positive correlation is observed between the parameters depth of cultivation and soil moisture ($r = 0.727$), which confirms the need to create different regression models.
Table 2. Crosstab correlation between examined parameters Depth of plowing, Speed of the aggregate, and Soil moisture.

| Tillage depth (a, cm) n=50 | Plowing | Aggregate speed (V, km/h) | Soil moisture (W, %) |
|---------------------------|---------|---------------------------|---------------------|
| Plowing                   | 1       | 0.082                     | 0.836*              |
| Aggregate speed (V, km/h) | -       | 1                         | 0.081               |
| Soil moisture (W, %)      | -       | -                         | 1                   |

*Correlation is significant at p < 0.05

Table 3. Crosstab correlation between examined parameters Depth of cultivation, Speed of the aggregate, and Soil moisture.

| Tillage depth (a, cm) n=50 | Cultivation | Aggregate speed (V, km/h) | Soil moisture (W, %) |
|---------------------------|-------------|---------------------------|---------------------|
| Cultivation               | 1           | -0.033                    | 0.727*              |
| Aggregate speed (V, km/h) | -           | 1                         | 0.010               |
| Soil moisture (W, %)      | -           | -                         | 1                   |

*Correlation is significant at p < 0.05

The average values of the observed parameter depth of cultivation of the agro-technical operations plowing and cultivation at the respective speeds are presented in Table 4. As it can be seen from the table, there are no statistically significant differences between the average values of the depth of plowing at a unit speed of 4 km/h (28.17 cm) and 4.5 km/h (28.40 cm). The same results can be seen for the average values of the depth of cultivation at unit speed 8 km/h (15.11 cm) and 9 km/h (15.05 cm). This could be explained by the reported weak correlations between these parameters (Table 2).

Table 4. Basic statistics and ANOVA of the observed parameter Depth of tillage for agrotechnical operations plowing and cultivation.

| Tillage depth (a, cm) n=50 | Plowing (n= 50) | Aggregate speed (V, km/h) | Cultivation (n= 50) | Aggregate speed (V, km/h) |
|---------------------------|-----------------|---------------------------|---------------------|---------------------------|
| Aggregate speed (km/h)    | \( \bar{x} \pm SD \) |                           | \( \bar{x} \pm SD \) |
| 4                         | 28.17±1.30 ns   | 8                         | 15.11±0.91 ns       |
| 4.5                       | 28.40±1.52 ns   | 9                         | 15.05±0.95 ns       |

ns - Same superscripts within the same column represent insignificant differences at p < 0.05; SD – Standard deviation; n – number of the observations

3.2. Regression models

The results of the composed regression models showing the influence of soil moisture on the depth of tillage at plowing and cultivation at different speeds of the aggregate are presented in Tables 5 and 6, Figure 2a-b and Figure 3a-b. Table 5 presents the regression equations showing the effect of soil moisture on plowing depth at a unit speed of 4 km/h. All regression models are statistically significant at p < 0.05. The value of the coefficient of determination of the Quadratic model is the highest \( R^2 = 0.682 \), i.e. about 68.2% of the variations in the depth of plowing are explained by the influence of the soil moisture at the speed of the aggregate unit 4 km/h.
Table 5. Model summary and parameter estimation showing the dependence of Depth of plowing (a, cm) from Soil moisture at speed of the aggregate 4 km/h and 4.5 km/h.

| Parameter estimates | R²    | Sig. | Equations |
|---------------------|-------|------|-----------|
| V = 4 km/h          |       |      |           |
| Linear              | 0.673 | 0.001| $a = 0.53x + 16.27$ |
| Logarithmic         | 0.668 | 0.003| $a = 7.97 + 11.63 \log(x)$ |
| **Quadratic**       | **0.682** | **0.000** | **$a = 37.33 - 1.39x + 0.04x^2$** |
| Exponential         | 0.675 | 0.000| $a = 18.42e^{0.02x}$ |
| V = 4.5 km/h        |       |      |           |
| Linear              | 0.720 | 0.002| $a = 0.62x + 14.36$ |
| Logarithmic         | 0.717 | 0.001| $a = -14.13 + 13.62 \log(x)$ |
| Quadratic           | 0.721 | 0.000| $a = 19.96 + 0.11x + 0.01x^2$ |
| Exponential         | 0.729 | 0.000| $a = 17.23e^{0.02x}$ |

