AGROCLIMATOLOGY AND MODELING

Water Deficit Effects on Maize Yields Modeled under Current and "Greenhouse" Climates

R. C. Muchow and T. R. Sinclair*

ABSTRACT

The availability of water imposes one of the major limits on rainfed maize (*Zea mays* L.) productivity. This analysis was undertaken in an attempt to quantify the effects of limited water on maize growth and yield by extending a simple, mechanistic model in which temperature regulates crop development and intercepted solar radiation is used to calculate crop biomass accumulation. A soil water budget was incorporated into the model by accounting for inputs from rainfall and irrigation, and water use by soil evaporation and crop transpiration. The response functions of leaf area development and crop gas exchange to the soil water budget were developed from experimental studies. The model was used to interpret a range of field experiments using observed daily values of temperature, solar radiation, and rainfall or irrigation, where water deficits of varying durations developed at different stages of growth. The relative simplicity of the model and its robustness in simulating maize yields under a range of water-availability conditions allows the model to be readily used for studies of crop performance under alternate conditions. One such study, presented here, was a yield assessment for rainfed maize under possible "greenhouse" climates where temperature and atmospheric CO_2 concentration were increased. An increase in temperature combined with decreased rainfall lowered grain yield, although the increase in crop water use efficiency associated with elevated CO_2 concentration, ameliorated the response to the greenhouse climate. Grain yields for the greenhouse climates as compared to current conditions increased, or decreased only slightly, except when the greenhouse climate was assumed to result in severely decreased rainfall.

R.C. Muchow, CSIRO Division of Tropical Crops and Pastures, Cunningham Laboratory, 306 Carmody Rd., St. Lucia, Q. 4067, Australia; and T.R. Sinclair, USDA-ARS, Agronomy Dep., Univ of Florida, Gainesville, FL 32611. Received 27 Aug. 1990. *Corresponding author.

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RECENTLY, Muchow et al. (1990) examined the effects of variation in solar radiation and temperature on the potential yield of maize across locations using a simple, mechanistic crop growth model. Leaf and crop development were calculated from daily mean temperature; daily biomass accumulation was calculated by estimating the amount of radiation intercepted and assuming a maximum crop radiation efficiency of 1.6 g MJ^{-1} (total solar radiation); and grain accumulation was simulated using a linear increase in harvest index during grain filling. This model was able to explain variation in potential grain yield from 8 to 18 t ha^{-1} at locations ranging from 14 °S to 40 °N.

Maize grown under rainfed conditions rarely reaches its potential yield because of water deficits. Many studies have examined the effects of water deficits on maize yield. However, the experimental results vary depending on the timing and intensity of water deficits, as well as location, soil type and cultivar (Denmead and Shaw, 1960; Claassen and Shaw, 1970; Grant et al., 1989; Sinclair et al., 1990). While some generalizations have been possible from these experiments, the inherent variability of field experiments where temperature, radiation, and water supply interact in determining grain yield, makes extrapolations from any single experiment difficult. An alternative approach is to use a crop growth model that accounts for these variables, in order to understand the water limitation to maize productivity.

Abbreviations: DAS, days after seeding; FTSW, fraction of transpirable soil water; TTSW, total potential store of transpirable soil water; and RT, relative transpiration rate.

In this paper, we extend the analysis of maize growth under variable temperature and solar radiation outlined by Muchow et al. (1990), by incorporating the effect of soil water supply. Similar to the approach used to examine the water limitation to soybean [*Glycine max* (L.) Merr.] yield (Sinclair, 1986; Muchow and Sinclair, 1986) and wheat (*Triticum aestivum* L.) yield (O'Leary et al., 1985; Amir and Sinclair, 1991), potential leaf area development and transpiration were decreased as functions of the fraction of total extractable soil water currently available in the root zone. Since these physiological processes are sensitive to the fraction of available soil water, the extractable soil water store needs to be modeled. Consequently, a soil water budget accounting for inputs from rainfall and irrigation, and for water use by soil evaporation and crop transpiration, needs to be incorporated into the simple crop growth model.

