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Modified crop model estimation of depleted and potential soybean yield

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ABSTRACT. Despite the great importance of soybeans in Brazil, there have been few applications of soybean crop modeling on Brazilian conditions. Thus, the objective of this study was to use modified crop models to estimate the depleted and potential soybean crop yield in Brazil. The climatic variable data used in the modified simulation of the soybean crop models were temperature, insolation and rainfall. The data set was taken from 33 counties (28 Sao Paulo state counties, and 5 counties from other states that neighbor São Paulo). Among the models, modifications in the estimation of the leaf area of the soybean crop, which includes corrections for the temperature, shading, senescence, CO_2, and biomass partition were proposed; also, the methods of input for the model's simulation of the climatic variables were reconsidered. The depleted yields were estimated through a water balance, from which the depletion coefficient was estimated. It can be concluded that the adaptation soybean growth crop model might be used to predict the results of the depleted and potential yield of soybeans, and it can also be used to indicate better locations and periods of tillage.

Keywords: leaf area index, water balance, crop model, *Glycine max.*

Modelo modificado de estimação da produtividade deplecionada e potencial da soja

RESUMO. Aplicações de modelos de previsão de produtividade na cultura da soja são muito raros. Assim, o objetivo desta pesquisa foi realizar a estimação da produtividade deplecionada e potencial da cultura de soja, usando modelos de previsão modificados. Os dados climáticos utilizados nos modelos de simulação foram a temperatura, precipitação e insolação. Os dados foram proveniente de 33 municípios (28 do estado de São Paulo, e cinco municípios de estados vizinhos). Dentre os modelos propostos modificados está a estimação da área foliar da soja, com correções para temperatura, sombreamento, senescência, CO_2, partição de biomassa, bem como os métodos de simulação das variávies climáticas do "input" para o modelo. As produções deplecionadas foram estimadas através do balanço hídrico, a partir do qual, o coeficiente de depleção foi estimado. Considerando as adaptações do modelo para a cultura da soja, pode-se concluir que o modelo pode ser usado para predição de resultados para produção deplecionada e potencial da soja. Também é possível determinar através do modelo os melhores locais de cultivo da soja no Estado de São Paulo.

Palavras-chave: índice de área foliar, balanço de água no solo, modelo, *Glycine max.*

Introduction

In order to predict and simulate experimental results, the knowledge of soybean crop physiology is fundamental for crop modeler scientists. To construct accurate model predictions for soybean crops, some specific aspects, such as photorespiration and the CO_2 assimilation rate, must be taken into consideration. Knowledge about the successive crop growth stages (phenology), species functionality (physiology) and interactions with the environment (eco-physiology) are necessary for the planning of crop cultivation and for the attainment of high yields and the modeling predictions.

The CROPGRO-Soybean model is a process-oriented model that simulates the carbon, water and nitrogen balance for the soybean crop at the plant and soil level (BOOTE et al., 1998). Its equations express the relationship among plant processes (phenological growth, photosynthesis, respiration, biomass accumulation, photoassimilate partitioning, and soil/plant water balance) and temperature, photoperiod, insolation, and the water and nitrogen stress. The modeling techniques can be used in industrial management to understand better storage formation, commercialization, resources administration, agricultural and political mapping, health areas, sports, research field definitions, and agriculture. Estimating the crop yield for a specific site can be performed by taking into account elements of the weather, such as the air temperature, rainfall and solar radiation, and the resource inputs and soil type.

Carbone et al. (2003) used the CROPGRO-Soybean model v. 35 for a comparison of the simulated and observed yield in 8 research stations and in three maturation groups (V, VI, VII); depending on the site, the crops were analyzed at several ages. The variation between the estimated and observed yield was due to the fact that the model did not take into consideration the influence of weeds, diseases, insects, and wind interference (BATCHELOR et al., 1993). Camargo et al. (1986) used climatic variables to build a crop model that satisfactorily estimated the crop yield; the accuracy of the model was confirmed in the regression by comparing the observed and estimated data (0.76 to 0.87) to calculate the coefficient of determination. More recent studies indicate that the use of an expolinear model is able to estimate and adequately describe the growth and development of the soybean crop conditions in Brazil and Argentina (CONFALONE et al., 2010). Under Brazilian conditions (Paraná State), Berka et al. (2003) have proposed a model for estimating soybean production that is integrated into a Geographic Information System; the model assumes that depletion factor productivity is a function of water stress.

Despite the great importance of soybeans in Brazil, there have been few applications of soybean crop modeling on Brazilian conditions. Also, there have been few studies indicating the parameters for an estimation of the leaf area and the assimilation rate of CO_2. Therefore, by using both modified crop models and parameters generated in Brazil, this study aims to provide estimates of the leaf area, photoassimilate partitioning and the conversion of radiant energy in carbohydrates to estimate the depleted and potential soybean crop yield in Brazil.