* Level of significance $p < 0.05$

The calculated regression equations showing the influence of the soil moisture on the depth of plowing at a unit speed of 4.5 km/h were statistically significant at $p < 0.05$ (Table 5). In this case, the value of the coefficient of determination of the Exponential model is the highest ($R^2 = 0.729$), i.e. the parameter soil moisture at the speed of the aggregate 4.5 km/h affects the depth of plowing about 72.9%. Figures 2a and 2b show the estimation of the curves of the developed regression models expressing the relation between soil moisture and the depth of plowing at the respective speeds. The Quadratic model best describes the studied dependences at the speed of the unit 4 km/h (Figure 2a), and the Exponential model respectively at speed of 4.5 km/h (Figure 2b).

![Figure 2a](image1.png) ![Figure 2b](image2.png)

**Figure 2.** Curve estimation of regression models showing the influence of the Soil moisture on the Depth of plowing.

The regression equations showing the influence of soil moisture on the depth of cultivation at speeds of the aggregate 8 km/h and 9 km/h are presented in Table 6. All models are statistically significant at $p < 0.05$. The values of the coefficient of determination for both examined speeds are the highest for the Quadratic model ($R^2 = 0.526; 0.557$), i.e. about 52.6% of the variations in the variable depth of cultivation are explained by the influence of soil moisture at speed of the aggregate 8 km/h and 55.7% at speed of 9 km/h.
Table 6. Model summary and parameter estimation showing the dependence of Depth of cultivation (a, cm) from Soil moisture at speed of the aggregate 8 km/h and 9 km/h.

| Parameter estimates | R²   | Sig.  | Equations                      |
|---------------------|------|-------|--------------------------------|
| V = 8 km/h          |      |       |                                |
| Linear              | 0.523| 0.000 | $a = 0.57x + 6.04$             |
| Logarithmic         | 0.519| 0.001 | $a = -10.05 + 9.11 \log(x)$   |
| **Quadratic**       | **0.526**| **0.000**| $a = 16.14 - 0.69x + 0.04x^2$ |
| Exponential         | 0.515| 0.001 | $a = 8.32e^{0.04x}$           |
| V = 9 km/h          |      |       |                                |
| Linear              | 0.535| 0.004 | $a = 0.58x + 5.82$             |
| Logarithmic         | 0.526| 0.001 | $a = -10.29 + 9.17 \log(x)$   |
| **Quadratic**       | **0.557**| **0.000**| $a = 29.85 - 2.44x + 0.09x^2$ |
| Exponential         | 0.523| 0.002 | $a = 8.18e^{0.04x}$           |

* Level of significance p < 0.05

Figure 3. Curve estimation of regression models showing the influence of the Soil moisture on the Depth of cultivation.

The estimation of the curves of the models determining the relation between soil moisture and depth of cultivation at speeds of 8 km/h and 9 km/h is presented in Figures 3a and 3b. The Quadratic model best describes the studied dependences for both observed speeds.

4. Conclusions

Strong, positive correlations were reported between the parameters Depth of plowing, Depth of cultivation, and Soil moisture ($r = 0.836; 0.727$), which justifies the creation of regression models.

The average value of depth of plowing at a unit speed of 4 km/h is 28.17 cm, and at 4.5 km/h is 28.40 cm. The average value of depth of cultivation at a unit speed of 8 km/h is 15.11 cm, and at 9 km/h is 15.05 cm. It was found that the different speeds did not have a statistically significant effect on the depth of tillage during plowing and cultivation.

The Quadratic model best describes the influence of soil moisture on the depth of plowing at a speed of the aggregate 4 km/h ($R^2 = 0.682$), and the Exponential model respectively at a speed of 4.5 km/h ($R^2 = 0.729$). The influence of soil moisture on depth of cultivation for both observed speeds (8 km/h and 9 km/h) is best defined with the Quadratic model ($R^2 = 0.526; 0.557$).
The developed models could be used in the optimization of the control systems of the machine-tractor units and to serve the farmers in the choice of some parameters for carrying out certain technological tillage.

5. References

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