engenharia agrícola
Journal of the Brazilian Association of Agricultural Engineering
ISSN: 1809-4430 (on-line)

CORN YIELD UNDER VARIOUS SIMULATED IRRIGATION DEPTHS

Doi:http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v36n3p503-514/2016

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ABSTRACT: Mathematical models are tools to estimate and understand system behaviors against diverse situations; they may help in decision-making through simplified representations of the reality, allowing simulating various scenarios and estimating impacts of different courses of action on production systems, assisting thus in activity planning. Thus, this paper proposed a simulation of corn crop yields according to different field experiment characteristics and weather conditions in which it was conducted, with the purpose of setting a simulation model already calibrated and tested for corn crop cycle in the region of Santiago – RS, Brazil. The increasing water levels had a positive effect on grain yield and corn dry matter. On the other hand, a level of 800 mm reduced corn yield, as well as water application efficiency decreased from 550 mm. The proposed model can be used as a tool for regional planning in corn crop implementation under irrigation and enables identifying irrigation strategies for high grain yields, being considered a tool for yield prediction in irrigated crops.

KEY WORDS: *Zea mays* L., irrigation strategies, yield model.

FUNÇÕES DE PRODUÇÃO DA CULTURA DO MILHO SUBMETIDO A DIFERENTES LÂMINAS DE IRRIGAÇÃO ATRAVÉS DE ESTUDO SIMULADO

RESUMO: O desenvolvimento de modelos matemáticos pode disponibilizar uma ferramenta para estimar e entender o comportamento do sistema em face de diferentes situações, auxiliando no processo de tomada de decisão através de uma representação simplificada da realidade, permitindo simular vários cenários e estimar a repercussão de diferentes cursos de ação sobre os sistemas produtivos, auxiliando no planejamento da atividade. Desta forma, o presente trabalho propõe uma simulação da produtividade da cultura do milho, levando em consideração as características de um experimento de campo e as características climáticas do ano agrícola em que o experimento foi conduzido, com o objetivo de aplicar um modelo de simulação já calibrado e testado para o ciclo da cultura do milho, na região de Santiago-RS. Verificou-se que, com o aumento nas lâminas de irrigação, ocorreu aumento na produtividade de grãos e matéria seca da cultura em estudo. A lâmina de 800 mm acarretou redução na produtividade, sendo que a eficiência de aplicação de água a partir de 550 mm foi reduzida. O modelo proposto pode ser utilizado como ferramenta para o planejamento regional na implantação da cultura de milho em condições de irrigação e possibilita a identificação de estratégias de irrigação que resultem em elevadas produtividades de grãos, podendo ser considerada uma ferramenta para previsão de rendimento das culturas em condições de irrigação.

PALAVRAS-CHAVE: *Zea mays*, L., estratégias de irrigação, modelo de produtividade.

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Recebido pelo Conselho Editorial em: 15/10/2013
Aprovado pelo Conselho Editorial em: 22/03/2016

INTRODUCTION

Corn is a major grain produced worldwide even for animal or human feed use, which comes from its production capacity, chemical and nutritional quality. The important production factors for proper crop yield are related to weather, soil and plant which vary from one region to another.

Regarding climate, water availability is a primary factor, since its limitation affect final crop yields. COSTA et al. (2008) observed water deficit effect on corn crop; they reported changes in plant growth, leaf area expansion during vegetative stages, as well as shoot dry matter production and reproductive stages.

Irrigation has been widely used to tackle water shortage, supplying thus water during dry periods. According to Mantovani; Bernardo; Palaretti (2009), irrigated agriculture has been an important strategy to optimize global food production, generating sustainable development in the field, steadily generating jobs and income.

However, activity planning, proper system management and high initial investment are required to use this technique. Moreover, part of producers fear such production predictions, hindering the implementation of this activity. To assist them, many researches have been developed to find the water level that results in increased corn grain production with the use of irrigation, such as SOARES (2010), PARIZI (2007) and NETO et al. (2012). However, these studies involve field experiments, requiring years of research, performance time and financial resources.

To that end, developing mathematical models provide a tool for estimating and understanding a system behavior against different situations, helping in decision-making processes by means of a simplified representation of the reality, which allows simulating several scenarios and estimating potential impacts of different courses of action on production systems, assisting thus in the activity planning.

According to ANDRADE et al. (2009), simulation models assume that processes involved in biological systems can be described through mathematical expressions. Therefore, systems can be considered compartments, with inputs and outputs of energy and matter, composed of elements that interact with each other, being self-regulated and equipped with limits in space and time. A population of plants, defined in a physical space, can be considered a system in which the elements are the plants, soil, water and air.

