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Calibration and use of CROPGRO-soybean model for improving soybean management under rainfed conditions

B. Ruíz-Nogueira [a], K.J. Boote [b], F. Sau [a,*]

[a] *Escola Politécnica Superior, Dep. de Producción Vexetal, Univ. de Santiago de Compostela, Spain*
[b] *Department of Agronomy, University of Florida, Gainesville, FL 32611, USA*

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Abstract

Crops such as soybean (*Glycine max* L.) are grown predominantly under rainfed conditions where water is a major limiting factor and the interannual variability in rainfall pattern is high. Crop modeling has proven a valuable tool to evaluate the long-term consequences of weather patterns, but the candidate crop models must be tested and calibrated for new regions prior to their use as extrapolation tools to predict optimum cultivar choice and sowing dates. The objectives of this paper were to calibrate the CROPGRO-soybean model for growth and yield under rainfed conditions in Galicia, northwest Spain, and then to use the calibrated model to establish the best sowing dates for three cultivars at three locations in this region. The starting point of the calibration process was the CROPGRO-soybean version previously calibrated for non-limiting water conditions. The original model, when simulated versus rainfed soybean field data sets, tended to simulate more severe water stress than actually occurred. In order to calibrate growth and yield for the actual soil we tried several ways for the modelled crop to have access to more water. Modifications were made on soil depth, water holding capacity, and root elongation rate. In addition, other changes were made to predict accurately the observed water-stress induced acceleration of maturity. Long-term simulations with recorded weather data showed that soybean is more sensitive to planting date under irrigated than rainfed management, in the three studied Galician locations. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: CROPGRO; Crop model; Calibration; *Glycine max* L.; Soil water; Soybean; Rainfed management; Sowing date

* Corresponding author. Tel.: +34-982-252303; fax: +34-982-241835.
E-mail address: fsausau@correo.lugo.usc.es (F. Sau).

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Nomenclature

cv.	cultivar
DSSAT	Decision Support System for Agrotechnology Transfer
DUL	drained upper limit or field capacity of soil
EP	transpiration of the crop
EP_0	climatic potential transpiration of the crop
ET	potential evapotranspiration of the crop
ET_0	daily reference evapotranspiration
JD	Julian date
K_1	coefficient involved in direct water deficit acceleration of phenology during the seed filling phase
K_2	maximum canopy-temperature increase 3 h after solar noon when there is zero transpiration
LAI	leaf area index
LL	soil water content lower limit or permanent wilting point
RER	root elongation rate
RMSE	root mean square error
RMSE-biomass	root mean square error for total above ground biomass at final harvest
RMSE-yield	root mean square error for seed yield
RWU	potential root water uptake
R1	beginning flower
R5	beginning seed
R7	physiological maturity
SAT	saturated soil water content
SR	daily total solar radiation
SWFAC	soil water factor
T_a	daily average temperature
T_b	base temperature
T_{max}	daily maximum temperature
T_{min}	daily minimum temperature
T_{opt1}	minimum optimum temperature
T_{opt2}	maximum optimum temperature
T_x	maximum temperature at which the rate of development returns to 0
TURFAC	turgor factor
VE	emergence
WR(L)	soil-rooting preference function

1. Introduction

In Galicia, northwest Spain, crops are mostly grown under rainfed conditions and the main limiting factor, for summer crops such as maize and soybean, is water. The interannual weather variability is high, but generally, the amount and frequency of precipitation diminishes in early June and remains below crop evapotranspiration until mid September. As soil water holding capacity and depth is generally low, when precipitation becomes scarce, available soil water diminishes rapidly and reaches a depletion level that limits and in some cases stops crop growth. On the other hand, potential crop evapotranspiration diminishes during summer due to the shortening of the day length and the decrease in vapour pressure deficit. In September, when rainfall resumes, if the crop has not yet reached its physiological maturity, crop water deficit diminishes, allowing a late increase in crop growth rate and therefore grain yield improvement. Furthermore, drought impact on soybean grain yield is not equivalent during the different parts of the crop cycle (Doss et al., 1974).

Under these growing conditions, sowing date and the maturity group of cultivars may have a large impact on soybean grain yield (Ruíz-Nogueira, 1999; Sau et al., 1999), and a limited amount of irrigation water at the optimum time could lead to significant crop production increases and money return. Although soybean is not a main crop in Galicia due to the present European Union agricultural policy, circumstances can change and it is important to know how to manage efficiently this crop if it has to be cultivated. In order to establish the best sowing date and maturity group, multilocation cultivar trials have been, for a long time, the primary way of getting information but they require long-term trials (Loomis and Connor, 1992). Nevertheless, during the last 15 years, crop modelling has proven to be a powerful tool to extend the validity of experimental data obtained under very specific weather and soil conditions to other cropping environments and to establish better cropping strategies, using long-term multi-year weather simulations and statistical analysis (Wilkerson et al., 1983; Parsh et al., 1991; Egli and Bruening, 1992; Singh et al., 1994; Jacobson et al., 1995; Boote et al., 1997).

The first objective of this research was to predict accurately soybean growth and yield under water-limiting conditions in northern Spain, where the CROPGRO-soybean model (Boote et al., 1998) had been previously calibrated and validated for non-limiting water conditions (Sau et al., 1999). Our null hypothesis was that the soybean model, having been calibrated under non-limiting water conditions for this region, would accurately predict growth and yield under rainfed conditions. Failure to accurately predict growth and yield could be variously attributed to parameterization of soil properties as well as certain crop traits, i.e. soil water holding capacity, soil profile depth, rate of root depth penetration, as well as drought effects to accelerate crop maturation. Therefore, sub-objective one included the subsequent calibration of these listed soil properties and crop traits in order to accurately predict growth and yield under rainfed conditions. A unique aspect in our study was that, in absence of actual data on soil water contents or rooting, in-season growth analyses as well as final yield and biomass were used to optimize the soil water supplying traits, and observed maturity dates were used to optimize water deficit effects to accelerate maturity by comparison with irrigated treatments. We feel this process to set soil water supplying traits is justified because there will continue to be the need to adapt models for new production regions, where actual soil water contents are not measured and because currently-available pedotransfer functions give imprecise estimates of soil water holding traits. The second objective was to establish the best sowing date, under rainfed and irrigated management, for three cultivars (Major, Labrador and Chandor) at three locations in Galicia, with different weather conditions (Lugo the coolest site, Ourense the warmest site and A Coruña) using the model and long-term recorded weather data. Because soybean is a rather new commodity to this region, there has been minimal experimentation to test sowing dates of different cultivars in different locations under rainfed versus irrigated conditions. Thus, researchers and producers do not know the optimum sowing dates for these cultivars, except in a few isolated experiments. Therefore, there is a real proposed benefit to producers in the region to use a simulation approach to attempt to extrapolate beyond these limited experiments in order to suggest optimum sowing dates under rainfed and irrigated conditions using long-term recorded weather data.

2. Materials and methods

2.1. Experimental design

2.1.1. Rainfed experiments

Two commonly grown short-season French cultivars (cvs.) of soybean (*Glycine max* (L.) Merr) [Major (000) and Labrador (00)] were sown under rainfed conditions, in 1993, 1994, 1995 and 1998 at the experimental farm of the University of Santiago de Compostela, located in Lugo, Galicia, northwest Spain (43°04′ N; 7°30′ W; 480 m elevation). Climatological data of the experimental years are summarised in Table 1. The rainfed experiments had one sowing date in 1993, 1994 and 1995 while the 1998 experiment had two sowing dates. The soil at the experimental site was a Typic Haplumbrept with a silty–sandy–clay texture. Table 2 lists the main characteristics necessary to estimate the available soil water holding capacity, using the DSSAT software (Decision Support System for Agrotechnology Transfer; IBSNAT, 1989). Row spacing was 0.4 m, and plant densities and sowing dates are shown in Table 3. The size of experimental plots or subplots was 6×4.4 m. In 1993, 1994 and 1995, the two treatments, cvs. Labrador and Major, were assigned in a randomised complete block design while in 1998, the four treatments were assigned in a split-plot factorial arrangement in a randomised complete block design with the planting dates representing whole plots and the two cultivars subplots. Before planting, seeds were inoculated with *Bradyrhizobium japonicum* and soil was fertilised with 65.5 kg P ha^{-1} as superphosphate and 132.8 kg K ha^{-1} as potassium sulphate, to minimise limitations from these two nutrients. In all experiments, treatments were replicated four times.

