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Water and Nitrogen Limitations in Soybean Grain Production
II. Field and Model Analyses*

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ABSTRACT

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A short-season and a long-season soybean (*Glycine max* (L.) Merr) cultivar were grown on two different soil types under both irrigated and water-limited conditions in a semi-arid tropical environment. In addition to differences in water holding capacity, the clay soil had less available soil nitrogen than the sandy loam soil. The experimental water regimes coupled with the differing soil types gave a wide range in yield response. A model analysis was done to simulate the crop growth to identify those factors that limited yield. Under irrigated conditions, the yields of crops grown on the clay soil were found in the model to be especially limited by low amounts of available soil nitrogen. With weekly irrigation of the sandy loam soil, the long-season cultivar in the simulation experienced brief episodes of water shortage which reduced the nitrogen fixation rate. An optimal irrigation schedule was simulated based on soil water depletion, which improved yield and saved water compared to the simulated weekly schedule. Terminal water deficits reduced yields more for the long-season cultivar both experimentally and in the simulations, as the short-season cultivar initiated seed growth earlier and produced greater seed mass before water shortage terminated crop growth.

A model analysis of the water limitations showed that water deficits at the beginning of seed fill had the greatest effect on yields. Greater soil water storage as simulated by greater depth of water extraction resulted in increased yields. Increased nitrogen supply to the crop simulated by either greater soil nitrogen availability or increased nitrogen fixation rates resulted in substantial yield increases.

INTRODUCTION

A number of field studies have examined the influence of various water and nitrogen treatments on soybean (*Glycine max* L. Merr.) growth and yield (Doss

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et al., 1974; Hatfield et al., 1974; Lawn, 1982; Muchow, 1985). While some generalizations have been possible from these experiments, the inherent variability of field experiments makes extrapolations from any single experiment difficult. Soil type, weather conditions, and cultivar differences all hinder assessments of the potential effects of water and nitrogen limitations on soybean yield.

However, a simple model that accounts for some of these variables may provide the basis for some extrapolative interpretations. Such a model could provide information about the status of the crop at any particular time during the growing season. Simple 'what if?' experiments can be performed with a model by adding water or nitrogen at specific times or by altering threshold conditions. Also, model analyses can be performed by altering variables and evaluating the impact of crop growth and yield. In this way, simple crop growth models provide means for examining further implications of field experiments.

In this paper, we assess the results of field experiments in which water deficits were imposed on two soybean cultivars with differing maturities. The 2-year experiment was performed on two soil types, the 1st year on clay and the 2nd year on a sandy loam soil. In addition to the physical differences between the soils, there were differences in the amount of nitrogen available from each soil. To evaluate the experimental results, the simple soybean growth model presented by Sinclair (1986) was used. The soil characteristics and weather conditions for each year were used in the model to simulate growth. The potential limitations of water and nitrogen for these conditions were examined with the model. Finally, an analysis of the effects of various periods of drought and of various levels of nitrogen input were studied with the model.

MATERIALS AND METHODS

Field experiments

Experiments were conducted at the Kimberley Research Station (15°38′ S, 128°43′ E) in northern Western Australia during the 1979 and 1980 dry seasons. The dry season is characterized by a predominance of clear skies with relatively high temperatures and radiation, and virtual absence of rainfall (Fig. 1, 2). The 1979 experiment was conducted on the Cununurra clay soil type (USDA Soil Taxonomy: Chromustert), whereas the 1980 experiment was conducted on Ord sandy loam soil (USDA Soil Taxonomy: Paleustalf). Cununurra clay is weakly self-mulching, grey, medium-to-heavy clay in contrast to the coarser-textured Ord sandy loam which is a fine sandy loam overlying sandy clay loam at 60 cm and medium clay at 90 cm (Bridge and Muchow, 1982).