The objectives of this study were threefold. Firstly, the response functions of leaf area development and transpiration to soil drying were determined experimentally and were incorporated into the simple maize model of Muchow et al. (1990). Secondly, the water-deficit model was used to interpret a range of field experiments conducted on an alfisol in tropical Australia, where water was withheld at different stages of growth for varying durations (Muchow, 1989 a,b). Thirdly, the model was used to examine the impact of possible "greenhouse" climates (i.e. increased temperature and atmospheric CO_2 concentration) on rainfed maize productivity in comparison to current climatic conditions at Katherine, Australia, and Champaign, IL. The consequences of climate change were simulated as increases in daily mean temperature, increases or decreases in daily rainfall, and an increase in the physiological efficiency of plant water use.

MODEL DESCRIPTION

The model presented by Muchow et al. (1990) to describe the response of maize growth and yield to solar radiation and temperature provided the model framework. Two important physiological processes in the model directly restricted by decreasing soil water content are leaf area development and radiation use efficiency. The model of Muchow et al. (1990) was altered so that each of these processes were dependent on relative soil water content. Functions, which were derived from experiments presented subsequently, were used as multipliers of physiological activity calculated for unstressed conditions and had values ranging from zero to one.

The degree of soil drying was expressed by the fraction of transpirable soil water (FTSW) defined by Sinclair and Ludlow (1986). Here FTSW is the fraction of water remaining in the soil out of the total potential store of transpirable soil water (TTSW). This TTSW differs from the more commonly used available soil water in that the lower limit is defined by the volumetric soil water content where daily transpiration rates of drought-stressed plants become less than 10% of well-watered plants. For these simulations, TTSW was set equal to 135 mm based on the field observations described subsequently. In more general use, it may be possible to estimate TTSW by defining the depth of water extraction and multiplying by the volumetric fraction of available soil water (usually about 0.13, Ratliff et al., 1983).

In the model, the estimate of FTSW was adjusted daily, based on addition and removal of water. Rainfall and irrigation were added directly to the water store. Any water in excess of TTSW plus 4 mm was assumed to be lost from the system as runoff or deep percolation. In addition, the soil infiltration rate was assumed to be limiting for any rain in excess of 40 mm, and only up to 40 mm per rain was retained in the soil.

Soil evaporation was calculated using the two-stage model as proposed by Doraiswamy and Thompson (1982) and O'Leary et al. (1985), and implemented in the spring wheat model developed by Amir and Sinclair (1991). Stage I evaporation occurred when water is present in the top 150 mm of soil and FTSW for the total soil profile was greater than 0.5. Evaporation rate was calculated from the Penman energy-balance equation and was based on the solar radiation which penetrates the crop canopy. Because the soil surface was moist in Stage I, it was assumed that the minimum soil evaporation rate was 1.5 mm d^{-1} (Amir and Sinclair, 1991). Due to an expected mulch effect of the killed weed cover remaining on the soil surface in these experiments, a maximum evaporation rate of 5 mm d^{-1} was assumed (Bond and Willis, 1969; Unger and Parker, 1976).

Stage II soil evaporation occurred when the water in the top layer was exhausted or the FTSW for the total soil profile was less than 0.5. In Stage II, the potential rate of soil evaporation was also calculated from the Penman equation, but it was decreased substantially as a function of the square root of time since the start of Stage II. Consequently, soil evaporation rates in Stage II were small and decreased with time. The calculation of soil evaporation returned to Stage I only when a rain or irrigation of greater than 4 mm occurred.

To complete the calculation of the soil water budget, daily transpiration rate was determined. Tanner and Sinclair (1983) showed that the ratio of crop biomass accumulation to transpiration is equal to a water use efficiency coefficient divided by a daily vapor pressure deficit. Consequently, daily transpiration rate was calculated directly from the daily rate of biomass accumulation multiplied by the water use efficiency coefficient, and divided by an estimate of the vapor pressure deficit (Sinclair, 1986; Amir and Sinclair, 1991). The water use efficiency coefficient was set at 0.09 mbar (9 Pa) as determined by Tanner and Sinclair (1983) for experimental maize crops. The calculation of daily vapor pressure deficit was suggested by Tanner and Sinclair (1983) to be approximately 0.75 of the difference between saturated vapor pressures calculated from daily maximum and minimum temperatures. The amount of water lost through transpiration was deducted from the soil water.

Transpiration also resulted in water loss from the top 150-mm soil layer, which supports Stage I soil evaporation. It was assumed that transpiration occurred preferentially from the top soil layer when the top layer was moist. However, as the top soil layer dried, it was assumed that water extraction by transpiration decreased as a function of the fraction of available transpirable soil water in the top layer. The function developed for the transpiration response to the entire soil layer was applied solely to the 150-mm layer. In effect, dehydration of the top soil layer resulted in less water being extracted daily from the top layer and increased extraction below 150 mm.

