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WATER USE EFFICIENCY AND YIELD-DEPENDENCES FOR CANOLA (*Brassica napus*, L.) UNDER IRRIGATION

SUMMARY

Worsened water availability conditions caused by the recent processes of climate warming evoke the attention of the scientists to the efficiency of the water use by crops. A useful tool for successful yield and water management is the yield-water relationship. The goal of the paper is to study the interrelations between water, water use efficiency and yield of canola and to calibrate some yield-water dependencies which can be recommended for prediction of the irrigation water amounts and the yield. A moderately early canola hybrid (*Brassica napus*, L.) was studied for its sensitivity and response to water. A field experiment in Sofia region, Bulgaria, was conducted. Three levels of soil moisture conditions in a chromic luvisols were tested: rain-fed; deficit moisture, managed by 50% deficit irrigation; and normal moisture conditions, managed by full irrigation at a refill point 80% of field capacity. The data from the experiment was processed by analysis of variance and regression analysis. The results show that soil moisture level has statistically significant impact on the yield accumulation. It contributed to increasing the seed yield from a minimum 1.319 Mg/ha at ET=189.0 mm under rain-fed conditions to a maximum of 4.889 Mg/ha at ET=310.0 mm under normal moisture conditions. The maximum irrigation water use efficiency in the experiment was 1.78 kg/m^3 at an irrigation depth of 94 mm, ET=268.5 mm and seed yield - 4.189 Mg/ha. The maximum water use efficiency occurs earlier than the maximum yield. By managing 12% less (than needed) seasonal evapotranspiration, the yield losses were only 6%. Elasticity (sensitivity of the crop to water) can be used as an indicator for the critical range of the seasonal evapotranspiration, in which the water use efficiency and the yield are maximal ($0 \leq EWP \leq 1$). The yield response factor K_y of FAO linear function was established as 1.52. The parameters of the local Davidov equations were calibrated as a=3.53 and k=1.58 for the single-power equation and q=2.39 and r=13.63 for the two-power equation. Davidov equations

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are recommended with priority for forecasting of canola yields on the base of the seasonal crop evapotranspiration.

Keywords: canola, irrigation, water use efficiency, elasticity, FAO yield response factor, Davidov's equations, Bulgaria

INTRODUCTION

Worsened water availability conditions caused by the recent processes of climate warming evoke the attention of the scientists to the efficiency of the water use by crops. In the countries, where the water resources are insufficient and unevenly distributed over the territory, yield is predicted by means of models that guarantee high water use efficiency, for the purpose of obtaining economically acceptable production results. A useful tool for successful yield and water management in these models is the yield-water relationship, written down in different analytical forms with calibrated coefficients for particular crops and environments. The yield-water dependences describe the impact of water on the yield accumulation at different water supply levels. Some authors have the opinion that when crop suffers of an evenly distributed throughout the growing season water deficit, the yield is a linear function of the evapotranspiration (Jensen, 1968; Stewart et al., 1973; Doorenbos, Kassam, 1979; Tzakiris, 1981; Varlev, Popova., 1999, Varlev, 2004). Downey, 1972 notices that the plants grown in an open field are not exposed to constant water deficit because the evapotranspiration after rain or an irrigation application is the maximum. The water stress starts when the soil starts to dry. The dynamics of the soil water regime is a good reason to think that the yield losses are not a simple function of the evapotranspiration. The results from testing the impact of a proviso regular throughout the growing season water deficit have revealed so far that the yield losses are dependent on the weather conditions. There are many authors who think that the yield-water dependence is a power function, which can be represented by a series of two-incurvation curves with an inflection point. These authors are convinced that except the meteorological peculiarities of the individual years, the yield-water dependence reflects the biological characteristics of the crops (Pare, Olivier, 1969; Davidov, 1982, 2004; Mate, 2001; Zhukov, Davidov, 2003). Stewart et al. (1973) have established that the reduction of the yield is not proportionate to the reduction of the water given by irrigation. Consistent with that, Zhivkov, (1994, 1995) has obtained 4-10%; 9-15%, 14-25 and 51% reduction of corn yield by 20, 40, 60, and 75% reduction of the irrigation depth. By applying 50% irrigation water deficit the yield reduction of corn on haplic chernozems is around 5-6% (Rafailov et al., 1998).