Material and methods

The data set of climatic variables (temperature, sunshine and rainfall) for testing and developing the modified soybean crop model were obtained from the "Ciências Exatas" Department of the University of São Paulo – College of Agriculture "Luiz de Queiroz" – Brazil (USP/ESALQ); the Water and Electricity Department of Sao Paulo State - Brazil (DAEE); the "Instituto Agronômico de Campinas" São Paulo State - Brazil (IAC); the Meteorology System of Paraná, Paraná State – Brazil (SIMEPAR); and the National Institute of Meteorology - Brazil (INMET). The data set was from 33 counties (28 Sao Paulo state counties and 5 counties from other states that neighbor São Paulo). Because there is a temporal and spatial variability in the estimates of the sunshine, solar radiation and photosynthetic active radiation (PAR) for the 18 counties of São Paulo State (the same data used in this study), we used all of the data available. Moreover, the variability in sample size for the sunshine, solar radiation and PAR depends on the location and time of year in the state of São Paulo (MARTIN et al., 2008a). Using the data from this study, Martin et al. (2008b) found that the normal distribution occurs in greater frequency and can be used to adequately simulate rainfall.

The Duration of the Vegetative Phase (DVP, d) was estimated, with modifications, according to the model presented by Rodrigues et al. (2001). We used parameters from the soybean cultivar Ocepar 8 ($a = 0.05327$ day^{-1}, $b = -0.00579$ h^{-1}, $c = 0.001909$ D^{-1} °C^{-1} and $D = 10$ days), which has a long juvenile period, and where flowering varies between 54 and 88 days after emergence. The DVP phase might be calculated as follows:

$$DVP = \frac{1}{a + b.Nm + c.Tm} + D \tag{1}$$

where:

a, b (day h^{-1}) and *c* (°C^{-1}) refer to the empirical parameters of the model, *Nm* is the photoperiod (h day^{-1}) and *Tm* is the average temperature (°C) during the vegetative phase:

$$\mathrm{Nm} = \frac{\sum_{i=1}^{DVP-10} \mathrm{Ni}}{\mathrm{DVP}} \tag{2}$$

$$\mathrm{Tm} = \frac{\sum_{i=1}^{DVP-10} \mathrm{Ti}}{\mathrm{DVP}} \tag{3}$$

In the Duration of the Reproductive Phase (DRP, day), it was assumed that the number of flowering days until the point of physiological maturity was constant and equaled 65 days. Thus, the duration of the cycle (DC, day) can be calculated by:

$$DC = DVP + DRP \tag{4}$$

The following was also considered: the emergence of 300,000 seedling plants per hectare and the effective number of seeds per hectare (Ns = 300,000 seeds ha^{-1}); 16 g mass per 100 seeds (MSR = 0.16 g seed $^{-1}$); the proportion of the embryo in the soybean seed of 15% (Mes = 0.15 g g^{-1} – 0.15 g of embryo per seed gram). Thus, the initial leaf dry biomass ($IDlL_{0,}$ kg ha^{-1}) can be calculated by:

$$\mathrm{ID}\,FSf_0 = \frac{Ns.Mcs.Mes.Mfe}{1000} \tag{5}$$

From the values of the dry biomass of live leaf (DPl, kg ha^{-1}) and the specific leaf area (Sla, m^2 kg^{-1} = m^2 of leaf per kg of dry leaf), which, for the soybean, varies from 15 to 33 m^2 kg^{-1} (DRIESSEN; KONIJN, 1992), the leaf area index can be calculated by (LAI, m^2 m^{-2}) the following:

$$\mathrm{LAI} = \frac{\mathrm{DPl_i.Sla_i}}{10000} \tag{6}$$

We assumed that, in relation to the relative crop development (Rdi), the temporal variation (daily scale) of the specific leaf area (SLa, m^2 kg^{-1}) can be characterized by the following equations:

$$\mathrm{Sla_i} = \mathrm{Sla_{max}} \ (\text{if Rdi} = 0);$$
$$\mathrm{Sla_i} = \mathrm{Sla_{mim}} - (\mathrm{Sla_{max}} - \mathrm{Sla_{mim}}).\ln(\mathrm{Dr_i}) \tag{7}$$
$$(\text{if Rdi} > 0)$$

[7] $\mathrm{Sla_i} = \mathrm{Sla_{max}}$ (if $\mathrm{Sla_i} > \mathrm{Sla_{max}}$),
in which $\mathrm{Sla_{max}}$ and $\mathrm{Sla_{min}}$ (8)

These two equations refer to the maximum and minimum limits of the specific leaf area (m^2 kg^{-1}), respectively. The general equation (reduced) corresponding to the photosynthesis can be characterized by the following: $CO_2 + H_2O \rightarrow CH_2O + O_2$. By considering the crop reflecting power (Crp = 0.2 J J^{-1}) and the interception of the photosynthetically active solar radiation (PAR, J m^{-2} s^{-1}), the solar radiation photosynthetically liquid active (PAR_liq, J m^{-2} s^{-1}) can be calculated as:

$$PAR\_liq_i = (1 - \Pr c).PAR_i \tag{9}$$

Thus, the answering curves of the assimilation of CO_2 (ADC, kg ha^{-1} h^{-1}), which correspond to a certain concentration of CO_2 in the atmosphere (CO = 340 vppm), can be described as (GOURDIAAN, 1982):

$$\mathrm{ADC_i} = \mathrm{PLMX_i}.\left[1 - \mathrm{e}^{-PLEA.\frac{PAR\_liq_i}{\mathrm{PLMX_i}}}\right].\left(1 + \beta.\ln\left(\frac{Cx}{Co}\right)\right) \tag{10}$$

where:

Cx refers to the actual concentration of CO_2 in the atmosphere (Cx = 385 vppm), PLEA and β refer to the empirical parameters described by Vries et al. (1983) (PLEA = 0.48 kg CO_2 ha^{-1} h^{-1} (J m^{-2} $s^{-1})^{-1}$ and β = 0.8 for species C_3 and β = 0.4 for species C_4) and PLMX refers to the auxiliary variable (kg ha^{-1} h^{-1}) and is calculated using the following expression:

$$\mathrm{PLMX_i} = 40.\left(\omega_0 + \frac{\omega_1}{\omega_2}.\mathrm{T_i}\right) \tag{11}$$

where:

Ti refers to the average temperature (°C) of the i^{th} day after the emergence, and ω_0, ω_1 and $\omega_{2,}$ depending on the temperature, refers to the empirical parameters that can be obtained in Vries et al. (1983).

The initial efficiency of the use of the absorbed light is characterized by biophysical processes with steady values. The maximum assimilation rate of carbon CO_2 depends on the species, a consideration of the biochemical processes and the ideal physiological conditions. The equation related to the calculation of the assimilation of CO_2 was established for the high temperature conditions (30°C) and the concentration of CO_2 in the atmosphere (340 vppm). Thus, the maximum assimilation of CO_2, under 30°C is 40 kg ha^{-1} h^{-1} (DORNHOFF; SHIBLES, 1970). The correction for the temperature is presented by Hofstra (1972), where the value obtained in the previous function must be multiplied by the value obtained in a linear one. The raw photosynthesis (FBf_i, kg ha^{-1} day^{-1} – kilogram of carbohydrate per hectare of leaf per day) is calculated as follows:

$$FBf_i = \frac{30}{44}.ADC_{i.}N_{i.}f\_LAI.f\_Dr \tag{12}$$

where:

f_LAI and f_Dr are factors of correction that refer to the leaf area rate and to the culture relative development, respectively. We began to consider the effect of the auto shading of the leaf area from the value of the leaf area rate factor (f_LAI) and with a leaf area rate (LAI, $m^2\ m^{-2}$) superior to 1 $m^2.m^{-2}$ in accordance with the following equations: $f\_LAI_i = 1$, $LAI_i \leq 1$; $f\_LAI_i = e^{\lambda_0 + \lambda_1 (LAI_{i+} \lambda_2)}$, $f\_LAI_i = 0.28$, in which λ_0, λ_1 and λ_2 refer to the empirical parameters ($\lambda_0 = 0.131\ m^2\ m^{-2}$, $\lambda_1 = -0.14\ m^2\ m^{-2}$ and $\lambda_2 = -0.064284\ m^2.m^{-2}$). The photosynthesis rate decreases with the age of the tissues, thus indicating the age of the plant. Therefore the f_Dr factor displays the following functional relationship with the relative culture development (Dr), $f\_Dr_i = 1$, if;

$Rdi \leq Dr\_f_{ini;}$

$$f\_Dr_i = e^{\frac{\ln(f\_Dr_{fim})}{f\_Dr_{ini} - Dr\_f_{ini}}(Dr_i - Dr\_f_{ini})} \quad (13)$$

where:

Dr_f_{ini}, Dr_f_{fim}, f_Rdi_{ni}, and f_Dr_{fim} ($Dr\_f_{ini} = 0.15$, $Dr\_f_{fim} = 1.00$, $f\_Rdi_{ni} = 1$ and $f\_Dr_{fim} = 0.45$) refer to the empirical parameters. The liquid photosynthesis (*FLf*, kg ha^{-1} day^{-1}) per unit of leaf area for a certain day is determined by calculating the difference between the raw photosynthesis (*RP*) from that day and the maintenance respiration of the previous day (MR_{i-1}): $FLf_i = FB_i - RM_{i-1}$. The liquid photosynthesis (*LP*, kg ha^{-1} day^{-1}) per unit of soil area exploited by the culture can be calculated by the following equation: $FL_i = FLf_i.LAI_i$. The formation of the photoassimilate partitioning is determined by fractions allocated to the different organs of the plant. The fraction of allocation will depend on the organ of the considered plant (the root, *f_Ri;* the stem, *f_Hi;* the leaf, *f_Fi;* or the reproductive organs, *f_ORi*) and the relative crop development (*Rdi*) obtained according to the formula of Driessen and Konijn (1992). Also, the fraction of allocation will be determined by the quantity of carbohydrate allocated to the root (CHO_R_i, kg ha^{-1}), the leaf (CHO_F_i, kg ha^{-1}), the stem (CHO_H_i, kg ha^{-1}) and to the reproductive organs (CHO_OR_i, kg ha^{-1}). The efficiency of the carbohydrate conversion of the dry phytomass is determined by the quantity of accumulated carbohydrate multiplied by the efficiency of conversion. Additionally, the calculation of the dry phytomass of the root, stem, leaf and reproductive organs can also be obtained in accordance with Driessen and Konijn (1992).