MATERIALS AND METHODS

Experimental Response of Transpiration and Leaf Development to Soil Drying.

The responses of transpiration and leaf area development to various degrees of soil drying were determined from a pot experiment similar to that conducted on soybean by Sinclair and Ludlow (1986). 'Dekalb XL82' maize was grown in 20-L pots in the field at Katherine, N.T., Australia. Twelve pots were filled with a potting mix consisting of equal volumes of peat and coarse sand. A second set of 12 pots were filled with Fenton clay loam (Lucas et al., 1987), which is a well drained red earth or alfisol (USDA Soil Taxonomy: Oxic or Rhodic Paleustalf). All pots were well watered and supplied with a complete nutrient solution until five or six leaves were fully expanded. The exposed soil surface was then covered with aluminum foil to prevent direct soil evaporation.

The initial weight of each pot at the commencement of the drying cycle was measured after fully watering the pots and allowing them to drain for 2 to 3 h. For the next 2 d, each pot was weighed during mid-morning and recharged with the amount of water transpired. These data on plant transpiration rates were used to normalize any differences in water loss among pots due to differences in the size of the transpiring surfaces. The area of each leaf on the plant was determined by multiplication of 0.75 times the product of measured blade length and width (McKee, 1964). Then six pots of each soil type were kept well watered and six were exposed to a drying cycle. Each pot was weighed daily and the area of the expanding leaves was measured. The leaf area development and transpiration rates of the drying pots were expressed as ratios of those in the well-watered pots. After weighing, the well-watered pots were recharged with water. Half the drying pots were watered with about half their daily water use, while no water was added to the remaining drying pots. This gave a range in soil water content in the drying pots.

The relative rates of both transpiration and leaf area development were expressed as functions of FTSW. To calculate FTSW in these experiments, TTSW was calculated as the weight difference between the initial weight of each pot after it had been watered and allowed to drain, and the weight when the daily transpiration rate decreased to less than 10% of the well-watered plants. The FTSW was calculated each day as the fraction of the transpirable soil water still remaining in the pot.

Response to Grain Yield to Water Deficit.

Field experiments were conducted from 1983 to 1988 at Katherine Research Station, N.T., Australia (14° 28′ S, 132° 18′ E; altitude 108 m) on Fenton clay loam. Dekalb XL82 maize was sown at the dates shown in Table 1. For each experiment represented by the different sowing dates, one treatment was well watered, and water was withheld in other treatments for specified periods during different stages of crop growth (Table 1). Except during the specified periods for limiting water, all treatments were sprinkler irrigated with 30 to 40 mm of water after four consecutive rainfree days.

All sowings were grown under identical cultural conditions as outlined in Muchow (1989 a,b). Two weeks prior to each sowing, glyphosate (*N*-[phosphonomethyl]glycine) at 175 mg m^{-2} was applied to kill *Urochloa mosambicensis* (Hack.) Dandy weed growth. Prior to each sowing, a broadcast application of 5 g m^{-2} of K as muriate of potash was made. At each sowing, 3 g m^{-2} of P as single superphosphate, $CuSO_4$ at 0.3 g m^{-2}, Z_4SO at 0.38 g m^{-2}, and Na_2Mo at 0.025 g m^{-2} were banded into the soil. At each sowing, 12 g m^{-2} of N was broadcast as ammonium nitrate and a side-dressing of 6 g m^{-2} of N as urea was broadcast at 35 and 70 d after sowing (DAS). Terbufos (Phosphorodithioic acid *S*-[[(1,1-dimethylethyl)thio]methy]*o,o*-diethyl ester) at 150 mg m^{-2} was also applied at sowing to control seed-harvesting ants.