Table 1
Mean daily solar radiation (SR), mean daily average temperature (T_a), mean daily reference evapotranspiration (ET_0) and cumulative rainfall measured for 10–11 days interval between May and November in 1993, 1994, 1995 and 1998

Period	SR (MJ m^{-2} d^{-1})	T_a (°C)	ET_0[a] (mm)	P (mm)	SR (MJ m^{-2} d^{-1})	T_a (°C)	ET_0[a] (mm)	P (mm)
		1993				*1994*		
May 1–10	15.7	13.5	3.2	17.6	18.3	12.8	4.0	12.0
May 11–20	10.9	11.5	2.1	38.6	14.0	10.9	2.8	91.0
May 21–31	14.7	11.9	2.9	80.8	17.7	13.8	3.3	14.0
June 1–10	18.6	16.2	4.1	35.8	18.1	15.0	3.8	3.6
June 11–20	20.5	16.2	4.6	15.8	19.4	16.3	4.6	26.2
June 21–31	15.3	17.5	3.4	62.6	21.1	17.6	4.7	2.2
July 1–10	18.3	16.3	4.0	11.4	18.2	18.5	4.1	2.0
July 11–20	21.5	16.6	4.8	0.4	18.7	19.3	4.3	18.2
July 21–31	22.3	18.6	5.1	9.4	16.5	19.9	4.1	1.0
August 1–10	20.7	18.5	4.7	0.4	14.1	19.3	3.4	18.6
August 11–20	21.4	20.6	5.2	3.2	17.1	18.8	3.7	2.4
August 21–31	16.5	15.7	3.6	48.3	16.6	19.0	4.1	4.6
September 1–10	13.8	17.5	3.1	4.2	11.4	15.9	2.6	1.3
September 11–20	9.8	14.7	2.1	52.6	10.0	13.5	2.0	44.2
September 21–31	12.1	10.9	2.3	33.5	8.9	12.8	1.8	29.0
October 1–10	6.5	11.4	1.3	80.0	7.3	15.2	1.6	18.0
October 11–20	4.8	10.7	0.9	141.6	3.5	15.2	0.7	53.2
October 21–31	12.6	9.0	2.3	1.4	5.8	11.3	1.1	36.8
November 1–10	6.4	10.4	1.2	32.3	5.8	11.6	1.2	88.6
November 11–20	6.1	7.7	1.1	10.5	6.5	10.0	1.2	8.2
November 21–31	5.2	5.9	0.9	35.8	4.7	8.9	0.9	2.8
		1995				*1998*		
May 1–10	20.4	16.3	4.5	54.2	11.6	11.2	2.3	55.4
May 11–20	14.5	13.6	2.6	42.6	17.4	16.3	3.8	18.4
May 21–31	19.0	13.9	4.1	12.3	18.4	13.2	3.8	31.6
June 1–10	26.1	14.2	5.3	0.0	15.2	15.6	3.3	20.6
June 11–20	21.7	16.5	5.0	3.4	17.3	15.2	3.7	0.8
June 21–31	19.4	19.6	4.4	11.5	23.3	17.5	5.2	0.2
July 1–10	15.9	18.4	3.8	46.6	17.1	16.6	3.7	34.4
July 11–20	16.9	20.5	4.0	6.8	22.3	19.8	5.3	0.2
July 21–31	19.7	21.2	5.1	3.6	18.8	18.5	4.3	3.4
August 1–10	15.1	18.9	3.4	15.3	18.0	20.4	4.4	0.2
August 11–20	18.8	21.1	4.5	0.6	16.3	21.1	3.9	16.4
August 21–31	22.4	19.5	5.2	0.0	17.8	20.4	4.2	0.2
September 1–10	10.1	16.5	2.6	5.0	13.4	18.8	3.1	1.6
September 11–20	7.4	13.3	1.5	85.5	11.5	17.4	2.6	7.6
September 21–31	12.2	14.4	2.5	7.2	10.9	16.3	2.4	79.4
October 1–10	7.5	15.3	1.5	36.6	7.2	11.7	1.4	17.2
October 11–20	8.6	16.3	1.9	6.8	6.3	13.9	1.3	4.2
October 21–31	7.6	13.4	1.6	42.3	5.7	12.6	1.1	7.6
November 1–10	5.8	11.7	1.2	6.4	5.3	11.2	1.0	22.2
November 11–20	6.5	11.7	1.2	40.2	2.8	13.0	0.6	3.0
November 21–31	4.8	8.5	1.0	20.8	0.9	6.2	0.4	2.7

Table 2
Characteristics of the different layers of the experimental soil profile

Soil layer (cm)	Clay fraction (%)	Silt fraction (%)	Coarse fraction (%)	Organic C (%)	Bulk density (g cm^{-3})	pH in water	LL[a] (% vol)	DUL[a] (% vol)	SAT[a] (% vol)	Soil rooting preference function[b]
0–15	21.0	26.0	9.9	2.83	0.95	6.5	12.1	23.5	34.8	1.00
15–30	21.0	27.0	4.8	2.34	1.12	6.4	12.5	24.4	35.0	0.75
30–50	18.0	32.0	6.9	0.56	1.26	6.0	11.1	23.0	35.4	0.50
50–65	15.0	29.0	2.2	0.48	1.31	5.5	10.1	22.2	34.4	0.35
65–130	11.0	19.0	0.2	0.41	1.35	4.9	8.5	20.2	32.1	0.20

[a] DUL and LL: drained soil water upper limit and wilting point, respectively, calculated by the DSSAT program.
[b] Soil rooting preference function used by the CROPGRO model.

2.1.2. Irrigated experiments

In the same experimental years, drip irrigated experiments were conducted on the same site and soil. Row spacing was 0.4 m, and cultivars, sowing dates, plant densities and total water applied are shown in Table 3. The size of the plots or subplots was identical to that of the rainfed experiments. The irrigated experiments of 1994 and 1995 are described in Sau et al. (1999) while the 1993 and 1998 irrigated experiments had a similar experimental design as the corresponding year rainfed ones.

2.1.3. Sampling for growth and yield

Samples of 0.5 m^2 were taken in each subplot at 10–20 day intervals throughout the entire crop life cycle. On each sampling date, dry matter partitioning and leaf area index (LAI) were evaluated in the same way as was done for the irrigated soybean experiments conducted in Lugo in 1994 and 1995 and described by Sau et al. (1999). At harvest maturity, at least 6 m^2 were hand harvested from each plot or subplot and yield components and harvest index were measured as described by Sau et al. (1999).

In addition, crop phenology and development was observed twice weekly using the growth staging method of Fehr and Caviness (1977).

2.2. The crop model and its simulation of water balance and effects on growth

CROPGRO-soybean (Boote et al., 1998) is a mechanistic process-level model that resulted from the progressively improved SOYGRO V4.2 (Wilkerson et al., 1983) original model. It allows the simulation of growth and yield, accounting for the effects of the weather variables and the main limiting factors as water and nitrogen.

The daily-soil water balance in CROPGRO-soybean uses the Ritchie (1985) one-dimensional 'tipping bucket' soil water balance approach, which predicts soil water flow and root water uptake for each of up to 10 soil layers. In the SOIL.SOL file where the soil profile is defined, each layer has a characteristic drained upper limit

Table 3
Cultivar planting date, plant density and total irrigation water applied (TIWA) of the different treatments of rainfed and irrigated soybean experiments conducted in Lugo between 1993 and 1998

Experiment	Treatment	Cultivar	Planting date, calendar and julian date (in brackets)	No. of plants m^{-2}	TIWA (mm)
Rainfed 1993	RF-M	Major	9 June (160)	39.1	0
Rainfed 1993	RF-L	Labrador	9 June (160)	39.9	0
Rainfed 1994	RF-M	Major	30 May (150)	49.2	0
Rainfed 1994	RF-L	Labrador	30 May (150)	51.4	0
Rainfed 1995	RF-M	Major	31 May (151)	50.4	0
Rainfed 1995	RF-L	Labrador	31 May (151)	51.0	0
Rainfed 1998	RF-M-1	Major	10 June (161)	50.0	0
Rainfed 1998	RF-L-1	Labrador	10 June (161)	50.0	0
Rainfed 1998	RF-M-2	Major	30 June (181)	53.3	0
Rainfed 1998	RF-L-2	Labrador	30 June (181)	50.4	0
Irrigated 1993	IR-M	Major	9 June (160)	33.1	160
Irrigated 1993	IR-L	Labrador	9 June (160)	39.7	160
Irrigated 1994	IR-M-1	Major	30 May (150)	49.2	357
Irrigated 1994	IR-L-1	Labrador	30 May (150)	50.5	357
Irrigated 1994	IR-M-2	Major	13 June (164)	43.3	314
Irrigated 1994	IR-L-2	Labrador	13 June (164)	41.7	314
Irrigated 1994	IR-C-2	Chandor	13 June (164)	48.8	314
Irrigated 1994	IR-M-3	Major	29 June (180)	52.1	314
Irrigated 1994	IR-L-3	Labrador	29 June (180)	51.7	314
Irrigated 1994	IR-C-3	Chandor	29 June (180)	52.5	314
Irrigated 1995	IR-M-0	Major	22 May (142)	50.0	205
Irrigated 1995	IR-L-0	Labrador	22 May (142)	49.2	205
Irrigated 1995	IR-C-0	Chandor	22 May (142)	49.6	205
Irrigated 1995	IR-M-1	Major	31 May (151)	49.9	205
Irrigated 1995	IR-L-1	Labrador	31 May (151)	50.0	205
Irrigated 1995	IR-C-1	Chandor	31 May (151)	50.4	205
Irrigated 1995	IR-M-2	Major	15 June (166)	49.2	184
Irrigated 1995	IR-L-2	Labrador	15 June (166)	50.0	184
Irrigated 1995	IR-C-2	Chandor	15 June (166)	49.2	184
Irrigated 1995	IR-M-3	Major	30 June (181)	49.2	184
Irrigated 1995	IR-L-3	Labrador	30 June (181)	51.3	184
Irrigated 1995	IR-C-3	Chandor	30 June (181)	50.0	184
Irrigated 1998	IR-M-1	Major	10 June (161)	46.7	262
Irrigated 1998	IR-L-1	Labrador	10 June (161)	50.0	262
Irrigated 1998	IR-M-2	Major	30 June (181)	54.2	250
Irrigated 1998	IR-L-2	Labrador	30 June (181)	50.0	250

