ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ
СОФИЯ

Том Volume 51 2018 Брой Issue 6

ANNUAL OF THE UNIVERSITY OF ARCHITECTURE, CIVIL ENGINEERING AND GEODESY
SOFIA

Получена: 11.10.2017 г.
Приета: 25.10.2017 г.

OPTIMIZING THE IRRIGATION OF CORN IN WATER DEFICIT CONDITIONS

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Keywords: *corn, wide-spaced irrigation, yield, water use efficiency, optimization*

ABSTRACT

Experiments with wide-spaced furrow irrigation of corn on vertisols and chromic luvisols are carried out in Sofia and Stara Zagora regions. The effect of different irrigation depths, number of irrigations and distances between irrigated furrows at full and deficit irrigation on the grain yield and the irrigation water use efficiency is tested. The data obtained is used in a planned B_3 type experiment. The combined effect of the factors is analyzed. After optimization of the obtained regression models, optimal values of the irrigation elements in water deficit conditions are established. The proposed graphical interpretation of the lines at the same level allows selection of irrigation scheduling according to the specific conditions. It is found that the maximum yield with maximum efficiency of irrigation water is obtained by distributing 91%M_{opt} in every other fixed furrow with a maximum number of irrigations.

1. Introduction

The full-irrigation practices that require significant water amounts and satisfy the crop water needs are in most cases economically inefficient. Innovative irrigation practices, which are oriented to saving water and enhancing the water efficiency, gain more economic advantages for the farmers and combine wider environmental benefits. Good knowledge on the

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possibilities of some technological improvements can provide for economic advantage of the production process and reducing of the environmental burdens [1].

Surface irrigation of corn is the most popular irrigation practice in Bulgaria. 74% of the irrigable area is equipped with gravity irrigational systems and 63% of the irrigated crops are grain crops, mainly corn. The effect of irrigation on corn yield has increased during the last two decades of the 20th century approximately 1,6 times [2], which is evidence for warming and drought processes. According to [3], the need for irrigation by 2070 will have increased twice. Irrigation nowadays is directed to the management of the specific productivity of the water in order to maximize the impact of the irrigational water and to minimize the yield losses.

Due to economic and social reasons during the last 30 years, the water losses along the irrigation networks have terrifically increased. Therefore, the farmers are greatly interested in water saving and technically simplified irrigation technologies with low investments in the irrigation set of their fields.

Except for the physical water scarcity in future, some soils hinder the regular surface irrigation process. Some clayey soils tend to water logging and slowing down the irrigation process, while when drying they form cracks. Such soils occupy a great part of the agricultural territories in Bulgaria which are under irrigation. The *vertisols* (heavy black clay soils) occupy about 0,6 million hectare in South Bulgaria. This is approximately 9% of the deep fertile soils and 5,34% of the country area. These soils have poor internal drainage and resultant flooding and water logging during the extreme rainy events. They have great Total Water Capacity – around 410 – 450 mm but only 150 – 170 of it is available for the crops [4, 5]. These soils have low hydraulic conductivity that makes them unsuitable for all-over surface watering but for localized wide-spaced irrigation like in every other or every third furrow [6] by exploring the their capillary potential. Chromic luvisols occupy 2,8 million ha, approximately 25,28% of the country surface area. Around 41,1% of them are used for agricultural production and 1 million ha are deep soils. They are spread mainly in South Bulgaria. They have heavy texture, especially in the illuvial layer [4, 5]. These soils also suffer of surface water logging in conditions of heavy rainfalls. They have great capillary potential of their illuvial layer for applying wide-spaced irrigation. According to [7], the lateral infiltration of the vertisols in Ethiopia is well enhanced when the soil moisture is in the range 50% of the available water capacity (AWC) and field capacity (FC).

The gravitational irrigation technologies perform possibilities for saving water though causing certain wetting irregularity in the soil. One such technology is wide-spaced irrigation for the row crops, through which small irrigation depths are distributed in every other (EOF) or every third furrow (ETF) [6, 8, 9, 10, 11, 12, 13]. A substantial increase of the irrigation water use efficiency (*IWUE*) can be achieved and the magnitude in water savings can be 40 – 50% at acceptable 15 – 20% lower yields [9, 10, 14, 15]. The evapotranspiration losses can be reduced by some 20 to 50% [17]. As a localized irrigation technology, the wide-spaced irrigation maintains the soil relatively dry. It avoids water losses from evaporation and deep percolation, protects the soil structure, contributes for relatively uniform watering over the irrigated territory, enables high water use and labor efficiency, etc. The results from [13] experiments are evidence for the higher absorption of the irrigational water by soil. They have established that the infiltration parameters of the every-other-furrow irrigation (EOF) are higher than those of the ordinary every-furrow irrigation (EF). [16] have measured the rate of advance of the water down the furrow when watering in EOF than in EF as low as 0,68 to 0,81, depending on the soil type and the slope. The stand point of [17] is that high yields can be obtained through wide-spaced irrigation with small irrigation depths. They have established that corn and soybean give yields close to the maximum ones if the irrigation depths are 50 – 80% of the optimum. With 73% of the optimum irrigation depth, distributed in EF and EOF, [12] obtained some 16% more yield in EOF.

Some authors have developed the idea of the wide-spaced irrigation in the sense of variation of the application number [12], i.e. different duration of the irrigation intervals and volume of the application depth, and with alternation of the wetted furrows [9, 10, 17]. In the first type of investigations, EOF with a smaller amount of irrigation water at 10-day irrigation intervals at sugar beet caused some yield reduction. However, frequent EOF at 6-day intervals produced a similar root yield to that of EF irrigation at 10-day intervals and saved about 23% of irrigation water. About 43% higher water use efficiency (*IWUE*) was obtained at more frequent EOF applications than at less frequent EF ones, because of reduction of the evapotranspiration losses by 20 to 50%. In the second type of investigations, the alternate furrow irrigation (AF) of corn with up to 50% reduction of the irrigation amount contributed for enhanced root development and high grain yield than the every other fixed-furrow irrigation (EOFF) and EF irrigation did. Hence, the irrigational water use efficiency (*IWUE*) was substantially increased. Similar conclusions derive [7] by comparing the traditional EF irrigation scheduling to the AF irrigation scheduling. Although the absolute grain yield was higher for the FF scheduling, *IWUE* was higher for the AF scheduling. The yield increase was 54% and the *IWUE* increase was 58%. This proves the fact that underwater scarce conditions, economically good yield can be obtained through AF scheduling compared to EF irrigation scheduling. On the other hand, where both water and agricultural labor are limiting, AF scheduling can be considered an option [7].