Seed, dressed with Metalaxyl (*N*-[2,6-Dimethylphenyl]-*N*-[methoxyacetyl]-DL-alanine methyl ester) at 2.1 mg g^{-1} for protection against preemergence herbicides, was sown into the mulch in 50 cm rows. Two weeks later, seedlings were thinned to 7 plants m^{-2}. Immediately after each sowing, Metolachlor (2-Chloro-*N*-[2-ethyl-6-methylphenyl]-*N*-[2-methoxy-1-methylethyl]acetamide) at 180 mg m^{-2} and atrazine at 125 mg m^{-2} were applied; these gave good weed control throughout the experiments. *Heliothis armigera* Hübner was controlled by applications of Permethrin (3-[2,2-Dichloroenthenyl]-2,2-dimethylcyclopropanecarboxylic acid [3-phenoxyphenyl]methyl ester) at 10 mg m^{-2} and leaf diseases were controlled using Chlorothalonil (2,4,5,6-Tetrachloro-1,3-benzenedicarbonitrile) at 125 mg m^{-2}, and the chemicals were sprayed together every 1 to 2 wk. Leaves remained free of disease throughout all experiments.

The dates of silking (extrusion of silks on more than 50% of the panicle) and maturity (presence of black layer on 90% of grains) were established by scoring five adjacent tagged plants. At silking and maturity, plants in a 2-m^2 quadrat were cut at ground level from the inner rows of each plot. A representative subsample of 10 maize plants was taken, and the fresh weights of the subsample and the remainder of the sample were determined. Net above-ground biomass was determined after drying the subsample at 80 °C. Where appropriate, the ears from the subsample were threshed and grain yield was determined.

Additional data were collected on the 10 Oct. 1984 sowing. Biomass was determined regularly during crop growth, and soil water content in the 180-cm soil profile was determined

Table 1. Effect of no water application either by irrigation or rainfall for specified intervals on observed silking date, and observed and simulated oven-dry grain yield, for different sowings. The mean daily vapor pressure deficit from sowing to maturity is also given. Simulated grain yields under well-watered conditions (fraction of transpirable soil water held at 1.0) are given in parentheses.

Sowing date	Water withheld	Vapor pressure deficit	Silking	Observed grain yield	Simulated grain yield
	days from sowing	kPa	days from sowing	g m^{-2}	
25 Nov. 83	nil	1.86	50	832	796 (796)
	10–28	1.86	53	742	796
7 Feb. 84	nil	1.87	49	809	837 (837)
	51–89	1.72	48	420	322†
10 Oct. 84	nil	2.44	51	817	832 (833)
	35–57	2.61	52	0	0†
	41–57	2.61	51	86	34†
6 Feb. 85	nil	1.93	49	809	810 (810)
	53–65	1.93	49	773	806
	53–65, 72–108	1.93	49	591	721
20 Aug. 85	nil	2.69	62	763	736 (884)
	20–44	2.69	63	522	573
	64–92	2.80	62	171	178†
30 Aug. 86	nil	2.59	53	820	832 (832)
	20–44	2.59	55	621	784
17 Feb. 87	21–28, 30–47, 49–110	2.21	56	100	57†
2 Feb. 88	nil	2.27	49	823	819 (819)
	18–36, 61–110	2.23	50	419	614†

† Soil water depleted to crop kill point.

using neutron moderation at the end of the drying cycle (57 DAS). The total amount of soil water extracted by the maize crop was calculated as the difference in the amount of water between the drained upper limit of Fenton clay loam and the amount measured at 57 DAS. The soil profile measured at 57 DAS for the 10 Oct. 1984 sowing was the driest profile measured for maize on this soil type.

Simulation Experiments.

The crop growth model was run for each of the sowings and treatments shown in Table 1. The meteorological inputs required to simulate each field experiment were the daily maximum and minimum temperature, solar radiation, precipitation, and irrigation. In addition to simulating actual available soil water, the model was run for each sowing of the well-watered treatment, holding FTSW each day at 1.0. These simulations were designed to test whether the irrigation schedule for the well-watered treatments was adequate to ensure these crops experienced no water deficit.

Simulations were also run to examine the effects of possible greenhouse climates on the productivity of rainfed maize. Crops sown on 6 Feb. 1985 at Katherine and on 4 May 1982 at Champaign (Muchow et al., 1990), were simulated using the observed daily radiation, temperature, and rainfall for these sites. The limitation on soil evaporation rate of 5 mm d^{-1} due to weed debris on the soil surface was deleted for the Champaign simulations. To simulate possible greenhouse climates, both temperature and rainfall were varied. Observed temperature was increased by either 2 or 4 °C to simulate possible temperature changes resulting from global warming. The amount of rain in each rainfall was changed by −30, −15, +15 or + 30% to evaluate a range of possible rainfall changes. All combinations of the above temperature and rainfall conditions were simulated.