Thus, the aim of this study was to evaluate the applicability of a production model using different irrigation levels for corn, and as a tool for irrigated agricultural planning, supporting decision-making processes in the region of Santiago, RS.

MATERIAL AND METHODS

The mathematical model used in this study took into account soil, air and plant characteristics to monitor water extraction in the soil and crop yield responses under different irrigation strategies.

Soil-plant-air system and irrigation management were considered interrelated parts and, because of this interaction, the model showed a view of two basic components: soil water flow and plant yield response (Figures 1 and 2).

For soil water flow, a set of nonlinear equations was solved numerically by the finite difference method with the aid of adjusted functions of physical and hydric soil characteristics. The Richards equation (1931) was used to describe changes in soil water content, including “TR” transpiration (z, t) and water extraction by plant roots.

$$\frac{\partial \psi}{\partial t} C(\Psi) = \frac{\partial}{\partial z} \quad k(\psi) . \frac{\partial \psi}{\partial z} + k(\psi) - TR \ (\psi, z, t) \qquad (1)$$

In which,

$C(\Psi)$ is the specific capacity represented by moisture derivative as function of pressure $\frac{\partial \theta}{\partial \psi}$, and,

TR (z, t) is the plant transpiration at depth z and time t.

Soil water flow was the variation of soil water content due to soil input processes based on the water balance equation.

$$\Delta W = P + I - R - (E_s + T_a) \pm Qz \tag{2}$$

In which,

ΔW is the water amount variation determined by the algebraic sum of contributions from surface runoff (R), soil evaporation (E_s), precipitation (P), irrigation (I) and capillary rise (+Qz) and withdrawal by plant roots or actual transpiration (T_a) and deep drainage (-Qz).

As basic components, we may cite: data reading and initial conditions, input data daily reading, maximum evaporation and transpiration estimates (upper boundary condition), depth and root system measures, lower boundary condition reading, differential equation solution through estimation of water extraction by roots and printing of daily output values as θ (z, t), TR (θ), q (o, t) and q (L, t). Among which, q (o,t) represents soil evaporation and q (L, t) stands for draining or capillary rise within the measured depth for soil water balance.

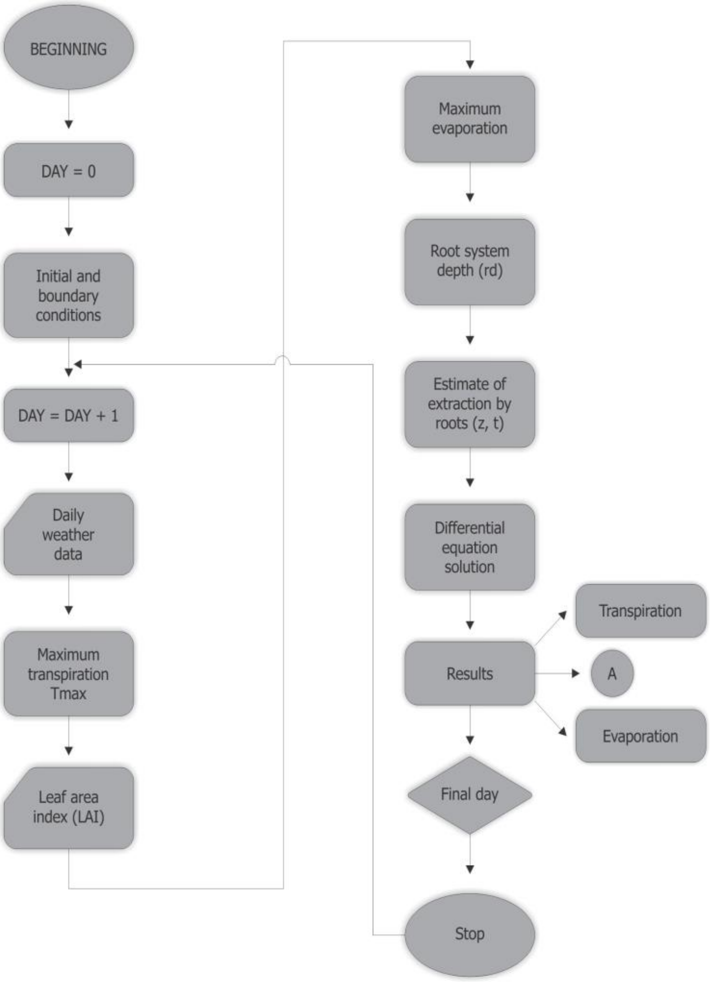

FIGURE 1. Water extraction model simplified flowchart (adapted by ROBAINA, 1992).