In both years, a split-plot design was used with water regimes as main plots and cultivars as sub-plots with four replications. Main plots measured 30 × 18 m and sub-plots were 30 × 2 m. An independently controlled solid-set overhead

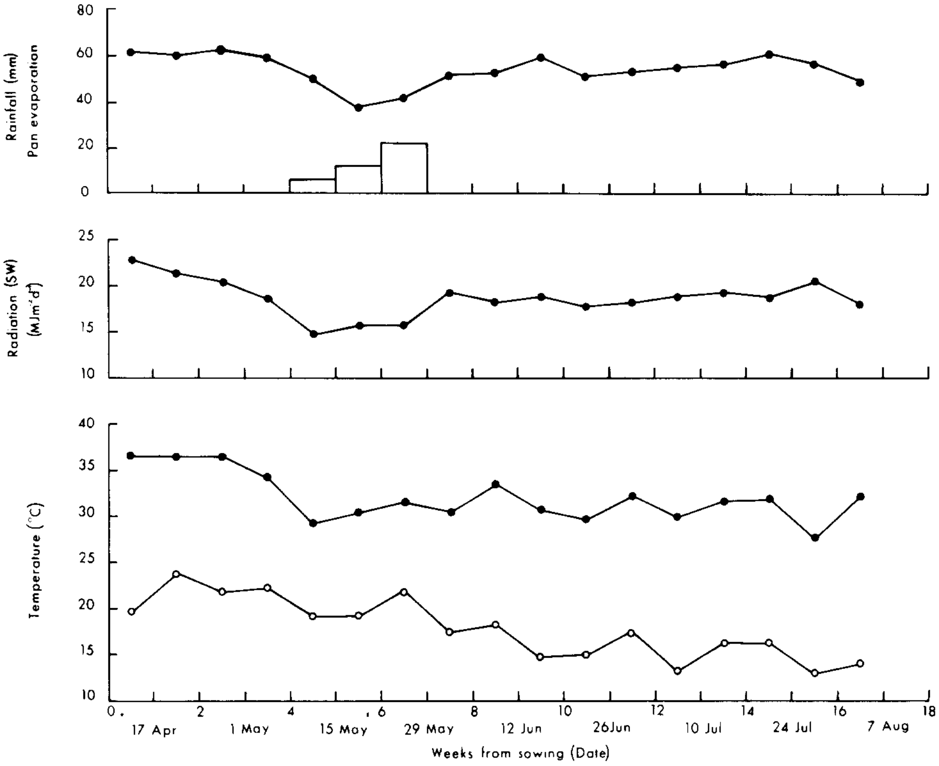

Fig. 1. Weekly rainfall (histogram), Class A pan evaporation, mean daily shortwave radiation, mean maximum (●) and minimum (○) temperature at Kimberley Research Station for the 1979 dry season

sprinkler irrigation system was installed in each main plot. Each main plot was separated by a 24-m-wide fallow area which was sufficient to prevent water application on adjacent main plots. The 'wet' regime received weekly sprinkler irrigations of 50–60 mm. The 'dry' regime received irrigation for the first 2 weeks after sowing and then no further irrigation was applied. This regime was designed to allow water deficits to develop slowly from seedling establishment as the soil water store was depleted. A 'wet/dry' regime received weekly irrigations until 4 weeks after sowing in 1979 and 6 weeks after sowing in 1980, and then no further irrigation. This regime was designed to impose a water deficit rapidly after a canopy with a large transpiring surface had developed. An early-maturing ('Buchanan') and a late-maturing ('Durack') cultivar, both with determinate growth habit, were sown.

All plots received superphosphate fertilizer (9.6% P, 0.33% Cu, 0.3% Zn, 0.04% Mo) at 250 kg ha^{-1} prior to sowing. In 1979, seeds were sown on 10 April in 50-cm rows to achieve a density of 25 plants m^{-2}, whereas in 1980 sowing was on 1 April in 25-cm rows to achieve a density of 35 plants m^{-2}.