No crop physiological parameter was altered for the first set of greenhouse climate simulations. However, increases in atmospheric CO_2 concentration may also have direct effects on the crop. Although the photosynthetic rates in maize are likely to be approximately equal to current rates (Gifford and Musgrave, 1970; Surano and Shinn, 1984), stomatal closure in response to increasing CO_2 concentration by 300 μL L^{-1} results in approximately a one-third increase in crop water use efficiency (Surano and Shinn, 1984). Rogers et al. (1983) found a 43% increase in maize water use efficiency when plant growth under 600 μL CO_2 L^{-1} was compared to growth under ambient concentrations. To mimic this response, the water use efficiency coefficient was increased from 9 to 12 Pa in a second set of simulations. All other crop parameters were unchanged.

RESULTS AND DISCUSSION

Experimental Response to Transpiration and Leaf Development to Soil Drying.

The relationships between FTSW and both relative transpiration and the leaf area development were unaffected by soil type (Fig. 1 and 2). Transpiration did not decline until FTSW fell below 0.3, with a substantial decline below a FTSW of 0.2 (Fig. 1). This response is similar to that reported for maize by Ritchie (1973) and by Grant et al. (1989), for sorghum [*Sorghum bicolor* (L.) Moench] (Rosenthal et al., 1989) and for several species of grain legumes (Sinclair and Ludlow, 1986). The results in Fig. 1 were fitted by nonlinear regression to the following logistic function,

$$RT = 1/[1 + 9 \times \exp(-15.3 \times FTSW] , \quad [1]$$

where RT is the relative transpiration rate, and the standard error for the coefficient 15.3 was 0.61. Function [1] was used in the model to adjust radiation use efficiency in response to soil water content, i.e. FTSW. For example, RT equals 0.92, 0.70, and 0.34 at FTSW equal to 0.3, 0.2, and 0.1, respectively.

The relationship between relative leaf area development and FTSW (Fig. 2) was similar to that for relative transpiration in that relative leaf area development declined once FTSW dropped below about 0.3. The function obtained by non-linear regression to describe relative leaf area development (RL) in Fig. 2 is,

$$RL = 1/[1 + 270 \times \exp(-32.2 \times FTSW)] . \quad [2]$$

where the standard error for the coefficient 270 was 288.3 and for 32.2 was 6.34. Function [2] indicates that the decrease in relative leaf area development as the soil dries is more precipitous than the relative gas exchange; for example, RL equals 0.98, 0.70, 0.08 at FTSW equal to 0.3, 0.2, and 0.1, respectively. Once FTSW falls below 0.2, leaf area development is rapidly inhibited with virtually no leaf area increase below FTSW of 0.1 (Fig. 2). This response in leaf area development is similar to that observed for soybean by Sinclair (1986) but differs from that observed for sorghum by Rosenthal et al. (1989), where relative leaf area development decreased below FTSW of 0.5 and reached zero at FTSW of zero. Function [2] was used directly in the model to describe alterations in leaf area development in response to soil dehydration.

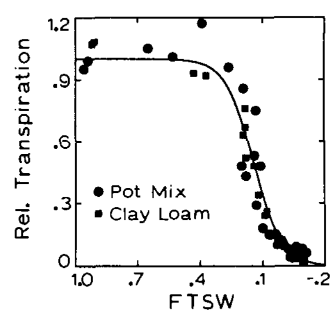

Fig. 1. Relationship between relative transpiration and fraction of transpirable soil water (FTSW) for Dekalb XL82 maize grown in pots filled with potting mix or Fenton clay loam. The solid line is the logistic function presented in the text (Function [1]).

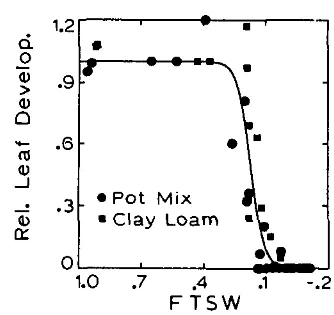

Fig. 2. Relationship between relative leaf area development and fraction of transpirable soil water (FTSW) for Dekalb XL82 maize grown in pots filled with potting mix or Fenton clay loam. The solid line is the logistic function presented in the text (Function [2]).

Field Response of Grain Yield to Water Deficit.