Deficit irrigation reasonably increases the *IWUE* and the economic profit of the water. Farmers are open to adjust their water use with some degree of yield risk to gain some economic profits [18]. Deficit irrigation should be well managed in order to gain a moderate risk for crop yield and farmer's income. The basic items for its planning and management are: 1) the efficiency of the irrigation technology applied and 2) the relation between the yield obtained and the water consumed/applied. According to [7], Oweis et al. (1999) have examined two levels of deficit irrigation (67 and 33% of the full crop water requirement) and suggested that economically reasonable yields could be obtained through deficit irrigation when the dose and intervals of irrigation are well monitored. They noted that deficit irrigation requires more control over the amount and timing of water application than full irrigation. They have concluded that with established crop water production functions and sensitive stages of crop growth to water stress, optimal deficit irrigation could be scheduled with minimum yield reduction compared to full irrigation.

Recently, wide-spaced furrow irrigation was tested for different soil types in Bulgaria – vertisols, luvisols and drained fluvi-calcaric fluvisols. The field experiments were conducted with corn and soybean. Both crops gave around 85% of the maximum yield when irrigated in EOFF with 50% of the optimum irrigation depth. The *IWUE* was increased with 71 – 79% for corn and 61% for soybean [11]. The highest *IWUE* for corn, watered in ETFF, was obtained by 33% of the optimum irrigation depth – 8,03 kg/m^3 in a very dry year [14]. Furthermore, an irrigation impact on the yield of corn was theoretically proved up to 2,8 m distance between the wetted furrows. The economic results of irrigation of corn depend both on the irrigation depth and on the level of maintain of the maximum allowable deficit (MAD). Most efficient is irrigation in EOFF with 50% of the maximum irrigation depth [14, 19, 20].

One of the reasons for reducing the corn cropped areas nowadays is the water deficit. Since the crop is very sensitive to soil and atmospheric moisture, the result of breaking its normal water supply is a productivity deceleration and a serious yield decrease [21]. The unsuitable current climate and economic agents of the agricultural production, comprising of tendencies of warming and drought, the destroyed irrigation and drainage network in the country and the high irrigational water prices, necessitate for spreading knowledge for irrigation technologies that accelerate the *IWUE*. So far, the approaches to establishing the effect of different factors on the yield and *IWUE* were based on single regression analyses.

Their effect was studied individually but not in their complexity. The yield-water relationship, for example, studied by a great number of authors, takes into account only the water amount. It does not consider the other parameters of the irrigation scheduling – the number of applications, the application depth, the pre-irrigation soil moisture, or the peculiarities of the irrigation technology, the wetting pattern and regularity. These features of the applied irrigation practice may have great impact on the final results of the production process: on the yield and on the economic results. The farmers can make decisions about the elements of the irrigation process by using a decision tool that accounts for more than one yield factor.

The goal of the paper is to suggest facilitating tools for managing corn irrigation scheduling under wide-spaced irrigation technology with fixed wetted furrows. The tools are developed on the base of a multiple regression analysis and an optimization.

2. Material and Methods

2.1. Description of the Experiment

A field experiment on wide-spaced irrigation of corn was conducted in the periods 1987 – 1989, 1996-1998 and 2003-2006. The field experiment during the first two periods was conducted in Sofia Region, 42.6^o N and 550 m a.s.l. The last-period field experiment was conducted in Stara Zagora Region at 42.4° N and 196 m a.s.l. The sites have temperate-continental and transitional-continental climate, respectively, with a monthly maximum of the rainfalls in June.

The studied hybrids: a moderate one (FAO 400) for Stara Zagora Region and a moderately late one (FAO 500) for Sofia Region, are well adapted to the natural conditions of the regions.

Three irrigation depths were tested: 1) $M_1 = MAD$ at 80% of field capacity (FC) (the irrigation depth was equal to the maximum allowable deficit at 80% of FC) – full irrigation; 2) $M_2 = MAD$ at 75% of FC; and 3) $M_3 = MAD$ at 70% of FC. The so described irrigation depths were distributed in every furrow (EF) (var. 2, 11 and 14 in Table 3). The distance between the furrows was standard – 70 cm. Once the water deficit in variants 2, 11 and 14 reached the particular for each of them percent of FC, an irrigation application was given to achieve a zero water deficit in the plot. Together with the three plots of scheduled irrigation and distribution of the water in EF, applications with $M_{11} = 50\%M_1$, $M_{12} = 33\%M_1$, $M_{21} = 50\%M_2$, and $M_{22} = 33\%M_2$, $M_{31} = 50\%M_3$ and $M_{32} = 33\%M_3$ of the scheduled application depths were given in EF, every other fixed furrow (EOFF) and in every third fixed furrow (ETFF) to other plots as described in Table 3. The wetted furrows in the wide-spaced irrigation plots were fixed for the whole period of irrigation. In this way, the surface irrigation was meant to be of localized type and mostly the capillary potential for redistribution of the irrigational water in soil was used. Variant 2 was considered the optimum one because [22] has found that the optimum regime for the water supply of the agricultural crops on *chromic luvisols* and *eutric vertisols* (the soils types of the experiment) is by allowing soil moisture depletion up to 80% of FC. Hence M_1 can be assumed for M_{opt}. The irrigation depths M_2 in var. 11 and M_3 in var. 14 caused some temporary water deficit in soil.

Through this scheme of the experiment, the combined effect of the three factors, i.e. the irrigation depth, the space between furrows and the number of applications on the yield and *IWUE* was studied. By distributing the irrigation water amount in EOFF and ETFF, the lateral infiltration of both soil types was in action so that runoff and seepage loss through the soil cracks were minimized.