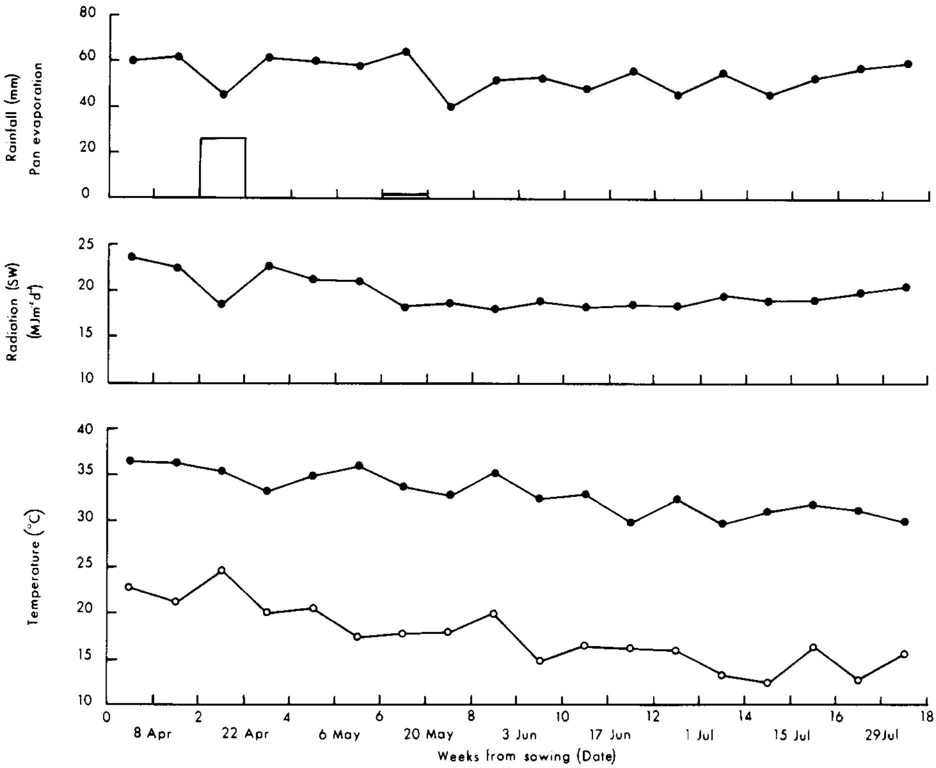

Fig. 2. Weekly rainfall (histogram), Class A pan evaporation, mean daily shortwave radiation, mean maximum (●) and minimum (○) temperature at Kimberley Research Station for the 1980 dry season

After sowing and prior to irrigation, pendimethalin (33% w/v 1-ethyl-propyl-3, 4-dimethyl-2, 6-dinitrobenzenamine) was applied at 4.5 l ha^{-1}. Three split irrigations of 20 mm each were given during the first week to assist seedling establishment. Leaf-eating and pod-sucking insects were controlled when necessary by applications of Thiodan (35.0% w/v Endosulfan) at 2.0 l ha^{-1}. Overall there were no problems with insects, disease or weeds, and nodulation was observed in all water regimes.

Regular observations were taken on ten plants on each sub-plot to record dates of emergence, beginning of flowering (50% of plants with open flowers), end of flowering (major flushes of flowering ceased with only sporadic flowers persisting), and maturity (95% of all pods had lost chlorophyll). At maturity, an area 1.0×1.0 m from the inner rows of each sub-plot was sampled and net above-ground dry matter production and seed yield were determined. Soil water content at sowing and at maturity was determined by gravimetric sampling using 5-cm cores. At sowing 1 core was taken per main plot and at maturity 2 cores were taken from each subplot. The depth of water extraction was assessed

TABLE 1

Soil and crop variables for the two years of experimentation at the Kimberley Research Station

Variables	1979	1980
Soil	Cununurra clay	Ord sandy loam
Water extraction depth (mm)	700	1200
Initial avail. water (mm)	65	75
Transition point from stage 1 to stage 2 soil evap. (mm)	6	10
Stage 2 soil evap. coeff. (mm $d^{-1/2}$)	3.5	5.0
Avail. soil nitrogen (g m^{-2})	1.9	4.8
Crop		
Plant population (pl m^{-2})	25	35
Day of zero plastochron index	11	7
Buchanan: day of termination of leaf growth	30	28
Buchanan: day of begin. linear harvest index	45	45
Durack: day of termination of leaf growth	43	40
Durack: day of begin. linear harvest index	59	55
Nitrogen fixation coeff. (mg N g^{-1} d^{-1})	0.70	0.55

by comparing the soil water profiles at sowing and maturity. The amount of soil nitrogen available for plant uptake was estimated in 1979 from the net amount above-ground nitrogen accumulated by a sorghum crop and in 1980 from the amount accumulated by a grass crop, both grown in plots adjacent to the main experiment under the wet water regime. Further experimental details on the 1980 study are given in Muchow (1985).