The crop response consisted of variations on grain yield and dry matter under different irrigation strategies used. The yield prediction was made as function of increasing dry matter content, measured in hourly basis by the model. To compute the current production rate in different time intervals represented by i, the following expression was used:

$$q_r = \frac{q_p^i}{2} + A\frac{TR^i}{2\Delta e^i} - \frac{1}{2}\sqrt{\left(q_p^i - A\frac{TR^i}{\Delta e^i}\right)^2 - 4(1-\varepsilon)\,.\,q_p^i\,.\,\frac{TR^i}{\Delta e^i}} \tag{3}$$

And the term q_r expressed in $kg.ha^{-1}.day^{-1}$.

The daily yield potential values (q_p) were estimated by the equation:

$$q_p = \left[n\,.\,Po + (1-n).Pc\right].\alpha\,.\,\beta\,.\,\lambda\,.\,\frac{IAF}{5} \tag{4}$$

In which,

q_p, is the dry matter potential yield ($kg\ ha^{-1}.day^{-1}$);

η is the time of the day when sky is overcast;

Po is the rate of dry matter for cloudy days;

Pc is the rate of dry matter for clear days, both expressed in $kg.ha^{-1}.day^{-1}$, and functions of latitude of the location and time of the year.

The value of the day fraction when the sky is cloudy, according to DE WIT (1978), was determined by:

$$n = 1.25 - 0.625\ x\ \frac{Rs}{Rc} \tag{5}$$

In which,

Rc is the photosynthetically active radiation in the absence of atmosphere ($MJ.m^{-2}.day^{-1}$),

Rs is the average global solar radiation at soil level ($MJ.m^{-2}.day^{-1}$), determined by the data from the agro-meteorological data collection station.

The influence of temperature on the daily yield potential was obtained by:

$$\alpha = 1 - \frac{T_m - T_{Li}}{T_{Ls} - T_{Li}} \tag{6}$$

In which,

T_{Li} refers to temperature lower limit, being considered equal to 20, and

T_{Ls} refers to temperature upper limit equal to 35.

We considered in this study a value of 30 for the yield reduction factor due to respiration - λ (FEDDES, 1978.

The relation between the total plant dry weight of the plant without roots and the total dry mass with roots, symbolized by β , considered in this study equal to 0.92 according to FEDDES (1978).

Each treatment leaf area index (LAI), in m² of leaf per m² of soil, was calculated by the expression:

$$LAI = a \cdot e^{-0.5\left(\frac{DAE - b}{c}\right)^2} \quad (7)$$

In which,

DAE refers to days after emergence of the experiment conducted in the field, the constants a, b and c were determined by fitting the data to the leaf area index determined from the data of the experimental physical model.

The values of Δe from [eq. (3)] refer to the shortage of water vapor pressure (hPa), and *TR* is the actual daily transpiration (mm.day^{-1}).

The accumulated potential yield (Q_p) over the crop growth cycle was:

$$Q_P = \sum_{i=1}^{n} q_p \cdot \Delta t \; . \quad (8)$$

In which,

Q_P is expressed in kg.ha^{-1};

n is the number of days to crop maturity (harvest), and

Δt is the period of one day.

Grain yield (*Yg*) with 13% moisture content was calculated by:

$$Yg = Q_P \cdot \frac{H}{0.87} \quad (9)$$

In which,

Q_P is the dry matter yield (kg.ha^{-1}), and

H is the harvest index (based on experimental physical model data).

The yield model simplified flowchart consisted of initial data reading (latitude, fr, A, E), daily input data reading (Tem and Rs - average global solar radiation at soil level (MJ.m^{-2}.day^{-1}), RH (relative humidity), LAI, ft, Rc (Photosynthetically active radiation in the absence of atmosphere, in MJ.m^{-2}.day^{-1}), Pc (Photosynthesis rate for clear days (kg.ha^{-1}.day^{-1})), Po (Photosynthesis rate for cloudy days, in kg.ha^{-1}.day^{-1}), TR), potential yield estimate (potential yield x time).

The mathematical model calibration was made based on data from a field experiment in the years 2008-2009 in the city of Santiago - RS (29° 09'50"S and 54º51'32"W, altitude 420 m). For that, we used an experimental area of *Fazenda Liberdade* located in the 4th district of Tupantuba using ‘Pioneer 32R22’ corn cultivar, developed by Pioneer seeds.

The physical model used to calibrate and test the model consisted of six irrigation strategies through a conventional sprinkling system at different irrigation strategies. Irrigation strategies consisted of supplying 0%, 20%, 40%, 60%, 80% and 100% of the reference evapotranspiration (ET_o) estimated by a class "A" pan method. Irrigation was carried out in a seven-day interval after rainfall event. Along crop cycle, leaf area index (m^2.m^{-2}), total dry matter (kg ha^{-1}), and root system depth (cm) were monitored, besides final grain and dry matter yields (kg ha^{-1}). All these data were applied for production model calibration.