The experiment was put in a randomized complete block design in three replications. The land preparation, the weed control and the fertilizer amount were in compliance with the usual agricultural practices in the region. The soil moisture was measured in var. 2, 11 and 14 by the gravimetric method. Soil samples were taken for each 10-cm layer within 1 m depth of the soil profile. The net application depth was calculated as (eq. 1):

$$m = 10H\alpha\left(\sigma_W^{FC} - \sigma_W^{80\% ofFC}\right)K \text{ , [23],} \tag{1}$$

where m – net irrigation application depth, mm;

H – depth of the active root zone, (we assumed H = 1 m);

α – bulk density, Mg/m^3;

$\sigma_W^{FC} - \sigma_W^{80\% ofFC}$ – the deficit of available water at 80%, 75% or 70% of FC, %;

K – a coefficient that reflects the water efficiency of the irrigation system (= 1,3 for the surface irrigation systems) [24].

The yields obtained were recalculated for 14% standard grain dampness and were statistically rated by analysis of variance [25].

The *IWUE* for every irrigated plot was calculated as (eq. 2):

$$IWUE_n = \frac{Y_n - Y_0}{M_n} \text{ , kg/m}^3\text{,} \tag{2}$$

where $IWUE_n$ – the irrigation water use efficiency in the n irrigated plot (variant), kg/m^3;

M_n – the irrigation depth of the n irrigated plot (variant), kg/m^3.

2.2. Weather and Soil Data

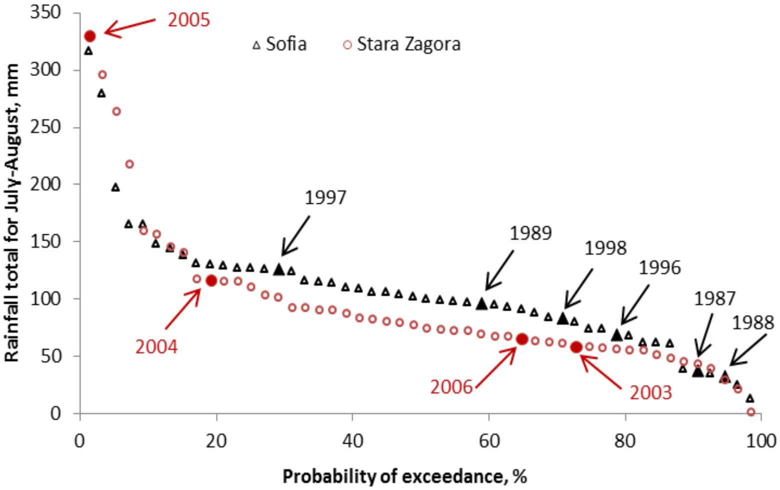


Figure 1. Empirical curve of the probability of exceedance of the rainfalls occurring during the irrigation season (July-August) in Sofia and Stara Zagora regions, period 1957 – 2006

The meteorological conditions were diverse hence the results were considered representative. Five of the experimental years were moderately dry to very dry (1987, 1988, 1996, 1998 and 2003), two of them were moderate (1989, 2006) and two – moderately wet (1997 и 2004), one – very wet year (2005) (Fig. 1). The probability of exceedance was calculated in a 50-year (1957 – 2006) statistical row. For the study period, it ranges from 1,39% to 92,7%. For the vegetation period of corn (April-September), the rainfall totals varied from 247 to 387 mm in Sofia Region and from 196 to 455 mm in Stara Zagora Region. For the irrigation period they varied from 33 to 126 mm for Sofia Region and from 58 to 117 mm for Stara Zagora Region. The monthly precipitation was highly variable as shown in Fig. 2.

The air temperature totals of the vegetation period April-September varied from 2901 to 3238°C, average 3112 °C for Sofia Region and from 2850°C to 3144 °C, average 3108 °C for Stara Zagora Region.

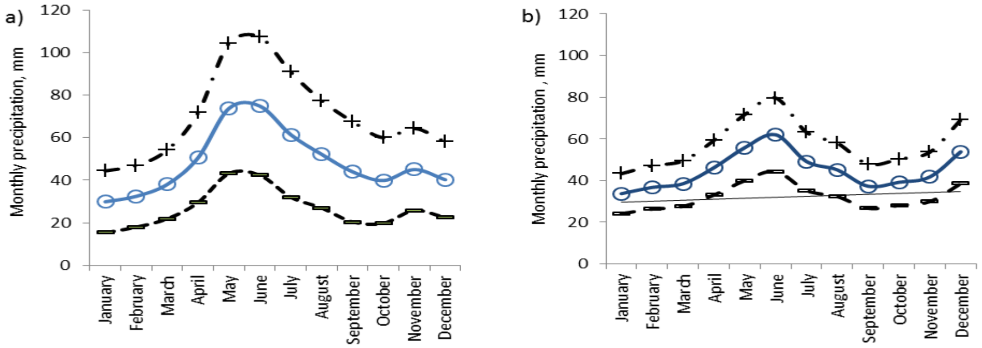


Figure 2. Average monthly precipitation at: a) Sofia; b) Stara Zagora. The circles and the solid lines represent the average monthly precipitation; the dashed lines and the markers on them represent the 95% confidence interval for the period 1957 – 2006

The soil types were clay-loamy. These soils hold great available water amounts. Their side infiltration is appropriate for conducting wide-spaced irrigation (Table 1) [6].