Model experiments

The simulation model described by Sinclair (1986) was used. The observed daily maximum and minimum temperature, solar radiation, precipitation and irrigation for each year were meteorological inputs for the simulations. Those variables dependent on soil characteristics were adjusted for each soil type as given in Table 1. The soil variables including the soil nitrogen uptake were obtained from direct studies on the two soil types.

The physiological variables in the model were unchanged from Sinclair (1986) except those that specifically defined the ontogeny of the crops in each of the 2 years (Table 1). The termination of leaf growth was taken as 2 days after the observed date of the beginning of flowering to allow for completion of leaf expansion (Sinclair, 1984), and similarly the beginning of linear harvest index increase was taken as 2 days after the observed date of end of flowering. Since no data were available to estimate the nitrogen fixation coefficient, a single value for both cultivars was selected for each soil that scaled the simulated seed yields to those observed in the wet regime. Consequently, a comparison of the relative yields among treatments simulated by the model is more reliable than a comparison of absolute yields.

Maturity date was not an input to the model, but rather predicted from the crop status. As defined by Sinclair (1986), the model was terminated when the leaf area index of the crop dropped below 0.1 during seed growth. For the drought treatments an additional termination criterion was included. Maturity was also defined to have occurred whenever the fraction of transpirable soil water (FTSW) was less than -0.06, which was the soil water amount when senescence occurred for soybean in glasshouse experiments (Sinclair and Ludlow, 1986).

In addition to using simulations to examine the experimental data, a set of simulations to study the effects of the water and nitrogen limitations on seed yield was performed. In the simulated water-limitation study, no water was applied for 20-day periods at various times during the season. Other than the water limitation periods, the soil was simulated to be fully recharged with water each day. The six periods of water limitation were: none; days 1–20; days 20–40; days 40–60; days 60–80; and days 80–100. In addition, soils with different depths of water extraction were simulated: 400, 700, or 1000 mm (or equivalently 52, 91, or 130 mm of water storage, respectively). Both a short- and a long-season cultivar were simulated with the termination of leaf growth occurring on day 25 and 40, respectively. The beginning of linear increase in harvest index was simulated to begin 18 days after the termination of leaf growth. All other variables were held constant, including soil nitrogen incorporated into the crop at 4 g N m^{-2}, nitrogen fixation coefficient at 0.65 mg N g^{-1} d^{-1}, and plant population at 35 plants per m^{-2}. The meteorological conditions were also held constant throughout the season for this analysis with maximum temperature of 35 °C, minimum temperature of 25 °C, and solar radiation of 20 MJ m^{-2} d^{-1}.

The nitrogen-limitation simulations were done with crops as described above where the soil was fully recharged with water each day. The soil nitrogen incorporated into the crop was varied between 2, 4 and 6 g N m^{-2} and the nitrogen fixation coefficient between 0.50, 0.65, and 0.80 mg N g^{-1} d^{-1}. No attempt was made to account for the inverse correlation commonly found between soil nitrogen and nitrogen fixation rate (Weber, 1966; Hatfield et al., 1974; Hinson, 1975). Again both a short- and a long-season cultivar were simulated.

RESULTS AND DISCUSSION

Experimental observations

In both years and for both soybean cultivars, water deficits substantially reduced crop duration, biomass production and seed yield (Tables 2 and 3).

TABLE 2

Observed and simulated above-ground biomass production ($\mathrm{g\,m^{-2}}$) at maturity and crop duration (days from sowing to maturity) for soybean cultivars Buchanan and Durack grown under three water regimes in 1979 and 1980

Cultivar	Water regime	Biomass ($\mathrm{g\,m^{-2}}$)		Duration (days)	
		Observed	Simulated	Observed	Simulated
1979					
Buchanan	wet	†A 190 b	277	A 100 b	84
	wet/dry	B 136 a	246	B 85 b	77
	dry	C 61 a	167	B 83 b	76
Durack	wet	A 426 a	430	A 104 a	104
	wet/dry	B 145 a	230	B 92 a	85
	dry	C 84 a	199	B 93 a	74
1980					
Buchanan	wet	A 554 a	565	A 86 b	87
	wet/dry	B 329 a	344	B 79 b	80
	dry	C 163 a	176	C 76 b	69
Durack	wet	A 625 a	655	A 97 a	96
	wet/dry	B 343 a	341	B 86 a	84
	dry	C 179 a	178	B 87 a	73

† After log transformation, values for each year within a cultivar across water regimes preceded by the same capital letter are not significantly different at $P < 0.05$;
Values within a water regime between cultivars followed by the same lower case letter are not significantly different at $P < 0.05$.