From the allocated fraction in each of the plant's organs, we can determine the quantity of carbohydrate allocated. That quantity of carbohydrate must be converted into dry biomass. Vries et al. (1983) demonstrated the approximate values of the conversion of carbohydrates into dry biomass for the soybean crop. The efficiency of the conversion varies according to the composition of the dry biomass (carbohydrates, proteins, lipids, lignin and organic acids) formed from the vegetable organ (leaf, stem, root or reproductive organ). However, the primary product of the photosynthesis is the carbohydrate, and its conversion in other organic compounds involves an energetic cost, which is represented by the respiration of synthesis. An approximation is presented by Vries et al. (1983), in which 1.0 kg of photosynthesized carbon results in 404 g of protein, 330 g of lipids, 472 g of lignin, 826 g of structural carbohydrate and 104 g of organic acids. By knowing the percentage of the composition of dry biomass in the soybean plant, we can calculate the efficiency of conversion (Ec) for each organ:

$$Ec = QCE.PCE + QP.PP + QL.PL + QLg.PLg + QAO.PAO \quad (14)$$

where:

QCE refers to the quantity of structural carbohydrate, *PCE* refers to the % composition of structural carbohydrate in the dry biomass, *QP* refers to the quantity of protein, *PP* refers to the percentage composition of protein in the dry biomass, *QL* refers to the quantity of lipids, *Pl* refers to the percentage of the composition. The total dry biomass of the leaf ($FSTf_i$, kg ha^{-1}) and of the root ($FSTr_i$, kg ha^{-1}) accumulated until the i^{th} day after the emergence is given by the following equation:

$$FSTf_i = FSTf_{i-1} + FSf_i - Sf_{i-1}$$

and (15)

$$FSTr_i = FSTr_{i-1} + FSr_i - Sr_{i-1}$$

where:

FSf_i and FSr_i refers to the dry biomass of the leaf and root, respectively, produced in the i^{th} day after the emergence; $FSTf_{i-1}$ and $FSTr_{i-1}$ refer to the total dry biomass of the leaf and root, respectively, accumulated until the i^{th} day after the emergence. Thus,

$$Sf_i = Fsen.FSf_i \quad \text{and} \qquad Sr_i = Rsen.FSr_i \tag{16}$$

where:

Fsen and Rsen refer to the leaf and root senescence factors that are the function of the relative development of the culture:

On average, the composition of the botanical seed of the soybean is as follows: 29% of carbohydrate, 37% of protein, 18% of lipids, 6% of liginin and 5% of organiSR.

$Fsen_i = 0$, if Rdi ≤ 0.2;

$$Fsen_i = \frac{f\_Sen\_fim - f\_Sen\_ini}{Dr\_f\_Sen\_fim - Dr\_f\_Sen\_ini}$$

$(Dr\_f\_Sen\_ini + Dr_i)$, if 0.2 < Rdi ≤ 0.65;

$Fsen_i = 1$, if Rdi > 0.65; $Rsen_i = 0$, if Rdi ≤ 0.2;

$$Rsen_i = \frac{r\_Sen\_fim - r\_Sen\_ini}{Dr\_r\_Sen\_fim - Dr\_r\_Sen\_ini}$$

$(Dr\_r\_Sen\_ini + Dr_i)$, if 0.2 < Rdi ≤ 0.65 [17]

where:

R*sen*$_i$ = 1 if Rdi > 0.65, and in which Dr_f_Sen_ini, f_Sen_ini, Dr_f_Sen_fim and f_Sen_fim refer to the empirical parameters of the leaf, and Dr_r_Sen_ini, r_Sen_ini, Dr_r_Sen_fim and r_Sen_fim refer to the empirical parameters of the root (Dr_f_Sen_ini = Dr_r_Sen_ini = 0.2, f_Sen_ini = 1. r_Sen_ini = 0, Dr_f_Sen_fim = Dr_r_Sen_fim = 0.65 and f_Sen_fim = r_Sen_fim = 1). Thus, the senescence of the roots was analogically calculated to the senescence of the leaf.

The total dry biomass of the stem (FSTh$_i$, kg ha^{-1}) and the reproductive organ (FSTor$_i$, kg ha^{-1}) accumulated until the ith day after the emergence are given by the following equation:

$$FSTh_i = FSTh_{i-1} + FSh_i \quad \text{and} \qquad FSTor_i = FSTor_{i-1} + FSor_i \tag{18}$$

The maintenance respiration can be quantified in each organ of the plant as follows: the root (MRr, kg ha^{-1} day^{-1}), the stem (MRh, kg ha^{-1} day^{-1}), the leaf (MRf, kg ha^{-1} day^{-1}) and the reproductive organs (MRor, kg ha^{-1} day^{-1}). The maintenance respiration of the plant (MR, kg ha^{-1} day^{-1}) is the sum of the maintenance respiration of the different living organs, which depends on the dry biomass and the maintenance respiration coefficient:

$$\begin{aligned} &RMr_i = FSr_i.CRm\_r_i, \\ &RMh_i = FSh_i.CRm\_h_i, \\ &RMf_i = FSf_i.CRm\_f_i, \\ &RMor_i = FSor_i.CRm\_or_i, \\ &RM_i = \left(RMr_i + RMh_i + RMf_i + RMor_i\right). \\ &m\_T.m\_Dr \end{aligned} \tag{19}$$

where:

CMR_, CMR_f, CMR_r and CMR_h refer to the maintenance respiration coefficient of the root (CMR_r = 0.01 kg kg^{-1} day^{-1} – kilogram of carbohydrate - CH$_2$O – per kilogram of dry biomass of the root - FSr – per day), of the stem (CMR_h = 0.015 kg kg^{-1} day^{-1} – kilogram of carbohydrate - CH$_2$O – per kilogram of dry biomass of the stem - FSf – per day), of the leaf (CMR_f = 0.015 kg kg^{-1} day^{-1} - kilogram of carbohydrate - CH$_2$O - per kilogram of dry biomass of the leaf - FSf – per day) and the reproductive organs (CMR_or = 0.017 kg kg^{-1} day^{-1} - kilogram of carbohydrate - CH$_2$O - per kilogram of the dry biomass of the reproductive organ - FSor – per day) respectively. Thus,

$$\begin{aligned} &m\_T_i = e^{0.0607.T_i - 2.1056}; \\ &m\_Dr_i = 1, \text{ if Rdi} \le 0.15; \\ &m\_Dr_i = e^{0.21246579 - 1.41643859.Dr_i} \\ &\text{if } 0.15 < \text{Rd}_i \le 1.00 \end{aligned} \tag{20}$$

The dry biomass of the grains (FSg, kg ha^{-1}) is calculated based on the dry biomass of the reproductive organs (FSor, kg ha^{-1}) (flower, pod and botanical seed) and by the following expression: $FSg = 0,8.FSTor_{i=DC}$. In this expression, 0.8 is the proportion of the seeds in relation to the total of the reproductive organs. Thus, the potential yield of grains (*PPg*, kg ha^{-1}) can be calculated by the equation $PPg = \frac{FSg}{1-u}$, in which u refers to the drift of water, and the basis of the mass is determined by the seed (where u = 0.13 g g^{-1} - 13 g of water in 100 grams of wet seed).

The gross daily production of carbohydrates will be depleted in function according to the real quantity of light (sunstroke) and by the real quantity of water available in the soil.

First, the rainy days and the quantity of rain on each day must be simulated. Moreover, a uniform distribution must be simulated. If the generated number is either lower or equal to the probability of the considered day, then the day is considered rainy; otherwise, the rain is equal to zero and the day is not considered rainy. Moreover, the minimum and maximum values that have occurred in the local historical series must be taken into consideration. The quantity of rain calculated for the rainy days is determined by the estimation of two random numbers with a uniform distribution (U_1 and U_2), so that they must be independent. Next, the values V_1 and V_2, $V_1 = 2.(U_1 - 1)$; $V_2 = 2.(U_2 - 1)$ and $VS = V1^2 + V2^2$ must be estimated. If the simulated value (VS) is more than 1, then the previous step must be recalculated.

Next, the accessory value (Vx) for the calculus of the simulated rain (SR) must be determined. This is given by the function:

$$Vx = V1.\sqrt{-2.\log(VS)/VS} \text{ and}$$
$$CS_i = Cm_i + Vx.C_{dp} \qquad (21)$$

The process must be re-started if the values of the simulated rain are superior or inferior to the maximum and minimum value of the historical average for the day. The application's normal bivariate simulation, which considers the temperature and photosynthetically active radiation, was tested, and the results were superior to other simulations by Martin et al. (2007), and its applications were used in this study.

The methodology proposed by Thornthwaite (1948) was used to calculate the potential evapotranspiration. The evapotranspiration of the culture, as well as the values of the coefficient of the culture, are presented and defined by Doorenbos and Kassam (1979). The normal hydric balance follows the sequence described by Thornthwaite and Mather (1955). For the soy bean crop, the coefficient of sensibility of the culture to the hydric deficiency was modified by the values described by Doorenbos and Kassam (1979). Thus, the relationship between the real and maximum evapotranspiration can be used to determine the depleted yield (DP, kg ha^{-1}) of the culture, in function to the potential yield (PP, kg ha^{-1}). Therefore,

$$PD = PP\left[1 - Ky_i\left(1 - \left(\frac{ETr_i}{ETc_i}\right)\right)\right] \qquad (22)$$

When the Dr ≤ 0.24, then the Ky will be 0.2; when the Dr is between 0.24 and ≤ 0.4, then the Ky will be 0.4; when the Dr is between 0.4 and ≤ 0.8, then the Ky will be 0.6; when the Dr is between 0.48 and ≤ 0.61, then the Ky will be 0.8; when the Dr is between 0.61 and ≤ 0.9, then the Ky will be 0.9; and when the Dr is superior to 0.9, the Ky is equal to 1. The field capacity was 50% and the permanent wilting point was 20%.