Table 1. Soil texture and hydraulic properties

Depth	Texture	Particle size distribution, %			Hydraulic conductivity at saturation (Ks) (cm/d)	Soil water (cm^3/cm^3)	
		Clay <0,001	Silt 0,05-0,001	Sand >0,05		Field capacity	Permanent wilting point
Chromic Luvisols (Sofia) [27]							
0-30	SL	32,0	32,0	36	93,0	0,22	0,10
30-60	SCL	41,5	27,0	31,5	17,6	0,23	0,11
60-100	SL	33,0	20,0	47,0	30,5	0,21	0,11
Vertisols (St. Zagora) [28]							
0-26	L	53,5	33,7	12,8	7,9	0,42	0,25
26-50	C	58,0	32,0	10,0	3,3	0,50	0,33
50-80	C	60,3	27,7	12,0	0,8	0,51	0,34
80-100	C	66,0	28,1	5,9	1,1	0,46	0,27

The soil type in Sofia Region was *chromic luvisols*, representative for the irrigated areas in South Bulgaria. Its texture is clay-loamy and slightly clayey (Table 1). The saturation conductivity of the 0 – 35-cm soil layer is far less than of the lower layers: 16 – 21 cm/d. In a precise multiple-layer investigation, [26] has found that the hydraulic conductivity of the

20 – 40-cm layer is high hence the exhaustion of soil moisture is intensive. Its total water content at FC is *TWC* = 327 mm, the total available water content is *TAWC* = 165 mm, and bulk density α = 1,5 Mg/m^3. The soil in Stara Zagora Region was *eutric vertisols*, loamy to clayey. Its hydraulic conductivity is very low – 2,4 cm/d. The total water content at FC is *TWC* = 452 mm and the total available water content is *TAWC* = 162 mm. Both soil types have good side infiltration and are suitable for wide-spaced furrow irrigation because a relatively uniform moisturizing of the rooting zone can be ensured and long-time kept.

2.3. Description of the Numerical Investigation

A multiple regression analysis of the total effect of the irrigation depth, number of applications and space between the irrigated furrows on the yield and *IWUE* was developed. By an optimization of the *IWUE* multiple regression model at maximum yield the area of maximum *IWUE* and the factor-values for its formation were determined.

In order to ignore the influence of the meteorological conditions, the yields and the *IWUE* were recalculated in relative units. The additional yield was calculated as (eq. 3):

$$RAdY_n = \frac{Y_n - Y_0}{Y_0} 100 \text{, \%,} \tag{3}$$

where $RAdY_n$ – relative additional yield in the *n* variant, %;

n – the number of the irrigated plot (variant) (*n* = 2, 3, …, 16);

Y_n – the yield from the *n* variant, kg/ha;

Y_0 – the yield from the rain-fed plot (var. 1), kg/ha;

$Y_n - Y_0$ – the additional yield, kg/m^3.

The relative *IWUE* was calculated as (eq. 4):

$$RIWUE = \frac{IWUE_n}{IWUE_2} 100 \text{, \%,} \tag{4}$$

where *RIWUE* – the relative *IWUE*, %;

$IWUE_2$ – the *IWUE* in var. 2.

The factors of the regression models were assumed to be the spatial pattern of water distribution (x_1), the number of irrigation applications (x_2) and the irrigation depth (x_3), while the relative additional yield (*RAdY*) and the relative irrigation water use efficiency (*RIWUE*) were assumed as estimated parameters (*Y*). The factors were coded as shown in Table 2. The minimum values were taken as -1 and the maximum level as 1.

In order to describe the response surface or the regression model, a second power polynomial was chosen. Its general appearance is (eq. 5):

$$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 \text{,} \tag{5}$$

where *b* – regression coefficients.

Statistica, Mathcad and Excel software were used to process the data and illustrate the results. In the optimization of the *RIWUE* model, the insignificant coefficients were included because they also contain certain process information.

Table 2. Levels of variation of the independent factors

Factors		Coded value of the factor			Natural value of the factor		
		Lower level	Basic level	Upper level	Lower level	Basic level	Upper level
Spatial pattern of water distribution	x_1	-1	0	1	EF	EOFF	ETFF
Number of irrigation applications	x_2	-1	-	1	2	-	5
Irrigation depth	x_3	-1	0	1	30%	70%	110%

3. Results and Discussions

3.1. Results for the Yield and IWUE

The results in Table 3 show that, dependent on the wetting pattern of the year, the number of applications in Sofia region varied from 3 to 5 and the irrigation depth in the variant of full irrigation (var. 2) varied from 60 mm to 180 mm. The number of applications in Stara Zagora region varied from 2 to 3 and the irrigation depth varied from 120 to 180 mm. The maximum irrigation depth in the experiment M_{max} = 320 mm was obtained in Sofia region, in the very dry 1987, var. 11, through four EF applications. The minimum irrigation depth M_{min} = 52 mm was obtained in Sofia region, in 1989, which was a year of moderate conditions, var. 13, through two ETFF applications (Table 3).

The highest yield was obtained in Sofia region by full irrigation (var. 2) in the very dry 1988. It was 14,24 Mg/ha. The yields obtained by applying M_{opt} were significantly higher than all the other yields, in all years and in both regions. In Sofia region they varied from 9,34 Mg/ha to 14.34 Mg/ha, while in Stara Zagora region they varied from 4,57 Mg/ha to 10,34 Mg/ha. The differences between the regions proceed from the meteorological conditions. All variants of wide-spaced irrigation had lower yields than those of the var. 2. The main reason was the water loss by deep percolation, or insufficiency of water for meeting the crop water needs, or both (Table 4).

The *IWUE* in Sofia region was highest in ETFF variants in the very dry 1998. It was 7,44 kg/m^3 and 7,61 kg/m^3 in var. 7 and var. 4, respectively. The *IWUE* varied from 0,81 kg/m^3 to 4,59 kg/m^3 in the variant of full irrigation (var. 2), depending on the wetting pattern of the year. In Stara Zagora region, the *IWUE* was lower and varied in a narrower interval – from 0,27 kg/m^3 to 2,88 kg/m^3 for all variants, due to the low water-releasing capability of the soil (Table 4).