However, between the 2 years, the two cultivars responded differently both to the weekly irrigation and to water deficits.

Under the wet regime there were no significant differences in biomass production and seed yield between the Buchanan and the Durack cultivars in 1980 compared to the two-fold differences between these cultivars in 1979. Surprisingly, the difference in crop duration between the two cultivars under the wet regime was 11 days in 1980 but only 4 days in 1979. Biomass production and seed yield under the wet regime were also much lower in 1979 than in 1980 despite longer crop durations in 1979 in both cultivars. One might conclude from these experimental observations that productivity under irrigated conditions is not necessarily enhanced by longer crop duration.

There were no significant differences in biomass production and seed yield between Buchanan and Durack in 1979 for either wet/dry or the dry regimes (Tables 2 and 3). However, in 1980, whilst biomass production was similar, seed yields were greater for Buchanan under both water deficit regimes. Biomass production under water deficits was much greater in 1980 than in 1979 in both cultivars, but only in Buchanan were seed yields greater.

TABLE 3

Observed and simulated seed yield (g m^{-2}) for soybean cultivars Buchanan and Durack grown under three water regimes in 1979 and 1980

Cultivar	Water regime	Absolute seed yield (g m^{-2})		Relative seed yield (%)	
		Observed	Simulated	Observed	Simulated
1979					
Buchanan	wet	†A 111 b	122	50	56
	wet/dry	B 77 a	86	35	39
	dry	C 33 a	59	15	27
Durack	wet	A 220 a	218	100	100
	wet/dry	B 69 a	68	31	31
	dry	C 41 a	35	19	16
1980					
Buchanan	wet	A 280 a	268	92	88
	wet/dry	B 122 a	136	40	45
	dry	C 64 a	48	21	16
Durack	wet	A 303 a	303	100	100
	wet/dry	B 67 b	113	22	37
	dry	C 34 b	37	11	12

Relative seed yield is the ratio, expressed as percentage, of absolute seed yield of that of Durack in the wet regime for each year.

† After log transformation, values for each year within a cultivar across regimes preceded by the same capital letter are not significantly different at $P < 0.05$;

Values within a water regime between cultivars followed by the same lower case letter are not significantly different at $P < 0.05$.

Therefore, the field studies resulted in two interesting observations. First, under the wet regime there was little difference in seed yield between Buchanan and Durack in 1980 while in 1979 there was a two-fold difference. Since this treatment was designed to eliminate any drought effects, there is no ready explanation of the yield differences for the two years. Second, in contrast to the wet regimes, Buchanan seed yields tended to be greater with water deficits than Durack. This raises the question of whether differences in relative seed yields for differing drought treatments can be strongly dependent on crop ontogeny.

Model observations

In 1980, there was a generally good agreement between the observed and simulated crop duration, biomass production, and seed yield in all water regimes, with results being most similar in the wet regime (Tables 2 and 3). In 1979, whilst there were some discrepancies between observed and simulated crop duration and biomass production , the simulated seed yields were generally similar to the experimental observations, particularly under the wet regime (Tables 2 and 3). In contrast to the 1979 experimental data, simulated seed yields in both the wet/dry and dry regime in 1979 were greater in Buchanan than in Durack; these observations are similar to both experimental and simulated results in 1980.

It seems possible to use the simulation model to examine the results of the experimental studies by analyzing the behavior of individual processes in the model. In the first case, the relatively small difference in simulated yield between Buchanan and Durack under the wet regime in 1980 was due to the relatively poor performance by the longer-season Durack. Durack was simulated to have more leaf area than Buchanan during seed growth, resulting in a greater water loss rate. For example, on day 75, the leaf area index was simulated to be 1.6 for Durack and only 0.7 for Buchanan. As a consequence, the amount of water supplied in weekly irrigations was insufficient to fully recharge the soil profile for Durack. The soil became sufficiently dry to reduce the nitrogen fixation rate for the simulated Durack crop at a time when the nitrogen required to support seed growth was considerably greater than that for Buchanan. The reduced nitrogen fixation rate inhibited simulated Durack production in the wet regime in contrast to Buchanan which was subjected to much less severe soil dehydration.

