

Evaluation and improvement of CROPGRO-soybean model for a cool environment in Galicia, northwest Spain

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Abstract

This paper describes the evaluation and improvement of the CROPGRO-soybean model for a cool environment in northwest Spain. The model was evaluated with a soybean (*Glycine max* L.) 1994 field data set with three cultivars and three planting dates. The original model proved to underestimate biomass and seed yield, so modifications were made to the temperature functions affecting N₂ fixation and photosynthesis, in order to fit better to the experimental data. The modified model was then tested, i.e., validated, with independent experimental data collected in 1995 at the same site with the same cultivars and four planting dates. Comparing observed with simulated data in 1994, the modified model decreased the root mean square error (RMSE) for biomass at harvest and seed yield from 1714 to 466 and from 940 to 333, respectively. For 1995, the validation year, RMSE for biomass decreased from 1366 to 352, although the yield was now overestimated with no significant change in RMSE. The average simulated harvest index (HI) for 1995 was greater than for 1994, the reverse of the measured values. Nevertheless, the modified model was more reliable in predicting crop performances under these cool conditions than the original model. Moreover, the predictions of the modified model for a warm climate (Gainesville, FL) were quite acceptable. We conclude that the modified model can be used successfully over a wider range of climates than the original version. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: CROPGRO; Crop model; Calibration; *Glycine max* L.; Soybean

1. Introduction

Crop models are available for almost all economically important crops and on many occasions they have been successfully used in research. In the future,

models may be useful for improving the efficiency of agricultural systems and could be a tool for farmers trying to improve the profitability of their farms (Jacobson et al., 1995). Nevertheless, before this is possible, models must be calibrated and evaluated for

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Abbreviations: *a*, intercept of the linear regression; *b*, slope of the linear regression; *d*, index of agreement; DSSAT, Decision support system for agrotechnology transfer; HI, harvest index; LAI, leaf area index; LAI_{max}, maximum leaf area index; LF_{max}, maximum leaf photosynthesis rate; pd, photothermal day; RMSE, root mean square error; R5, beginning seed; R7, physiological maturity; SLA, specific leaf area; SR, daily total solar radiation; *T*_b, base temperature; *T*_{max}, daily maximum temperature; *T*_{min}, daily minimum temperature

each climatic region where they are intended for use in decision making.

Soybean crop models have been available since the 1980s when the original version of SOYGRO V4.2 (Wilkerson et al., 1983) was released. Subsequently, the model was improved (SOYGRO V5.0) with the incorporation of the Ritchie (1985) water balance and a preliminary phenology model (Wilkerson et al., 1985). In order to improve the code and be compatible with the standard input and output formats of the IBSNAT project (IBSNAT, 1993), SOYGRO V5.4 was released (Jones et al., 1987), and two years later the model was further modified as Version 5.42 (Jones et al., 1989) for release with the Version 2.1 of the DSSAT (Decision support system for agrotechnology transfer; IBSNAT, 1989). The next major improvement of the soybean model was the inclusion of soil N balance, N uptake features and an N₂ fixation sub-model. This version was released under the name of CROPGRO, a generic model to simulate three grain legume crops: soybean (*Glycine max* L.), common bean (*Phaseolus vulgaris* L.), and peanut (*Arachis hypogaea* L.). Boote et al. (1998) described the most recent CROPGRO version released in December 1996 (CROPGRO V3.1). The structure of the soybean model included in the DSSAT program is very flexible, so the adaptation of the model to a new climatic area is less time consuming than the design of a new model.

The previous version of the DSSAT soybean model (SOYGRO V5.42) underestimated biomass and grain yield by 50%, under non limiting conditions, in north-west Spain, at an elevation of 480 m (Sau and Ruíz-Nogueira, 1996). In this version, photosynthetic CO₂ fixation reaches zero when mean temperatures fall below 5°C. Brisson (1989) pointed out that this base temperature could be too high for cultivars from the earlier maturity groups (0, 00, 000). Moreover, Caulfield and Bunce (1988) showed varietal differences in tolerance to low temperature for photosynthesis and Berry and Bjorkman (1980) proposed that photosynthesis acclimates to low temperature. In the present version of CROPGRO-soybean, the effects of temperature on the photosynthetic process are calculated with leaf-level functions that differ from SOYGRO V5.42; however, the functions have not been extensively tested for cool environments and do not include varietal differences on acclimation to low temperature.

It can be expected, therefore, that grain yield would be underestimated under cold conditions. The leaf photosynthesis response to temperature for CROPGRO-soybean was derived from the data of Harley et al. (1985) on light and CO₂ saturated photosynthesis of soybean leaves in response to temperature. This study was based on short-term measurements with no temperature acclimation. The derived function for CROPGRO-soybean uses a linear function for photosynthetic electron transport with a base temperature (T_b) of 8°C to an optimum of 37°C, with exponentially increasing heat damage above 30°C that progressively reduces the rate to zero at 48°C. Boote and Pickering (1994) describe temperature effects on P_{max} (light saturated leaf photosynthesis) and quantum efficiency, and their operation in the hedgerow canopy assimilation model. The effect of these two temperature functions in the canopy assimilation model, gave a broad optimum for canopy photosynthesis from 25°C to 37°C. The climate in northern Spain (480 m elevation) is cool by comparison to the main areas where soybean is cultivated, particularly compared to the climate in Florida, North Carolina, Iowa and Ohio where CROPGRO-soybean was predominantly tested (Table 1). Mean daily minimum temperatures in June for Florida, North Carolina, Iowa and Ohio were 21.1°C, 18.3°C, 14.9°C, and 12.8°C, respectively, averaged over 5 or more years. By contrast, the mean daily minimum temperature in Lugo, Spain, was 10.1°C in 1994 and 11.4°C in 1995. Temperatures in northern Spain are cool and presumably limit photosynthesis ('simulated' optimum temperature = 25.0–37.0°C), nitrogen fixation (optimum temperature = 23.0°C–35.0°C), pod addition (optimum temperature = 21.0°C–26.5°C), seed growth rate (optimum temperature = 21.0–23.5°C), leaf area expansion (optimum temperature = 22.0°C and above), vegetative and reproductive stage progression (optimum temperature = 28.0–35.0°C and 26.0°C–30.0°C respectively) throughout the season.

The objective of this research was to evaluate the performance of CROPGRO-soybean in a cool region by comparison to field experiments, consisting of three cultivars and three planting dates, carried out under non-limiting conditions in 1994 in Lugo, Spain, and as necessary, to modify components of the model enable a more accurate prediction of crop growth and yield. Once this had been carried out, the modified

Table 1

Mean daily solar radiation (SR), and mean daily maximum (T_{\max}) and minimum (T_{\min}) temperatures every 10–11 days between May and November in 1994 and 1995

Period	1994			1995		
	SR (MJ m ⁻²)	T_{\max} (°C)	T_{\min} (°C)	SR (MJ m ⁻²)	T_{\max} (°C)	T_{\min} (°C)
May 1–10	18.3	19.5	6.1	20.4	23.2	9.3
May 11–20	14.0	14.0	7.8	14.5	17.8	9.4
May 21–31	17.7	19.2	8.5	19.0	19.8	8.0
June 1–10	18.1	20.8	9.3	26.1	18.7	9.7
June 11–20	19.4	22.4	10.3	21.7	22.6	10.4
June 21–30	21.1	24.9	10.6	19.4	25.0	14.2
July 1–10	18.2	25.0	12.1	15.9	23.4	13.3
July 11–20	18.7	24.5	14.2	16.9	26.0	14.9
July 21–31	16.5	25.2	14.6	19.7	28.2	14.1
Aug 1–10	14.1	24.8	13.9	15.1	24.6	13.2
Aug 11–20	17.1	24.7	13.0	18.8	27.2	14.9
Aug 21–31	16.6	24.6	13.5	22.4	26.1	12.9
Sept 1–10	11.4	21.6	10.3	10.1	21.8	11.2
Sept 11–20	10.0	18.3	8.7	7.4	16.4	10.2
Sept 21–30	8.9	16.8	8.9	12.2	18.5	10.2
Oct 1–10	7.3	21.4	9.0	7.5	21.6	8.9
Oct. 11–20	3.5	19.7	10.7	8.6	22.6	10.0
Oct 21–31	5.8	15.3	7.4	7.6	18.8	7.9
Nov 1–10	5.8	14.5	8.7	5.8	16.7	6.7
Nov 11–20	6.5	16.6	3.4	6.5	14.7	8.6
Nov 21–30	4.7	15.5	2.4	4.8	11.5	5.4

model was validated with a field experiment conducted in 1995, at the same site on three cultivars grown at four planting dates.

