GIS Odyssey Journal

2025 • Volume 5 • Number 2

https://doi.org/10.57599/gisoj.2025.5.2.55

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NEW DESIGN STANDARDS FOR TERRITORIAL PLANNING OF ARABLE LAND

Abstract: The objective of the paper is to develop design standards for agricultural territory development by taking into account the characteristics of the modern agricultural machinery and the environmental requirements for maintaining healthy soil. The dimensional elements of a field plot under two agricultural machinery classes at two relevant agricultural practices were studied: 1) medium-class agricultural machinery and conventional tillage; 2) high-class agricultural machinery and zero tillage. Five design solutions for a field territory arrangement were developed. The draft projects were based on data from field experiments, in which winter wheat and corn were grown, on *Chernozems*. Data of three types of agricultural machines was gathered and processed: a seeder, a sprayer and a fertilizer spreader. The experimental data were processed in a single-factor and a multifactor regression analyses. The relationship between the field area, the length-width ratio, the machine working stroke and machine working hours was studied. It was established that the high-class agricultural machinery, combined with zero tillage technology, determines more rational field structure and contributes to more sustainable use of soil. New possible dimensions for a crop rotation field were established: up to 180 ha of a field area; more than 1300 m of working stroke; and 12:1 length-width ratio. An update of agricultural territory design standards was suggested.

Keywords: agricultural territory, agricultural machinery, sustainable land use, regression analysis, design standards

Received: 15 May 2025; accepted: 27 June 2025

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Introduction with analysis of the state of the problems

A scientifically based territorial development of the agricultural lands contributes to increasing sustainability of agriculture. Designing agricultural territory structure depends on a number of factors, such as: economic farm plan and region; soil, terrain and meteorological conditions; technical infrastructure; risk of erosion; farming systems and classes of agricultural machinery (D'Souza, 1996; Czyzewski, 2018; Hong, 2018; Ozden & Ozer, 2019). The linear dimensions and the area characteristics of the crop rotation field plots, the density of agricultural road network and soil status are closely connected to agricultural machinery class and the operational characteristics (Nikolov & Kirechev, 2014; Tsiaras et al., 2017; Lovarellia et al., 2018; Abbaspour-Gilandeh et al., 2020).

Currently, agricultural land in Bulgaria is being cultivated predominantly by medium-class agricultural machinery (Nikolov & Kirechev, 2014; Veleva et al., 2023). The maximum area of a field plot is up to 100 ha and the length of the working stroke does not exceed 1000 m (Moteva & Spalevic, 2016). Recently, land consolidation for land use under Agreement between land users (art. 37в, Agricultural Land Ownership and Use Act, prom. SG, No. 17 of 1 Mar 1991, last am. SG, No. 70 of 20 Aug 2024) is a precondition for cultivating land on a larger scale – in bigger fields with high-class machinery (Veleva et al., 2023). Tenants and land owners tend to buy high class farming machines, so that their number steadily increases but still over 75–80% of the available agricultural machinery in the country is physically and morally obsolete and does not meet the requirements of modern and efficient agriculture. Nowadays is observed continuous increase in the volume of imported equipment (Stoyanov & Beloev, 2008). The standards for the development of agricultural territories from the recent past (Information Bulletin No. 6 of the Land Reform Directorate of the Ministry of Agriculture, Food and Forestry, Sofia, 1992) are becoming increasingly inapplicable. Machines that are certified as high-class have high pulling power and large working width. This contributes to a smaller number of passes through the field, and hence less area is in risk of soil compaction and less area is under agricultural roads (Utamima et al., 2019).

Modern gentle soil cultivation technologies are also entering agriculture, especially with applying the heavy high-class machinery that causes high secondary soil compaction under the tracks (Li et al., 2025). The new century began with a new perspective on soil conservation: conservation tillage technologies gained popularity. Traditional tillage systems are considered to cause soil degradation and are incompatible with ecological land use. It has been proven that conservation tillage technologies control water and wind erosion, preserve and improve soil fertility, improve humus balance, reduce nutrient and moisture loss, improve crop productivity and labour efficiency, and reduce specific energy consumption and production costs. Conservation practices protect soil from secondary compaction and reduce soil temperature during the hot months of the year. Plant residues, left in the form of mulch on the surface, protect soil from erosion and contribute to soil moisture preservation, thereby preserving soil biological processes. The application of green manure enriches soil with nutrients. Reducing tillage contributes to low energy intensity of production (Nikolov & Kirechev, 2014; Arnhold et al., 2014;

Abbaspour-Gilandeh et al., 2005). Currently, under appropriate conditions, conventional (traditional) tillage is being replaced by minimal or zero tillage. In South American countries, Canada and the US, 90% of the area sown with cereals is cultivated by conservation technologies, 50-60% of which are zero tillage technologies (Calistu & Jităreanu, 2014). The combination of high class mechanization technique with advanced soil tillage technologies seems to be the new reality in agricultural land use and production.

There is an interdependence between the terrain characteristics and efficiency of agricultural machinery. Field configuration, density of agricultural road network and soil type influence agricultural machinery efficiency (Palmer et al., 2003). Myyrä (2001) (in (Timo, 2007)) studies the economic impact of different field shapes on agricultural machinery performance. He characterizes field shape by $\frac{P}{F}$ index, which is the ratio of the perimeter P to the area F of the field. The higher the index, the more negative the impact of the field shape on the machine performance and the economic results. Algirdas et al., 2007 evaluate machine efficiency in fields of different shapes and sizes through "operation time utilization factor": the time to perform a certain technological operation in relation to the total working time. This ratio depends on field length, working width, speed of movement, time duration of turning and raising-lowering of the rear attachment. They find that the utilization of working time of a ploughing unit varies from 0.56 to 0.88 with respect to field length from 200 to 1000 m. In terms of the use of working time, a longer field implies higher efficiency. According to the same authors, with the increase of the field area and the linear dimensions, the influence of the shape on the operation time utilization decreases. The effect that field size and shape have on the working time is almost entirely related to the time spent for making turns.