The goal of the paper is to study the interrelations between water, water use efficiency and yield of canola and to calibrate some yield-water dependencies which can be recommended for prediction of the irrigation water amounts and the yield in the temperate continental climate conditions of Bulgaria.

MATERIAL AND METHODS

A field experiment with irrigation of winter canola was carried out in Sofia region, Bulgaria (42.6^o N, 550 m a.s.l.) during three growing seasons 2010-2011, 2011-2012 and 2012-2013. The climate of the region is temperate-continental. The average annual temperature of the site is 10.3^{o}C. The place is one of the most humid in the country. The average annual precipitation is 610 mm (Geography of Bulgaria, 2002). The rainfall totals of the period March-July in 2011, 2012 and 2013 were 132.8, 174.6 and 187.6 mm respectively.

As to the 50-year (1974-2013)rainfall probability of exceedance, the period March-July in 2011 and 2012 was dry and average in 2013. Analogously, this period is featured cool in 2011 and warm in 2012 and 2013. As to vapour pressure deficit, it was dry in 2011 and 2012 and average in 2013 (Table 1).

Table 1. Probability of exceedance

Year	March-July	March-April	April-June	June-July
Rainfalls				
2011	85.0	100.0	100.0	20.0
2012	92.5	97.5	80.0	95.0
2013	60.0	80.0	35.0	30.0
Air Temperature				
2011	75.0	72.5	85.0	50.0
2012	10.0	50.0	12.5	2.5
2013	30.0	50.0	17.5	45.0
Vapour pressure deficit				
2011	35.0	60.0	55.0	25.0
2012	5.0	12.5	5.0	5.0
2013	52.5	65.0	22.5	65.0

The experiment was put in a randomized complete block design in three replications. Irrigation was in three levels: rain-fed, 50% deficit irrigation, and full irrigation at a refill point 80% of field capacity (RP_{80}). The canola variety Triangle, which is popular on Bulgarian market, has been tested. The soil was chromic luvisols with total water content TWC=327 mm, available water content AWC=165 mm, and bulk density α=1.5 g/cm^3. Land preparation, fertilizers and weed control were applied according to the standard agricultural practices in the region. Sowing was done each year in the period 25-30th September.

The irrigation application depth at RP_{80} was m=60 mm and was calculated as:

$$m = 10H\alpha(\beta_{FC} - \beta_{RP_{80}})$$

where β is the moisture percentage by weight (Kostyakov, 1951). The depth of root expansion was adopted as H=1.0 m. The soil water content in the root zone was estimated in each 10 days by the soil sampling method.

The 10-day crop evapotranspiration was calculated by the water balance equation:

$$ET_c = W_{i-1} - W_i + m + R$$

where ET_c–10-day actual crop evapotranspiration, mm; W_{i-1} – soil water content in the 1-m soil layer on the first day of the 10-day period, mm; W_i – soil water content in the 1-m soil layer on the tenth day of the 10-day period, mm; R – the 10-day effective rainfall total, mm. The spring-summer evapotranspiration totals were calculated through summarizing the 10-day values.

Variance analysis was applied to the yield results. Regression analysis was applied to establish the impact of the irrigation depth on the irrigation water use efficiency (*Irr.WUE*).

FAO yield-evapotranspiration dependence

$Y_{def}^{i}/Y_{\max} = 1 - K_y\left(1 - ET_{def}^{i}/ET_{\max}\right)$ (Doorenbos, Kassam, 1979) and

Davidov power equations

$Y_{def}^{i}/Y_{\max} = 1 - a\left(1 - ET_{def}^{i}/ET_{\max}\right)^{k}$ and

$Y_{def}^{i}/Y_{\max} = \left(1 - \left(1 - ET_{def}^{i}/ET_{\max}\right)^{q}\right)^{r}$ (Davidov, 1982, 2004) were calibrated,

where: Y_{def}^{i} - yield under irrigation deficit in plot *i*, Mg/ha; Y_{max} – yield under full irrigation, Mg/ha; ET_{def}^{i} - actual crop evapotranspiration at Y_{def}^{i}, mm; ET_{max} – maximum evapotranspiration in the experiment, mm; *a* – parameter; *q* – power index that reflects the impact of the water supply on the yield (q<1), *r* - power index that reflects the sensibility of the crop to the water deficit; *k* – power index; K_y – yield factor (=const. for a certain crop).