(DUL) or field capacity, a lower limit (LL) or permanent wilting point, a saturated soil water content (SAT), and a soil-rooting preference function (WR(L)) that quantifies the potential root hospitality of the layer. Actual root length density depends on: (1) crop allocation of dry matter to roots; (2) rate of root depth progression (equivalent to root elongation rate [RER]); (3) WR(L); and (4) the soil water content in each zone. Roots tend to grow faster into moist soil layers than in dry or saturated layers. Root potential water uptake from each soil layer is computed as a function of water content and root length density in each layer. When the potential root water uptake (RWU), summed over all soil layers, can not supply the climatic potential transpiration (EP_0), then the actual transpiration (EP) is equal to RWU, the soil water factor ($SWFAC = EP/EP_0$) diminishes and gross photosynthesis is reduced in direct proportion, thus decreasing dry matter growth for that day. In addition, when RWU is lower than 1.5* EP_0, the turgor factor ($TURFAC = EP/(1.5*EP_0)$) is smaller than 1.00, and LAI increase is slowed down. In the DSSAT default option, potential evapotranspiration of the crop (ET) is estimated using the procedure described by Ritchie (1985) where ET is calculated using the equilibrium evapotranspiration concept as modified by Priestley and Taylor (1972).

2.3. *Scheme of the logic of the model calibration for water limiting conditions*

The CROPGRO-soybean model (DSSAT 3.1, December 96 release) was previously calibrated for the cultivars Labrador, Major and Chandor under the cool conditions of northern Spain when water is not limiting; this version of the model acceptably predicts grain production in warmer environments such as Gainesville, Florida (Sau et al., 1999). So, it can be assumed that accurate estimations of grain production, when water is not a limiting factor, can be done for other locations in Galicia, where temperature regimes are intermediate between Lugo and Gainesville (Ruíz-Nogueira, 1999). On the other hand, if this version of the model can be calibrated for the rainfed conditions of Lugo, it could be useful to estimate water-limitations on yield, as well as the best planting date for rainfed crops at Lugo and other locations in Galicia.

A soil file compatible with CROPGRO-soybean was prepared using the DSSAT program that estimates DUL, LL and SAT as a function of the clay, silt, sand, coarse fractions, and carbon content of the different layers of the soil (IBSNAT, 1989). The input soil characteristics, and the calculated DUL, LL, and SAT are shown in Table 2.

The starting point of the calibration process of the model was the version of the model calibrated by Sau et al. (1999) with experiments conducted under non-water limiting conditions, the soil file generated by the DSSAT program and the soil-rooting preference function for the different soil layers shown in Table 2.

3. Results and discussion

3.1. *Predictions with unmodified model parameters*

Despite obtaining correct predictions of grain yield, total above ground biomass and physiological maturity date for the irrigated experiments, we observed that for the rainfed experiments, the original model underpredicted the average grain yield (2133 kg ha^{-1}) by 505 kg ha^{-1} (root mean square error [RMSE] = 560) and total above ground biomass (3867 kg ha^{-1}) by 831 kg ha^{-1} (RMSE = 985), while the predicted physiological maturity (R7) date was late by 9.5 days (RMSE = 10.1) when compared with the observed data (Fig. 1a–c). In addition, before calibration, time series graphs showed that the simulations predicted earlier water deficit effects on the accumulation of total biomass and pod mass in almost all the rainfed treatments. The trend is illustrated for the cultivar Labrador in 1994 and 1995 growing seasons in Fig. 2a–d. It is obvious that the observed dry matter accumulation continued longer into a drought period than the model, prior to calibration, predicted. All this evidence shows that the model tended to simulate an earlier and more severe water stress than actually occurred in the soybean experimental plots, and the crop extracted more water than the CROPGRO-soybean model is predicting.

3.2. *Evaluation of rainfed experimental data to determine root growth rate, soil depth or soil water-holding traits*

In order to calibrate growth and yield for the actual soil, we propose several ways, for the modelled crop to have access to more water: (1) increasing the root elongation rate; (2) increasing the depth of the soil profile; and (3) increasing the

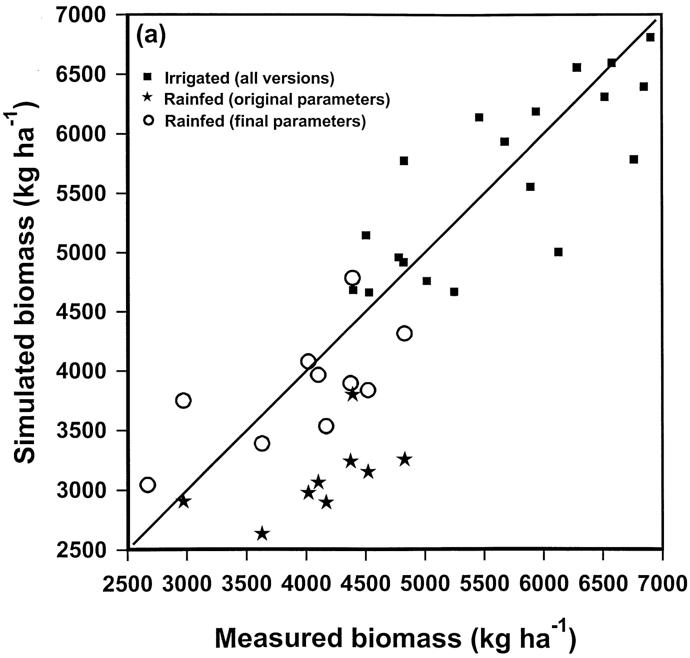
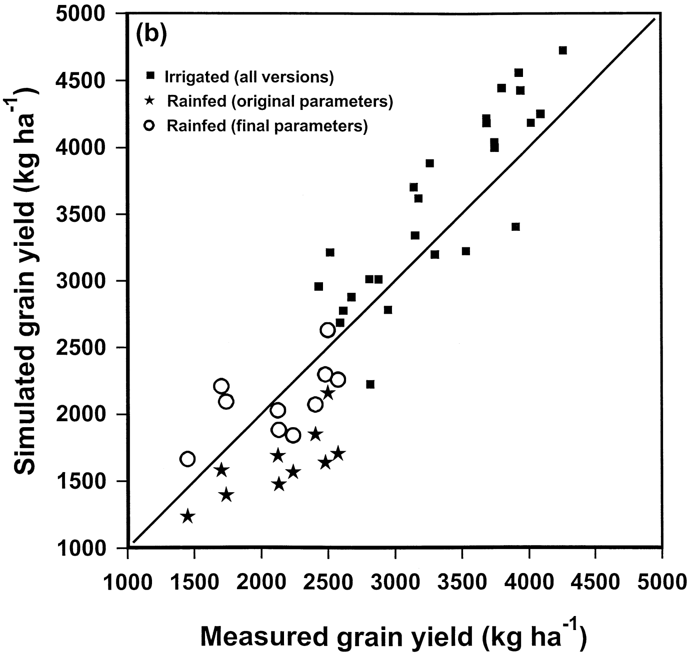


Fig. 1. Measured and simulated values with CROPGRO-soybean model using original parameters, and final parameters (modified soil [soil depth increased from 1.3 to 1.5 m and drained upper limit of each soil layer incremented by 2%] root elongation rate increased from 2.50 to 2.59 cm [physiological day]$^{-1}$ and direct water deficit acceleration of maturity [increase in K_1 coefficient from 0.2 to 1.5]), for (a) total biomass at harvest, (b) grain yield and (c) days from sowing to physiological maturity for the rainfed and irrigated 1993, 1994, 1995 and 1998 experiments. Each point represents the mean of four replicates.



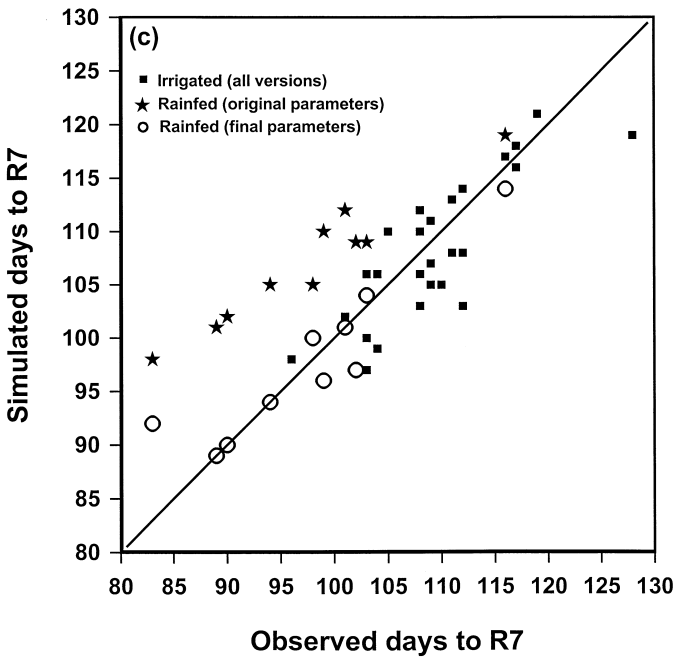


Fig. 1. (*continued*).