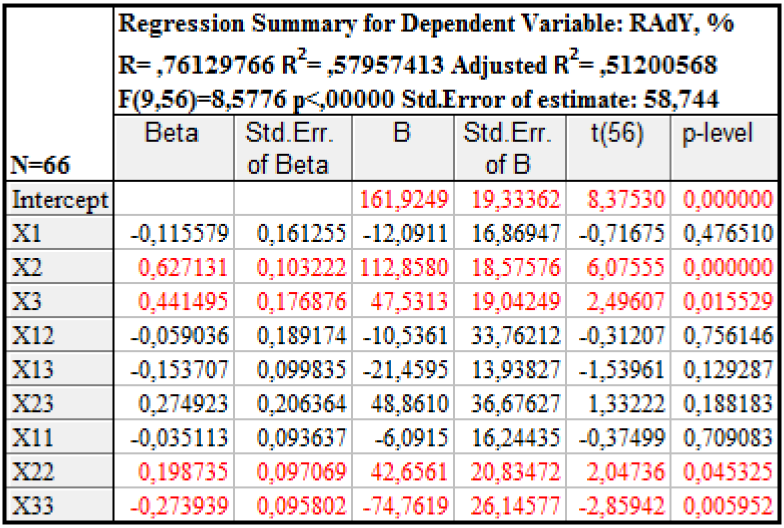
3.2. Estimation of the Effect of the Irrigation Depth, the Number of Irrigation Applications and the Distance Between the Irrigated Furrows on the Relative Additional Yield

The results from the regression analysis for the parameter *RAdY* are presented in Table 5. This table was extracted from Statistica software. It is seen that the coefficient of determination is R^2 = 0,58 and the Fisher's Test is F (9, 56) = 5,84 at a probability

$p < 0,00000 < 0,05$. These statistical features are sufficient grounds to consider the model adequate to the behavior of the studied parameter (*RAdY*). This model describes 58% of the parameter variation. The data in Table 5 shows that there is no interaction between the studied factors and hence there is no combined effect on *RAdY*. Each of them has effect on the yield by itself. In order to estimate the individual effect of each factor, a procedure of consecutive cutoff of the effect of each of them was applied. The results show that the greatest impact on the yield has the number of applications, while the irrigation depth has almost half of this effect. The space pattern of water distribution, i.e. EF, EOFF or ETFF, has the least effect.

Through optimizing the resulting functional, it was established that the maximum additional yield $RAdY_{max}$=380,414% is obtained through the maximum irrigation depth (320 mm) and a maximum number of applications.

Table 5. Results from the regression analysis for the *RAdY*



Regression Summary for Dependent Variable: RAdY, %
R= ,76129766 R²= ,57957413 Adjusted R²= ,51200568
F(9,56)=8,5776 p<,00000 Std.Error of estimate: 58,744

N=66	Beta	Std.Err. of Beta	B	Std.Err. of B	t(56)	p-level
Intercept			161,9249	19,33362	8,37530	0,000000
X1	-0,115579	0,161255	-12,0911	16,86947	-0,71675	0,476510
X2	0,627131	0,103222	112,8580	18,57576	6,07555	0,000000
X3	0,441495	0,176876	47,5313	19,04249	2,49607	0,015529
X12	-0,059036	0,189174	-10,5361	33,76212	-0,31207	0,756146
X13	-0,153707	0,099835	-21,4595	13,93827	-1,53961	0,129287
X23	0,274923	0,206364	48,8610	36,67627	1,33222	0,188183
X11	-0,035113	0,093637	-6,0915	16,24435	-0,37499	0,709083
X22	0,198735	0,097069	42,6561	20,83472	2,04736	0,045325
X33	-0,273939	0,095802	-74,7619	26,14577	-2,85942	0,005952

After suspending the insignificant coefficients, the relative additional yield (in an encoded mode) can be calculated as (eq. 5):

$$RAdY = 161.92 + 112.86x_2 + 47.53x_3 + 42.66x_{22} - 74.76x_{33}\,. \qquad (5)$$

The lines of identical response indicate the cross-section of the response surface area at the optimum value (FF) of the factor x_1 (Fig. 3). The figure gives an idea of the effect of the main factors on the yield when the water distribution is in EF. It is obvious that by an irrigation depth in the interval 80%M_{max}-M_{max}, and a maximum number of applications, delivered in FF, a yield close to $RAdY_{max}$ can be obtained.

The graph in Fig. 4 shows the impact of x_1 (water distribution spatial pattern) and x_3 (irrigation depth) when the value of x_2 (number of applications) is maximum (= 5). It is seen that, if the irrigation depth is in the interval 80%M_{max}-M_{max}, the water distribution space pattern has no significant effect on *RAdY*. This means that in this interval, there is enough water for its distribution in soil by deep and side infiltration and it reaches every part of the root zone. A yield that is close to $RAdY_{max}$ can be obtained through an irrigation depth in the interval 80%M_{max}-M_{max} and is distributed either in EF or in EOFF.

Table 3. Number of applications and irrigation depths

Var No.	Irrigation schedule	Irrig. Depth Code	Relative Irrig. Depth	Appl. Depth	Water distribution pattern	1987		1988		1989		1996		1997		1998		2003		2004		2005		2006	
						Appl. nb	Irr. Dpth	Appl. nb	Irr. Dpth	Appl. nb	Irr. Dpth	Appl. nb	Irr. Dpth	Appl. nb	Irr. Dpth	Appl. nb	Irr. Dpth	Appl. nb	Irr. Dpth	Appl. nb	Irr. Dpth	Appl. nb	Irr. Dpth	Appl. nb	Irr. Dpth
			%	mm		nb	mm	nb	mm	nb	mm	nb	mm	nb	mm	nb	mm	nb	mm	nb	mm	nb	mm	nb	mm
1	Rain-fed	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
2	M_1=40%*MAD*	M_1	100%M_1	60	EF	5	300	4	240	3	180	3	180	3	180	3	180	3	180	3	180	2	120	3	180
3	Irrigated together with Var.2	M_1	100%M_1	60	EOFF	-	-	-	-	-	-	3	180	3	180	3	180	3	180	3	180	2	120	3	180
4		M_1	100%M_1	60	ETFF	-	-	-	-	-	-	3	180	3	180	3	180	3	180	3	180	2	120	3	180
5		M_{11}	50%M_1	30	EF	-	-	-	-	-	-	3	90	3	90	3	90	-	-	-	-	-	-	-	-
6		M_{11}	50%M_1	30	EOFF	5	150	4	120	3	90	3	90	3	90	3	90	3	90	3	90	2	60	3	90
7		M_{11}	50%M_1	30	ETFF	-	-	-	-	-	-	3	90	3	90	3	90	3	90	3	90	2	60	3	90
8		M_{12}	33%M_1	20	EF	-	-	-	-	-	-	3	60	3	60	3	60	-	-	-	-	-	-	-	-
9		M_{12}	33%M_1	20	EOFF	-	-	-	-	-	-	3	60	3	60	3	60	-	-	-	-	-	-	-	-
10		M_{12}	33%M_1	20	ETFF	5	100	4	80	3	60	-	-	-	-	-	-	-	-	-	-	-	-	-	-
11	M_2=50%*MAD*	M_2	100%M_2	80	EF	4	320	3	240	2	160	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	Irrigated together with Var.11	M_{21}	50%M_2	80	EOFF	4	160	3	120	2	80	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13		M_{22}	33%M_2	80	ETFF	4	104	3	78	2	52	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	M_3=60%*MAD*	M_3	100%M_3	100	EF	3	300	2	200	2	200	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	Irrigated together with Var.14	M_{31}	50%M_3	100	EOFF	3	150	2	100	2	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16		M_{32}	33%M_3	100	ETFF	3	99	2	66	2	66	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 4. Yield and irrigation water use efficiency (IWUE)