Interrelations of yield, evapotranspiration, and water use efficiency were established from a marginal analysis of the water production functions (Liu et al., 2002).

RESULTS AND DISCUSSION

Following the dynamics of the meteorological conditions, in 2011 was given one irrigation application and in 2012 and 2013 - two irrigation applications.

Table 2. Results from the field experiment

Year	Variants	Irrigation depth, mm	ET, mm	Seed yield, Mg/ha
2011	Raifed	-	189.8	1.319
	50% irrigation deficit	30	228.2	3.894+++
	Full irrigation	60	260.0	4.889+++
2012	Raifed	-	220.6	2.833
	50% irrigation deficit	60	255.3	3.838+
	Full irrigation	120	272.5	4.797+++
2013	Raifed	-	260.0	2.517
	50% irrigation deficit	60	296.0	4.123+++
	Full irrigation	120	310.0	4.737+++

+significant at P=5%; ++significant at P=1%; +++significant at P=0.1%

The results in Table 2 show significant impact of irrigation on the yield. The seed yield under rain-fed conditions varies from 1.319 to 2.833 Mg/ha. The yield under 50% deficit irrigation varies from 3.838 to 4.123 Mg/ha and the yield increase insignificant at probability P=5% and P=0.1%. The yield under full irrigation is considerably higher – from 4.737 to 4.889 Mg/ha and is significant at P=0.1%. These results confirm the results, obtained in different parts of the world. As to Istanbulluoglu et al. (2010) and their review, the seed yield of canola, obtained in rain-fed and irrigation conditions, varies from 1.0 to 5.3 Mg/ha. Alberta

Agriculture (1980) reported for 1.0-2.6 Mg/ha seed yields without irrigation, which were considered good, and 3.2-4.0 Mg/ha under full irrigation. As to North (2010), the yield in rain-fed conditions in Australia also tended to be 1.7-1.8 Mg/ha, while the best on-farm yields were 1.8-3.6 Mg/ha. The yields from the experimental fields were as high as 3.8-5.2 Mg/ha. The yield of irrigated winter canola in Nebraska, USA was reported to be ≈3.0 Mg/ha (Aiken, Lamm, 2006).

Crop sensibility to water was evident from the relation *ET* increase – yield-increase. It is seen in Table 2 that the actual evapotranspiration under rain-fed conditions is in the range of 189.8-260.0 mm, in conditions of 50% irrigation deficit – 228.2-296.0 mm, and under full irrigation – 260.0-310.0 mm. By giving 50% of the necessary irrigational water in 2012-2013, *ET* increased with 14-16% while yield increased with 35-64%. By giving the whole needed amount of irrigational water, *ET* increased with 19-24% and the yield - with 69-88%. In 2011, depending on the meteorological conditions, an increase of 20% and 37% of *ET* caused unproportioned double and triple yield increase respectively. These results are evidence for different efficiency of the irrigational water in the range of the irrigation depth (Fig. 1). It is seen that the irrigation water use efficiency (*Irr.WUE*), as dependent on the irrigation depth, increases in a polynomial law, and the approximation of the data has high coefficient of determination R^2=0.67.