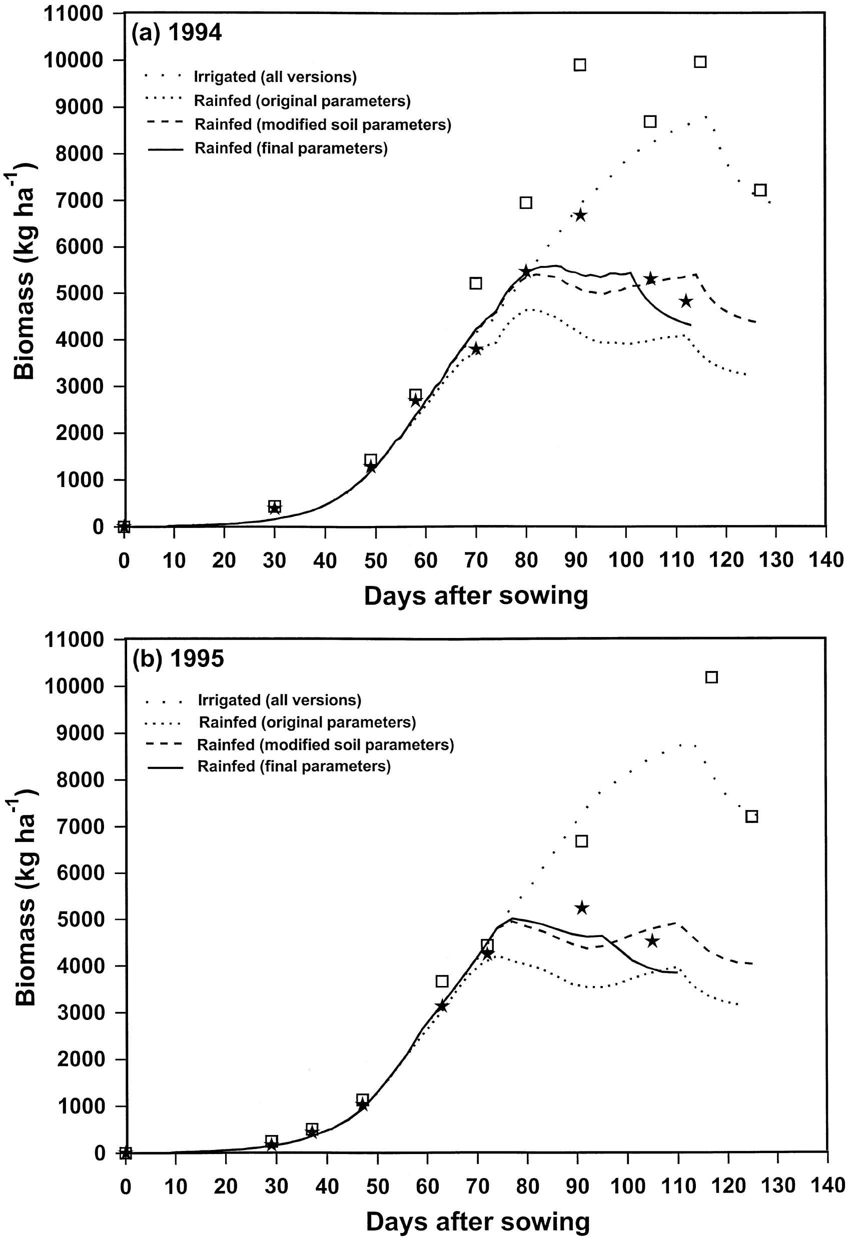
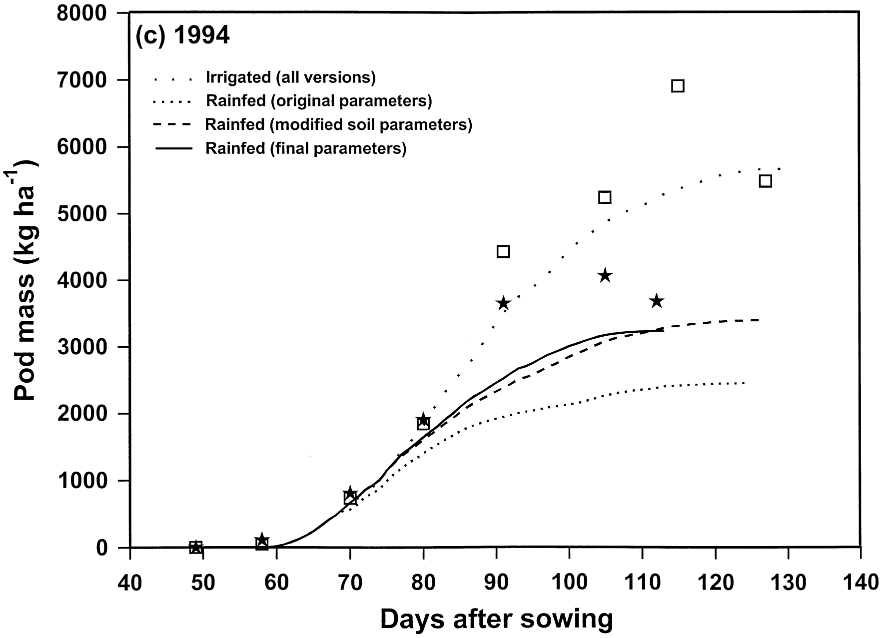


Fig. 2. Observed (points; □: irrigated; ★: rainfed) and simulated (lines) dynamics for cv. Labrador rainfed treatment and matching irrigated treatment of 1994 and 1995 experiments obtained with CROPGRO-soybean model using original parameters and two different modifications: modified soil parameters, and, final parameters [soil, root elongation rate and K_1]: (a and b) total above ground biomass accumulation and (c and d) total dry weight accumulation in pods. See the text and Fig. 1 caption for details on modified soil parameters and on final parameters. Each point represents the mean of four replicates.



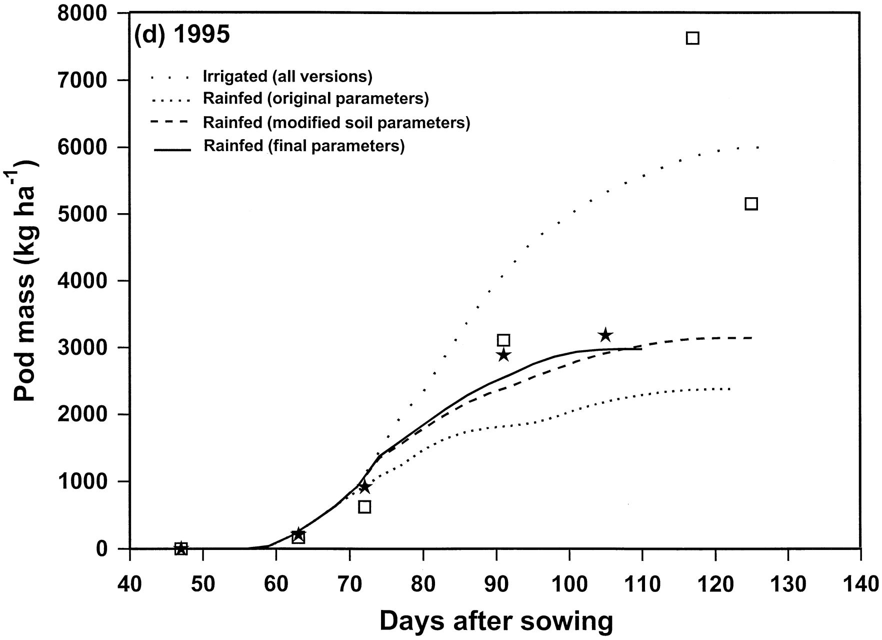


Fig. 2. (*continued*).

water holding capacity of the different layers of the soil profile (increasing DUL while holding LL constant).

In our calibration procedure, we varied each of the three proposed variables and minimised RMSE for both seed yield (RMSE-yield) and total above-ground biomass at final harvest (RMSE-biomass). In addition, we visually evaluated whether the predicted time course of total biomass and pod mass, better described the observed growth curves, i.e. did the increased access to water extend or prolong the predicted growth over time as was observed in the data. Finally, based on RMSE-yield, RMSE-biomass, and growth curves, we selected the most probable of each of the three ways to improve water access. We varied the three parameters in three combinations of two at a time and graphed improvement of RMSE against variation of one while also varying the second parameter.