Due to the diversity of the terrain conditions, there is no universal algorithm for calculating the optimal movement of the aggregates. The shape and the linear dimensions, in connection with other factors, can reduce working time by 16% while achieving 10% product savings (Timo, 2007). The reduction of resources such as machines, fuel and personnel can result in lower prices at the market (Utamima et al., 2019).

The objective of the article is to develop design standards for structuring agricultural territory, taking into account the modern trends in the use of agricultural machinery and environmental requirements for soil cultivation.

Material and methods

The study started with elaborating draft projects for agricultural land development in the region of village of Traykovo, Montana District, Northwest Bulgaria (43.7491° North latitude, 23.2028° East longitude) (Fig. 1.). The relief of the land is flat. The altitude varies between 130 and 164 m. The territory falls within the temperate continental climate zone. The soil species are *Calcic Chernozems* and *Haplic Chernozems*, both of them medium sandy loam, which have good structure and are suitable for zero-tillage technology. The following steps were fulfilled:

Fig.1. Geographical situation and orthophoto image of village of Traykovo, Lom Municipality, Montana District, Bulgaria
Source: https://bg.wikipedia.org/wiki/Трайково;
Google maps https://www.google.com/maps/place/3645+Traykovo,+Bulgaria/

1. Five draft development projects for the agricultural area were developed in AutoCad Environment.

– The draft projects comprise areas under field crop rotations and fodder crop rotations. Further in the study, only the field crop rotations, intended for cereal crops, were considered.
– The area of each crop rotation was divided into field plots, meeting a number of design requirements. One of them was to ensure efficiency of agricultural machinery, i.e. the spatial dimensions of the plots to be adequate to the technological level of mechanization. The area and the linear dimensions of each field plot ensure the day shift productivity of the machines, optimal one-way path length in the working direction; integer number of loadings of the hopper with working material (seeds, fertilizers, working liquid for spraying herbicides and other preparations); minimal loss of time for reversing the direction of movement, avoiding unnecessary maneuvers; minimal energy consumption; etc.).

  From ecological point of view, the spatial structure of a field plot in the draft projects ensures minimal number of passes of the machines through the field in order to minimize the area with secondary soil compaction, i.e. completion of the working material (seeds, fertilizers, spraying liquids) and filling of the combines with the harvest should occur when the machine approaches the border of the field plot; complete coverage of the field plot by the movements of the machines; minimum area under earth roads, etc.

  To meet these requirements, the long sides of the field plot in the working direction should be parallel, the length-width ratio should be performed according to standards. According to Timo (2007), when the paths are in the direction of the long and straight side of a 10-ha field, the compacted soil in the reversing area is 5% of the whole area of the field.
– Two of the draft project variants were tailored to medium class machinery and conventional tillage and were subjected to the popular from the past territory design codes (Vuchkov et al., 1988). The other three variants were based on spatial

experimental data, gathered from agricultural producers, who used high class machinery and zero-tillage technology (Moteva & Spalevic, 2016).

2. Data of the type and number of operations performed (sowing, spraying and fertilization) and the operational characteristics of the machines (area coverage of a single-way path) in winter wheat and corn fields were processed (Table 1). The data was kindly provided by the Control and Technical Inspection Department (CTID) of the General Directorate of Agriculture and Regional Policy of the Ministry of Agriculture, Food and Forestry.

According to CTID, high-class sowing machines have 6 m working width and 10 ha/h productivity rate. When reducing the rate by 20% for movement, loading and reversing the direction, the shift productivity of the machine would be 8 ha/h. Assuming 10 h net-working time of, 80 ha would be daily processed. If the speed of the sowing machine is 8 km/h, the seed quantity in the hopper – 3.7 t, daily 26 ha would be sown. To meet the daily rate of 80 ha, three loadings would be needed.

The same source says that a high-class sprayer with a capacity of 3300 l of the tank, 30 m coverage, and moving with 10–12 km/h, would treat with 30 reverse movements a 40-ha field and the travelled distance would be 13 km. Further, if the working time of the sprayer is 6 h/d, 180 ha/d or 30 ha/h would be treated.

Table 1. Types and number of operations in wheat and corn fields under conventional and zero tillage, and the coverage of agricultural machinery

Types of operations	Medium class machinery, conventional tillage				High class machinery, zero tillage			
	Winter wheat		Corn		Winter wheat		Corn	
	Nb of operations	Para-meters, m	Nb of operations	Para-meters, m	Nb of operations	Para-meters, m	Nb of operations	Para-meters, m
Tillage	-	-	1	1,8	-	-	-	-
Discus (disk harrow)	3	5	-	-	-	-	-	-
Cultivation	-	-	2	4.2	-	-	-	-
Sowing (conventional sowing machine)	1	3.6	1	4.2	1	6	1	7
Digging (harrow)	-	-	2	4.2	-	-	-	-
Spraying (sprayer)	2	12	2	12	1	24	1	24
Fertilising (fertilizer spreader)	1	30	1	4.2	1	30	-	-
Harvesting (combine harvester)	1	7	1	4.2	1	7	1	7

Source: Control and Technical Inspection Department (CTID) of the General Directorate of Agriculture and Regional Policy of the Ministry of Agriculture, Food and Forestry

A high class fertilizer spreader with 2500 kg capacity of the hopper, 30 m coverage, at 200 kg/ha fertilization rate and moving with 18 km/h, would be loaded in every 12.5 ha of covered area.