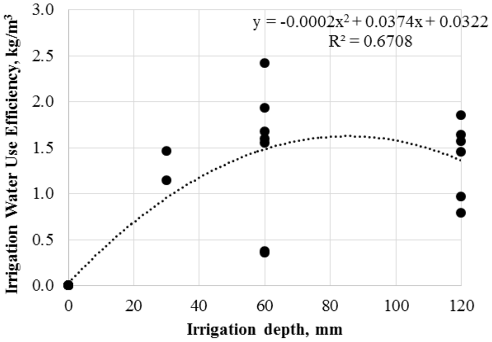

Figure 1. Impact of the irrigation depth on the irrigation water use efficiency

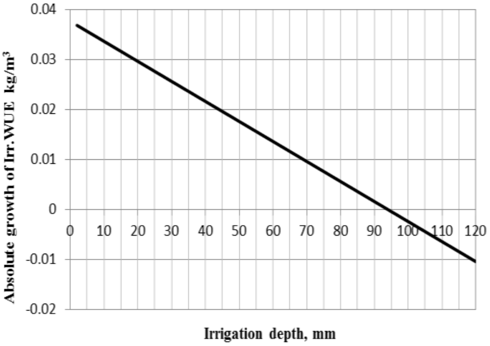

Figure 2. Rate of change of the Irrigation WUE

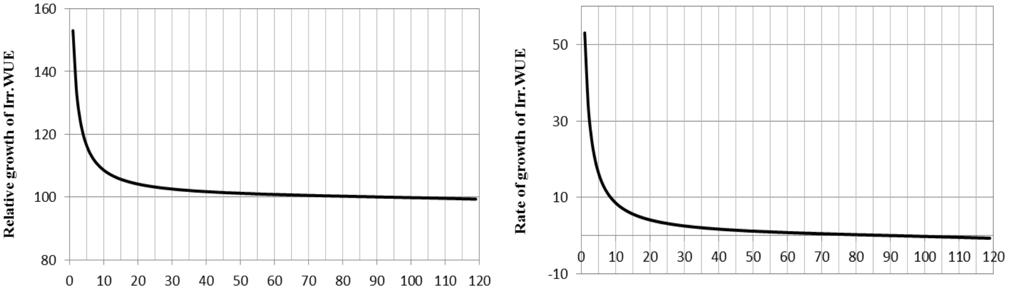

Figure 3. Relative growth (a) and rate of growth (b) of IrrWUE

The absolute growth on a chain basis is const.=-0.0004, the average is 0.0186 kg/m^3 (Fig. 2). The line of the absolute growth crosses the x-axis at the point when the relative growth is 100% (Fig 3a) and the rate of growth is zero (Fig.3b). This point is the point of *Irr.WUE* =1.78 kg/m^3. It is seen that *Irr.WUE* is maximum at irrigation depth M=94 mm. According to the quadric approximation, the relative growth and the rate of growth are greatest in the range approximately 0-30 mm of the irrigation depth, after which they sharply drop.

The results of the yield losses caused by the deficit of irrigation water make it possible to assess the nature of the “yield - irrigation depth” relationship in terms of its proportionality and to provide practical advice for the farmers for managing of the irrigation scheduling. The dependence of the yield losses on the irrigation depth in the experiment is linear and inversely proportional. The coefficient of proportionality is a=-0.4943 (Fig. 4). The relative yield losses when maintaining 50% deficit irrigation are 15-30% and when without irrigation are 30-50%. Our results correspond to those reported by Fanaei et al. (2009) for 54-82% relative yield losses in different drought conditions in comparison with optimum moisture conditions. As to them, drought is one of the strongest abiotic stress factors for the development and productivity of canola.

The issued up to here yield response to the irrigation water has only local meaning and is useful for local water management, confirmed by Hexem and Heady (1978). This relationship is influenced by the geographical location, especially by the weather. It is hardly applied for irrigation system management outside of the soil and climatic conditions for which this relationship is established. One of the more relevant and widely used relationships is that of the yield to evapotranspiration. It is universal and is bound mostly to the crop biology, to its sensitivity to water and ability to use water efficiently. After a thorough review of the research work in this field Vaux and Pruitt (1983) have concluded that crop yield is a linear function of the evapotranspiration. Their follower in Bulgaria is Varlev (2004). Dooreboos & Kassam (1979) have introduced the crop factor K_y to describe the relationship between the yield loss and the deficit of evapotranspiration. On Fig. 4 is shown the yield-evapotranspiration relationship for canola, which is based on the data of the experiment. As a result of a regression analysis, the value of the crop factor was established as K_y=1.52, with a high coefficient of determination R^2=0.73. The value of the crop factor, i.e. the slope of the straight line to x-axis shows great sensitivity of canola to water. It reveals that a small deficit of evapotranspiration can cause high reduction of the yield:

$$Y_{def}^{i} / Y_{\max} = 1 - 1.52\left(1 - ET_{def}^{i} / ET_{\max}\right).$$

The marginal approach to calculation of K_y (Liu et al., 2002) is based on the calculation of the marginal (maximum) water use efficiency (*MWUE*). The interrelations between the yield (*Y*), the seasonal evapotranspiration (*ET*) and *WUE* based on the elasticity (*EWP*) were studied. Elasticity is treated as the sensitivity of the crop to water in yield accumulation. Elasticity is limited by the maximum water use efficiency *(MWUE*), which is the first derivative of the yield-evapotranspiration function, and can be expressed as:

$$EWP = MWUE/WUE = (dY/Y)/(dET/ET).$$

It is evident that elasticity is different in different parts of the yield-evapotranspiration function.

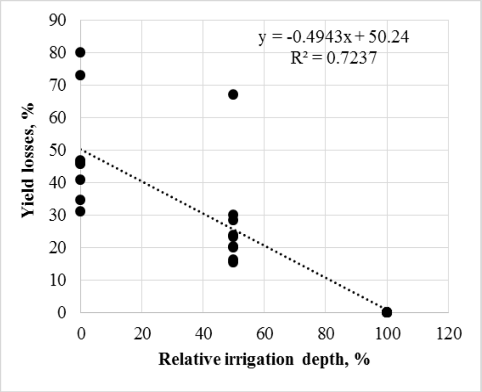

Figure 4. Relative yield losses, %

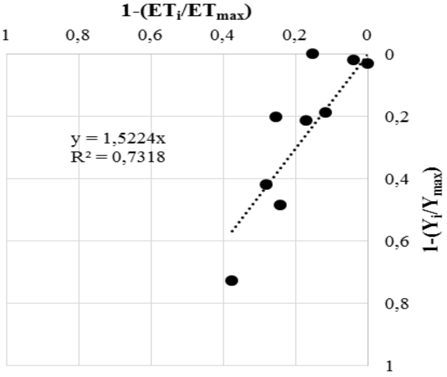

Figure 5. The “yield-evapotranspiration” dependence in FAO methodology

If a linear approximation is considered (Fig. 6ab), then: $Y = a_1 + b_1 ET$, *MWUE*=const.=2.451.*WUE* is calculated as $WUE = Y/ET = a_1/ET + b_1$ and performs a parabola with an asymptote *MWUE*=b_1 (when a≠0) (Fig. 6b), and *EWP* is calculated as $EWP = b_1 ET/(a + b_1 ET)$ (Fig 6c).

For *EWP*>0, *WUE* increases. In this linear relationship $Y_{\max} = a_1 + b_1/ET_{\max}$, i.e. the crop accumulates maximum yield at maximum evapotranspiration.

Then $1 - Y/Y_{\max} = b_1 ET/(a_1 + b_1 ET)(1 - ET/ET_{\max})$
and $K_y = b_1 ET/(a_1 + b_1 ET) = 1.52$.

The crop yield response factor can be calculated directly from the linear expression for *EWP* by substituting *ET* with $ET_{\max}$.

In case of a quadric approximation (Fig. 7), then:

$$Y = a_2 + b_2 ET + c_2 ET^2,$$

$$WUE = a_2/ET + b_2 + c_2 ET ,$$

$$MWUE = b_2 + 2c_2 ET ,$$

$$EWP = b_2 + 2c_2 ET/(a_2 + b_2 ET + c_2 ET^2).$$

It is seen on Fig. 7b, that with the increase of *ET*, *MWUE* decreases linearly; the dependence *WUE*-*ET* is a parabola that reaches maximum at $ET = \sqrt{a_2/c_2}$, then decreases; *Y* reaches maximum at $ET = -b_2/2c_2$; *MWUE* occurs before the maximum yield. Assuming that the yield *Y* is maximal at maximum evapotranspiration, then:

$$1 - Y/Y_{\max} = -c_2 ET_{\max}^2 / Y_{\max} (1 - ET/ET_{\max})^2 \text{ and}$$
$$K_y = -c_2 ET_{\max}^2 / Y_{\max} \ .$$

The yield response factor in the quadratic equation is $K_y = 4.69$.