2. Materials and methods

2.1. Experimental design

Three commonly used French cultivars of soybean (*Glycine max* (L.) Merr.), [Major (000), Labrador (00) and Chandor (0)] were grown in two consecutive years (1994–1995) at the experimental farm of the University of Santiago de Compostela, located in Lugo, Galicia, northwest Spain (43.04' N; 3.30' W; 480 m elevation). The soil at the experimental site is a Typic Haplumbrept. Climatological data for the experimental years are summarized in Table 1. The 1994 experiment had three planting dates (30 May, 13 June, 29 June) and the 1995 experiment had four planting dates (22 May, 31 May, 15 June and 30 June). In both years, the row spacing was 0.4 m and the planting density in the treatments was around 50 plants m⁻² (the actual

field-sampled planting densities were used for model simulations). Treatments were assigned in a split-plot factorial arrangement in a randomized complete block with the planting dates representing whole plots and the cultivars subplots. Subplot size was 6 m × 4.4 m. Drip irrigation was established for all plots and managed to avoid water stress in the plants. Before planting, soil was fertilized with 65.5 kg P ha⁻¹ as superphosphate and 132.8 kg ha⁻¹ as potassium sulfate to minimize limitation from these two nutrients. The soil pH in water was 6.5. Before planting, seeds were inoculated with *Bradyrhizobium japonicum*. Due to poor emergence of Chandor for the first planting date in 1994, plant density of this cultivar was significantly below that of the other cultivars and the corresponding data for the first planting date was deleted.

2.2. Sampling

Samples of 0.5 m² were taken in each subplot at 10–20 day intervals throughout the entire crop life cycle. A four-plant subsample was taken and separated into

leaf (petioles were included in leaf fraction), stems, and pods. Later during seed fill, the pods were also separated into pod walls and seeds. All the subsample components and remaining plants were dried separately to constant weight, in a convective oven at 70°C for more than 48 h. Specific leaf area (SLA) was evaluated with a Delta-T Image Analysis System, in order to estimate leaf area index (LAI) from SLA and leaf weight per square meter.

Crop phenology and development was observed twice weekly using the growth staging method of Fehr and Caviness (1977).

At harvest maturity, at least 6 m² were hand harvested from each subplot. Seed yield, biomass, yield components, and harvest index (HI) were measured after each plant component was oven-dried to constant dry weight at 70°C.

3. Results and discussion

3.1. Scheme of the logic of the model modification process

The 1994 experimental data set was used to calibrate the CROPGRO-soybean model, whereas the 1995 data were reserved for validating/testing the improved model.

Firstly, the GENCALC program of the DSSAT V3.1 (Hunt et al., 1993) was used to calibrate the genetic coefficients (phenology, seed size, determinancy, etc.) of Major, Labrador and Chandor from the 1994 experimental data. Light saturated leaf photosynthesis (LF_{max}) is also a genetic coefficient that GENCALC seeks to adjust, but in this case, the value was constrained to the upper limit proposed by the literature (1.4 mg CO₂ m⁻² s⁻¹; Sinclair, 1980). In addition, duration between beginning seed filling (R5) and physiological maturity (R7) had to be manually fitted in order to achieve a sufficiently long life cycle (Table 2). The requirement for larger accumulative values from R5 to R7 than those reported by Grimm et al. (1994), suggests that temperature functions for late season reproductive development may not be correct. Nevertheless, initial simulations (original model) resulted in 28% underprediction of seed yield and total biomass at harvest (Fig. 1 (a) and Fig. 1 (b)), despite having the correct timing of 'beginning seed' (R5; Fig. 1 (d)) and physiological maturity (R7; Fig. 1 (e)), as well as the upper constraint on LF_{max} . The maximum leaf area index (LAI_{max}) was also underpredicted (Fig. 1 (c)). Underpredictions of LAI_{max} , total dry matter, and seed yield were more prevalent for the first than for the second or third planting dates, suggesting that cool

Table 2

Genetic coefficients of three cultivars of soybean before and after the model adaptation to cool environments

Genetic coefficients	Original model			Final model		
	Major	Labrador	Chandor	Major	Labrador	Chandor
Critical short day length (h)	14.2	14.0	13.7	14.2	14.0	13.7
Slope of response to photoperiod (h ⁻¹)	0.129	0.148	0.171	0.129	0.148	0.171
Time from emergence to R1 (pd ^a)	17.00	16.60	18.60	17.00	16.60	18.60
Time from R1 to R3 (pd ^a)	4.00	5.20	4.90	4.00	5.20	4.90
Time from R1 to R5 (pd ^a)	8.20	10.50	10.20	8.20	10.50	10.20
Time from R5 to R7 (pd ^a)	42.00	44.00	39.20	42.00	44.00	39.20
Time from R1 to end leaf (pd ^a)	32.00	34.80	30.00	32.00	34.80	30.00
Maximum leaf photosynthesis (mg CO ₂ m ⁻² s ⁻¹)	1.40	1.40	1.40	1.40	1.40	1.40
Specific leaf area (cm ² g ⁻¹)	395.0	397.0	387.0	395.0	397.0	387.0
Maximum leaf size (cm ²)	180.0	180.0	180.0	180.0	180.0	180.0
Maximum fraction of partitioning to seeds	1.00	1.00	1.00	1.00	1.00	1.00
Maximum weight per seed (g)	0.20	0.172	0.190	0.180	0.155	0.171
Seed filling duration (pd ^a)	24.00	24.00	24.00	25.00	25.00	25.00
Seeds per pod (n°. pod ⁻¹)	1.97	2.03	2.01	1.97	2.03	2.01
Pod addition duration (pd ^a)	9.10	7.46	9.00	10.01	8.21	9.90
Shelling percentage	77.0	77.0	77.0	74.0	74.0	74.0

^a Photothermal day.