Using the above and other data, field crop rotations in three variants were designed to match the productivity of this high-class machinery.

3. The impact of the dimensional characteristics of the newly designed field plots in all five variants on the field machines efficiency was estimated and analysed. The analysis was done in the following order:

– Data of area (F) and length-width ratio ($\frac{L}{W}$) of each field plot of the designed crop rotations were recorded. They were accepted factors.
– Distance travelled (S), distance travelled per unit area (S_o) and operating time utilization factor (τ) were estimated. They were accepted variables as dependant on the factors above.
– The physical values of the factors $\frac{L}{W}$ and F were coded as x_1 and x_2, respectively. They were coded for the purpose of creating mathematical models and joint analysis. Coding allowed finding optimal solutions in the MathCad Environment (Gavioli et al., 2019).

The coding was performed, as the minimum and maximum values of the factors x_1 and x_2, denoted as x_{min} and x_{max}, were assigned as -1 and 1, respectively. The calculated intermediate codes x_{ci} of the natural values of the factors (x_i) in the experiment are in the interval between x_{min} and x_{max}. Their values were obtained as (equation (1)):

$$x_{ci} = \frac{2(x_i - x_0)}{x_{max} - x_{min}} \tag{1}$$

where x_{ci} – code of intermediate value x_i.
x_o – basic level

The intermediate codes are negative if the natural value is in the interval (x_{min}, x_o) and positive if the natural value is in the interval (x_o, x_{max}).

– By assuming that the machine unit has the same speed during operating and reversing, the operating time utilization factor was calculated as (equation (2)):

$$\tau = \frac{t}{T}, \tag{2}$$

where: t – machine travel time only for the useful working strokes (excluding turns), h;
T – total machine travel time (including turns), h.

– For τ and S were built 3D dependency models (equations (3)) and the dependencies were visualized (Shavazipour et al., 2021):

$$\tau = f(\frac{L}{W}, F) \text{ and } S = f\left(\frac{L}{W}, F\right) \tag{3}$$

where: L – field length (km)
W – field width (km)
$\frac{L}{W}$ – length-width ratio
F – field area (ha)
τ – operating time utilization factor
S – distance, traveled by the machine (km)

The surfaces from equations (3) were described by a second power polynomial (equation (4)):

$$Y = b_0 + b_1x_1 + b_2x_2 + b_{12}x_1x_2 + b_{11}x_1^2 + b_{22}x_2^2, \quad (4)$$

4. Considering the results from the 3D analysis about the statistical significance of the factors, 2D dependency models were built in Excel Environment to establish the dependency of τ and S on the linear and area dimensions of the field (equations (5)):

$$\tau = f(\frac{L}{W}) \text{ and } S = f(F) \quad (5)$$

5. Finally, a procedure in Mathcad Environment was performed to determine the values of the factors F and $\frac{L}{W}$, for which τ and S (equations (3)) take on a maximum and minimum value, respectively.
6. Next, the intersection of the two hypersurfaces was determined. Based on the models of τ and S, described by equation (4), the lines of equal response of both parameters τ and S were constructed in Mathcad Environment. Further, maximization and minimization of the functionals were performed. Maximum value of the operational time use factor: $\tau_{max}\,(\frac{L}{W}, F)$ and the minimum value of the distance traveled: $S_{min}\,(\frac{L}{W}, F)$ were estimated. After jointly solving the functionals of τ and S, the equation of their intersection was obtained. For every solution of the intersection equation, τ_{max} and S_{min} were simultaneously fulfilled. After decoding the values of the real ones, the range of change of the spatial dimensions $\frac{L}{W}$ and F, including medium and high-class agricultural machinery, was determined. When the operating time is maximally used and the travel distance is minimal, machinery works most efficiently.

Results and discussion

The draft project on Fig. 2a is an example of medium-class agricultural machinery. The maximum field plot area is 100 ha, the maximum length of working stroke is 1000 m, and maximum length-width ratio is $\frac{L}{W}$ = 8 (Vuchkov et al., 1988; Moteva & Spalevic, 2016). The two draft projects for medium class machinery, conventional tillage, and standard old codes contain totally 30 field plots with 60.4 ha average area of a plot. The total number of field plots processed in the following analysis is 30. The average area of a crop rotation is 360.5 ha (Table 2).

The draft project on Fig. 2b is an example of high class machinery and zero-tillage technology. The linear dimensions are nearly twice bigger, taken from practice. They meet the spatial design requirements, adequate to the capabilities of the high-class agricultural machinery – max 200 ha of a field plot and max 2000 m of working stroke (Moteva & Spalevic, 2016). The length-width ratio was that which was experimented in practice. The data of linear and areal dimensions in the draft projects are given in Table 3. The field plots are totally 33 with average area of a plot 99.8 ha. The average area of a crop rotation is 399.8 ha

Fig. 2. Examples of a territorial development draft project for agricultural land, village of Traykovo, Montana region: a) for medium class machinery, conventional tillage, and standard old codes; b) for high class machinery and zero-tillage technology (the yellow colour and its nuances denote the field crop rotations, the green one – the fodder crop rotation, which was not considered in the study)
Source: own study

Table 2. Areal characteristics of the field crop rotations per draft project for middle class machinery

Field crop rotations No.	Area of a crop rotation (ha)	Number of fields	Ave area of a field (ha)	Area of a crop rotation (ha)	Number of fields	Ave area of a field (ha)	Ave area of a crop rotation (ha)	Number of fields	Ave area of a field (ha)
	Ist variant			IInd variant			Totally for both variants		
1	471.0	8	58.9	364.7	5	72.9			
2	444.8	6	74.1	249.7	6	41.6			
3	-	-	-	272.4	5	54.5			
Totally for a variant	915.8	14	65.4	886.7	16	55.4			
							360.5	30	60.4