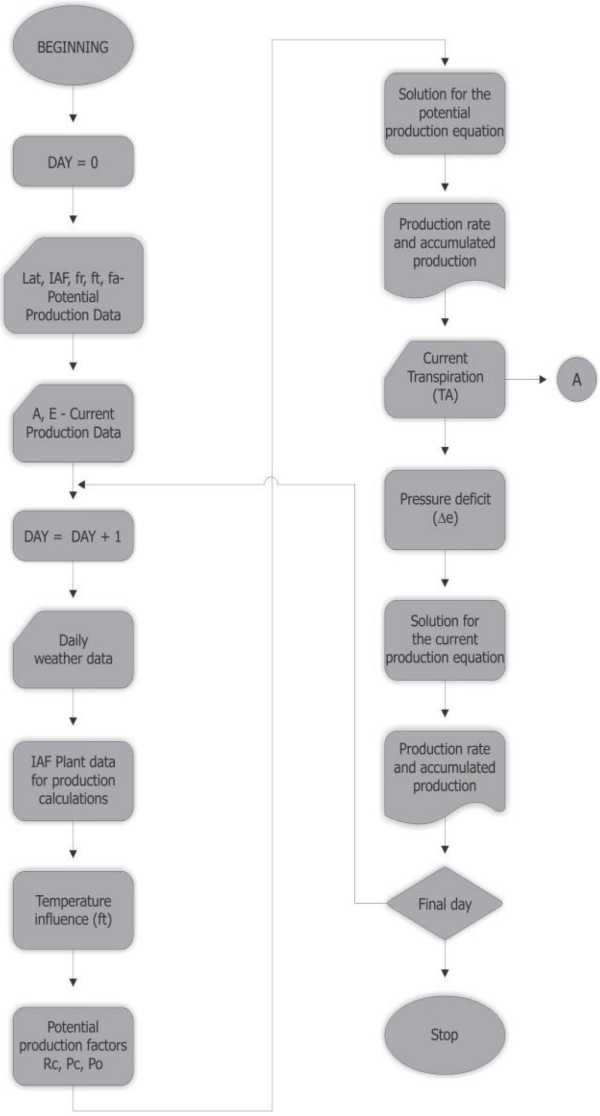

FIGURE 2. Simplified flowchart of the crop yield model (ROBAINA, 1992).

Under the experiment conditions, the production model showed calibration within an acceptable range to simulate crop production. Data testing showed variation of less than 10% and there was statistic equality of field-measured to model-simulated data. Because of that, we tested other rain fractions (%) and irrigation strategies (mm), such as: 25%, 50%, 75% and 100% of rain, with irrigation levels of 0%, 25 %, 75% and 100% over each rainfall fraction simulated.

Water yield (WY) and water-use efficiency (WUE) were determined for all rain rates and irrigation fractions. For calculations of WY, we used an analysis proposed by PEREIRA et al. (2009), in which WY (kg.m^{-3}) was defined as the ration between crop production and the amount of water used, as follows:

$$WP = \frac{Ya}{TWU} \tag{10}$$

In which,

Ya is the production of grain and dry matter achieved by the crop, in kg.ha^{-1}, and

TWU is the amount of water used to achieve Ya, including rainfall, in m^3.

The WUE (kg.m^{-3}) was calculated by the ratio between grain yield (kg ha^{-1}) plus dry matter (kg.ha^{-1}) and the total volume of applied water (m^3) during the crop cycle (FARIA et al. 2012).

RESULTS AND DISCUSSION

Table 1 shows the values of total applied water (mm), effective precipitation (mm), grain yield ($kg.ha^{-1}$) and dry matter yield ($kg.ha^{-1}$) for corn crop as function of daily transpiration provided by the water extraction model from the soil by plant roots.

From Table 1, it is observed that irrigation strategies, regardless rainfall fraction, showed variability greater than 20% in simulated production. According to GOMES (1981), CV values (%) between 20 and 30 are considered as high variability, and above 30%, very high. Values above 30% were found in rainfall fractions of 75%, 50% and 25%, which proves that different irrigation strategies result in corn yield variability.

Grain yields above the national average were obtained by applying a rainfall fraction of 75%, irrigation strategy of 25%, rainfall fraction of 50%, and irrigation strategy of 50%, respectively (6,717.9 $kg.ha^{-1}$ and 4,192.5 $kg.ha^{-1}$, respectively).

TABLE 1. Total applied water (irrigation + rainfall, in mm), effective precipitation (mm), grain yield ($kg.ha^{-1}$), dry matter yield ($kg.ha^{-1}$) and field capacity (%) as function of simulation of different irrigation levels for corn crop.