Var.	Irrigation schedule	Irrig. Depth Code	Relative Irrig Depth %	Appl. Depth mm	Water distribut. pattern	Yield, Mg/ha										$IWUE_n$, kg/m^3									
						1987	1988	1989	1996	1997	1998	2003	2004	2005	2006	1987	1988	1989	1996	1997	1998	2003	2004	2005	2006
1	Rain-fed	-	-	-	-	2,69	3,70	6,91	4,13	7,14	5,21	3,74	3,36	7,56	7,83	-	-	-	-	-	-	-	-	-	-
2	M_1=40%*MAD*	M_1	100%M_1	60	EF	12,24	14,34	9,34	9,79	8,53	12,57	7,05	4,57	9,57	10,34	3,21	4,59	1,35	2,54	0,81	4,09	1,84	0,67	1,68	1,39
3	Irrigated together with Var.2	M_1	100%M_1	60	EOFF	-	-	-	10,74	8,04	11,90	6,61	4,29	9,22	10,09	-	-	-	5,71	1,51	5,3	1,59	0,52	1,38	1,26
4		M_1	100%M_1	60	ETFF	-	-	-	9,15	8,19	12,58	6,08	3,84	8,32	8,92	-	-	-	6,28	2,65	7,61	1,30	0,27	0,63	0,61
5		M_{11}	50%M_1	30	EF	-	-	-	7,52	7,95	8,55	-	-	-	-	-	-	-	3,05	0,47	3,72	-	-	-	-
6		M_{11}	50%M_1	30	EOFF	9,25	11,63	9,01	8,80	7,72	9,98	6,33	4,08	8,61	9,32	4,4	6,84	2,33	6,17	1,57	4,82	2,88	0,80	1,75	1,66
7		M_{11}	50%M_1	30	ETFF	-	-	-	7,85	7,56	9,68	5,17	3,78	8,03	8,64	-	-	-	5,73	1,72	7,44	1,59	0,47	0,78	2,51
8		M_{12}	33%M_1	20	EF	-	-	-	6,02	7,69	6,78	-	-	-	-	-	-	-	1,45	0,77	4,09	-	-	-	-
9		M_{12}	33%M_1	20	EOFF	-	-	-	6,69	7,20	7,68	-	-	-	-	-	-	-	2,87	0,77	4,96	-	-	-	-
10		M_{12}	33%M_1	20	ETFF	5,91	8,80	8,30	-	-	-	-	-	-	-	3,24	8,0	2,32	-	-	-	-	-	-	-
11	M_2=50%*MAD*	M_2	100%M_2	80	EF	10,21	12,26	9,09	-	-	-	-	-	-	-	2,37	3,64	1,37	-	-	-	-	-	-	-
12	Irrigated together with Var.11	M_{21}	50%M_2	80	EOFF	8,07	10,40	8,81	-	-	-	-	-	-	-	3,39	5,78	2,38	-	-	-	-	-	-	-
13		M_{22}	33%M_2	80	ETFF	5,59	7,67	8,12	-	-	-	-	-	-	-	2,71	5,21	2,28	-	-	-	-	-	-	-
14	M_3=60%*MAD*	M_3	100%M_3	100	EF	9,88	12,03	9,28	-	-	-	-	-	-	-	2,42	4,31	1,19	-	-	-	-	-	-	-
15	Irrigated together with Var.14	M_{31}	50%M_3	100	EOFF	7,44	9,36	8,12	-	-	-	-	-	-	-	3,19	7,12	1,21	-	-	-	-	-	-	-
16		M_{32}	33%M_3	100	ETFF	4,66	7,26	7,90	-	-	-	-	-	-	-	1,99	8,3	1,47	-	-	-	-	-	-	-
$LSD_{5\%}$						*2,33*			*2,13*			*5,53*													
$LSD_{1\%}$						*3,19*			*2,93*			*7,66*													
$LSD_{0,1\%}$						*4,34*			*4,02*			*10,57*													

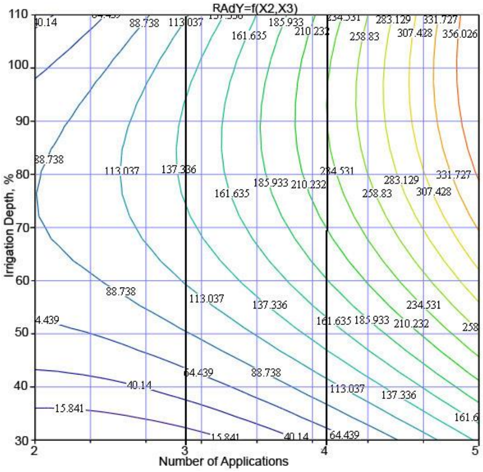


Figure 3. Dependence of *RAdY* on the number of applications (x_2) and the irrigation depth (x_3) (x_1 = EF)