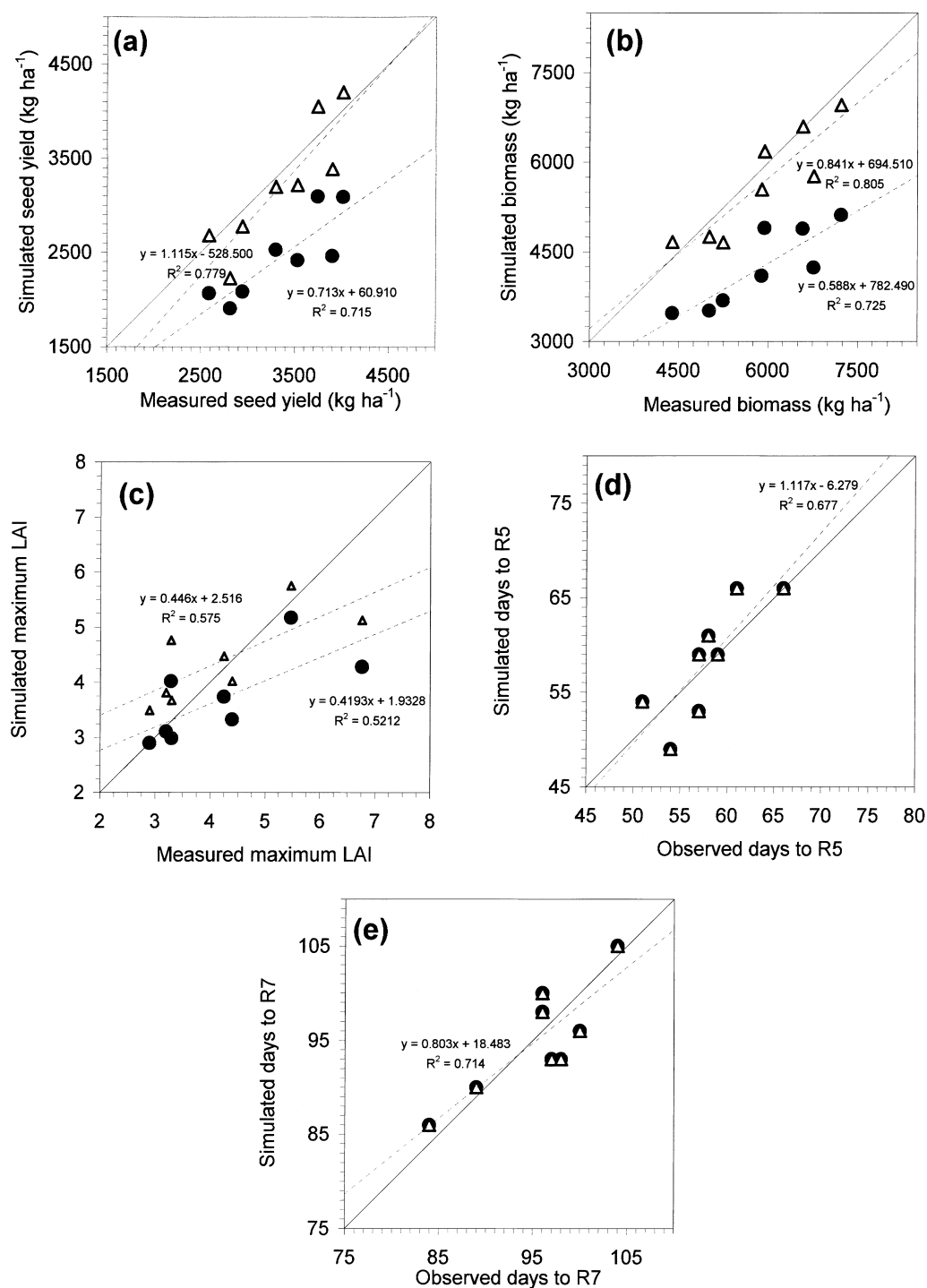


Fig. 1. Measured and simulated values with the CROPGRO-soybean original (●) and modified model (final model: simulation 13; △) for (a) seed yield, (b) total biomass at harvest, (c) maximum leaf area index (maximum LAI), (d) days from sowing to beginning seed (R5) and (e) days from sowing to physiological maturity (R7) for the 1994 experiment. Each point represents the mean of four replicates.

temperature early in the season could be a significant problem for accurate simulations with the present version of CROPGRO-soybean. Processes which are sensitive to temperature during early season include photosynthesis, vegetative development, nodulation, and N_2 fixation. As underpredictions occurred for all three cultivars, it was felt that the problem was not cultivar specific.

With the original model, time series graphs showed delayed and slow simulated dry matter accumulation in biomass and pods, and leaf area growth for the early planting date when compared with experimental data (Fig. 2 (a), Fig. 2 (b) and Fig. 2 (c)). This suggested the need to re-evaluate the cardinal temperature coefficients affecting leaf photosynthesis, rate of leaf appearance, and leaf area expansion. Temperature response curves for a species as a whole are a simplification because varietal differences in tolerance to cold temperature have been reported for photosynthesis (Caufield and Bunce, 1988; Marrowitch et al., 1986), and seed growth (Sexton et al.,

1994). Furthermore, simulated leaf N concentration was low and leaf carbohydrate concentration was high (Fig. 3 (a) and Fig. 3 (b)). As the model is configured, this drop in N concentration and accumulation of carbohydrates in the leaves is caused by N stress associated with slow nodule growth and low N_2 fixation. Because the plants were well nodulated and nodules were active (based on visual inspection) in all treatments in both years, it was concluded that the temperature functions affecting nodule growth rate and specific N_2 fixation rate also required re-evaluation. Insufficient N_2 fixation in the model has a similar effect to decrease photosynthesis, as low N concentration in leaves reduces leaf photosynthesis and slows leaf area growth. Problems with the temperature functions for nodule growth and nodule specific activity were recently highlighted by comparison of the model predictions to Iowa experimental data by Sexton et al. (1998). Moreover, some authors have shown varietal differences in tolerance to cold temperature for nodule growth

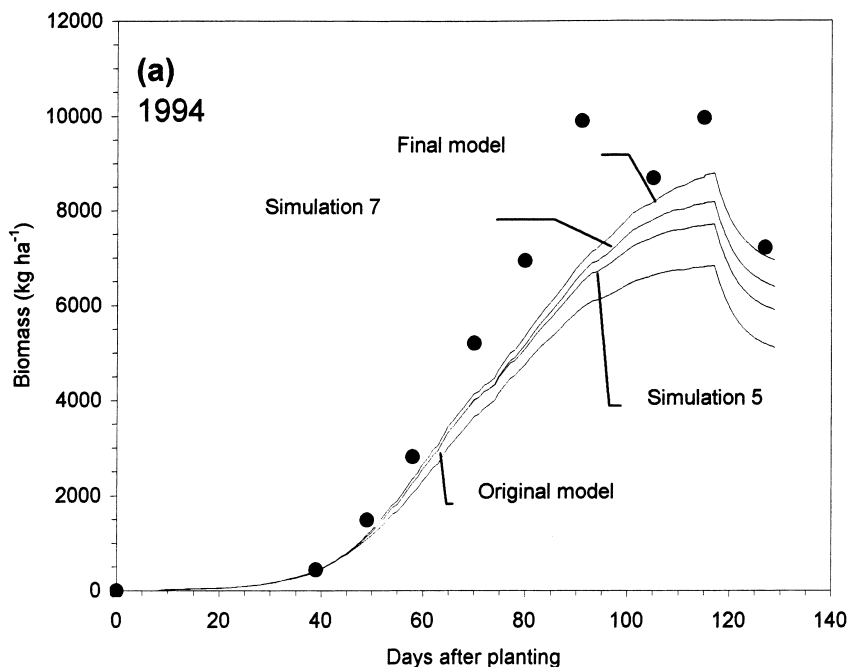


Fig. 2. Observed (points) and simulated (lines) dynamics for cv. Labrador first planting of the 1994 experiment obtained with the CROPGRO-soybean original model and three different modifications (simulation 5, simulation 7 and final model): (a) total biomass (b) weight of pods and (c) leaf area index (LAI). Differences between the original model and the modified models are described in the text and the foot notes of Table 3. Each point represents the mean of four replicates.

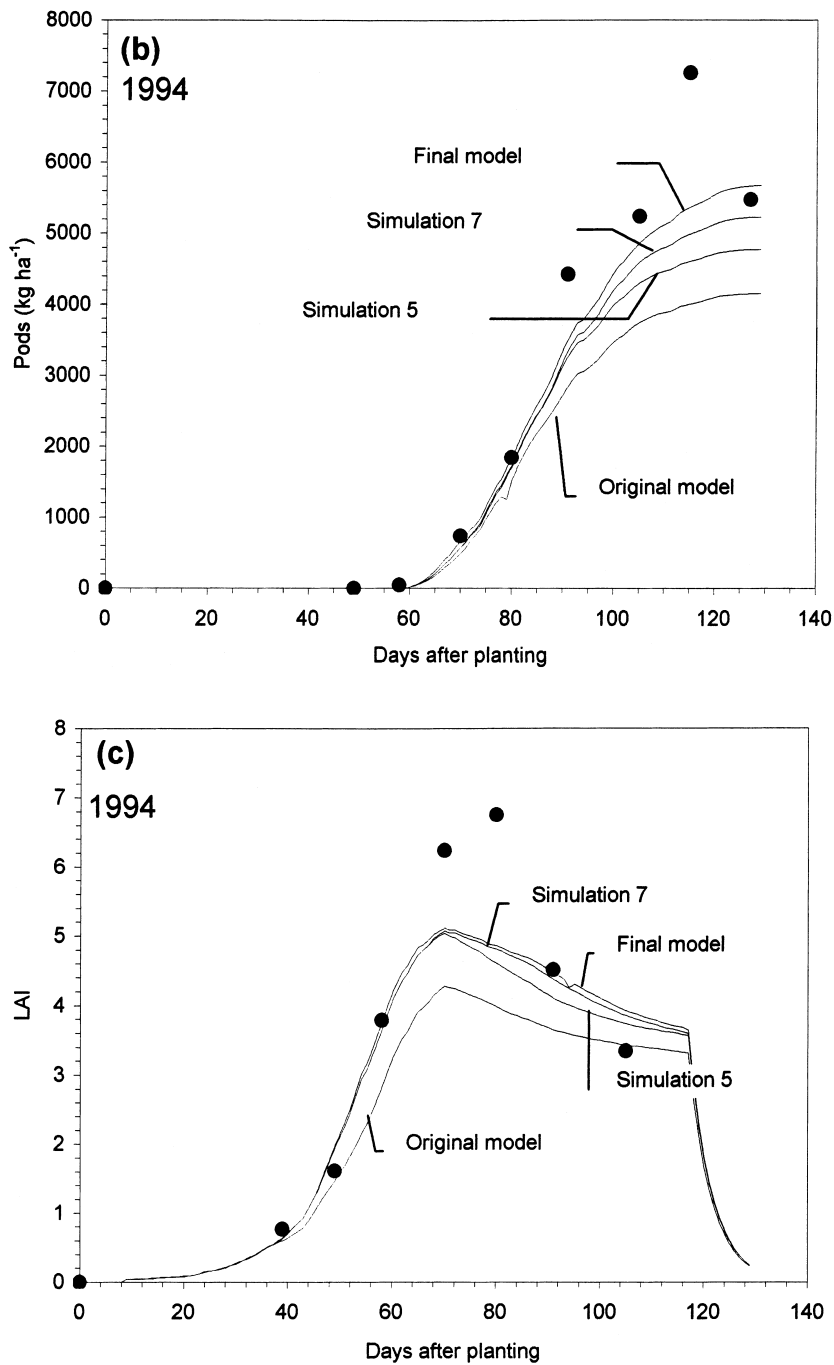


Fig. 2. (Continued)

(Thomas and Sprent, 1984) and also that strains of *Bradyrhizobium* differed in cold tolerance (Bailey, 1988; Layzell et al., 1984). Finally, we re-evaluated

temperature functions for reproductive development and pod addition, as well as partitioning of assimilates to the seeds at low temperatures.