Rainfall fraction (%)	Irrigation (%)	Total water applied (mm)	Effective precipitation (mm)	Grain Yield ($kg.ha^{-1}$)	DM. yield ($kg.ha^{-1}$)
100	0	347.0	347	7487.7	18482.4
	25	401.3	347	10287.4	23411.0
	50	455.6	347	13074.7	27653.5
	75	509.9	347	14940.5	30131.6
	100	564.2	347	15745.5	31110.9
	Mean			**12307.1**	**26157.8**
	S.D.			**3415.1**	**5220.5**
	CV (%)			**27.7**	**19.9**
75	0	289.1	289.1	4241.4	11827.9
	25	343.4	289.1	6717.9	17002.9
	50	397.7	289.1	9704.3	22440.7
	75	452.0	289.1	12344.6	26604.9
	100	506.3	289.1	14144.5	29109.9
	Mean			**9430.5**	**21397.2**
	S.D.			**4033.4**	**7045.8**
	CV (%)			**42.7**	**32.9**
50	0	198.2	198.2	1079.8	3916.2
	25	252.5	198.2	2162.4	6860.5
	50	306.8	198.2	4192.5	11718.4
	75	361.1	198.2	6743.6	17053.2
	100	415.4	198.2	9273.7	21705.6
	Mean			**4690.4**	**12250.7**
	S.D.			**3350.2**	**7267.4**
	CV (%)			**71.4**	**59.3**
25	0	101.6	101.6	268.5	1453.5
	25	155.9	101.6	452.9	2016.6
	50	210.2	101.6	996.0	3672.4
	75	264.5	101.6	2057.1	6587.9
	100	318.8	101.6	3625.9	10428.1
	Mean			**1480.1**	**4831.7**
	S.D.			**1386.1**	**3710.9**
	CV (%)			**93.7**	**76.8**

Grain yields above the national average were obtained by applying a rainfall fraction of 75%, irrigation strategy of 25%, rainfall fraction of 50%, and irrigation strategy of 50%, respectively (6,717.9 kg.ha^{-1} and 4,192.5 kg.ha^{-1}, respectively).

Figures 3 and 4 show the behavior of irrigation strategies and rainfall fraction of simulated rain, in grain yield and dry matter yield of corn.

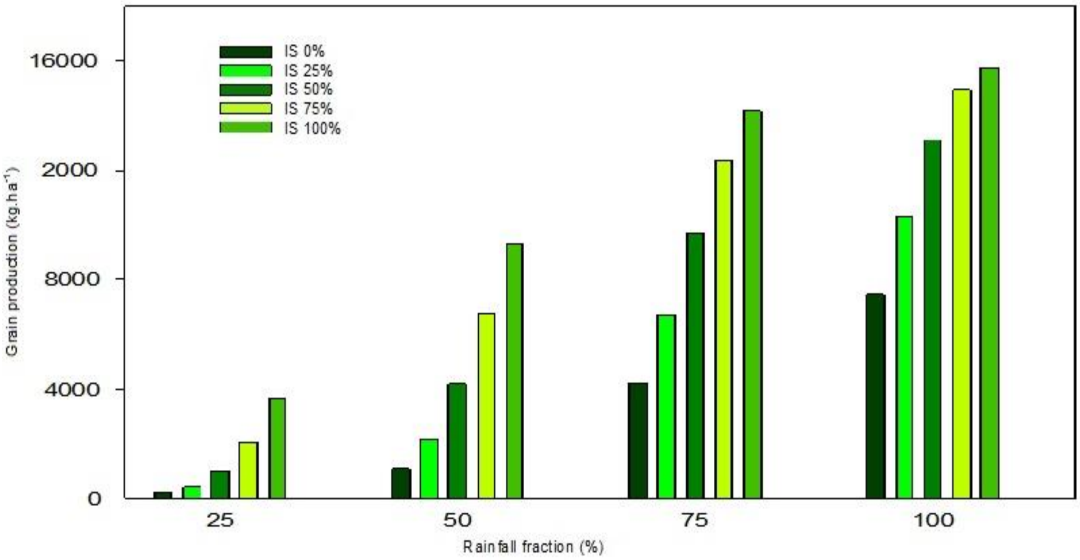

FIGURE 3. Performance of irrigation strategies (IS) and rainfall fractions (%) simulated in grain yield (kg.ha^{-1}) of corn crop.

