STATISTICS

Temperature and Solar Radiation Effects on Potential Maize Yield across Locations

R.C. Muchow, T.R. Sinclair,* and J.M. Bennett

ABSTRACT

The objective of this analysis was to use a simple, mechanistic crop growth model to examine the effects of variation in solar radiation and temperature on potential maize (*Zea mays* L.) yield among locations. Crop phenology and leaf growth were calculated from daily mean temperature data obtained at the five locations studied. Daily biomass accumulation was calculated by estimating the amount of radiation intercepted and assuming maximum crop radiation use efficiency of 1.6 g MJ^{-1}. Grain yield accumulation was simulated using a linear increase in harvest index during grain filling. Observed and simulated grain yields were compared for several sowings at each of five locations ranging from latitude 14°S to 40°N lat. Averaged across sowings, respective observed and simulated oven-dry grain yields (g m^{-2}) were 816 and 830 at Katherine, Australia; 953 and 908 at Gainesville, FL; 1059 and 1106 at Quincy, FL; 1091 and 1119 at Champaign, IL; and 1580 and 1626 at Grand Junction, CO. Temperature primarily affected growth duration with lower temperature increasing the length of time that the crop could intercept radiation. The solar radiation response was related to the amount of incident radiation and to the fraction of radiation intercepted by the crop. In the tropics (Katherine), high temperature decreased the duration of growth and grain yield, despite high levels of radiation. Only at locations with low temperature and consequent long growth duration, and with high radiation were maize yields simulated to be more than 1600 g m^{-2} (300 bushels per acre at 15.5% moisture).

SOLAR RADIATION and temperature are two weather variables that have a direct and significant effect on crop production. Under well-watered conditions and ample nutrition, in the absence of pests and diseases, maize yield has been shown to be closely related to the amount of radiation intercepted by the crop (Loomis and Williams, 1963; Tollenaar and Bruulsema, 1988; Muchow, 1989a). The study by Ottman and Welch (1988) highlights the importance of the radiation regime on grain yield. They observed that supplemental radiation at different levels in the canopy delayed leaf senescence and increased oven-dry grain yield from 10.6 to 16.3 t ha^{-1}.

Both the amount of radiation incident on the crop and the proportion of this radiation that is intercepted are important determinants of maize yield. Leaf canopy development as influenced by ambient temperature determines the leaf area index of the crop, and thereby determines the proportion of the incident radiation which is intercepted (Muchow and Carberry, 1989). Temperature also affects the duration of crop growth (Allison and Daynard, 1979), and hence the maximum time that the incident radiation can be intercepted. Of particular importance is the length of the grain filling period since the dry matter accumulated in the grain in maize is largely from dry matter that the crop accumulates after flowering. It has been shown that the duration of grain filling is decreased with increasing temperature and that the shorter grain-filling period is often associated with lower grain yield (Hunter et al., 1977; Badu-Apraku et al., 1983). However for field-grown maize, Muchow (1989b) observed that while the duration of grain filling was shorter at higher temperature, grain yield was unchanged due to coincidentally higher incident radiation at the higher temperature.

Statistical analysis of long-term weather data has shown that seasons with lower temperature generally result in increased maize production (Gilmore and Rogers, 1958; Thompson, 1986). However, these analyses are confounded because high temperature was frequently associated with low rainfall. Runge (1968) reported that high temperature (32.2 and 37.8 °C) may not have a detrimental effect on maize yield if sufficient moisture is available. Variation in incident radiation was not considered in any of these studies. It is not possible to independently assess the impact of temperature and solar radiation on maize yield by simple comparison of observed yields because temperature and incident radiation are confounded under field conditions.

An alternative approach to regression analysis for determining the individual contribution of temperature and solar radiation on crop yield is to use a simple mechanistic model of crop growth. Monteith and Scott (1982) used this approach to analyze the effects of weather on crop yield by simply accounting for the effect of temperature on leaf area development and crop ontogeny, and the influence of solar radiation on biomass accumulation. Similarly, Spaeth et al. (1987) used this approach to analyze year-to-year variation in high-yielding soybean (*Glycine max* L. Merr.).

This work was undertaken to develop a simple, mechanistic growth model for maize to simulate the major effects of temperature and solar radiation on maize growth, development, and yield. The objective of this study was to use the model to analyze for unstressed maize crops the yield responses to variation in temperature and solar radiation among diverse locations. The effects of solar radiation and temperature on maize yield were studied by examining observed and simulated yields among locations, and by a simple sensitivity analysis of simulated grain yield response to variation in solar radiation and temperature.

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MATERIALS AND METHODS

Model Description

Phenological development was described as a function of daily thermal units and total leaf number (Fig. 1). Daily thermal units for this development were calculated by averaging maximum and minimum temperatures and subtracting a base temperature of 8 °C (Jones and Kiniry, 1986). Crop emergence occurred 87 thermal units after sowing (Muchow and Carberry, 1989).

As shown in Fig. 1, the appearance of successive fully expanded leaves was calculated as an exponential function of cumulative thermal units using a base temperature of 8 °C (Muchow and Carberry, 1989). The area of individual leaves was calculated by defining the total number of leaves to be produced on each plant and the area of the largest leaf. First, the leaf number (*LNM*) having the largest area was computed from the total number of leaves initiated (*TLN*) using the equation developed by Stapper and Arkin (1980)

$$LNM = 3.53 + 0.46 \times TLN. \quad [1]$$

The value of TLN is an input to the model which must be initially defined.