Source: own study

The design solutions for the territorial structure of crop rotations show better results for high-class agricultural machinery compared to medium-class machinery (Tables 2 and 3): the average number of field plots is less; the average area of a field plot F is 39.4 ha larger; the length-width ratio $\frac{L}{W}$ is higher in value and more favorable for the machinery; the length of the passes per unit area S_o is three times shorter for corn and less than twice for winter wheat; the operation time utilization factor τ is higher, which shows that the idle runs of the machines are less (Table 4). These data show that when working with high-class machinery using zero-tillage technology vs medium class machinery using conventional tillage technology the area under earth roads, the reverse movements, and soil area under compaction are less and the operation of the machines is more efficient. It is evident that the zero-tillage technology, practiced with high-class machinery is much gentler on the soil and the use of land and machinery is more efficient.

Table 3. Areal characteristics of the field crop rotations per draft project for high class machinery

Field crop rotations No.	Area (ha)	Number of fields	Ave area of a field (ha)	Area (ha)	Number of fields	Ave area of a field (ha)	Area (ha)	Number of fields	Ave area of a field (ha)	Ave area of a crop rotation (ha)	Number of fields	Ave area of a field (ha)
	I^st variant			II^nd variant			III^rd variant			Totally for the 3 variants		
1	253.1	4	63.3	154.9	5	31.0	189.1	3	63.0			
2	738.3	5	147.7	724.4	5	144.9	601.1	4	150.3			
3	-	-	-	224.9	4	56.2	314.1	3	104.7			
Total	991.4	9	110.1	1104.2	14	78.9	1104.3	10	110.4			
Totally for a variant										399.8	33	99.8

Source: own study

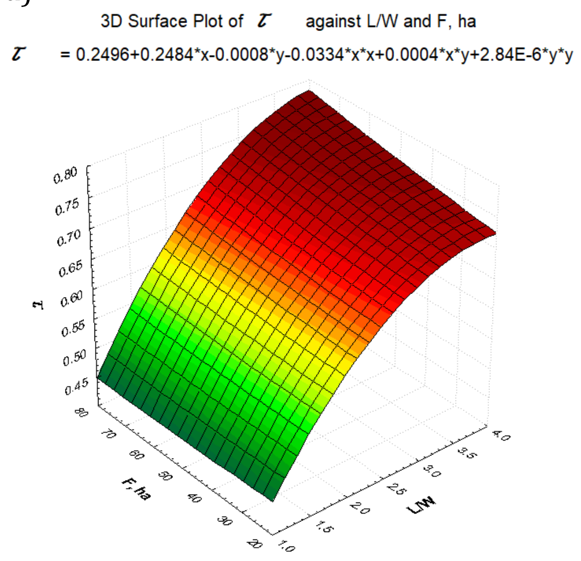
Table 4. Length of agricultural machinery passes per unit area S_o (km/ha) and operating time factor τ

Variants	Average number of field plots	Average area of a field F (ha)	Averagelength-width ratio $\frac{L}{W}$	Length of passes per unit area S_o (km/ha)		Operating time use factor τ
				Winter wheat	Corn	
Medium class machinery & conventional tillage	15	721,4	2.07	11.38	19.40	0.56
High class machinery & zero tillage	11	998.2	2.77	8.64	6.52	0.69

Source: own study

The operating time utilization factor τ is essential for the rational use of agricultural machinery. Minimizing idle runs has economic and environmental importance, which is why the field structure must be in accordance with the technical characteristics of agricultural machinery. On Fig. 3ab is shown the dependence of the operation time utilization factor τ on the area F and length-width ratio $\frac{L}{W}$. On Fig. 3a is seen that τ does not change with change of F. It changes with change of the ratio $\frac{L}{W}$. τ reaches a maximum of 0.78 at $\frac{L}{W} = 4$. For high-class machinery (Fig. 3b) τ reaches a maximum of 0.9 at $\frac{L}{W} = 10$. The working time is better utilized by high-class machinery (around 90%) versus medium-class machinery (around 78%). For the efficient use of the machines field area is not a limiting factor. Length-width ratio $\frac{L}{W}$ can reach higher than the recommended $\frac{L}{W} = 8$ (Vuchkov et al., 1988) values, especially when working with high-class machinery.

a)



b)

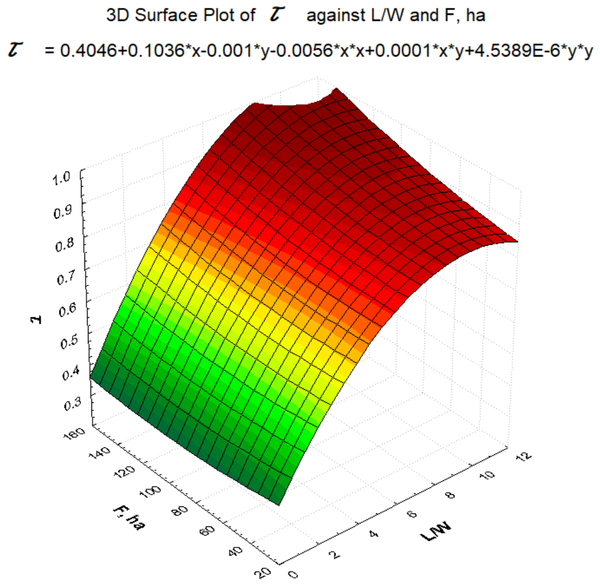


Fig. 3. Dependence of the operation time utilization factor τ on the area F and the ratio $\frac{L}{W}$ when using: a) medium-class agricultural machinery;
b) high-class agricultural machinery
Source: own study

Fig. 4ab shows the dependence of the way travelled S on the length-with ratio $\frac{L}{W}$ and the area F. Unlike τ, S does not depend on $\frac{L}{W}$ but on the area F.