We first varied soil depth and rate of root elongation, while maintaining the original soil water-holding characters unchanged. Initially there was large reduction in RMSE-yield as soil depth was increased beyond 1 m, reaching low RMSE with 1.3–1.5 m depth (at clearly defined RER; Fig. 3). The RMSE-yield was also sensitive to increasing RER, with clear minimum values of RMSE-yield obtained at specific values of RER when soil depth was equal or deeper than 1.3 m. Minimum RMSE-yield (303) occurred with 1.5 m depth and 3.2 cm physiological day^{-1} RER, while minimum RMSE-biomass (634) was reached with 1.3 m soil depth and 3.1 cm day^{-1} RER. Thus, increasing combinations of the two parameters, soil depth and root

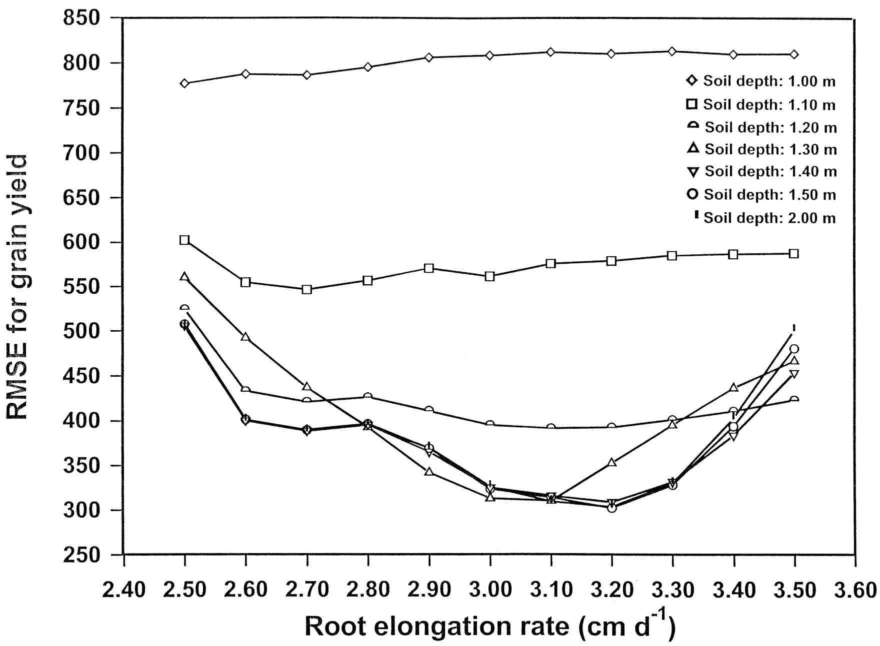


Fig. 3. Root mean square error (RMSE) for grain yield predictions of CROPGRO-soybean model for the 1993, 1994, 1995 and 1998 rainfed experiments, for different soil depths and root elongation rates.

elongation rate, increased crop access to water and minimised RMSE-yield. We can not yet consider this combination of parameters as the optimum for minimising RMSE-yield, because we have not considered variation of each of these parameters with variation in soil water-holding capacity.

Next, we varied water-holding capacity and soil depth, while holding root elongation rate at its initial default value of 2.5 cm day^{-1}. The soil water-holding capacity was varied by changing the original calculated DUL values (Table 2) of the different soil layers by the same volumetric percentage, and maintaining constant the original LL, SAT. This procedure allowed obtaining the minimum RMSE-yield (Fig. 4) and biomass at harvest for different soil depths. A clear minimum was reached with a DUL increase of 2% for 1.3, 1.4 and 1.5 m soil depths. The lowest RMSE for yield and biomass (232 and 508, respectively) were reached with 1.5 m soil depth, although RMSEs were quite similar for these three soil depths. No improvement in yield and biomass predictions was observed when soil depth was deeper than 1.5 m, so we considered 1.5 m as the maximum soil depth to be taken into account. In addition, the average yield and biomass simulated for the rainfed treatments, 2138 and 3858 kg ha^{-1} respectively, were now very close to the measured values, 2134 and 3867 kg ha^{-1}.

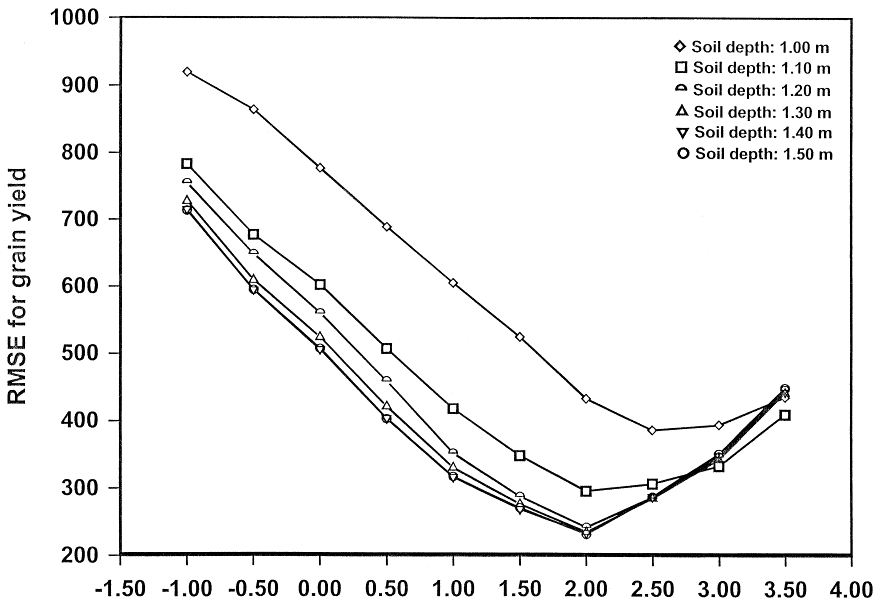


Fig. 4. Root mean square error (RMSE) for grain yield predictions of CROPGRO-soybean model for the 1993, 1994, 1995 and 1998 rainfed experiments, for different soil water holding capacity modifications of the original calculated values (Table 2) and soil depth. Modifications of the soil water holding capacity were obtained by varying the original calculated drained upper limit values (DUL; Table 2) of all the soil layers with the same percentage in volume, and maintaining the remaining soil parameters and original root elongation rate (2.5 cm physiological day^{-1}).

Considering that the adequate soil depth is 1.5 m, we next tried different DUL variations in combination with three RER values, 2.4, 2.5 and 2.6 cm physiological day^{-1} (Fig. 5). This confirmed that the best adjustment or minimum RMSE for grain yield and biomass at harvest was obtained with a 2% DUL increase and the original model RER value (2.5 cm day^{-1}). The prior RMSE at RER of 3–3.2 cm day^{-1} in Fig. 3 was higher than that shown in Fig. 5 and did not consider increases in DUL which were shown to be very important in Figs. 4 and 5.

With these modifications to soil water traits (in Fig. 2), model predictions for grain yield and biomass were improved, and the drought-induced differences between irrigated and rainfed simulations of total biomass and pod dry matter started later in the growing season, and fit better to the observed data (Fig. 2). Nevertheless, the difference between observed and simulated days to maturity (R7) were still just as large. The predicted maturity was late by an average of 10 days (RMSE = 10.7) while the predictions by the original model were late by 9.5 days (RMSE = 10.1), because the smaller simulated water deficit tended to allow normal physiological maturity date. So, it is evident that the model needed to be modified to predict accurately the water-stress induced acceleration of maturity.

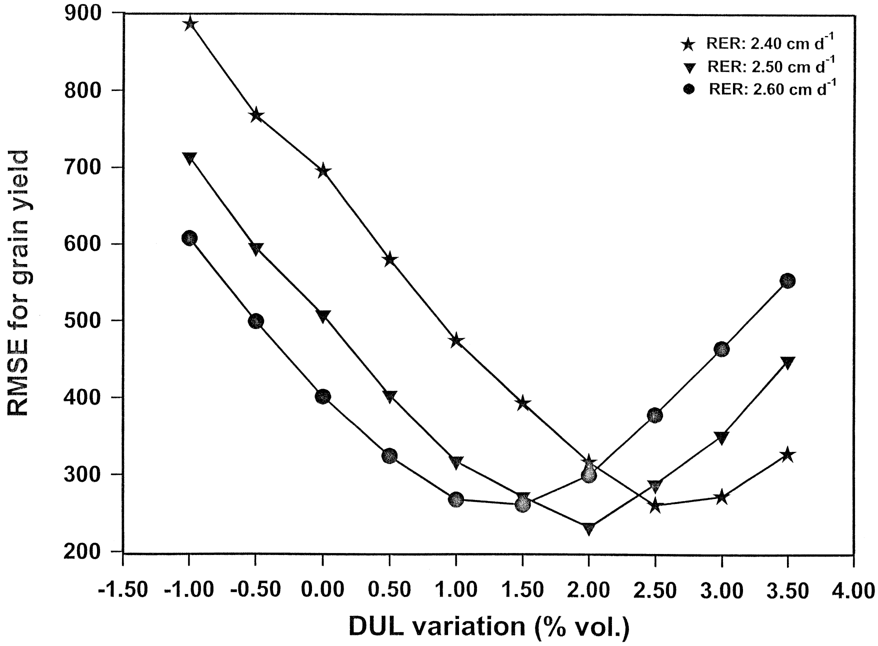


Fig. 5. Root mean square error (RMSE) for grain yield predictions of CROPGRO-soybean model for the 1993, 1994, 1995 and 1998 rainfed experiments, for different soil water holding capacity modifications (Table 2), three root elongation rate values (2.4, 2.5 and 2.6 cm physiological day^{-1}) and a soil depth of 1.5 m. Modifications of the soil water holding capacity were obtained by varying the original calculated drained upper limit values (DUL) of all the soil layers with the same percentage in volume, and maintaining the remaining soil parameters and original root elongation rate (2.5 cm physiological day^{-1}).