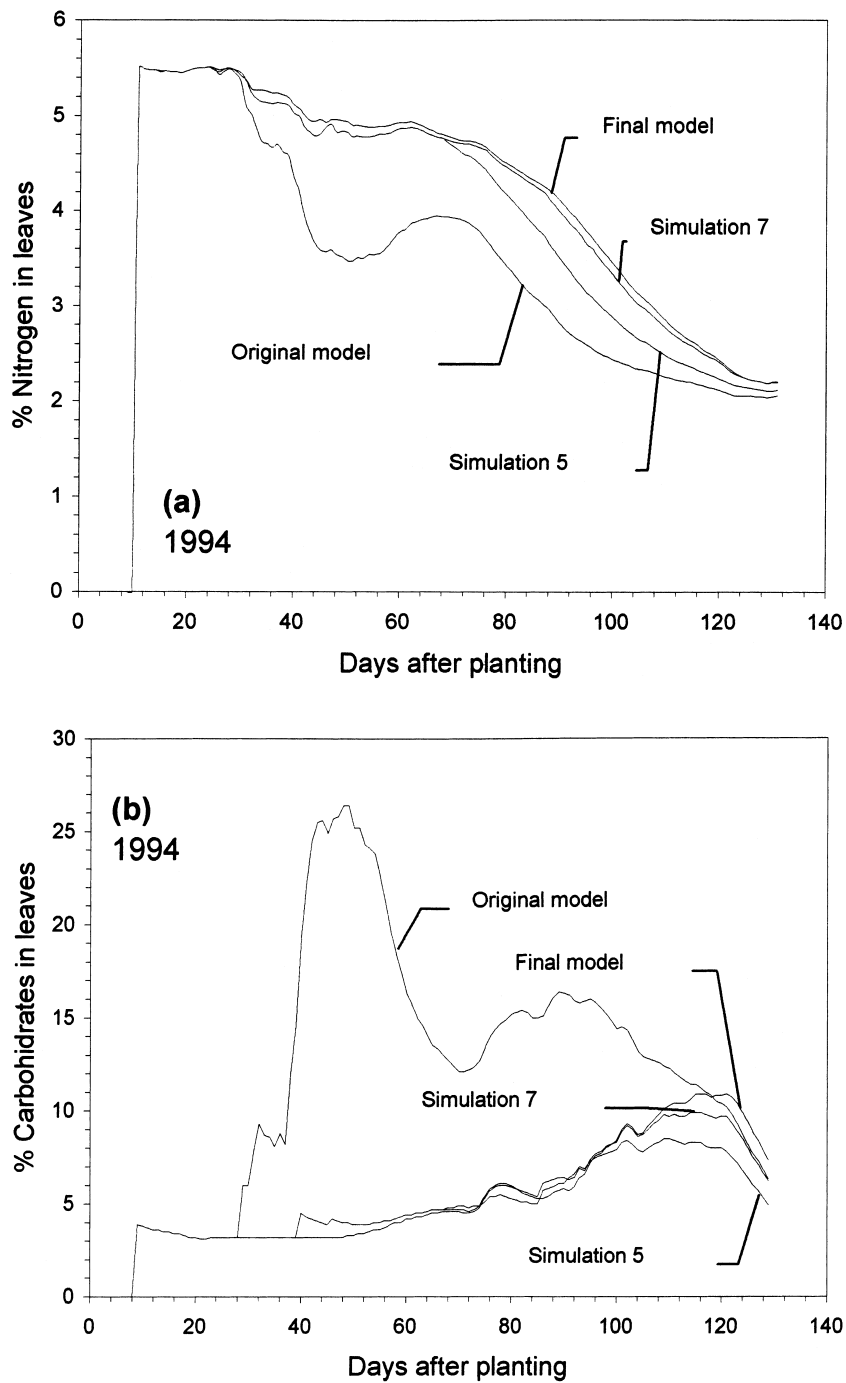


Fig. 3. Simulated dynamics for cv. Labrador first planting of 1994 obtained with the CROPGRO-soybean original model and three different modifications (simulation 5, simulation 7 and final model): (a) nitrogen percentage in leaves and (b) carbohydrate percentage in leaves. Differences between the original model and the modified models are described in the text and the foot notes of Table 3.

3.2. Statistical and graphical procedures to demonstrate model improvement

Since the unmodified model underpredicted LAI, crop biomass, and pod growth under cool conditions, our objective was to demonstrate an improvement in the predictions allowed after making changes to individual temperature functions affecting photosynthesis, nodule growth, specific nitrogenase activity (N_2 fixation), N mobilization, leaf area expansion, leaf appearance rate, pod addition, and partitioning to seeds. Temperature functions of various modeled plant processes were evaluated independently, one at a time, while comparing the modified CROPGRO-soybean model to the 1994 data. Those individual modified functions which proved to be beneficial were combined in several ways to illustrate further improvements possible in model performance for the 1994 data set. The following criteria were used to assess model improvement: a decrease in root mean square error (RMSE), improved a and b values of linear regression between predicted and observed data and an index of agreement (d ; Willmott, 1982). Predicted time series graphs of biomass, pods and LAI growth were also compared visually to determine improvements in various temperature functions for plant growth processes. Dry matter accumulation slopes are, for example, indirect estimations of leaf photosynthesis. Furthermore, 1 : 1 graphs of biomass at harvest, seed yield and LAI were used, along with evaluation of RMSE, a and b values of linear regression and the d -statistics, to illustrate the final level of model improvement relative to the 1994 data. Finally, validation was carried out by comparing the predictions of the model with coefficients modified from the 1994 data, to the 1995 experimental data. The same 1 : 1 graphs and statistical tests (mean, RMSE, a and b of linear regression, and d -statistics) were used to determine the degree of model predictability.

3.3. Model modification based on 1994 data

Most of the improvement made to the model resulted from modifying the temperature functions affecting leaf photosynthesis and N_2 fixation. Smaller contributions were made by altering temperature functions affecting vegetative node appearance, leaf area

expansion, rate of pod addition, or partitioning to reproductive growth (Table 3).

3.3.1. Photosynthesis processes

Modifying the temperature functions for leaf photosynthesis significantly improved the model fit and increased the mean simulated biomass and seed yield while decreasing the RMSE (Table 3). Decreasing the base temperature (T_b) for leaf photosynthesis from 8°C to 6°C increased the biomass at harvest by 267 kg ha⁻¹ and the yield by 161 kg ha⁻¹ while decreasing RMSE in both cases (simulation 2 in Table 3).

Another temperature function allows night time minimum temperature (T_{min}) to affect the next day's light-saturated photosynthesis rate (LF_{max}). This is an asymptotic function which ranges from zero at 0°C increasing to 1.0 (no limitation on LF_{max}) when the minimum night temperature is above 19°C. The threshold values of this function were changed to -2 and 17°C, respectively. This change in T_{min} acted similarly to the T_b change, increasing biomass and yield at harvest by 250 and 150 kg ha⁻¹ respectively, and reducing RMSE (simulation 3 in Table 3).

Combining the two temperature modifications for leaf photosynthesis created additional positive changes; decreasing RMSE (by 28% and 31% for biomass and yield, respectively) and increasing d -values as well as giving better slopes of predicted versus observed biomass and yield (simulation 4 in Table 3).

A decrease of 2°C in the base temperature (T_b) or the minimum night temperature (T_{min}) response would have an effect on leaf photosynthesis equivalent to a 2°C acclimation effect.