Since the multifactor analysis showed that every variable depends mainly on one factor, a single-factor analysis was conducted in Excel Environment to establish the models of dependence. The dependence of τ on $\frac{L}{W}$. is very strong for both machinery classes (Fig. 5). The second-power function has a coefficient of determination of approximately R^2=1 for medium-class machinery (Fig. 5a) and R^2=0.85 for high-class machinery. For high-class machinery (Fig. 5b) τ keeps high at a large range of $\frac{L}{W}$ – from value 8 to 12. This gives the possibilities for designing fields with longer strokes.

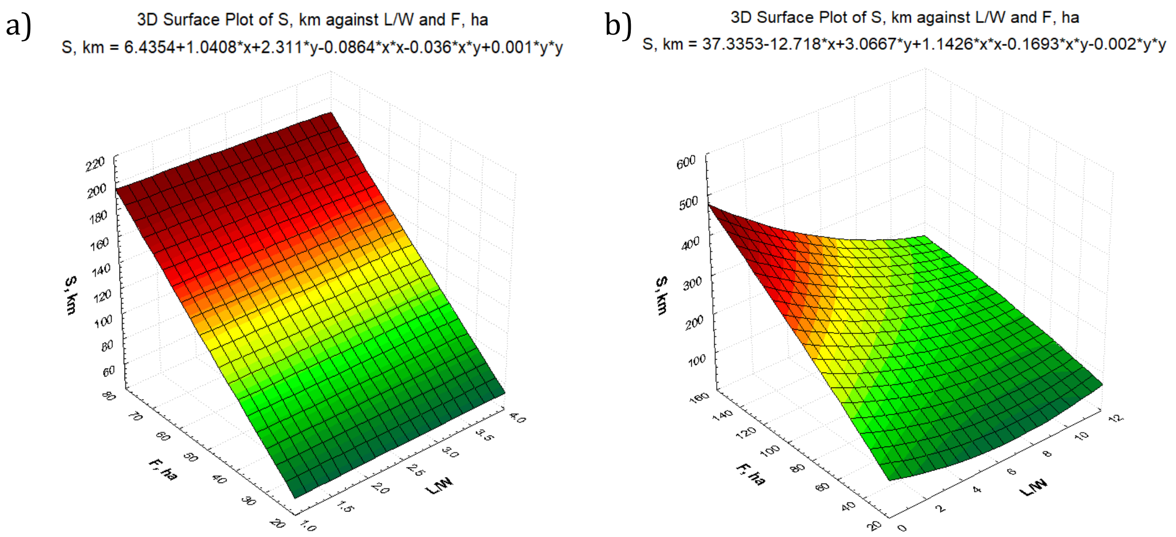


Fig. 4. Dependence of the distance traveled S on the area F and the ratio $\frac{L}{W}$ when using: a) medium-class agricultural machinery; b) high-class agricultural machinery
Source: own study

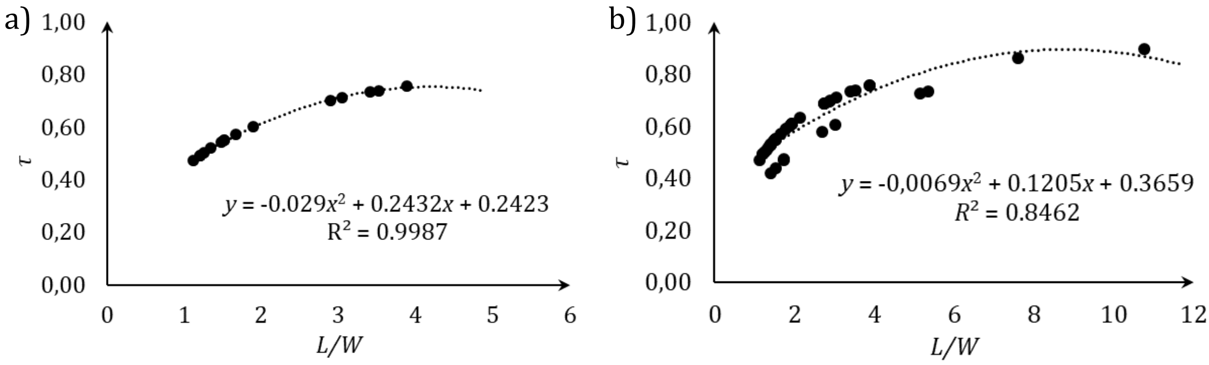


Fig. 5. Dependence of τ on the ratio $\frac{L}{W}$, when using: a) medium-class agricultural machinery; b) high-class agricultural machinery
Source: own study

The travelled distance S performs linear dependence on the field area F with a high degree of determination: R^2=0.99 for medium-class machinery and R^2=0.95 for high-class machinery (Fig. 6ab). The larger the area, the longer the travel distance.