Results and discussion

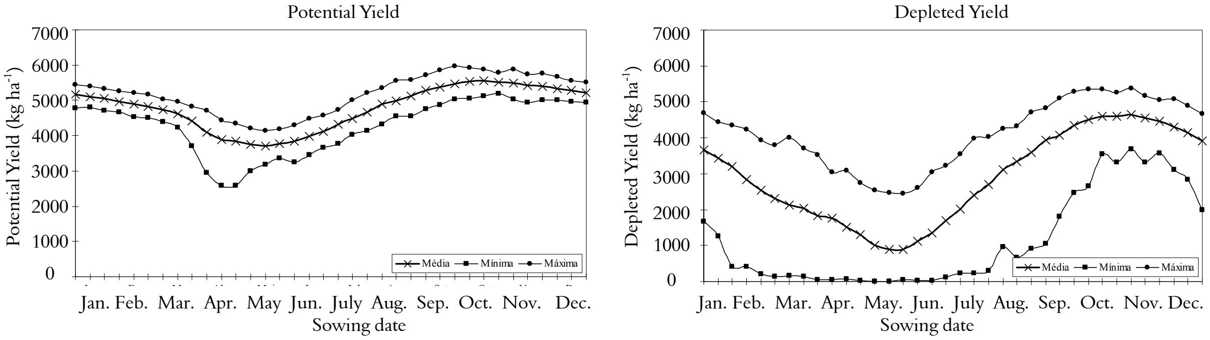
The results of 500 simulations for each location during 36 periods of sowing in Campinas, Pindorama and Cascavel municipalities are shown in Figure 1. The estimates were made for all 33 locations, but, due to the volume of information, we decided to present and discuss the results of three locations. The variation of the potential and depleted yield for the State with simulated sowings in January, May and September are presented in Figure 2. The curves of the potential yield (minimum, maximum and mean) reach the maximum productivity for each situation when the sowing was performed from September to October; during this period, the maximum productivity is reached because the characteristics of the environment are nearer to the comfort zone of the crop.

By the proposed model, the number of days between the germination and flowering is a function of the interaction between the temperature and photoperiod factors (RODRIGUES et al., 2001). The model contemplates the minimum and maximum values for the temperature and photoperiod; these values vary from 19 to 32°C (temperature) and 11 to 14 hours (photoperiod). In this study, there are daily average temperatures less than 19°C, so, in a sense, the model might be deficient, as it will generate contrasting values, such as the productivities generated when the sowing is performed during the period in which the daily average temperature is inferior to that value.

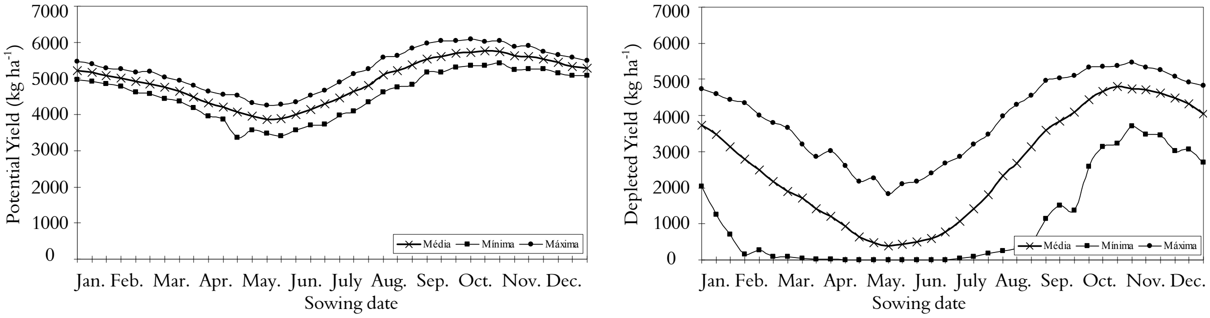
To calculate the number of days for the flowering, it must be taken into account that when the temperature is higher, then the effect of the photoperiod over the number of necessary days for the flowering is lower, which makes the number of days of flowering approximately 35 days (at 32°C). The effect of the genotype that will be used must also be considered, thus making the triple interaction (genotype-temperature-photoperiod) extremely difficult to explain and represent mathematically. By considering this complex triple interrelation, the model reasonably represented the behavior of the potential productivities because it reduced the cycle when the temperature was elevated; however, due to the high availability of solar radiation, the production was superior in comparison to the period with a long photoperiod, in which the number of days of the cycle was higher. Also, the production of the leaf area was low because of the reduced quantity of energy in the environment, thus limiting the source of carbohydrates and, consequently, the yield.

The rate of the leaf area is one of the most important parameters when working on the questions linked to the modeling of agricultural production. Moreover, it is complex because the parameter is a function of the interaction with other factors, which causes many researchers to avoid directly using the rate of the leaf area (WIT, 1978). Many models determine their average calculations during the cycle of the development of the culture. However, in order to make the results more precise and eliminate many empirical questions that aid in solving the problem, the use of mathematical equations that vary the function of the relative development are desired because they determine the daily values of the LAI. Through its auto-regulation systems, the plant, restricts its LAI, which is frequently presented as a parabola or something similar in the explicative texts. Those limitations imposed by the plant were reproduced as factors of the depletion of the relative development and the leaf area index.