The results obtained show that if the objective of the procedure is to obtain a maximum yield ($Y_{\max}$=4.444 Mg/ha), the evapotranspiration should be maximum ($ET_{\max}$=310.0 mm). $ET_{\max}$ is with 12% higher than *ET* at *MWUE* (268.5 mm), while $Y_{\max}$ is with 6% higher than *Y* at *MWUE*.

There are two typical *EWP* values, proceeding from the quadric approximation. One of them is *EWP*=1 that indicates *MWUE*. The other one is *EWP*=0 that indicates $Y_{\max}$ and $ET_{\max}$.

Calculation of *EWP* can be useful for indication of the critical range of the seasonal evapotranspiration around which the productivity and the yield would be maximal ($0 \leq EWP \leq 1$). Further, this information can be used for predicting the needed water amounts for irrigation according to the seasonal weather and precipitation forecasts.

Some local researchers like Davidov (1982, 2004) have the opinion that the yield-evapotranspiration relationship has more complicated nature. The calibrated parameters of two Davidov equations for canola are as follows: *a*=3.53 and *k*=1.58 in the single-power equation

$$Y_{def}^i / Y_{\max} = 1 - 3.53 \left(1 - ET_{def}^i / ET_{\max}\right)^{1.58} \text{ (Fig. 8) and}$$

q=2.39 and *r*=13.63

in the two-power equation

$$Y_{def}^i / Y_{\max} = \left(1 - \left(1 - ET_{def}^i / ET_{\max}\right)^{2.39}\right)^{13.63} \text{ (Fig. 9).}$$

Both approximations have very high coefficients of determination, which in turn are much higher than that of FAO linear approximation. The results indicate that the Davidov functions approximate the experimental data more accurately, compared with the quadric function either.

All the calibrated equations can be used for yield prediction for canola but with priority given to Davidov equations.

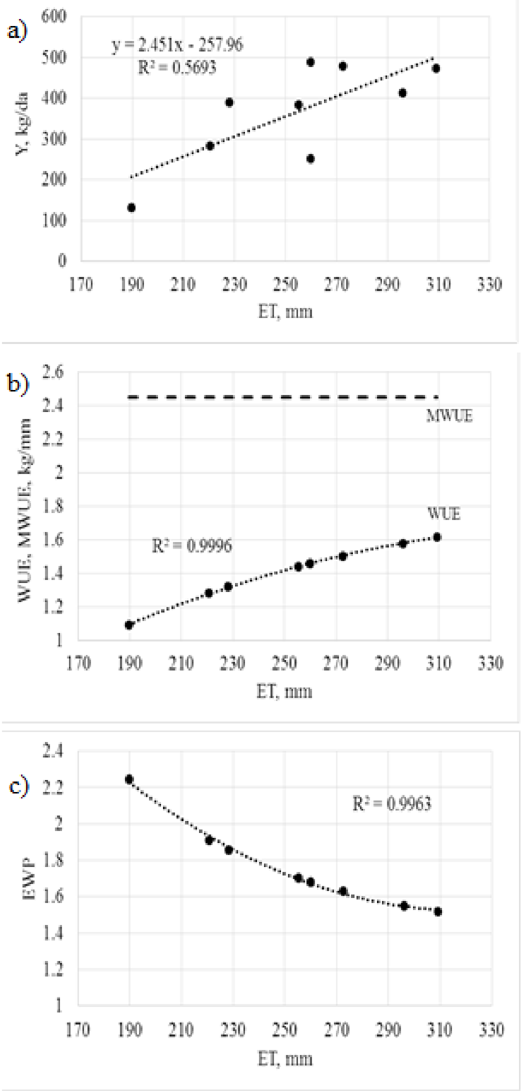

Figure 6. Evapotranspiration-Yield-Water-use efficiency- Maximum water-use efficiency-Elasticity relations in a linear approximation of the dependence yield-evapotranspiration