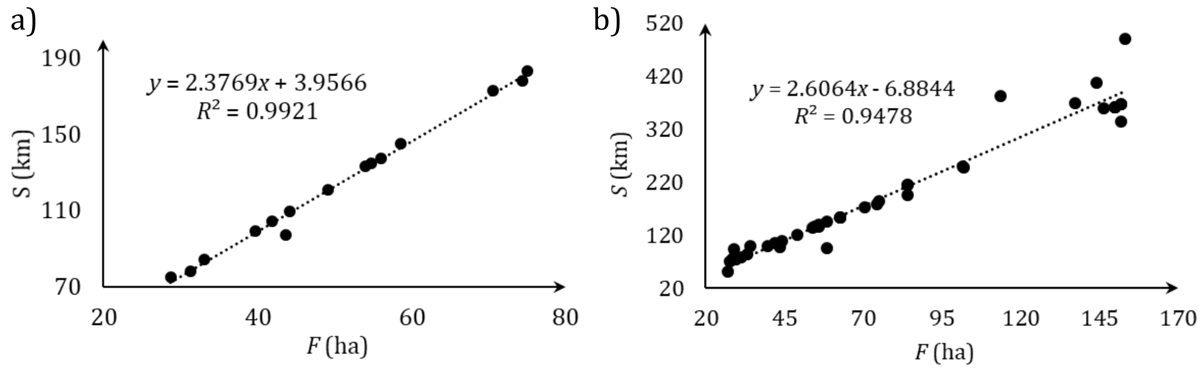


Fig. 6. Dependence of S on the ratio $\frac{L}{W}$ when using: a) medium-class agricultural machinery; b) high-class agricultural machinery
Source: own study

As next step, the procedure of coding was implemented. The lowest, the highest and the basic value of the natural factors, also their codes are presented in Table 5. The length-width ratio $\frac{L}{W}$ is denoted as x_1, while the area F is denoted as x_2. The smallest ratio in the data is $x_{1,min} = 1.1$ (a square), the greatest one is $x_{1,max} = 10.8$ (a rectangle). The codes of these values are -1 and 1, respectively. The smallest area is $x_{2,min} = 27.2$ ha, the biggest is $x_{2,max} = 152.9$ ha. The codes are -1 and 1, respectively.

Table 5. Coding of factors and variables

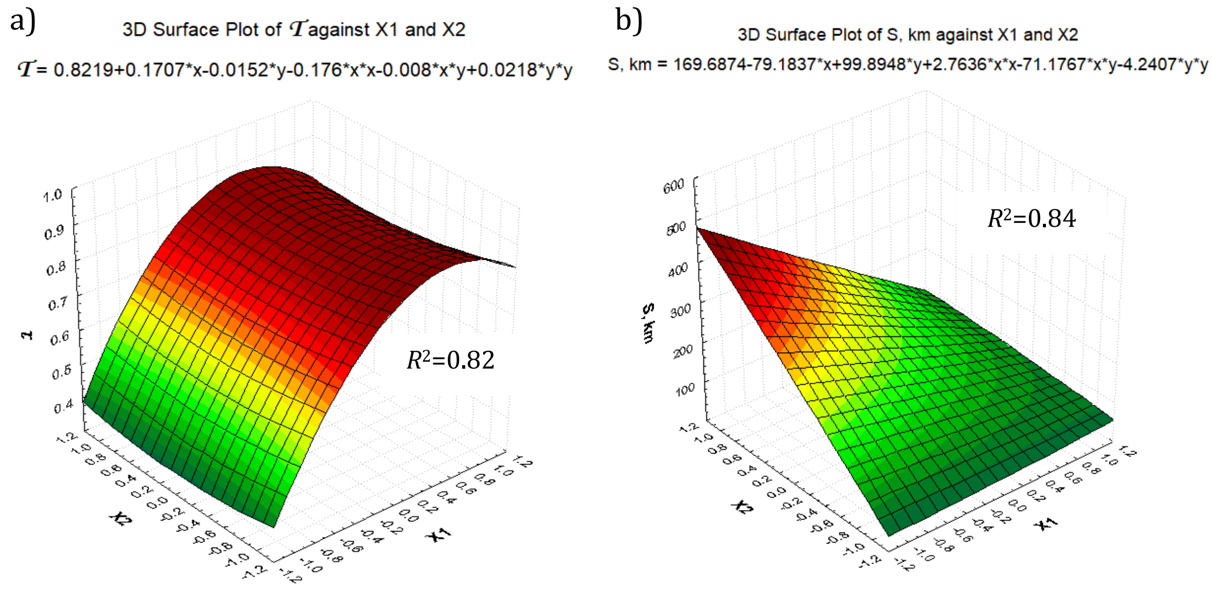
Factors	Natural values of factors			Coding of factors		
	Lowest level	Basic level	Highest level	Lowest level	Basic level	Highest level
Length-width ratio $\frac{L}{W}$, [x_1]	1.1	5.9	10.8	-1	0	1
Field area F (ha), [x_2]	27.2	90.0	152.9	-1	0	1

Source: own study

After performing a multiple regression analysis, including all data of both classes machinery, the following combined models were obtained in coded (Fig. 7ab):

$$\tau = 0.8219 + 0.1707x_1 - 0.0152x_2 - 0.176x_1^2 - 0.008x_1x_2 + 0.0218x_2^2 \quad (6)$$

$$S = 169.6874 - 79.1837x_1 + 99.8948x_2 + 2.7636x_1^2 - 71.1767x_1x_2 - 4.2407x_2^2 \quad (7)$$



N=44	Regression Summary for Dependent Variable: Tau R= .91878733 R²= .84417015 Adjusted R²= .82366622 F(5,38)=41.171 p<.00000 Std.Error of estimate: .04858					
	Beta	Std.Err. of Beta	B	Std.Err. of B	t(38)	p-level
Intercept			0.821877	0.042198	19.47664	0.000000
X1	0.560198	0.233588	0.170694	0.071175	2.39823	0.021491
X2	-0.090845	0.340223	-0.015154	0.056753	-0.26701	0.790901
X1X2	-0.039822	0.345086	-0.008025	0.069542	-0.11540	0.908738
X1X1	-0.443321	0.103708	-0.175954	0.041162	-4.27472	0.000124
X2X2	0.067171	0.069204	0.021823	0.022483	0.97063	0.337868