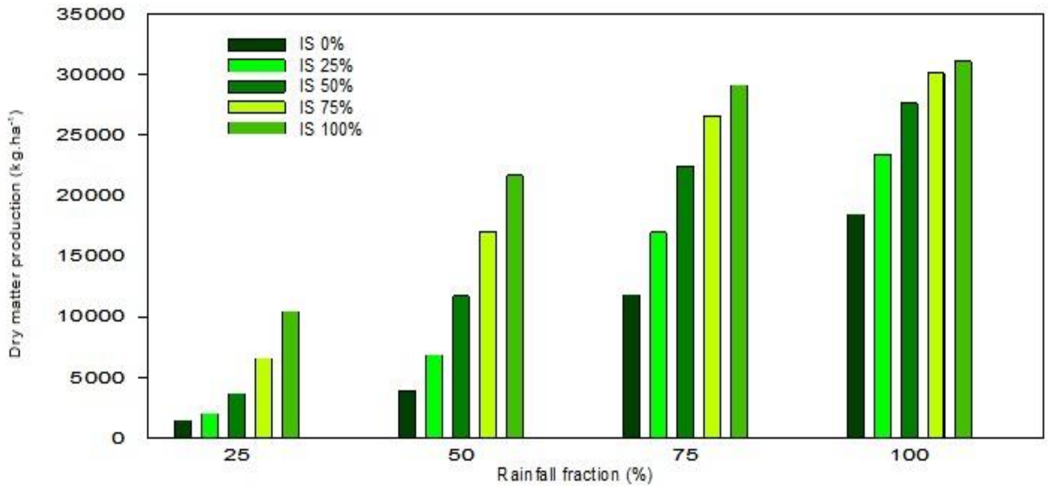

FIGURE 4. Performance of irrigation strategies (IS) and rainfall fractions (%) simulated in the production of corn dry matter (kg.ha^{-1}).

Figures 3 and 4 demonstrate that increasing rainfall fractions and irrigation strategies led to higher grain yield and dry matter values. Such major yields were achieved when the amount of irrigated water was above 500 mm, which resulted in in yields above 15 t. Table 2 shows the water yield values (WY) and water-use efficiency (WUE) as function of grain yield and dry matter yield in different irrigation strategies simulated.

TABLE 2. Water yield values for grain yield (WY/GR), water yield for dry matter yield (WY/DM), water-use efficiency for grain yield (WUE/GR) and efficiency of water application for dry matter yield (WUE/DM) found for different irrigation levels in the simulation for corn crop.

Rainfall fraction (%)	Irrigation (%)	WY/GR ($kg.m^{-3}$)	WY/DM ($kg.m^{-3}$)	WUE/GR ($kg. m^{-3}$)	WUE/DM ($kg. m^{-3}$)
100	0	2.16	5.33	2.16	5.33
	25	2.96	6.75	2.56	5.83
	50	3.77	7.97	2.87	6.07
	75	4.31	8.68	2.93	5.91
	100	4.54	8.97	2.79	5.51
75	0	1.47	4.09	1.47	4.09
	25	2.32	5.88	1.96	4.95
	50	3.36	7.76	2.44	5.64
	75	4.27	9.20	2.73	5.89
	100	4.89	10.07	2.79	5.75
50	0	0.54	1.98	0.54	1.98
	25	1.09	3.46	0.86	2.72
	50	2.12	5.91	1.37	3.82
	75	3.40	8.60	1.87	4.72
	100	4.68	10.95	2.23	5.23
25	0	0.26	1.43	0.26	1.43
	25	0.45	1.98	0.29	1.29
	50	0.98	3.61	0.47	1.75
	75	2.02	6.48	0.78	2.49
	100	3.57	10.26	1.14	3.27

Table 2 shows WY had variations from 0.26 to 4.89 $kg.m^{-3}$ for grain yield, and from 1.43 to 10.95 $kg.m^{-3}$ for dry matter yield. Increasing water levels raised the WY values for all rainfall fractions. Thus, the maximum WY corresponded to the highest grain yield. Yet WUE ranged between 0.26 and 2.93 $kg.m^{-3}$ for grain yield and from 1.43 to 6.07 $kg.m^{-3}$ for dry matter yield.