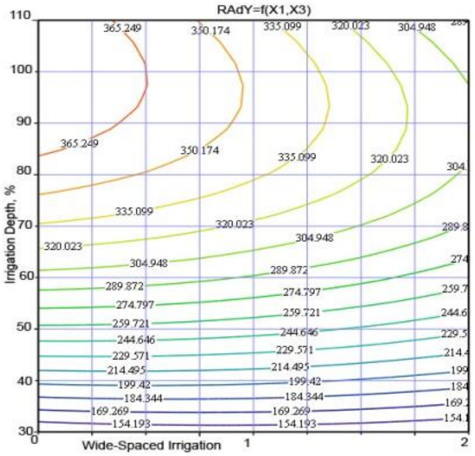


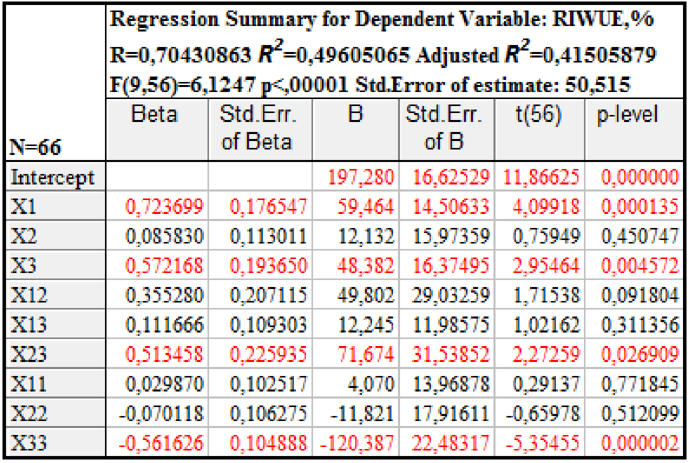
Figure 4. Dependence of *RAdY* on the space pattern of irrigation water distribution (x_1) and the irrigation depth (x_3) (x_2 = 5)

After maximization of *RAdY* functional, it was obtained that $f_{\max} = \begin{pmatrix} -1 \\ 1 \\ 0,788 \end{pmatrix}$ and the value of the function at the issued point is $f_{\max}$ = 380,414. It means that when watering in EF with maximum number of applications and M_{opt}, the maximum relative additional yield is $RAdY_{\max}$ = 380,414%.

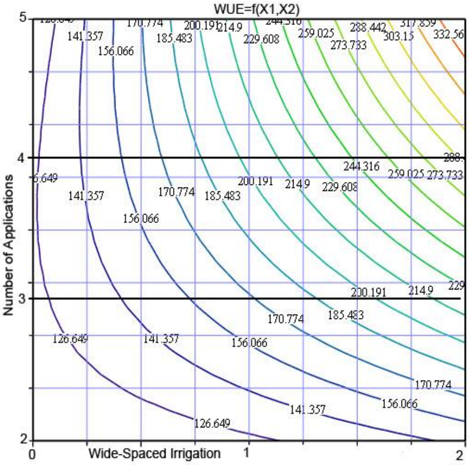
3.3. Estimation of the Effect of the Irrigation Depth, the Number of Irrigation Applications and the Distance Between the Irrigated Furrows on *RIWUE*

The results from the regression analysis for the parameter *RIWUE* are presented in Table 6. The presented table in Fig. 3 was extracted from Statistica software. The coefficient of determination is R^2 = 0,50. The Fisher's Test is F (9, 56) = 6,12 at a probability $p < 0,00001 < 0,05$. These statistical features are sufficient grounds to consider the model adequate to the behavior of the studied parameter. This model describes 50% of the parameter variation. The effect of the individual factors on *RIWUE* was estimated through a procedure of consecutive cutoff of the impact of each of them. It was found that the irrigation depth and the water distribution space pattern have like effect. The number of applications has the least effect. It is seen from Table 6 that the effect of the number of applications is statistically insignificant, while the combined effect of the number of applications and the irrigation depth is significant. In Fig. 5 is seen that the *RIWUE* is maximum when the irrigation depth is distributed by maximum number of applications in ETFF. Furthermore, it can be seen in Fig. 6 that in the ETFF technology, if the irrigation depth is small, the number of applications has no significant effect on *RIWUE*. Its effect increases with the increase of the irrigation depth but in any case, it is less than that of the simultaneous effect of the number of applications and the irrigation depth.

Table 6. Results from the regression analysis for the *RIWUE*



N=66	Regression Summary for Dependent Variable: RIWUE,% R=0,70430863 R^2=0,49605065 Adjusted R^2=0,41505879 F(9,56)=6,1247 p<,00001 Std.Error of estimate: 50,515					
	Beta	Std.Err. of Beta	B	Std.Err. of B	t(56)	p-level
Intercept			197,280	16,62529	11,86625	0,000000
X1	0,723699	0,176547	59,464	14,50633	4,09918	0,000135
X2	0,085830	0,113011	12,132	15,97359	0,75949	0,450747
X3	0,572168	0,193650	48,382	16,37495	2,95464	0,004572
X12	0,355280	0,207115	49,802	29,03259	1,71538	0,091804
X13	0,111666	0,109303	12,245	11,98575	1,02162	0,311356
X23	0,513458	0,225935	71,674	31,53852	2,27259	0,026909
X11	0,029870	0,102517	4,070	13,96878	0,29137	0,771845
X22	-0,070118	0,106275	-11,821	17,91611	-0,65978	0,512099
X33	-0,561626	0,104888	-120,387	22,48317	-5,35455	0,000002



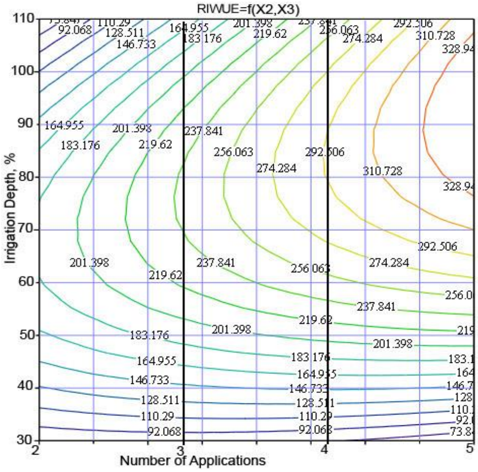


Figure 5. Dependence of *RIWUE* as on the water distribution space pattern (x_1) and the number of applications (x_2) ($x_3 = M_{max}$)