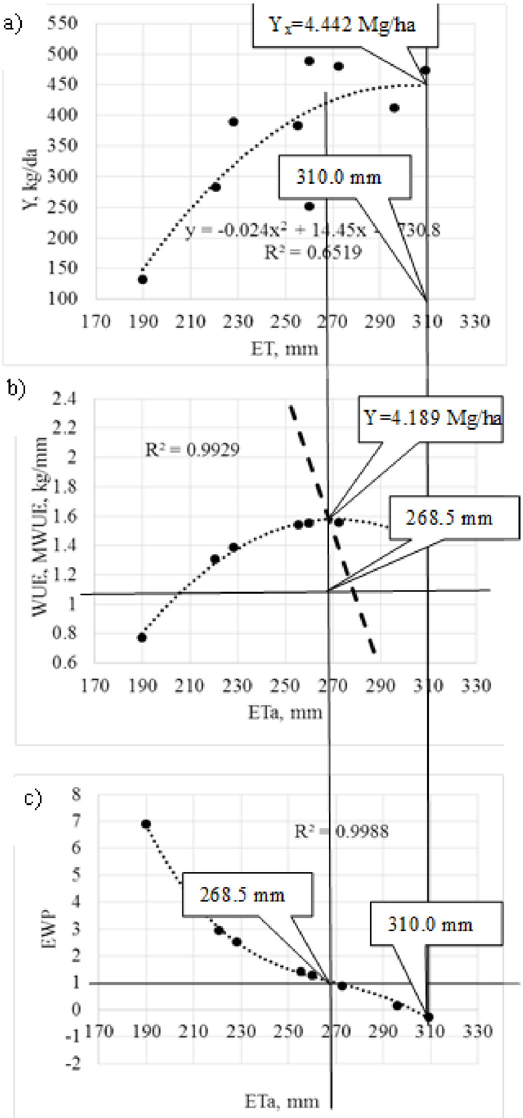

Figure 7. Evapotranspiration-Yield-Water-use efficiency- Maximum water-use efficiency-Elasticity relations in a quadratic approximation of the dependence yield-evapotranspiration

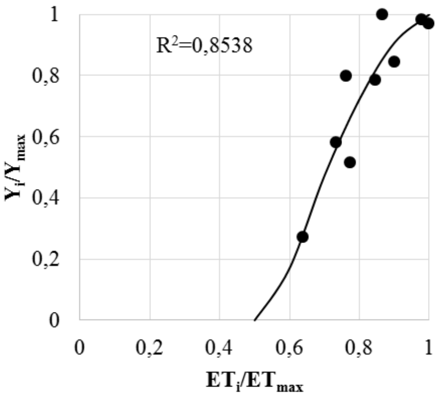

Figure 8. Davidov single-power approximation

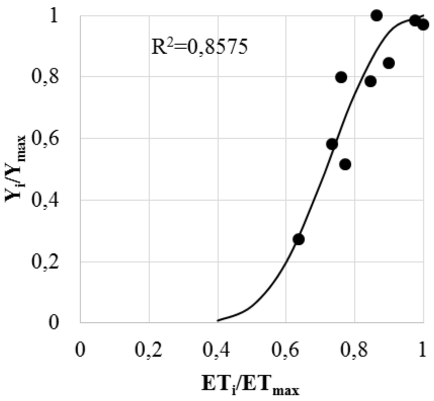

Figure 9. Davidov two-power approximation

CONCLUSIONS

1. Irrigation has statistically significant impact on canola yield. In a three-year period, it contributes for seed yield increase from a minimum of 1.319 Mg/ha under rain-fed conditions to a maximum of 4.889 Mg/ha under full irrigation.
2. Water use efficiency occurs not with the maximum yield but a bit earlier. The maximum irrigation water use efficiency in the experiment was obtained at an irrigation depth of 94 mm and was 1.78 kg/m^3. By managing 12% less (than needed) seasonal evapotranspiration, the yield losses can be only 6%.
3. Elasticity is an indicator for the critical range of the seasonal evapotranspiration, in which the water use efficiency and the yield are maximal ($0 \leq EWP \leq 1$). This information is useful for prediction of the irrigation water amounts according to the seasonal weather and precipitation forecasts.
4. The yield response factor in FAO linear function is K_y=1.52. It indicates canola high sensitivity to water. The parameters of Davidov single-power equation are a=3.53 and k=1.58. The parameters of Davidov two-power equation are q=2.39 and r=13.63. Davidov approximations are more accurate than those of FAO linear equation and the quadric function. They are recommended with priority for forecasting canola yields on the base of the seasonal evapotranspiration.

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