To examine further this water limitation under the wet regime in 1980, an optimal irrigation scheme was simulated. Whenever the FTSW dropped below 0.5 the crop was simulated to receive a 75-mm irrigation. Consequently, the FTSW was never allowed to drop sufficiently low to decrease nitrogen fixation, leaf growth or carbon accumulation rates. Little simulated yield increase was obtained from the optimal irrigation for Buchanan because the experimental irrigation scheme already provided adequate soil water for this cultivar. On the other hand, the simulated seed yield of Durack was increased by 20% over the experimental regime (Table 4). Interestingly, the optimal irrigation schedule used in the simulation, rather than weekly irrigation schedule used experimentally, resulted in substantial water savings and improvements in irrigation water-use efficiency by reducing drainage losses for both cultivars (Table 4).

The large difference in simulated yield under the wet regime between Buchanan and Durack in 1979 was due to the very low productivity of Buchanan. For the simulated Buchanan crop the low availability of soil nitrogen for plant uptake and the early termination of leaf growth resulted in both very low leaf area index and vegetative biomass accumulation. Consequently, the simulated seed-yielding potential of Buchanan was markedly decreased. This yield depression associated with low soil nitrogen was examined further in simulations for the wet regime in 1979 by changing only the soil nitrogen available for incorporation into the crop from 1.9 g N m^{-2} to the 1980 value of 4.8 g N m^{-2}. Increasing available soil nitrogen without lowering the nitrogen fixation

TABLE 4

Simulated seed yield (g m^{-2}) and irrigation rate (mm) of optimal irrigation schedule for soybean under the wet regime in 1980 compared to actual values

Cultivar	Actual irrigation	Simulated optimal irrigation†	Change‡ (%)
	Seed Yield (g m^{-2})		
Buchanan	280	286	+ 2
Durack	303	365	+20
	Irrigation (mm)		
Buchanan	669	450	−33
Durack	737	525	−29

† Soil water not allowed to deplete below 0.5 fraction of transpirable water.
‡ % Change of simulated optimal irrigation from experimental irrigation.

coefficient resulted, as expected, in substantial simulated yield increases for both cultivars in 1979 — with Buchanan having the greater percentage increase (Table 5). However, the 1979 field experiment did have a lower plant population (25 plants per m^{-2}) than the 1980 field experiment (35 plants m^{-2}). Simulations using an available soil nitrogen of 1.9 g N m^{-2}, but with the higher 1980 plant population, increased the simulated seed yield of Buchanan and Durack by only 10% and 5% respectively under the wet regime, indicating that the difference in the plant population between the 2 years had only a small impact on yield.

The second major experimental observation of interest was the tendency for seed yields of Buchanan under drought to be greater than those of Durack, particularly in 1980. The simulations similarly showed Buchanan to have the greater seed yield under all dry regimes. The reason for this result in the simulations was that the water deficits shortened the seed growth period of Durack

TABLE 5

Simulations of seed yields (g m^{-2}) with increased available soil nitrogen for soybeans grown under the wet regime in 1979

Cultivar	Similated seed yield (g m^{-2})		
	1.9 g N m^{-2} Soil nitrogen	4.8 g N m^{-2} Soil nitrogen	% Change
Buchanan	122	249	+104
Durack	218	337	+ 55

TABLE 6

Simulated yields (g m^{-2}) for soybeans having different times from sowing to termination of leaf growth and different depths of water extraction subjected to various periods of water limitation

Term. leaf growth (days)	Depth of water extraction (mm)	Period of water limitation (days)					
		None	1-20	20-40	40-60	60-80	80-100
		Seed Yield (g m^{-2})					
25	400	325	322	231	197	238	319
	700	325	324	302	251	290	324
	1000	325	324	316	295	315	324
40	400	516	511	417	321	330	365
	700	516	515	499	403	398	421
	1000	516	515	513	477	461	465

more than of Buchanan. The advantage of the shorter-season cultivar was that it initiated seed growth earlier and produced greater seed mass before water deficits terminated crop growth.