The timing and intensity of water deficit varied among sowings, resulting in oven-dry grain yields ranging from 0 to 773 g m^{-2} (Table 1). As reported previously by many workers (e.g. Denmead and Shaw, 1960; Grant et al., 1989), water deficit around silking was confirmed in our studies to markedly depress grain yields (Table 1). However, in the different sowings in our experiments, timing of water deficit was confounded with varying evaporative demand because daily vapor pressure deficit varied from 1.72 to 2.80 kPa. For example, when water was withheld in the 2 Feb. 1988 sowing from 18 to 36 and 61 to 110 DAS, grain yield was higher than in the 20 Aug. 1985 sowing when water was withheld from only 64 to 92 DAS (Table 1). This occurred because the daily vapor pressure deficit was much higher in the 20 Aug. 1985 sowing (2.80 vs. 2.23 kPa).

The profile of soil water extraction when water was withheld from 35 to 57 DAS in the 10 Oct. 1984 sowing showed that little water was extracted below a depth of 120 cm (Fig. 3). By 57 DAS in this treatment, the maize crop had extracted 137 ± 12 mm of water below the drained upper limit. When this treatment was then fully irrigated after 57 DAS, there was no recovery and no further increase in biomass production (Fig. 4). This observation was used to define the termination of crop growth or the "kill point" of the crop in terms of soil water content. Consequently, for the Katherine site TTSW was set equal to 135 mm and it was assumed crop growth was terminated (kill point) when FTSW was less than 0.0.

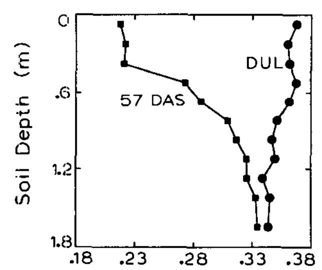

Fig. 3. Volumetric water content at different depths in the profile of Fenton clay loam, at the drained upper limit (DUL) and at the lower limit measured at 57 days after seeding for Dekalb XL82 maize sown on 10 Oct. 1984.

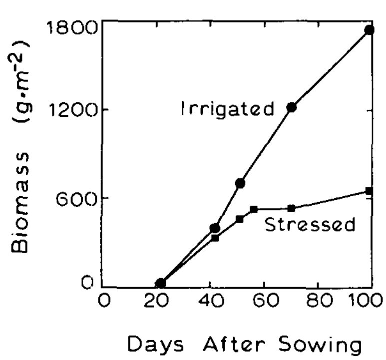

Fig. 4. Biomass accumulation over time for Dekalb XL82 maize sown on 10 Oct. 1984 and grown under fully irrigated conditions and where water was withheld from 35 to 57 days after seeding.

Simulations of Katherine Experiments.

Using the observed daily maximum and minimum temperature, solar radiation, precipitation, and irrigation to do simulations for each sowing and treatment at Katherine, generally close agreement was obtained between observed and simulated grain yields (Fig. 5). In all but four cases, the simulated yields were within 55 g m^{-2} of observed yields. Three of the cases where deviation between simulated and observed yields were greatest were due to an overprediction in yield by the model. There is a possibility that the relatively low observed yields in these cases may have occurred due to factors in addition to the simulated environmental factors.

Use of the model also allowed greater understanding and wider interpretation of the field experiments. One example is the well-watered treatment sown on 20 Aug. 1985, where the observed grain yield was 763 g m^{-2} and the simulated grain yield was 736 g m^{-2} (Table 1). Redoing the simulation for this sowing but holding FTSW at 1.0 (i.e. the potential yield simulated by Muchow et al., 1990) produced a grain yield of 884 g m^{-2}. This simulated result indicates that the irrigation schedule for this "well-watered" treatment was inadequate to prevent some water deficit under the high prevailing vapor pressure deficit during the growth of this treatment (Table 1). Inspection of the trends of FTSW simulated using the actual irrigation schedule showed that FTSW ranged from 0.45 down to 0.04 during the period from 55 to 90 DAS. Functions [1] and [2] result in decreased rates of biomass accumulation and leaf area development when FTSW falls below about 0.3. Interestingly, for every other sowing, the irrigation schedule in the well-watered treatment was adequate to prevent the occurrence of water deficit (Table 1).