3.3. Modelling drought-induced acceleration of physiological maturity

In all 4 years, the observed date of physiological maturity of rainfed treatments was accelerated by 6 to 20 days (13.1 days on average) as compared with the 10 matching irrigated treatments. The timing of computed water deficit for rainfed plants occurred after beginning flowering (R1) and, usually, after the beginning seed (R5) stage. The fraction (1.00–SWFAC) is the degree of reduction of transpiration and photosynthesis which have a 1:1 relationship in the model. Thus, water deficit took place primarily during seed filling.

As indicated previously, there was no computed water deficit prior to flowering, and there was almost no acceleration of the observed flowering date (0.4 days). There was slight acceleration in time to observed beginning seed (2.3 days total, 1.9 days for interval R1–R5), but there was very slight computed water deficit prior to R5 only in 1993. By contrast, 1-SWFAC ranged from 0.06 to 0.34 (averaged 0.2) during the period R5–R7 in the 4 years, which caused a reduction of 10.4 days of the observed period between R5 and R7.

Acceleration of maturity has been previously reported for soybean where water deficits occurred during the seed filling period (Korte et al., 1983a, b; Specht et al., 1986). Specht et al. (1986) noted a 7–13 day acceleration under water deficit, with later maturity of irrigated crops in proportion to amount of irrigation applied (the slope on maturity was 0.26 to 0.35 days later maturity per centimetre of irrigation water applied). Water deficit during seed filling accelerates leaf senescence and shortens the seed filling period (de Souza et al., 1997). Nevertheless, no-one has specifically reported on mechanisms for modelling such accelerated senescence and maturity. Is the accelerated maturity caused primarily by (1) water deficit per se, or (2) by increased canopy temperature due to decreased transpiration? These two possibilities were explored as candidate mechanisms. The CROPGRO-soybean model has features in its phenology subroutines and in its species-file that allows a water deficit driven acceleration of the progress from R5 to R7, but that feature had not been tested on specific data (Boote et al., 1997, 1998). The drought-related data sets on which CROPGRO-soybean had been tested were primarily of mid-life cycle droughts and droughts occurring between flowering and early podset (Wilkerson et al., 1983; Boote et al., 1997). For these drought patterns, R7 is not accelerated and may even be delayed if pod addition is delayed by extreme stress (Bovi, 1981; Boote et al., 1997; Wilkerson et al., 1983). CROPGRO does increase leaf senescence under water deficit, but that is not the modelled signal causing final physiological maturity despite loss of leaf area.

We tested two primary methods to account for the acceleration of maturity: (1) accelerating the rate of reproductive progress by the value $(1.00+K_1*(1.00\text{-SWFAC}))$, where K_1 is a constant that can be calibrated; or (2) accelerating the rate of reproductive progress due to canopy temperature increase caused by a diurnal cycling increment related to $K_2*(1\text{-SWFAC})$, where K_2 is the maximum temperature increase three hours after midday when there is zero transpiration by the crop (SWFAC = 0). Small variations on each concept were also attempted and discussed.

For method 1, the default value for the K_1 constant was already set at 0.2 in the standard soybean species-file, but with little evidence. With this K_1 value and as indicated above, the physiological maturity of rainfed crops was predicted 10 days too late on average. Increasing K_1 from 0.2 to 0.5, 1.0, 1.2 and 1.4 caused the deviation to decrease from 10 to 7.3, 2.5, 1.3 and 0 days, respectively, all the while decreasing the RMSE of prediction for crop maturity. There was almost no effect of this parameter change for irrigated crops where SWFAC was optimum approximately all the time. The 'layman's' meaning of a K_1 of 1 is that the rate of progress toward R7 would go twice as fast, assuming that SWFAC was zero (of course, with zero ET plant death would occur soon anyway), or 50% faster where SWFAC was 0.5. This must be viewed as a calibration, and not as an independent test, although it worked over the 4 years and two cultivars. We are not completely satisfied with a coefficient (K_1) as high as 1.4, and furthermore, would like to have a somewhat earlier signal. TURFAC is such an earlier-occurring signal of water stress; thus useful when TURFAC drops below 1. Using TURFAC instead of SWFAC in the phenology subroutine, allowed a K_1 value of 1 to fit the predicted R7 date with 0.3 day average difference and even lower RMSE. Using TURFAC has the nice features of a lower K_1 and allowing an earlier signal, especially in some years. Nevertheless, this required an internal code change from the standard model, so we do not recommend it at present.

For method 2, water deficit is assumed to act on reproductive development due to an increase in canopy temperature dependent on K_2*(1-SWFAC). The standard version of CROPGRO drives phenology with a 24 h temperature cycle sinusoidally from minimum daily temperature (T_{min}) to maximum daily temperature (T_{max}) at 3 h after solar noon, and decaying after sunset to T_{min} at dawn the next day; however, there is presently no simulated temperature increase with soil water deficit. We created a diurnally cycling temperature increment above the standard, related to K_2*(1-SWFAC), where K_2 is the maximum temperature increase at 3 h after noon when there is zero transpiration by the crop (SWFAC = 0). Thus, the predicted increment has its own diurnal cycle, being zero at dawn but reaching the predicted maximum value at 3 h after solar noon. For reasons explained below, this approach did not work well, and gave only 0.1 day earlier R7 when we allowed K_2 to be equal to 5°C. This was surprising to us until we considered that the drought periods were only during seed filling, and that the cardinal temperatures used for rate of reproductive progress during seed filling are −48, 26, 34 and 45°C for base temperature (T_b), minimum optimum temperature (T_{opt1}), maximum optimum temperature (T_{opt2}) and T_x (maximum temperature at which the rate returns to 0), respectively. With this function, there is only a small acceleration of maturity as temperature increases up to 26°C, while temperatures above T_{opt1} = 26°C do not accelerate maturity, and those above T_{opt2} actually delay it. We are quite confident in the T_{opt1} value, as it was determined from field data by Grimm et al. (1993, 1994), although we are not so confident in the T_b value of −48°C, because the majority of the data did not extend far into the cool range. We are also confident that temperatures above 26°C do not accelerate soybean reproductive development after flowering (Pan, 1996). Even allowing the K_2 increment offset to act in a constant manner for all 24 h, which may happen if soils are dry and relatively warmer day and night, only accelerated the life cycle by 0.6 days with a K_2 of 5°C. Because the present temperature function from R5 to R7 is slowly responsive below 26°C, and not responsive to increasing temperature above 26°C, there was basically no amount of temperature increment that would explain the degree of acceleration observed in the rainfed plots. Thus, we gave up on the temperature-effect idea and used the water deficit effect, by itself, as the best indicator to drive acceleration of maturity.

With the drought acceleration of maturity, the R7 prediction is now correct but simulated grain yield and biomass, 1968 and 3671 kg ha^{-1}, respectively, were slightly diminished due to the shortening of the crop cycle. So further minor adjustment was made to increase the amount of water extraction by the rainfed crops. Maintaining soil depth at 1.5 m, we tried to separately vary RER and the soil water-holding capacity to minimise RMSE-yield and RMSE-biomass. This time, the best fit was obtained through a slight increase in RER, which change was selected. The higher water availability caused maturity to be slightly lengthened, so an iterative adjustment of K_1 and RER proved to be necessary. We decided to stop the calibration process because we judged predictions to be sufficiently accurate with $K_1 = 1.5$ and RER = 2.59 cm day^{-1} (final parameters). With these coefficients (Figs. 1 and 2), the differences between average measured and simulated grain yield, biomass at harvest and days to physiological maturity were +37 kg ha^{-1}, +36 kg ha^{-1} and −0.2 day, respectively and, the corresponding RMSE were: 303, 588 and 3.5.

3.4. Summary of parameter modifications

Soil depth was increased from 1.3 to 1.5 m, DUL values of all soil layers was raised by 2% vol, and the original RER, 2.5 cm day^{-1} was replaced by 2.59 cm day^{-1}. Finally, the original K_1 for the water-deficit acceleration of seed filling phase of the cycle, was increased from 0.2 to 1.5. With these changes, no modifications were observed in the predictions of the irrigated treatments while the RMSE for simulated grain yield, biomass at harvest and days to physiological maturity were reduced from 560, 985 and 10.1 to 303, 588 and 3.5, respectively.