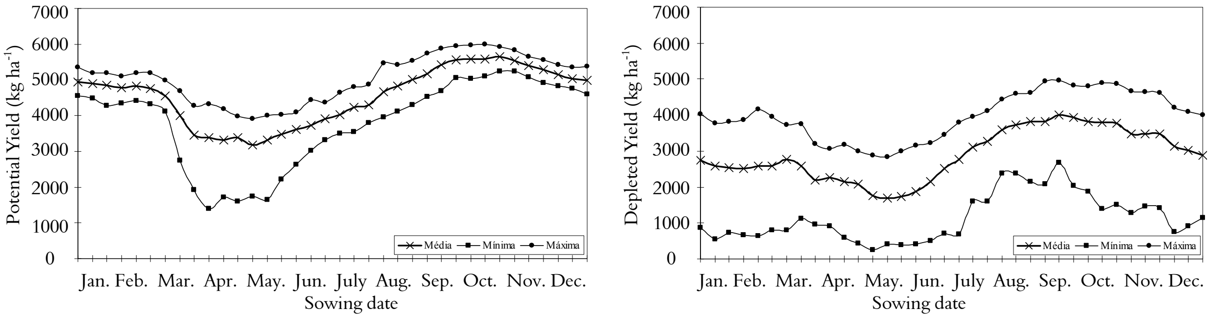
The maximum LAI of the plant must be truncated to avoid the presence of a leaf area that consumes more photo assimilated (respiration) than the productive capacity of the plant. Factors which are naturally regulated by the plants and environment, such as the auto-shading and the loss of the capacity of photosynthesis with the aging of the tissues, must be observed in the construction of models. All of those factors must be taken into account, as well as the models proposed by Pereira and Machado (1986). In Piracicaba (São Paulo State), the maximum LAR from the soybean cultures obtained by Câmara and Heiffig (2000) varied from 5 to 8. In the present model, the maximum value of the LAI was limited to 5 to avoid the existence of a major consumption of carbohydrates in relation to its production. The annual variation of the grain yield is also a function of the assimilation of CO_2, which varies according to the energy in the environment. As previously stated, the production is smaller when the sowings are performed in the low temperature and the photoperiod. The model for estimating the assimilation of used CO_2 is interesting because it takes into account not only the solar radiation photosynthetically active, but it also considers the quantity of CO2 in the atmosphere.



Campinas



Pindorama



Cascavel

Figure 1. Mean Yield, minimum and maximum, during 36 days of sowing and obtained through bivaried normal simulation. The values refer to 500 simulations for Campinas, São Paulo State, Pindorama, São Paulo State and Cascavel, Paraná State.