N=44	Regression Summary for Dependent Variable: S, km R= .92878596 R²= .86264335 Adjusted R²= .84457011 F(5,38)=47.730 p<.00000 Std.Error of estimate: 47.362					
	Beta	Std.Err. of Beta	B	Std.Err. of B	t(38)	p-level
Intercept			169.6874	41.14052	4.12458	0.000195
X1	-0.250255	0.219306	-79.1837	69.39107	-1.14112	0.260960
X2	0.576684	0.319421	99.8948	55.33092	1.80541	0.078939
X1X2	-0.340125	0.323986	-71.1767	67.79935	-1.04981	0.300435
X1X1	0.006705	0.097367	2.7636	40.13002	0.06887	0.945458
X2X2	-0.012570	0.064972	-4.2407	21.91996	-0.19346	0.847629

Fig. 7. Dependence of the operation time utilization factor τ and the travelled distance S on x_1 (area F) and x_2 (the length-width ratio $\frac{L}{W}$), including both machinery classes
Source: own study

Based on these models, the lines of equal response for both variables τ and S were obtained (Fig. 8ab). Maximization of the functional for τ and minimization of the functional for S (equations (3)) in Mathcad Environment was performed. The results confirm those from the multifactor analysis that F does not affect τ when $\frac{L}{W} < 6$ (the basic level). When the length-width ratio increases, i.e. the shape of the field plot changes to a rectangle with long parallel sides, the influence of the area F becomes more significant (the yellow to orange lines on Fig. 8a). The smaller the area, the less the influence of $\frac{L}{W}$.

On Fig. 8b is seen that a square field ($x_2 = -1$, i.e. $\frac{L}{W} = 1$) with the largest area ($x_2 = 1$, i.e. $F_{\max}$ in the experiment) has the longest run S (the orange line on Fig. 8b).

To find the maximum value of τ and the minimum value of S, maximization and minimization of the functionals (6) and (7), respectively, were performed. The maximum value of τ in coded values was obtained at (equation (8)):

$$\tau_{max}(1.0,\ 0.45\ ) = 0{,}856 \tag{8}$$

The minimum value of S was (equation (9)):

$$S_{min}(-1,\ -0.332\ ) = 41{,}3 \tag{9}$$

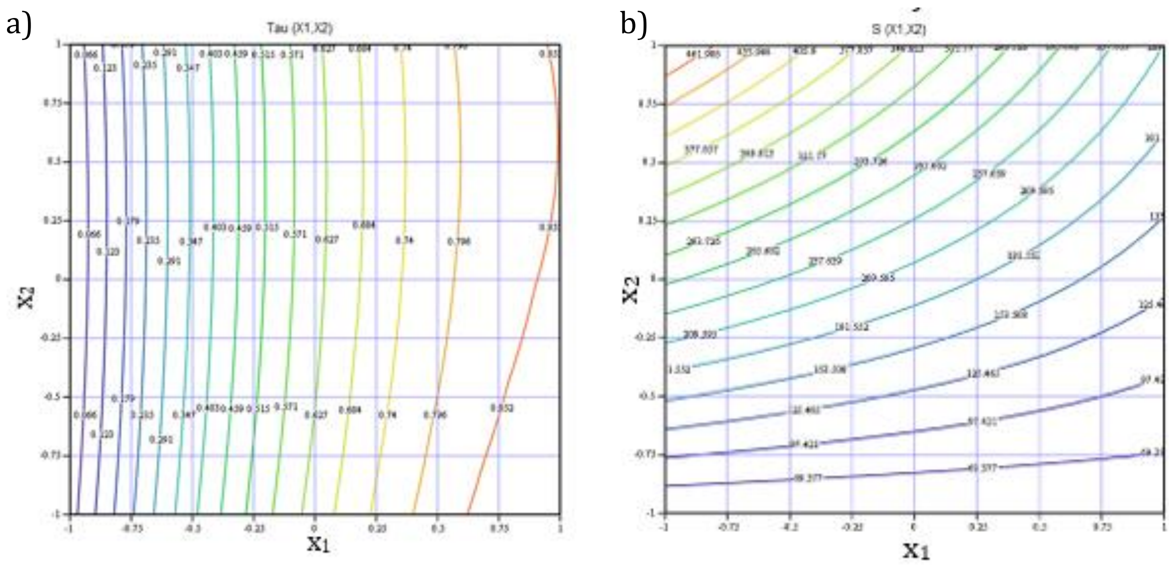


Fig. 8. Lines of equal response depending on the area F and the aspect ratio $\frac{L}{W}$:
a) for the operation time utilization factor τ; b) for the distance traveled S
Source: own study

After converting the coded values into real values, it was found that τ in the experiment is maximum at length-width ratio $\frac{L}{W}$ =11 (rectangle) in an area F = 152.9 ha. At this point, the operating time utilization factor takes the value τ = 0.856.

The distance travelled from the experiment is minimal for length-width ratio $\frac{L}{W} = 1$ (a square) in an area F = 64.13 ha and is S = 41.3 km.