3.5. Theoretical best sowing dates under irrigated and rainfed management in Lugo, Mabegondo and Ourense

With the parameter modifications described above, the 'final' model version gives good predictions of grain yield and phenology in a cool environment as Lugo (43°04′ N; 7°30′ W; 480 m elevation), under different levels of water availability and planting dates. In addition, parameter modifications did not affect significantly the accuracy of predictions for a warm environment such as Gainesville, Florida (Sau et al., 1999). Thus, we can assume that the modified model will give accurate predictions in locations with intermediate temperatures, such as Mabegondo (43°14′ N; 8°15′ W; 97 m elevation) and Ourense (42°19′ N; 7°52′ W; 143 m elevation) and can be used to improve the crop management under irrigated and rainfed conditions in these three Galician locations. With the objective of establishing the best theoretical sowing dates, we tried 20 planting dates, the 1st, 11th and 21st day of each month from 1 February until 11 August with long-term recorded weather data, 30 years at Lugo (1970–1999) and, 15 years at Mabegondo and Ourense (1985–1999). For the three locations we used the soil file of Lugo, obtained after the calibration process, the soil water balance started on 30 January and, soil water was assumed to be at field capacity each year at this time. This is probably a valid asumption since long-term average January rainfall at Lugo, Mabegondo and Ourense is 124.7, 115.6, 90.2 mm, respectively.

The results of these simulations for cv. Labrador in the three locations are presented in Fig. 6. According to the simulations, the best sowing date under irrigated conditions is situated around 1 May (121 JD) for Lugo and 1 April (91 JD) for Mabegondo and Ourense. These dates seemed to be too early because empirical local experience showed that it is best to wait with sowing maize until mid-May and beginning-May, in Lugo and Mabegondo, respectively (Juan Piñeiro, personal communication). Normally, the optimum sowing date of soybean in the region is slightly later than that of maize. This later sowing date allows for a shorter time to emergence to minimize the sensitive period for attacks from insects (*Delia platura*) and soil diseases (*Fusarium* spp., *Pythium* spp. and *Rhizoctonia*, spp.), and thus allows a high emergence percentage (Ventury and Amaducci, 1988).

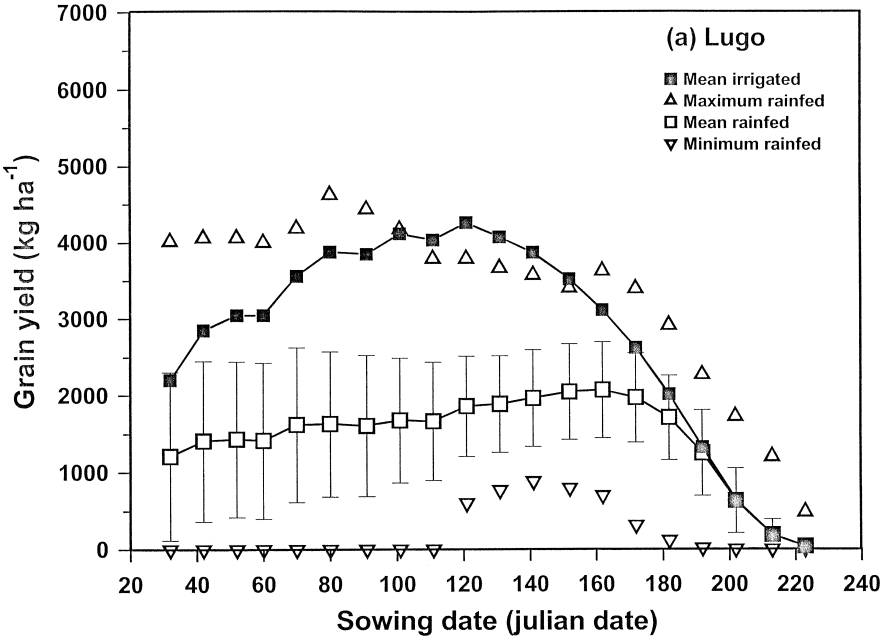


Fig. 6. Average, maximum, minimum and standard error of the mean of predicted rainfed grain yield for cv. Labrador, and predicted average grain yield for cv. Labrador under non water limiting management, for different sowing dates using the final CROPGRO-soybean model and long-term recorded weather data of Lugo (a), Mabegondo (b) and Ourense (c), 30, 15 and 15 years, respectively.

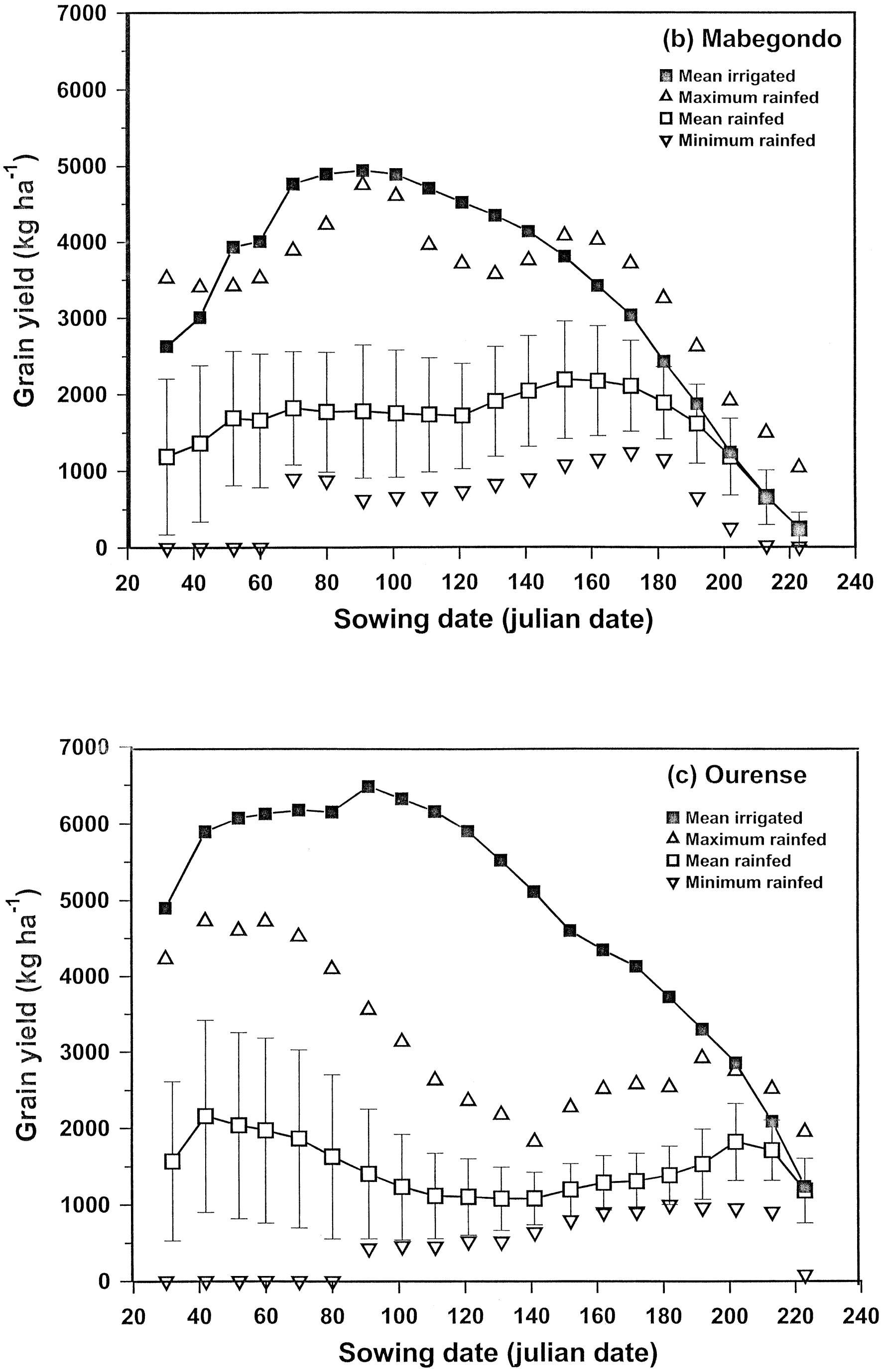


Fig. 6. (*continued*).

On the other hand, the present version of CROPGRO-soybean does not consider the reduction effect that low temperatures have on percentage emergence. The model only simulates a delay in time to emergence from cooler temperatures as well as death of all the foliage if temperatures drop below −2.2°C (Fig. 7). Zero values on Fig. 6 for minimum rainfed grain yield are caused by these freeze occurences with the early or late sowing dates. In order to avoid freeze damage and with this concern for temperature effect on percent emergence, it is reasonable to propose that actual optimum planting dates are later than the simulated ones.