3.3.2. N_2 fixation processes

Independently decreasing the lower temperature for optimum nodule growth from 28°C to 22°C and for nitrogenase activity rate from 23 to 20°C, reduced the RMSE for biomass from 1714 to 1173, and for seed from 940 to 643 (simulation 5 in Table 3). At the same time, the simulated biomass increased from 4241 to 4790 kg ha⁻¹ and seed yield from 2455 to 2776 kg ha⁻¹. Fig. 3 (a) illustrates how these changes caused the leaf N concentration to remain higher and the carbohydrate concentration of the leaf lower (Fig. 3 (b)) during vegetative growth, thereby result-

Table 3

Average biomass and seed yield simulated by the original CROPGRO-soybean model (December 1996 release, simulation 1) and modifications affecting processes of photosynthesis (simulations 2, 3 and 4), nitrogen metabolism and mobilization (simulations 5, 6 and 7), vegetative expansion (simulations 8 and 9) and pod set (simulations 10 and 11) as well as a combination of photosynthesis and nitrogen metabolisms (simulations 12 and 13), compared with the experimental averages for the 1994 experiment

Simulation	Average biomass (kg ha ⁻¹)	<i>a</i> ^a	<i>b</i> ^a	RMSE ^a	<i>d</i> ^a	Average seed yield (kg ha ⁻¹)	<i>a</i> ^a	<i>b</i> ^a	RMSE ^a	<i>d</i> ^a
(1) Original model	4241	783	0.588	1714	0.544	2455	61	0.713	940	0.570
Photosynthesis changes										
(2) <i>T_b</i> -Pg ^b	4508	932	0.608	1456	0.597	2616	139	0.738	785	0.629
(3) <i>T_{min}</i> -Pg ^c	4491	822	0.624	1470	0.596	2605	99	0.747	795	0.625
(4) (2) + (3)	4747	977	0.641	1227	0.653	2759	185	0.767	650	0.696
Nitrogen metabolism changes										
(5) <i>T_{opt}</i> -N ₂ fixation ^d	4790	484	0.732	1173	0.679	2776	-264	0.906	643	0.726
(6) X seed ^e	4539	458	0.694	1409	0.618	2718	-158	0.857	685	0.695
(7) (5) + (6)	5097	166	0.838	875	0.797	3043	-537	1.067	425	0.863
Vegetative expansion										
(8) <i>T_b</i> -VS ^f	4396	1031	0.572	1565	0.572	2539	75	0.734	858	0.600
(9) <i>T_b</i> -SLA ^g	4242	719	0.599	1711	0.545	2454	47	0.717	942	0.570
Pod set										
(10) <i>T_b</i> -Pod set ^h	4208	804	0.579	1756	0.534	2557	423	0.636	845	0.594
(11) Limit partitioning ⁱ	4129	800	0.566	1834	0.520	2617	335	0.680	797	0.618
Combining photosynthesis and N changes										
(12) (4) + (7)	5640	709	0.838	451	0.931	3361	-416	1.125	296	0.927
Final model										
(13) (12) + genetic coefficients changes	5639	695	0.841	466	0.927	3215	-528	1.115	333	0.910
Measured average (kg ha ⁻¹)	5882					3356				

^a *a* and *b* values of linear regression of predicted vs. observed data, root mean square error (RMSE) and index of agreement *d* (Willmott, 1982).

^b Base temperature for leaf photosynthesis decreased from 8°C to 6°C.

^c Threshold values for the function calculating *T_{min}* effect on the subsequent day's light saturated photosynthesis rate were moved from 0 and 19°C to -2°C and 17°C.

^d Lower optimum temperature for nodule growth decreased from 28°C to 22°C and lower optimum temperature for nitrogenase activity from 23°C to 20°C.

^e N mobilization rate increases as a function of transition from 0% to 100% actual partitioning to seed (formerly the rate increased as a function of transition from 0% to 100% actual partitioning to pod wall plus seed).

^f Base temperature for main stem node appearance decreased from 7°C to 5°C.

^g Reduced effect of low temperature on leaf expansion: relative specific leaf area at 12°C changed from 0.25 to 0.35.

^h Base temperature for pod addition decreased from 14°C to 10°C.

ⁱ No temperature limitation to partitioning to seeds (formerly partitioning to seeds decreased from a relative value of 1 at 20°C to 0 at 5°C).

ing in higher leaf photosynthesis and dry matter growth (Fig. 2 (a)). Nodule growth and specific nitrogenase activity are relatively recent additions to CROPGRO and the temperature functions have not been adequately tested for cool regions. N_2 fixation processes were assumed to have a temperature sensitivity similar to vegetative processes, but dependant on modeled soil temperatures which have a different pattern from air temperatures, especially during spring in cool regions. These new cardinal temperatures for nodule growth and N_2 fixation were also shown suitable to explain observed soybean growth in field studies in Iowa carried out by Sexton et al. (1998).

We evaluated the soybean literature for temperature effects on nitrogenase activity and nodule growth rate. From data given by Dart and Day (1971); Waughman (1977); Lindeman and Ham (1979), a T_b of 5°C and T_{opt} (optimum temperature) of 25°C – 30°C could be derived for short-term nitrogenase activity of detached nodules. Activity was good at relatively cool temperatures, i.e., 70% of the maximum at 10°C , and 95% of the maximum at 20°C . Layzell et al. (1984) furthermore observed considerable acclimation to low temperature, where plants held at 9.5°C for four days recovered to rates comparable to 20°C -treated plants. Thus, we feel justified in decreasing the temperature optimum for N_2 fixation rate from 23 to 20°C . Data which document root-zone temperature effects on nodule growth rate are less clear, because reliable data are scarce and the interpretation involves time lags in growth under low root-zone temperature. Lindeman and Ham (1979) reported that nodule mass and number were optimum at 25°C , and were comparable at 20°C if additional time was allowed. This is sufficient reason for decreasing the lower temperature for optimum nodule growth rate from 28 to 22°C , until further evidence is available.

Sexton et al. (1998) have also shown the need to delay foliar N mobilization later into active seed growth, thereby maintaining leaf N concentration and leaf photosynthesis late in the season. The model was altered so that N mobilization was accelerated as a function of transition from 0 to 100% actual partitioning of assimilates to seed (previously the increased rate followed partitioning to pod wall plus seed). This change by itself delayed the onset of rapid N mobilization by about 10 days (as shown in Fig. 3 (a)) and

increased biomass at harvest maturity from 4241 to 4539 kg ha^{-1} and seed yield from 2455 to 2718 kg ha^{-1} (simulation 6 in Table 3). The RMSE for biomass decreased from 1714 to 1409 and the RMSE for seed yield from 940 to 685.

Combining the delayed N mobilization effect with the temperature functions for nodule growth/ N_2 fixation decreased RMSE by 49 and 55% for biomass and seed yield, respectively at harvest maturity (simulation 7 in Table 3).

3.3.3. Vegetative and leaf area expansion

Temperature functions affecting rate of vegetative node expression and leaf area expansion were also evaluated. Decreasing the base temperature for rate of main stem node appearance (V stage) from 7°C to 5°C slightly increased seed yield and biomass, particularly due to an early increase in LAI at the beginning of the growing season (simulation 8 in Table 3). This change was not included, however, because it did not match with the observed data on node numbers and because the published literature shows clearly that T_b for the rate of node expression in soybean lies between 7°C and 9°C (Hesketh et al., 1973; Sinclair et al., 1991).

CROPGRO-soybean also has a temperature effect on relative leaf area expansion, by which the relative specific leaf area (SLA) of new leaves increases from 0.25 at 12°C to 1.00 at 22°C . We attempted to make leaf area expansion less sensitive to temperature (relative SLA from 0.35 at 12°C up to 1.00 at 22°C) but the response was unexpected. While LAI was clearly increased by this change (simulation 9 in Table 4), the increase in SLA depressed leaf photosynthesis to an extent that crop dry matter accumulation and seed yield were unchanged (simulation 9 in Table 4). This modification was not included.