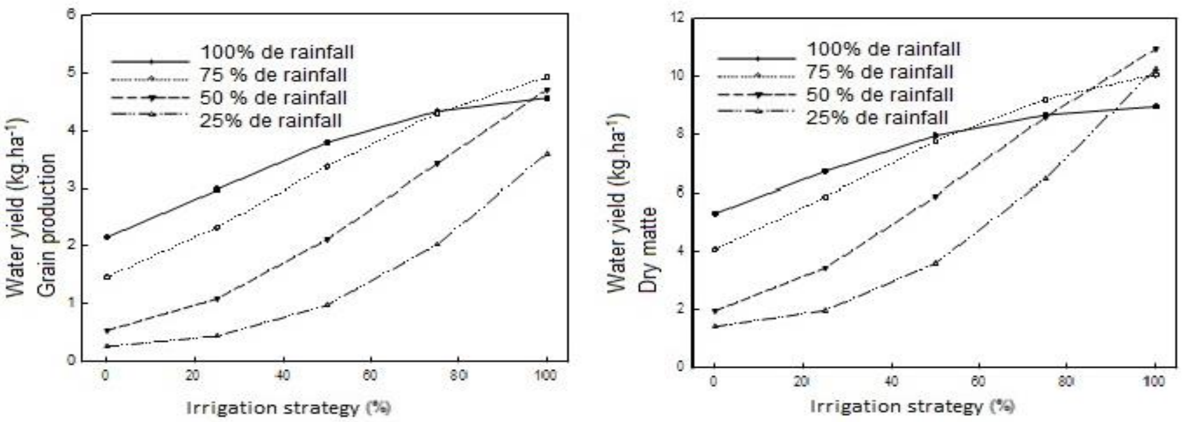

FIGURE 5. Shows the water yield performance (WY - $kg.m^{-3}$) for grain yield ($kg.ha^{-1}$) and dry matter yield ($kg.ha^{-1}$) in relation to the different strategies irrigation and rainfall fractions.

Through Figure 5, it is observed that the increased irrigation strategy resulted in increased WY, both in grain yield and dry matter yield. The reduction in the rainfall fraction from 100% to 75% and 50% resulted in increased WY for the irrigation strategy of 100%, namely, adopting a rainfall fraction of 75% and 50% of that required to elevate soil moisture to field capacity allowed increasing water yield. Figure 6 shows the water-use efficiency performance (WUE) obtained for grain yield ($kg.ha^{-1}$) and dry matter yield ($kg.ha^{-1}$) in relation to different irrigation strategies and rainfall fractions for the corn crop.

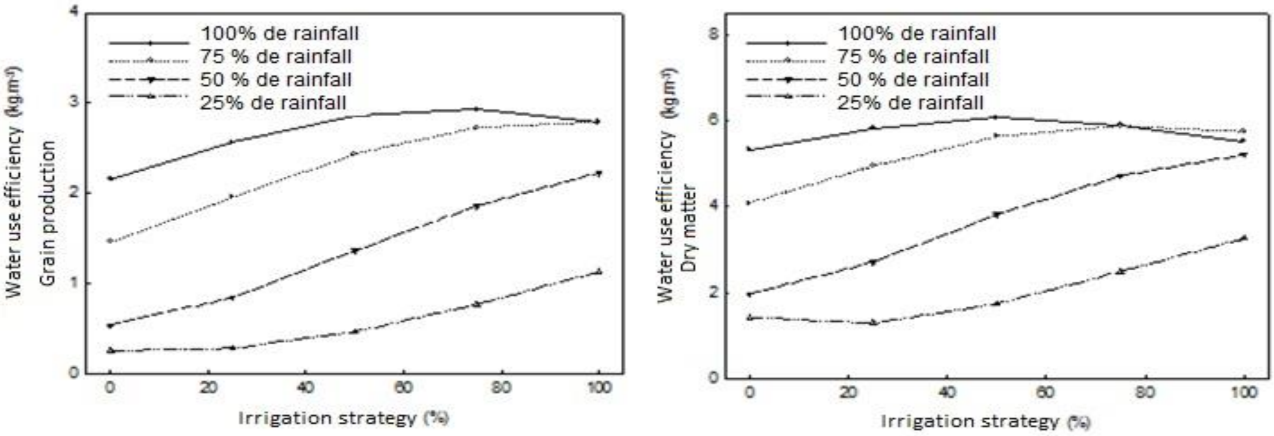

FIGURE 6. Relation between water-use efficiency ($kg.m^{-3}$) obtained for grain yield ($kg.ha^{-1}$) and dry matter yield ($kg.ha^{-1}$) in different irrigation strategies in corn crop.

Both in grain yield and in dry matter yield, the WUE, in a rainfall fraction of 100%, showed increase up to irrigation strategy of 75%, decreasing in irrigation strategy of 100%. The lower rainfall fractions resulted in lower WUE values.

Figure 7 shows the relation between simulated grain yield ($kg.ha^{-1}$) at different irrigation strategies and total amount of water applied. For adjustment, we simulated a rainfall fraction and irrigation depth, higher than the previously tested, in order to identify the production decrease point.

Production curve was adjusted to a y-type equation: $y = a.\exp\left(-0.5\left(\frac{|x-b|}{c}\right)^{d}\right)$, in which coefficients were: a = 16281.779, b = 730.637, c = 327.378 d = 3.821 and r^2 = 0.995.