Model analyses

The model was used to analyze the water limitation on soybean yield. The simulation results were consistent with a number of generalizations about soybean production (Table 6). First, the longer-season crop out-produced the shorter-season crop for all conditions tested. In this test, none of the water deficits were sufficiently intense to result in zero seed yield. Since there was no constraint on the total length of the growing season, the longer-season crop had the advantage of extra days of growth. For the crops with no water limitation, the season lasted 112 days for the longer-season crop and 92 days for the shorter-season crop. A second observation from these simulations is that water deficits under any condition always resulted in a yield reduction, similar to the field observations of Doss et al. (1974). The least simulated-yield reductions occurred on the deepest soils and for the period of water limitation earliest in the season. A 20-day period of no water application early in the season had only a mild effect because leaf area was insufficient to result in high transpiration rates and substantial depletion of soil water. Third, deeper soils invariably gave the greater yields. These simulations demonstrated a vulnerability of soybean crops on shallow soils.

A fourth result from the water limitation analyses was that water deficits occurring at the beginning of the linear increase in harvest index tended to have the greatest effect on yield. While this observation has been made experimentally in soybean (Doss et al., 1974; Korte et al., 1983), it might be assumed

TABLE 7

Simulated yields ($g\ m^{-2}$) for soybeans having different times from sowing to termination of leaf growth, different amounts of available soil nitrogen and different nitrogen fixation coefficients

Term. leaf growth (days)	Soil N ($g\ N\ m^{-2}$)	Nitrogen fixation coeff. ($mg\ N\ g^{-1}\ d^{-1}$)		
		0.50	0.65	0.80
		Seed Yield ($g\ m^{-2}$)		
25	2	130	215	318
	4	208	325	460
	6	290	428	583
40	2	220	368	542
	4	325	516	725
	6	399	603	829

that the response results from interference of water deficits with reproductive processes such as pollination, fertilization, and early embryonic growth (Shaw and Laing, 1966). The model contains none of these responses; rather the greater sensitivity during this early reproductive development was associated with the greatest demand for water during this period. Consequently, in the simulations, the period of maximal leaf area and biomass accumulation rate resulted in the greatest soil water depletion rate, and hence the greatest resultant depression in physiological activity. Much of the observed yield reductions associated with water shortage at flowering and early pod-fill may have little to do with any direct effects of water deficits on reproductive physiology.

The analysis of the nitrogen limitation on soybean yield showed that any increase in the nitrogen input to the crop always increased yield (Table 7). Increases in either the amount of soil nitrogen incorporated in the crop or the nitrogen fixation coefficient increased simulated yields. The negative feedback of increased available soil nitrogen on the nitrogen fixation coefficient that is commonly observed with soybean was not considered in the model. These simulations showed a synergistic effect when both variables were increased. With no constraint on the length of the growing season, large nitrogen inputs for the longer-season crop were simulated to produce yields substantially greater than any observed values. The crop simulated to grow for 125 days and a final harvest index of 0.75 yielded 829 $g\ m^{-2}$. These results support the view that nitrogen input is a major constraint to high soybean yields.

CONCLUSIONS

The results of the field and modeling analyses showed the great importance of both the water and nitrogen limitations on soybean yield. The field experiments clearly confirmed the drastic decline in yields with limited water availability. However, by analyzing the 1980 data for the irrigated treatment with the model it also appeared that under conditions that are seemingly adequately irrigated, brief episodes of water shortage can develop that have negative impacts on yield. Certainly the model showed that water can be managed in a semi-arid tropical environment so the ratio of yield to amount of irrigation water applied can be substantially improved over that obtained experimentally with scheduled irrigations. Simulated water deficits at any period during crop growth reduced yield, with the greatest yield decreases resulting from water shortages which occurred during periods of greatest water use, i.e. at the beginning of seed growth.

Comparison of the experimental results between the two levels of soil nitrogen available for plant uptake showed the importance of the nitrogen limitation on yield. The low yield of irrigated Buchanan in 1979 was shown from the model analysis to be primarily due to the low soil nitrogen. Any simulated increases in the nitrogen input resulted in increased crop yields. The simulations indicated that the nitrogen input as limited by the incompatibility of high soil nitrogen and nitrogen fixation rate might be a particularly restrictive aspect of soybean growth.

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