3.3.4. Reproductive processes

Sensitivity tests were also conducted to determine the effect of modifying temperature functions for pod addition rate and a hypothesized limitation of partitioning to seed growth. Decreasing T_b for pod addition from 14°C to 10°C increased seed yield from 2455 to 2557 kg ha^{-1} and decreased the RMSE (simulation 10 in Table 3). However, this change decreased biomass (increasing its RMSE) and in consequence increased harvest index (HI). This modification increased simulated HI to values much greater than those observed

Table 4

Average pod yield, harvest index (HI) and maximum leaf area index simulated by the original CROPGRO-soybean model (December 1996 release, simulation 1) and modifications affecting processes of photosynthesis (simulations 2, 3 and 4), nitrogen metabolism and mobilization (simulations 5, 6 and 7), vegetative expansion (simulations 8 and 9) and pod set (simulations 10 and 11) as well as a combination of photosynthesis and nitrogen metabolisms (simulations 12 and 13), compared with the experimental averages for the 1994 and 1995 field experiments.

Simulation	1994			1995		
	Pod yield (kg ha ⁻¹)	HI	LAI _{max}	Pod yield (kg ha ⁻¹)	HI	LAI _{max}
(1) Original model	3311	0.578	3.69	4078	0.605	3.90
Photosynthesis changes						
(2) T_b -Pg ^a	3512	0.580	3.80	4271	0.607	4.00
(3) T_{min} -Pg ^b	3497	0.579	3.80	4248	0.606	3.99
(4) (2) + (3)	3688	0.581	3.91	4453	0.607	4.10
Nitrogen metabolism changes						
(5) T_{opt} -N ₂ fixation ^c	3727	0.578	4.23	4495	0.609	4.34
(6) X seed ^d	3585	0.598	3.73	4391	0.621	3.94
(7) (5) + (6)	4012	0.595	4.29	4807	0.621	4.39
Vegetative expansion						
(8) T_b -VS ^e	3414	0.576	3.86	4224	0.601	4.21
(9) T_b -SLA ^f	3308	0.578	3.83	4060	0.605	4.00
Pod set						
(10) T_b -pod set ^g	3378	0.609	3.45	4119	0.627	3.73
(11) Limit partitioning ^h	3495	0.634	3.43	4216	0.649	3.70
Combining photosynthesis and N changes						
(12) (4) + (7)	4409	0.593	4.47	5185	0.621	4.56
Final model						
(13) (12) + genetic coefficient changes	4412	0.567	4.39	5214	0.598	4.47
Measured average	4704	0.571	4.20	4696	0.547	5.57

^a Base temperature for leaf photosynthesis decreased from 8°C to 6°C.

^b Threshold values for the function calculating T_{min} effect on next day's light saturated photosynthesis rate were moved from 0°C and 19°C to -2°C and 17°C.

^c Lower optimum temperature for nodule growth decreased from 28° to 22°C and lower optimum temperature for nitrogenase activity from 23°C to 20°C.

^d N mobilization rate increases as a function of transition from 0% to 100% actual partitioning to seed (formerly the rate increased as a function of transition from 0% to 100% actual partitioning to pod wall plus seed).

^e Base temperature for main stem node appearance decreased from 7°C to 5°C.

^f Reduced effect of low temperature on leaf expansion: relative specific leaf area at 12°C changed from 0.25 to 0.35.

^g Base temperature for pod addition decreased from 14°C to 10°C.

^h No temperature limitation to partitioning to seeds (formerly partitioning to seeds decreased from a relative value of 1 at 20°C to 0 at 5°C).

and also increased RMSE (simulation 10 in Tables 3 and 4).

There is another function that limits partitioning to seeds from a relative value of 1.00 at 20°C to zero at 5°C. The effect was removed by setting the function to 1.00 at all temperatures below 20°C. This increased

yield from 2455 to 2617 kg ha⁻¹ and decreased RMSE (simulation 11 in Table 3). This decreased biomass and increased RMSE caused an even larger increase in seed HI than the previous modification (simulation 11 in Tables 3 and 4). Given these conflicting effects on different crop variables, there appeared to be no over-

whelming evidence that this change was necessary to achieve an adequate pod addition and timing. The same effect could be achieved by increasing or decreasing the pod adding phase.

3.3.5. *Combinations and final calibration to 1994 data*

Having evaluated the temperature functions on individual processes without finding sufficient improvement from any function, we combined the temperature modifications made to photosynthesis and N_2 fixation processes (simulation 12 in Tables 3 and 4). This combination of temperature modifications was adequate for predicting seed yield, but under-predicted biomass and stalk weight, and over-predicted HI.

The result of enhancing N_2 fixation and delaying leaf N mobilization (in simulation 12) was to increase HI from 0.578 to 0.593, seed weight from 175 to 198 mg and shelling percentage from 74.1 to 76.1. Thus, one minor set of changes in cultivar traits was made in order to reduce potential seed size to 0.90 of the original, reduce the genetic potential shelling percentage from 77% to 74%, and increase the seed filling duration from 24 to 25 days (Table 2). This resulted in a decrease in HI, seed weight, and shelling percentage, with small rises in stalk, and pods along with a slight drop in seed yield (final model in Tables 3 and 4). We ended the calibration process at this point, because seed yield, biomass and LAI_{max} were now within 4–5% of observed and predicted HI was very close to the average measured value (Table 3). In addition to the statistics in Table 3 and the means in Table 4, visual improvement is obvious by comparing the 1 : 1 graphs of seed yield, biomass at harvest and maximum LAI to the original 1 : 1 graphs (Fig. 1(a), Fig. 1(b), Fig. 1(c)).

As illustrated by Fig. 2(a), the simulated dry matter for Labrador for the first planting date was still slightly under-predicted, but was much improved over the original model simulations. It should be noted that those data come from small sampling areas (0.5 m²) compared to the 6 m² for seed yield and biomass at harvest maturity. A certain degree of inflationary bias in smaller sampling areas can be expected. The model calibration (statistical improvements, etc.) were made from the large plot samples collected at harvest maturity.

3.4. *Model validation with 1995 field experiment data*

3.4.1. *Comparison of unmodified model to 1995 data*

The original and the modified model were run with 1995 field experiment data in order to evaluate the degree of improvement. As for 1994, the original model under-predicted biomass at harvest by 20% and seed yield by 12%, despite having a correct estimation of the phenological development (Table 5, Fig. 4(a), Fig. 4(b), Fig. 4(d), Fig. 4(e)). LAI_{max} was also underestimated by 30% (Fig. 4(c)) but HI was over-predicted, with smaller HI in 1995 than in 1994 (Table 4). The under-predictions of LAI_{max} and total dry matter were more prevalent for the earlier planting dates while the differences between predicted and measured seed yields seemed to be equivalent for the four planting dates (Fig. 4(a), Fig. 4(b), Fig. 4(c)). Time series graphs, with the original model, showed a delayed and slower simulated dry matter accumulation and LAI progression for the first planting date in 1995 when compared with measured data (Fig. 5(a), Fig. 5(c)). Simulated pod dry matter accumulation was smaller than observed, although the onset timing of pod growth was adequately predicted (Fig. 5(b)).

3.4.2. *Comparison of modified model with 1995 data – photosynthesis processes*

Making the photosynthesis processes less sensitive to cool temperature (by decreasing T_b for leaf photosynthesis from 8 to 6°C, or decreasing the effect of minimum temperature, or both, simulations 2, 3, and 4) all served to improve the model fit with 1995 data, as shown by decreased RMSE and higher d -values for biomass and seed yield (Table 5). For the combination of both temperature modifications (simulation 4), RMSE was decreased from 1366 to 916 for biomass, and from 428 to 181 for seed yield. Thus, changes made to photosynthesis parameters based on 1994 calibrations, served to improve model performances in 1995.