After jointly solving the functionals (6) and (7), the equation of their intersection was determined (equation (10)):

$$1.171202 + 1.029303x_1 - 0.514x_2 - 0.35533x_1x_2 - 0.70215x_1^2 + -0.104826x_2^2 = 0 \tag{10}$$

At each point of this line, both conditions – maximum utilization of the operating time and minimum length of the travelled path are simultaneously met (Fig. 9). The two surfaces intersect in the area of ratio $\frac{L}{W} = 1$ to 4 and field plot area F = 45 to150 ha. When the field area is $F = 45$ ha and its length-width ratio is $\frac{L}{W} = 1$, the operating time utilization is maximum at a minimum travelled path. The same is valid for $F = 150$ ha atlength-width ratio $\frac{L}{W} = 4$. In order to use agricultural machinery as efficiently as possible and to minimize the distance traveled within the fields, the shape of the field should vary from a square with an area of F = 45 ha to a rectangle with an area of $F = 150$ ha and a length-width ratio of the sides $\frac{L}{W} = 4$. This means that the sides of the field should vary from 670 × 670 m to 2500 × 600 m. Outside these limits, agricultural machinery will be used inefficiently and there will be larger areas with soil compaction caused.

These values of the structural characteristics of a plot guarantee the best ecological effect from the cultivation of land. By considering the intersection line, one can choose such a combination of factors that will ensure maximum utilization of the operation time and a minimum travelled path.

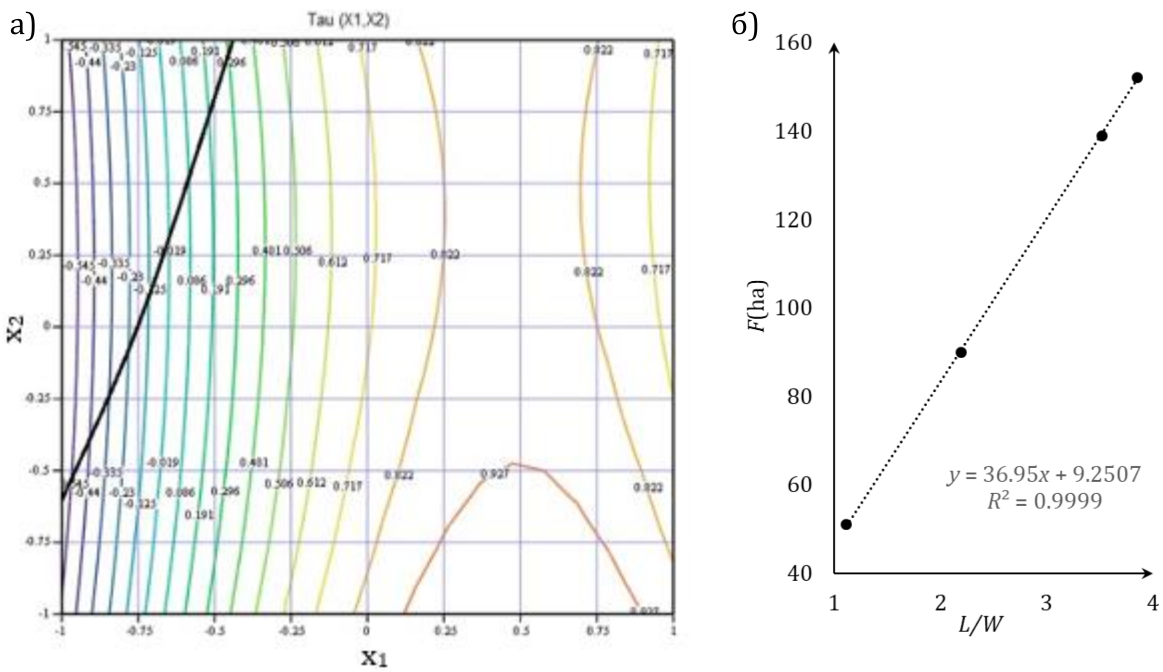


Fig. 9. Intersection of the hypersurfaces of τ and S:
a) in coded values; b) in natural values
Source: own study

Conclusions

The proposed approach allows to design optimal fields in shape and sizes in order to increase the economic efficiency of production and reduce soil compaction. High-class agricultural machinery and zero-tillage technology allow consolidation of land use and reduction of passages through the cultivated areas, which reflects the sustainable use of soil resources. The distance travelled per unit area can be about one third shorter when growing wheat and up to three times shorter when growing corn compared to using medium-class agricultural machinery and conventional tillage.

The average area of a field of a crop rotation, when working with high-class agricultural machinery is 89 ha, but it is possible to reach more than 160 ha. The area of the field is a statistically significant, but not limiting factor for the efficient use of machines. The distance travelled is S = 41.3 km and is the shortest within the experiment for a square-shaped field with an area of 64.13 ha. If the requirement for maximum efficient use of the agricultural machinery is also applied, the area is reduced to 45 ha. To account for maximum efficiency of agricultural machinery with a minimum distance travelled when changing the shape of the field to rectangular with an increase in area, the established dependence on the graph in Fig. 10 can be used. The maximum indicators up to which these requirements are satisfied are a ratio of sides of 4 and an area of 150 ha. Beyond these values, soil quality and the use of agricultural machinery deteriorate.

With high-class agricultural machinery, the operating time utilization factor of agricultural machinery is higher. If only maximum use of the operating time of the machinery is taken into account, considerably higher than the currently recommended for medium-class machinery length-width ratio can be recommended. When cultivating the soil with high-class agricultural machinery, it can reach 12. On the other hand, if the aim is to minimize the risk of secondary soil compaction, the field area should not exceed 150 ha.

The update of the design standards for structuring of the agricultural area should include maximal values of field plot spatial dimensions: 150 ha for the area, 11 for the length-width ratio, 1200 m for the length and to 600 m for the width. These dimensions should be taken into account only when high class agricultural machinery is used. For medium-class machinery the existing standards should be applied.

Acknowledgements

This research work under Contract BN-316/2025 "Strategic Approach to Spatial Planning of Agricultural Territories in Bulgaria " is financially supported by the Center for Research and Design at UACEG.

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