Another example of the use of the model to interpret an experiment was in the treatment where water was withheld from 64 to 92 DAS in the 20 Aug. 1985 sowing. The observed yield in this treatment was only 171 g m^{-2} and the harvest index was 0.18. In the model, soil drying occurred rapidly during the dry period due to the presence of a large leaf canopy (LAI of 3.6 simulated at 64 DAS) and an inadequate amount of irrigation prior to withholding water at 64 DAS. Consequently, the simulated crop reached the crop kill point (FTSW less than 0.00) at 73 DAS, and produced

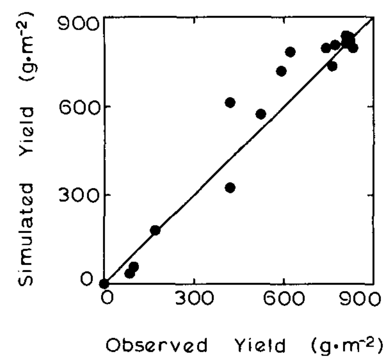

Fig. 5. Comparison of simulated and observed grain yields for the 18 experimental tests. Solid line represents 1:1 correspondence between simulated and observed grain yields.

a grain yield of 178 g m^{-2} with a harvest index of 0.18. The model simulations indicated the importance of the crop reaching the kill point only 9 d after withholding water, with a consequent massive reduction in grain yield.

Model Sensitivity to Climate Change.

When actual daily temperature and solar radiation under rainfed conditions were used as the input data to the model, the simulated grain yield for the 6 Feb. 1985 sowing at Katherine was 576 g m^{-2} (Table 2). Modeling an increase in temperature of 2 °C with actual rainfall decreased yield because the duration from sowing to maturity was decreased from 99 to 91 d. However, the shortening of the growing season resulted in little saving in water (Table 2) due to the higher daily vapor pressure deficit calculated from the higher daily mean temperature. With a further 2 °C increase in temperature, grain yield decreased substantially due to the crop dying well before the expected maturity date.

As expected, grain yield was decreased by less rain and increased by more rain (Table 2). However, the combination of increasing temperature and decreasing rainfall was especially severe in decreasing yield, because the soil water became sufficiently low that the crops were killed. The yield gain achieved with a 30% increase in rainfall under current temperature conditions (687 vs. 576 g m^{-2}) was completely negated by a 4 °C rise in temperature (551 g m^{-2}) due primarily to a decrease in crop duration from 99 to 84 d. Water use was less responsive to temperature change than grain yield, because essentially all available water was used during crop growth irrespective of the climatic conditions (Table 2).

An increase in the water use efficiency coefficient resulting from increased atmospheric CO_2 concentration increased grain yield under all conditions, particularly under lower rainfall and higher temperature conditions where crops did not reach the kill point (Table 2). Importantly, simulated grain yields using a water use efficiency coefficient of 12 Pa were greater than the simulated yield for current conditions (576 g m^{-2}) at all temperatures except where rainfall was decreased. Even under conditions of decreased rainfall and higher temperature, the loss in grain yields when compared to current conditions was rather modest. These results do not indicate catastrophic effects resulting from a greenhouse climate change. Water use was relatively unaffected by a higher water use efficiency coefficient. The only exception occurred under lower rainfall and higher temperature conditions where the increase in biomass production resulted in greater crop transpiration.

At Champaign, the observed and simulated grain yields under fully irrigated conditions for the 4 May 1982 sowing were 1101 and 1115 g m^{-2}, respectively (Muchow et al., 1990). In the absence of irrigation, the simulated grain yield was 831 g m^{-2} (Table 3). An increase in temperature decreased the duration from sowing to maturity, and consequently, decreased grain yield under current or greater rainfall. In contrast to the simulations at Katherine (Table 2), an increase in temperature actually improved yield under some lower rainfall conditions, as the crop was more advanced in grain growth before the crop kill point was reached (Table 3). An increase in rainfall increased yield more at Champaign than at Katherine (Tables 2 and 3), and at Champaign the yield increase due to 30% higher rainfall was only partially negated by a 4 °C increase in temperature. This result was obtained due to lower unadjusted mean temperature at Champaign compared with Katherine (23.6 vs. 26.3 °C; Muchow et al., 1990), and consequent lower daily vapor pressure deficit at Champaign. At both Champaign and Katherine, water use was less responsive to climate change than was grain yield (Table 3) because much of the available water was used no matter what the climatic conditions.