3.4.3. *Comparison of modified model with 1995 data – N_2 fixation processes*

As for 1994, changes of the functions affecting nitrogen fixation and mobilization greatly increased biomass, seed yield and HI. The modifications affecting nodule growth and nitrogenase activity, reduced

Table 5

Average biomass and seed yield simulated by the original CROPGRO-soybean model (December 1996 release, simulation 1) and modifications affecting processes of photosynthesis (simulations 2, 3 and 4), nitrogen metabolism and mobilization (simulations 5, 6 and 7), as well as a combination of photosynthesis and nitrogen metabolisms (simulations 12 and 13), compared with the experimental averages for the 1995 experiment

Simulation	Average biomass (kg ha ⁻¹)	<i>a</i> ^a	<i>b</i> ^a	RMSE ^a	<i>d</i> ^a	Average seed yield (kg ha ⁻¹)	<i>a</i> ^a	<i>b</i> ^a	RMSE ^a	<i>d</i> ^a
(1) Original model	5051	268	0.754	1366	0.729	3051	−289	0.968	428	0.867
Photosynthesis changes										
(2) <i>T</i> _b -P _g ^b	5303	485	0.760	1131	0.787	3211	−126	0.967	287	0.935
(3) <i>T</i> _{min} -P _g ^c	5270	428	0.764	1161	0.779	3187	−223	0.989	305	0.928
(4) (2) + (3)	5539	621	0.776	916	0.843	3357	−83	0.997	181	0.974
Nitrogen metabolism changes										
(5) <i>T</i> _{opt} -N ₂ fixation ^d	5570	411	0.814	864	0.861	3388	−225	1.047	175	0.976
(6) X seed ^e	5402	115	0.834	1007	0.826	3353	−610	1.149	198	0.973
(7) (5) + (6)	5937	300	0.889	517	0.948	3687	−499	1.214	312	0.939
Combining photosynthetic and N changes										
(12) (4) + (7)	6448	916	0.873	332	0.977	3999	−68	1.179	583	0.819
Final model										
(13) (12) + Genetic coefficient changes	6457	851	0.889	352	0.975	3856	−364	1.234	466	0.867
Measured average	6340					3449				

^a *a* and *b* values of linear regression of predicted versus observed data, root mean square error (RMSE) and index of agreement *d* (Willmott, 1982).

^b Base temperature for leaf photosynthesis decreased from 8°C to 6°C.

^c Threshold values for the function calculating *T*_{min} effect on next day's light saturated photosynthesis rate were moved from 0°C and 19°C to −2°C and 17°C.

^d Lower optimum temperature for nodule growth decreased from 28°C to 22°C and lower optimum temperature for nitrogenase activity from 23°C to 20°C.

^e N mobilization rate increases as a function of transition from 0% to 100% actual partitioning to seed (formerly the rate increased as a function of transition from 0% to 100% actual partitioning to pod wall plus seed).

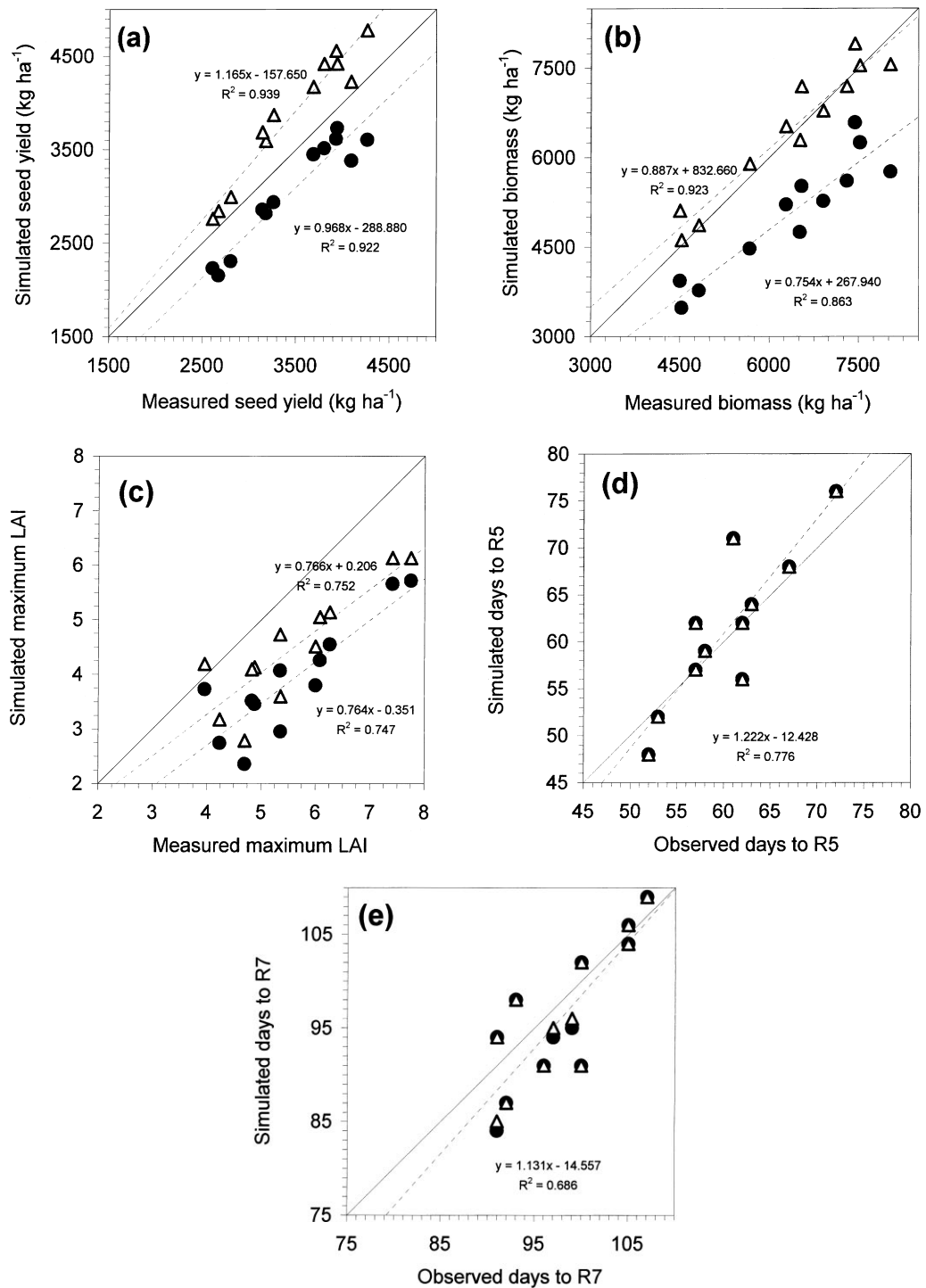


Fig. 4. Measured and simulated values with the CROPGRO-soybean original (●) and modified model (final model: simulation 13; △) for (a) seed yield, (b) total biomass at harvest, (c) maximum leaf area index (maximum LAI), (d) days from sowing to beginning seed (R5) and (e) days from sowing to physiological maturity (R7) for the 1995 experiment. Each point represents the mean of four replicates.