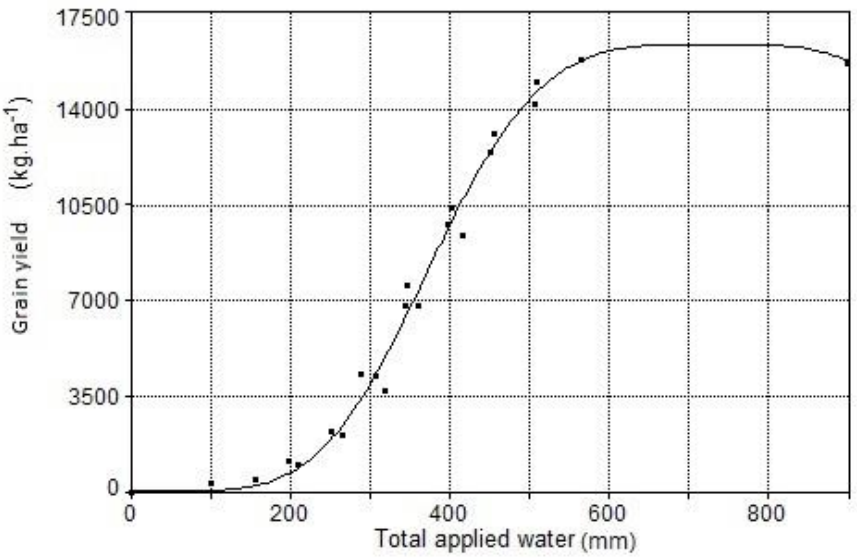

FIGURE 7. Relationship between grain yields ($kg.ha^{-1}$) simulated by the model for different irrigation strategies and total water applied to corn crop.

Through Figure 7, it is observed that grain yield increased up to 600 mm, approximately. These values are in accordance to those reported in the literature for proper water requirement of this crop. The limit of the rational area of water input starts from 600mm on, which characterizes the limit of the rational production area for this production factor.

Figure 8 shows the response of water-use efficiency (WUE) as a function of the total water applied (mm). The production curve was adjusted to an equation of the type $y = a.\exp\left(-0.5\left(\frac{|x-b|}{c}\right)^{d}\right)$, with coefficients equal to: a = 2.909, b = 507.713, c = 167.308 d = 2.021 and r^2 = 0.981.

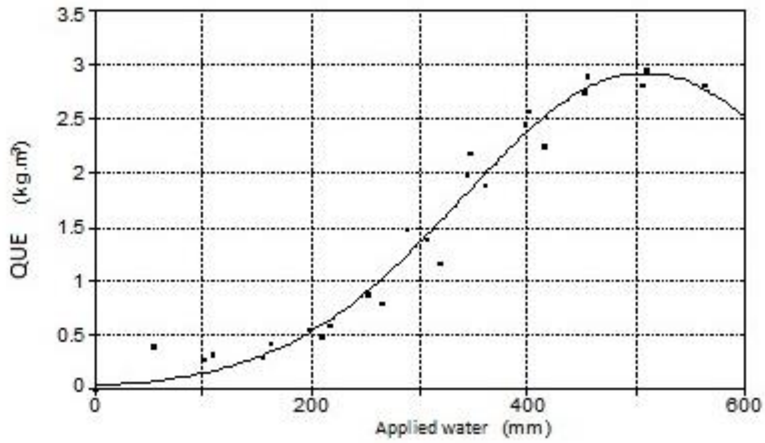

FIGURE 8. Relationship between the variation of water-use efficiency (kg.m^{-3}) and total water applied (mm) for corn crop.

Through Figure 8, it can be seen that the WUE showed a decrease from level 550 mm on, approximately. This leads us to infer that levels above that would reduce plant use. Pegorare et al. (2009), evaluating the effect of different water levels in supplemental irrigation of corn crops, in the city of Dourados, found an increase of 130% in applications of 510 mm compared to non-irrigated treatments.

CONCLUSIONS

The production model was shown to be an effective tool for predicting corn crop yield in irrigation conditions, which can assist in decision making of producers and technicians of the region under study, as a tool for regional planning, enabling the identification of different irrigation strategies.

The application of 75% and 100% of ETo is recommended since these water levels promoted higher water yield indexes and water-use efficiency.

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ERRATUM

In the paper "CORN YIELD UNDER VARIOUS SIMULATED IRRIGATION DEPTHS", with DOI number: 10.1590/1809-4430-Eng.Agric.v36n3p503-514/2016, published in the journal Agricultural Engineering 36 (3):503-514, on the page 503:

Where it reads:

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It should read:

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