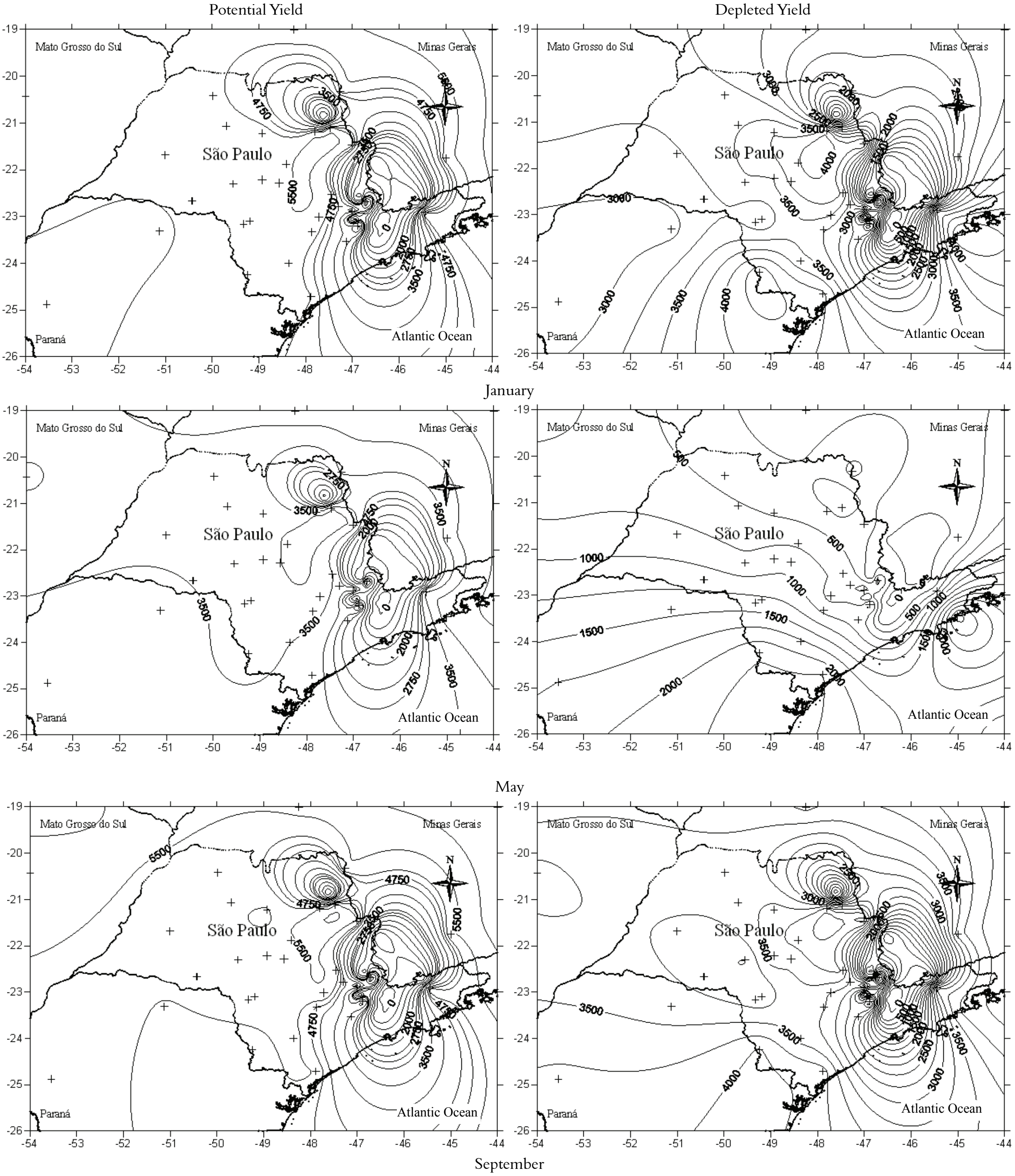


Figure 2. Isolines of the mean potential and depleted yield for the 25 locations. The data were obtained using the Krigagem method of interpolation for January, May and September.

Despite being extremely harmful to the planet, increasing the quantity of CO_2 in the environment would increase the production of soybeans in the region of São Paulo (SIQUEIRA et al., 1994) by approximately 22-32%. The higher rates of CO_2 assimilations occur when the temperature is between 30 and 35°C, and the higher rates occur more often in September (for the present case). When the temperature values differ from those intervals, the factor of reduction must be applied, in which those values and parameters would certainly be different for the national genotypes. The results obtained by the model can be compared to the results obtained by Cooper (2003), in the USA, where the recorded yields varied from 4,000 kg ha^{-1} (1966) to 7,911 kg ha^{-1} (1983). In Australia, the maximum productions varied from 8,004 to 8,604 kg ha^{-1} (1983). Despite those elevated production values, the genetic production of the soybean reaches 18,000 kg ha^{-1} (flowering), before decaying to 4,600 kg ha^{-1} during the period of physiological maturity (VENTIMIGLIA et al., 1999). Other expressive results were obtained by Nishi and Hungria (1996), who obtained productions superior to 4,000 kg ha^{-1} in experimental parcels working with re-inoculation. Other experiments in the field presented elevated values in the soybean production, such as the results from Pires et al. (2000), who estimated an average potential yield of 15,007 kg ha^{-1} in R2 and 10,282 kg ha^{-1} in R5, and, when influenced by the spacing between the rows, estimated the potential yield at 10,962 kg ha^{-1} in 20 cm and 9,602 kg ha^{-1} in 40 cm. In the experiment in Rio Grande do Sul state, the values of the yield varied from 3,929 kg ha^{-1} (OCERPA) to 6,436 kg ha^{-1} (FT-2003) in 96/97 (NAVARRO JÚNIOR; COSTA, 2002). When considering the average productivity obtained in the competition assays of soybeans in Rio Grande do Sul State, Lange and Federizzi (2009) found that the genetic gains ranged from zero to 71.5 kg ha^{-1} during the 19 years of evaluation. According to that study, the average production was 2500 kg ha^{-1} regardless of the maturation cycle, yet the productivity varied according to the regions.

As for the depleted productivity in relation with the precipitation (Figure 1), we verified that the simulated values for the precipitation were similar to the observed values. From the basic statistics (medium, minimum and frequency, data not presented), that type of simulation can be used for the representation of precipitation in a region. We verified that the depletion factor in the function of the sensibility of the culture on the water deficiency (Ky) acted intensely in the depletion of the potential productivities. In terms of the relative development, the major subdivision was in a higher number of the Ky classes, where it proportioned higher reductions on the potential productivities in comparison to the original proposed by Driessen and Konijn (1992). Besides, a representation of reality would be more reliable if the coefficient of the culture was better determined (even on a daily scale) to maximize the present model.

To bring the simulations closer to reality, the daily values of the rain were used in the water balance project. Thus, it becomes possible to verify the existence or absence of water stress conferred on the soybean plant. The development of the plants relies on rain, and it will not develop late in situations where stress is absent. The coefficient of sensibility of the culture to the water stress (Ky) potentiates the effect of the correction factors and the culture senescence, thus obtaining a yield of grains closer to the actual yield. Accordingly, by using the same stress coefficient (Ky), Berka et al. (2003) observed that the agrometeorological model overestimates the values by 10% in the yield when compared to the data obtained by SEAB, (Parana State), which determined the maximum yields of up to 3,070 kg ha^{-1}. Along with the water stress, the reduction of the vegetative (mass formation) and the reproductive period (transference of photoassimilated) must be considered. Thus, the seedlings from the last ten days of January to the first ten days in September were at an extreme risk for low productivity, and there was a significant increase of the frustrations of the crop. Therefore, the seedling from the last ten days of January to the first ten days in September became extremely risky for low productivity and the significant increase of the frustrations of the crop.

Conclusion

The adaptation of the soybean growing model can be used in the prediction of the potential and depleted yield results for the crop, and it can also be used for the indication of better locations and periods of tillage.

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