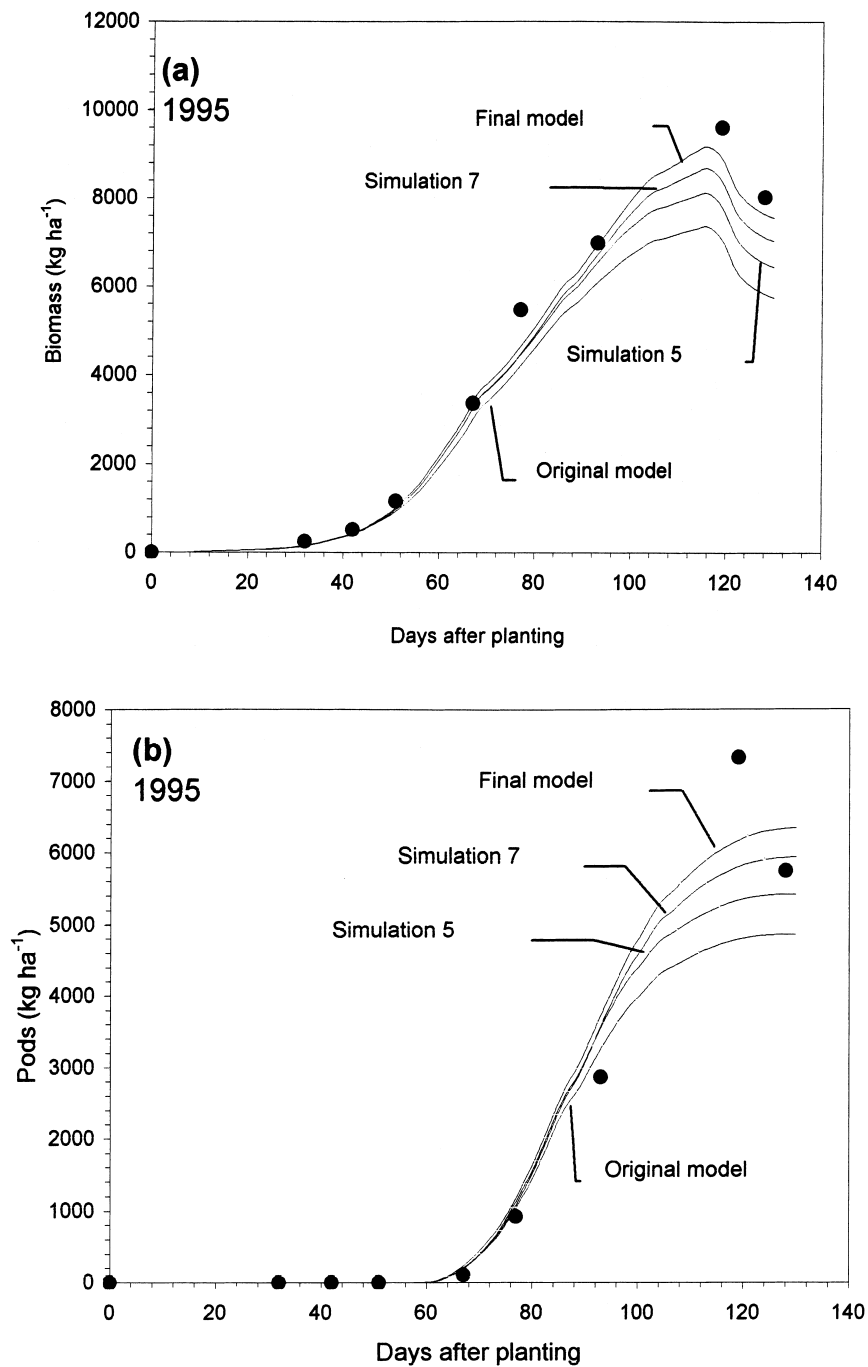


Fig. 5. Observed (points) and simulated (lines) dynamics for cv. Labrador first planting of the 1995 experiment obtained with the CROPGRO-soybean original model and three different modifications (simulation 5, simulation 7 and final model): (a) total biomass (b) weight of pods and (c) leaf area index (LAI). Differences between the original model and the modified models are described in the text and the foot notes of Table 4. Each point represents the mean of four replicates.

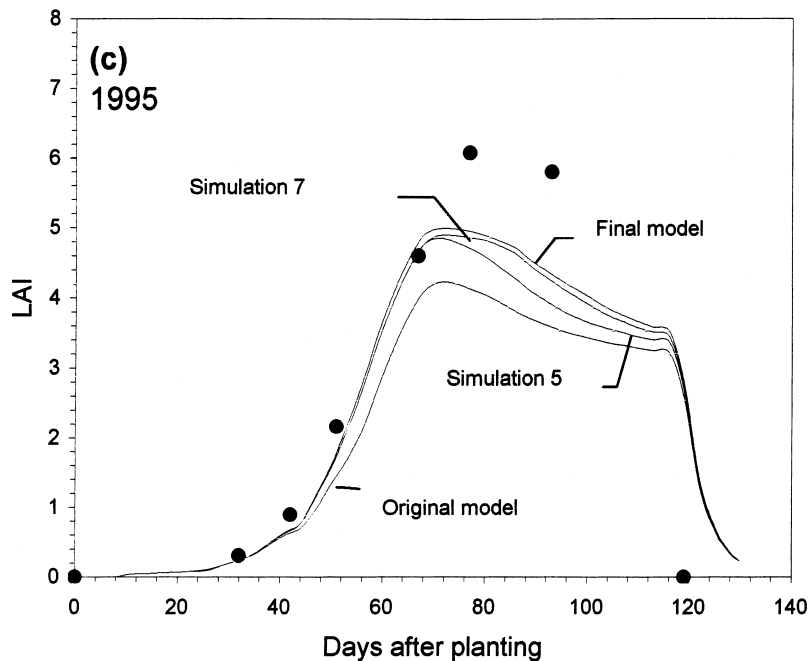


Fig. 5. (Continued)

the RMSE for biomass from 1366 to 864 and for seed yield from 428 to 175 (simulation 5 in Table 5). The separate consequences of delaying nitrogen mobilization from the leaves were also positive, as biomass and seed yield were increased and RMSE decreased, for biomass, from 1366 to 1007 and for seed yield from 428 to 198 (simulation 6 in Table 5). Combining the two changes affecting nitrogen metabolism further increased biomass and seed yield, with the RMSE for biomass decreasing to 517, but for seed yield increasing to 312.

3.4.4. Comparison of modified model with 1995 data – combinations of modifications

Combining all the effects of modifying temperature functions for photosynthesis and N_2 fixation, increased the predicted biomass and yield (simulation 12 in Table 5). Predicted biomass was very close to the observed average in 1995, but seed yield was clearly overestimated, as was HI (Table 4). As noted previously for the 1994 calibration, increasing N_2 fixation and delaying N mobilization increased HI and seed size, causing increased seed yield. The minor genetic coefficient calibrations based on 1994 (final model,

simulation 13), served to decrease (as for 1994) seed yield, seed size, and HI in 1995 (giving a more reasonable RMSE of 466 for seed in 1995, without measurably changing the prediction of biomass or its RMSE of prediction).

Overall, the modifications of the original model based on the 1994 data, improved biomass prediction in 1995 with a decrease in the RMSE from 1366 to 352 without any effect on seed yield. Since biomass predictions were good, the problem was one of partition of biomass to seed yield which could result from either duration or intensity of seed growth. Measured LAI_{max} in 1995 was significantly larger in 1995 than in 1994 and the model, while predicting higher LAI in 1995, was not able to simulate the full extent of this difference between the two years (Table 4). The greater vegetative growth observed in 1995 was associated with the smaller HI measured in 1995 compared to 1994.

Comparing the 1 : 1 graphs of seed yield, biomass at harvest and maximum LAI (final model) to the original 1 : 1 graphs (Fig. 4(a), Fig. 4(b), Fig. 4(c); original model) visual improvement was evident only for biomass and a slight improvement was seen for

LAI_{max} . Seed yield predictions were not improved, but the slope of predicted versus observed seed yield was increased. Fig. 5(a) and Fig. 5(c) show that the progressive changes to the model gradually improved the fit to measurements of biomass and LAI during the growing season for the first planting of Labrador in 1995 although Fig. 5(b) shows that the final model overpredicted the dry matter accumulation in pods.

3.5. Summary of modifications and validation

Changing the photosynthetic functions by decreasing base temperatures to make photosynthesis less sensitive to cool temperature, suggests two possibilities: either (1) the original functions were incorrect even for the warm locations under which the model was first tested, or (2) there can be photosynthetic acclimation to cool temperature around 2–3°C, when temperatures remain consistently low. We favor the latter explanation. Decreasing optimum temperature for nodule growth rate and for specific nitrogen fixation activity could also be viewed as an acclimation phenomenon; however, Sexton et al. (1998) showed these changes were appropriate to even relatively cool years in midwestern USA. The changes made to the cardinal temperature functions of the CROPGRO-soybean in the present study confirm the direction of modifications to N_2 fixation/N metabolism made by Sexton et al. (1998) with the additional suggestion to decrease base temperature for soybean photosynthesis.

Overall, the calibration with 1994 data, improved the fit to 1995 data on biomass. Therefore, we are relatively confident in the changes affecting dry matter accumulation. On the other hand, the model did not adequately account for the decrease in HI in the warmer 1995 season. Our experience does, however, suggest the need to test crop models with data from highly diverse climates, varying in temperature, irradiance, and rainfall, and shows resulting value in improving various functions, such as temperature effects on C and N balance processes.

Moreover, while changes in temperature functions for photosynthesis and N_2 fixation clearly improved model performance in the cool environment in northern Spain, they had little effect on model performance in warm environments. To address this question, simulations were compared with data collected on

Bragg soybean in Gainesville (Florida), over four seasons (1976, 1978, 1979, and 1984) (see Boote et al. (1997) for a description of those trials). There were seven treatments, both rainfed and irrigated, in each year except 1976. The original model predicted a mean seed yield of 3007 kg ha⁻¹, with a RMSE of 324 and a d -value of 0.960. Decreasing the T_b of photosynthesis, the T_{min} affecting photosynthesis, and the temperature coefficients on N_2 fixation, resulted in a seed yield of 3016 kg ha⁻¹ with a RMSE of 360 and a d -value of 0.956. While in Florida seed yield increased only by 0.3% and biomass by 2.9%, the same change for northern Spain (simulation 13 versus 1, in Table 3), increased seed yield by 31% and biomass by 33%. Thus, making the functions for photosynthesis and N_2 fixation less sensitive to cool temperatures, had little effect on model performance in a warm climate. Later comparisons (data not shown) indicated that the later onset of N remobilization was responsible for most of differences in model performance in Florida.

We conclude that modifications to temperature functions of photosynthesis and N_2 fixation/metabolism made as a result of this exercise and experimentation should improve CROPGRO-soybean performance for cool regions without significant negative impacts for the more typical, warmer soybean growing regions.

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