Long-term CROPGRO simulations illustrate that in order to reduce the average time to emergence below 10 days, it is necessary to delay the sowing date after 1 June (152 JD), 21 and 1 May (141 and 121 JD) for Lugo, Mabegondo and Ourense, respectively (Lugo in Fig. 7; for Mabegondo and Ourense, results not shown). For these planting dates, the maximum average simulated grain yield was reached with cv. Labrador for Lugo (3525 kg ha^{-1}) and Mabegondo (4138 kg ha^{-1}) and with cv. Chandor for Ourense (5978 kg ha^{-1}). From these dates forward, a regression analysis of the simulation results, under non-limiting water management, shows that when water is not limiting, a 1 day delay in sowing causes a reduction in grain yield of 57.4 ($R^2=0.994$), 50 ($R^2=0.991$) and 41.5 kg ha^{-1} ($R^2=0.960$), for Lugo, Mabegondo and Ourense, respectively. As a consequence, the sowing date is more important in the coolest location than in the warmest. The simulated reduction of

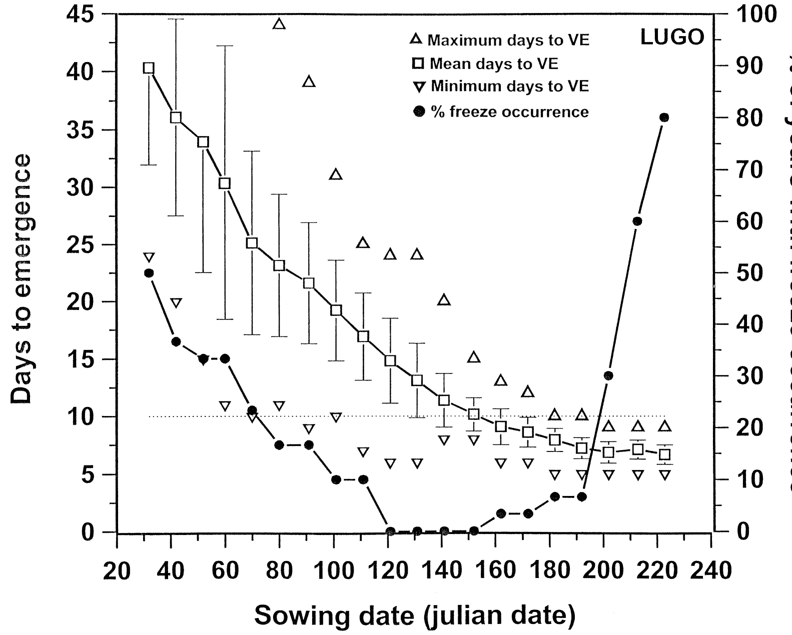


Fig. 7. Average, maximum, minimum, standard error of the mean of predicted time from sowing to emergence (VE) and percent of years with freeze occurrence (minimum temperature below −2.2°C) vs. sowing date in a rainfed soybean crop in Lugo, using the final CROPGRO-soybean model (cv. Labrador) and long term recorded weather data of Lugo (30 years).

grain yield for 1 day delay in sowing, under irrigated conditions, in all these locations is higher than that described by Egli and Bruening (1992) for simulated data in Kentucky (< 31 kg ha^{-1}).

For the three locations, the optimum calculated sowing date is considerably later under rainfed management and a 1 day delay has less effect on yield until after 21 June (172 JD; Fig. 6). The later sowing date provides for less depletion of water reserves prior to onset of seed growth. In addition, later sowing causes the timing of seed growth to occur later when temperature is more moderate, vapour pressure deficit is less and rainfall probability increases. The difference between rainfed and irrigated average simulated grain yield diminishes gradually as the sowing date is delayed. Under rainfed management, the maximum average simulated grain yield was reached with cv. Labrador for Lugo (2076 kg ha^{-1}, sowing date: 11 June (162 JD) and Mabegondo (2193 kg ha^{-1}, 1 June [152 JD]) and with cv. Chandor for Ourense (1922 kg ha^{-1}, 21 July [202 JD]). This predicted late sowing date in Ourense is due to the lower late season freeze probability associated to this relatively warm location, in addition to factors mentioned previously that minimised water deficit during grain fill.

4. Conclusions

We conclude that the increase of DSSAT calculated soil water holding capacity, the slight increase in the root elongation rate and making the late phenological development accelerate more rapidly under water deficit, improved CROPGRO-soybean performance under rainfed conditions in Galicia. Data on growth, yield, and maturity under four varying rainfall years were very useful to allow optimising parameters related to these processes. A delay in soybean planting date in late spring has more negative consequence under irrigated than under rainfed management.

Acknowledgements

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References

Boote, K.J., Jones, J.W., Hoogenboom, G., Wilkerson, G.G., 1997. Evaluation of the CROPGRO-soybean model over a wide range of experiment. In: Kropff, M.J., Teng, P.S., Aggarwal, P.K. (Eds.), Applications of System Approaches at the Field Level: Proceedings of the Second International Symposium on Systems Approaches for Agricultural Development. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 113–133.

Boote, K.J., Jones, J.W., Hoogenboom, G., 1998. Simulation of crop growth: CROPGRO model. In: Peart, R.M., Curry, R.B. (Eds.), Agricultural Systems Modeling and Simulation, Chap. 18. Marcel Dekker, New York, pp. 1–42.

Bovi, O.A., 1981. Effects of Water Stress on Dry Matter Accumulation of 'Bragg' Soybean. MS thesis, University of Florida, Gainesville.

Doss, B.D., Pearson, R.W., Rogers, H.T., 1974. Effect on soil water stress at various growth stages on soybean yield. Agron. J. 66, 297–299.

Egli, D.B., Bruening, W., 1992. Planting date and soybean yield: evaluation of environmental effects with a crop simulation model: SOYGRO. Agr. Forest Meteorol. 62, 19–29.

Fehr, W.R., Caviness, C.E., 1977. Stages of Soybean Development (Special Report 80). Iowa State University of Science and Technology, Ames, IA.

Grimm, S.S., Jones, J.W., Boote, K.J., Hesketh, J.D., 1993. Parameter estimation for predicting flowering date of soybean cultivars. Crop. Sci. 33, 137–144.

Grimm, S.S., Jones, J.W., Boote, K.J., Herzog, D.C., 1994. Modeling the occurence of reproductive stages after flowering for four soybean cultivars. Agron. J. 87, 1085–1087.

International Benchmark Sites Network for Agrotechnology Transfer, 1989. Decision support system for agrotechnology transfer Version 2.1 (DSSAT V2.1). Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu, HI.

Jacobson, B.M., Jones, J.W., Welch, S.W., 1995. Decision Support System to Assess Agronomic, Economic, and Environmental Impacts of Soybean and Corn Management. ASAE paper No. 952696. Am. Soc. Agric. Engineering. St Joseph, MI, pp. 17.

Korte, L.L., Specht, J.E., Williams, J.H., Sorensen, R.C., 1983a. Irrigation of soybean genotypes during reproductive ontogeny. I. Agronomic responses. Crop. Sci. 23 (3), 521–527.

Korte, L.L., Specht, J.E., Williams, J.H., Sorensen, R.C., 1983b. Irrigation of soybean genotypes during reproductive ontogeny. II. Yield component responses. Crop. Sci. 23 (3), 528–533.

Loomis, R.S., Connor, D.J., 1992. Strategies and tactics for rainfed agriculture. In: Loomis, R.S., Connor, D.J. (Eds.), Crop Ecology: Productivity and Management in Agricultural Systems, Chap, 13. Cambridge University Press, Cambridge, pp. 378–399.

Parsh, L.D., Cochran, M.J., Trice, K.L., Scott, H.D., 1991. Biophysical simulation of wheat and soybean to assess the impact of timeliness on double-cropping economics. In: Hanks, J., Ritchie, J.T. (Eds.), Modeling Plant and Soil Systems, Agronomy, 31. ASA-CSSA-SSSA, pp. 511–534.

Pan, D., 1996. Soybean Responses to Elevated Temperature and CO_2. PhD dissertation, University of Florida, Gainesville, FL.

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat and evaporation using large scale parameters. Monthly Weather Review 100, 81–92.

Ritchie, J.T., 1985. A user-oriented model of the soil water balance in wheat. In: Fry, E., Atkin, T.K. (Eds.), Wheat Growth and Modeling. NATO-ASI Series. Plenum Press, pp. 293–305.

Ruíz-Nogueira, B., 1999. Efecto de la fecha de siembra sobre el rendimiento de la soja (*Glycine max* (L.) Merr.) en Galicia: evaluación y mejora del modelo CROPGRO-soybean para Galicia. PhD thesis, Servicio de Publicaciones de la Universidad de Santiago de Compostela, Spain. CD-ROM publication, ISBN 84-8121-750-6.

Sau, F., Boote, K.J., Ruíz-Nogueira, B., 1999. Evaluation and improvement of CROPGRO-soybean model for a cool environment in Galicia, northwest Spain. Field Crop Res. 61, 273–291.

Singh, P., Boote, K.J., Rao, A.Y., Iruthayaraj, M.R., Sheikh, A.M., Hundal, S.S., Narang, R.S., Singh, P., 1994. Evaluation of the groundnut model PNUTGRO for crop response to water availability, sowing dates, and seasons. Field Crop Res. 39, 147–162.

de Souza, P.I., Egli, D.B., Bruening, W.P., 1997. Water stress during seed filling and leaf senescence in soybean. Agron. J. 89, 807–812.

Specht, J.E., Williams, J.H., Weidenbenner, C.J., 1986. Differential responses of soybean genotypes subjected to a seasonal soil water gradient. Crop Sci. 26, 922–934.

Venturi, G., Amaducci, M.T., 1988. La Soja. Mundi-Prensa, Madrid.

Wilkerson, G.G., Jones, J.W., Boote, K.J., Ingram, K.T., Mishoe, J.W., 1983. Modeling soybean growth for crop management. Trans. ASAE 26, 63–73.