Figure 6. Dependence of *RIWUE* as on the number of applications (x_2) and the irrigation depth (x_3) (x_1 = ETFF)

After suspending the insignificant coefficients, the relative additional yield (in an encoded mode) can be calculated as (eq. 6):

$$RIWUE = 197.280 + 59.464x_1 + 48.382x_3 + 71.674x_{23} - 120.387x_{33}\,. \qquad (6)$$

After maximization of REWUE functional, it was obtained that $f_{\max} = \begin{pmatrix} 1 \\ 1 \\ 0{,}547 \end{pmatrix}$ and the value of the function at the issued point is $f_{\max}$ = 347,28. It means that when watering in

ETFF with maximum number of applications and 92%M_{opt}, the maximum relative water use efficiency is $RIWUE_{max} = 347{,}28\%$.

3.4. Optimizing the *RIWUE* Functional at Maximum *RAdY*

The lines of equal level of the *RIWUE* function as dependent on the space between furrows and the irrigation depth at the optimum value of the factor x_2 (number of applications =5) are shown in Fig. 7. It is seen that close to $RIWUE_{max}$ can be obtained by an irrigation depth in the interval 80%M_{max}-M_{max} and a maximum number of applications.

The equation that fits the hyper-surface, which is a result of the intersection between both functionals: *RAdY* and *RIWUE,* has the following appearance:

$$35.355 + 71.555x_1 - 100.726x_2 + 0.851x_3 + 60.338x_{12} + 33.705x_{13} + 22.813x_{23} + \\ +10.16x_{11} - 54.48x_{22} - 45.625x_{33} = 0. \tag{7}$$

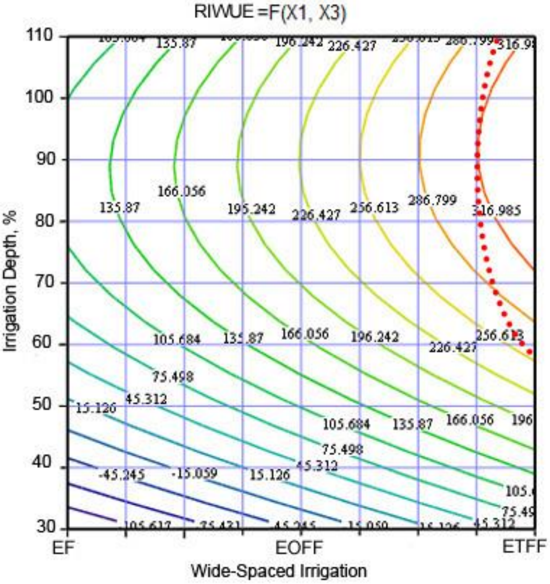


Figure 6. Obtaining optimum RIWUE on the space pattern of irrigation water distribution and the irrigation depth and a maximum additional yield

The parity restriction (eq. 7) between *RAdY* and *RIWUE* is shown by the dotted line in Fig. 7. The graph shows that significant *RIWUE* can be achieved when the irrigation depth is in the range M=20%M_{opt}-M_{opt} (M_{opt}=91%M_{max}). The maximum *RIWUE*=318,06% can be obtained by supplying the irrigational water in ETFF by a maximum number of applications.

4. Conclusions

The present study is focused on the assessment of the impact of the spatial pattern of water distribution, number of irrigation applications and irrigation depth on the yield and water use efficiency under furrow irrigation of corn.

Maximum additional yield $RAdY_{\max}$ = 380,33% can be obtained when distributing the optimum irrigation depth in every furrow by a maximum number of applications. Nearly a maximum yield can be obtained by an irrigation depth in the interval 80%$M_{\max}$-$M_{\max}$, and a maximum number of applications. The number of applications has the greatest impact on *RAdY*, while the irrigation depth has almost twice less impact. This is valid for all patterns of water distribution – EF, EOFF or ETFF.

Maximum *IWUE* ($RIWUE_{max}$ = 347,33%) can be obtained when distributing 92%M_{opt} through maximum number of applications in every furrow. The irrigation depth and the space pattern of water distribution have a like effect on *RIWUE*. The number of applications has the least effect. If the irrigation depth is in the interval 80%$M_{\max}$-$M_{\max,}$ maximum *IWUE* is obtained

Maximum *IWUE* ($RIWUE_{\max}$ = 318,06%*)* and maximum *RAdY* can be obtained by distributing the irrigational water in EOFF, maximum number of applications and 91%M_{opt}. Also, significant efficiency of irrigation water can be obtained when the irrigation depth is 20% lower than the optimal one.

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ОПТИМИЗАЦИОННО РЕШЕНИЕ ЗА НАПОЯВАНЕ НА ЦАРЕВИЦА В УСЛОВИЯ НА ВОДЕН ДЕФИЦИТ

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Ключови думи: *царевица за зърно, напояване през бразди, добив, ефективност на използване на поливната вода, оптимизация*

РЕЗЮМЕ

В районите на Стара Загора и София, върху смолница и излужена канелена горска почва, са проведени експерименти с напояване на царевица за зърно през бразди. Изпитано е влиянието на различни напоителни норми, брой поливки и разстояния между поливните бразди върху добива зърно и ефективността на използване на поливната вода. Получените данни са използвани за провеждане на планиран експеримент от типа B_3. Анализирано е комплексното влияние на факторите. След оптимизация на получените регресионни модели са установени оптимални стойности на елементите на поливния режим в условия на воден дефицит. Предложената графична интерпретация на линиите на еднакво ниво позволява да се подберат поливни режими съобразно конкретните условия. Установено е, че максимален добив с максимална ефективност на използване на поливната вода се получава при разпределение на напоителна норма 91% от M_{opt} през бразда, с максимален брой поливки.

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