Similar to Katherine, an increase in the water use efficiency coefficient from 9 to 12 Pa caused grain yields at Champaign to increase relative to the yield simulated for current conditions (831 g m^{-2}), except for the most severe conditions (Table 3). At Champaign, a 30% decrease in rainfall resulted in severe

Table 2. Simulated grain yield and water use of maize grown at Katherine, Australia, in response to climate change simulated as an increase in daily mean temperature of 2 and 4 °C, an increase or decrease in rainfall by 15 and 30%, and an increase in the water use efficiency coefficient from 9 to 12 Pa. Sowing date was 6 Feb. 1985.

	Water use efficiency coefficient 9 Pa Grain yield (g m^{-2})				Water use efficiency coefficient 12 Pa Grain yield (g m^{-2})		
	Change in temperature (°C)				Change in temperature (°C)		
Change in rainfall (%)	0	+2	+4	Change in rainfall (%)	0	+2	+4
−30	463†	131†	136†	−30	583†	528	479
−15	516†	130†	159†	−15	643	585	527
0	576†	524	184†	0	712	644	577
+15	636	572	514	+15	769	698	619
+30	687	621	551	+30	799	729	649
	Water use (mm)				Water use (mm)		
	Change in temperature (°C)				Change in temperature (°C)		
Change in rainfall (%)	0	+2	+4	Change in rainfall (%)	0	+2	+4
−30	322	260	262	−30	320	318	315
−15	352	277	279	−15	348	346	341
0	382	381	296	0	374	371	364
+15	412	408	400	+15	397	394	382
+30	440	435	423	+30	409	408	395

† Soil water depleted to crop kill point.

Table 3. Simulated grain yield and water use of maize grown at Champaign, Illinois in response to climate change simulated as an increase in daily mean temperature of 2 and 4 °C, an increase or decrease in rainfall by 15 and 30%, and an increase in the water use efficiency coefficient from 9 to 12 Pa. Sowing date was 4 May 1982.

	Water use efficiency coefficient 9 Pa *Grain yield* ($g\ m^{-2}$)				Water use efficiency coefficient 12 Pa *Grain yield* ($g\ m^{-2}$)		
Change in rainfall (%)	Change in temperature (°C) 0	+2	+4	Change in rainfall (%)	Change in temperature (°C) 0	+2	+4
−30	118†	188†	250†	−30	491†	607†	454†
−15	488†	361†	425†	−15	903	873†	814†
0	831	761†	735†	0	1010	958	907
+15	915	871	824	+15	1069	992	941
+30	971	910	884	+30	1103	1017	952
	Water use (mm)				Water use (mm)		
Change in rainfall (%)	Change in temperature (°C) 0	+2	+4	Change in rainfall (%)	Change in temperature (°C) 0	+2	+4
−30	403	404	404	−30	429	430	404
−15	487	462	461	−15	532	531	492
0	580	537	535	0	562	538	520
+15	604	586	570	+15	575	548	533
+30	625	603	595	+30	587	559	543

† Soil water depleted to crop kill point.

drought stress and the crops were killed prior to maturity. Only a small decrease in water use was achieved at Champaign by increasing the water use efficiency coefficient to 12 from 9 Pa.

CONCLUSIONS

The simple model framework outlined by Muchow et al. (1990) to describe potential maize yield as functions of temperature and radiation was readily extended to describe the response to limited water. The key additional functions were the responses of leaf area development and of gas exchange to the fraction of transpirable soil water available in the root zone. To estimate the fraction of transpirable soil water, a soil water budget that accounted for inputs from rainfall and irrigation and water use by soil evaporation and crop transpiration was incorporated into the model. With these additions, this simple model was sufficiently robust to simulate the effect of water deficits on observed maize productivity where yields ranged from 0 to 773 $g\ m^{-2}$.

This work also highlighted two uses of model simulation, namely interpretation of field experimental data where complex interactions occur and examination of the impact of varying input conditions or rate variables. The interpretation of the effect of timing of water deficit under different environmental conditions was facilitated by the model. It also allowed the assessment of whether the well-watered experimental treatments actually experienced no water deficit. The impact of possible greenhouse climates on rainfed maize productivity was also examined using the model. While an increase in temperature and lower rainfall decreased grain yield, the compensating effect of an increase in the crop water use efficiency because of stomatal closure in response to increasing CO_2 concentration caused overall, little or no decrease in simulated grain yield as compared to current conditions. These results indicate that catastrophic effects resulting from a greenhouse climate change are unlikely unless there are dramatic decreases in rainfall.

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