The fully expanded area (A, cm^2) of each leaf was calculated from leaf number (*LN*) and area of the largest leaf (*AM*, cm^2) using the method of Dwyer and Stewart (1986) and the coefficients of Muchow and Carberry (1989)

$$A = AM \times \mathrm{EXP}[-0.0344 \times (LN-LNM)^2 + 0.000731 \times (LN-LNM)^3]. \quad [2]$$

Muchow and Carberry (1989) observed that the combined area of all the leaves expanding on a plant at a given time was equivalent to the fully expanded area of the two developing leaves immediately above the last fully expanded leaf. Consequently, prior to the full expansion of the last two leaves on the plant the total leaf area per plant was calculated as the sum of the area of all fully expanded leaves plus the fully expanded leaf area of the next two leaves.

The fraction of total leaf area which was senesced (*FAS*) increased with thermal units (TU) from emergence according to the exponential relationship given by Muchow and Carberry (1989)

$$FAS = 0.00161 \times \exp(0.00328 \times \mathrm{TU}). \quad [3]$$

Green leaf area index was calculated as the difference between total and senesced leaf area per plant multiplied by the plant population (Fig. 1).

Daily biomass accumulation was computed as the product of the daily incident solar radiation (*SR*), the proportion of radiation intercepted by the canopy, and the radiation use efficiency (*E*) of the crop. As shown in Fig. 1, the proportion of incident radiation intercepted by the crop was calculated as an exponential function of green leaf area index (de Wit, 1965). A radiation extinction coefficient of 0.4 was used (Muchow, 1988a; Muchow and Davis, 1988). Muchow and Davis (1988) observed a maximum radiation use efficiency for maize during vegetative and early grain growth of 1.6 g MJ^{-1} under fully irrigated, high N conditions. Williams et al. (1965) and Sivakumar and Virmani (1984) also observed a value of 1.6 g MJ^{-1} for above-ground biomass production of maize during vegetative growth. Similarly, Kiniry et al. (1989) summarized a large number of studies with maize showing an average value of 1.6 g MJ^{-1}.

Muchow (1988b) observed that the radiation use efficiency declined during the latter part of grain growth as a consequence of mobilization of leaf N to the grain. This transport of N was due to the demand by the grain which could not be met solely by soil N uptake. Tollenaar and Bruulsema (1988) have similarly reported a decline in radiation use efficiency in maize during grain growth. Consequently, based on these experimental observations the radiation use efficiency from crop emergence until 500 thermal units (base 0 °C) after silking was set to 1.6 g MJ^{-1}, and thereafter it was set at 1.2 g MJ^{-1}.

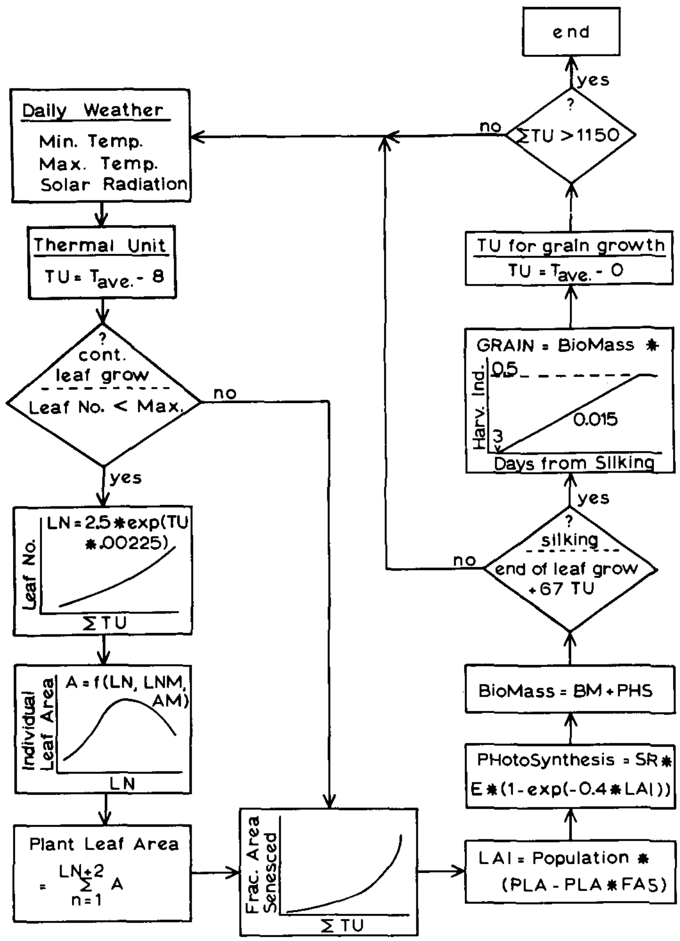

Fig. 1. Flow diagram showing operation of the maize growth model on a daily time step.

Silking was found to occur 67 thermal units after the flag leaf was fully expanded (Muchow and Carberry, 1989). Grain growth was assumed to begin 3 d after silking (Muchow, 1988b). Grain yield accumulation was described as a function of biomass accumulation and a linear increase in harvest index (Fig. 1). Muchow (1989b) observed that the harvest index of maize increased linearly with time during grain filling and was relatively stable across environments at 0.015 d^{-1}. Since harvest index is the ratio of grain mass to biomass, an incremental increase in harvest index defines the required increase in grain mass. Towards the end of grain filling, harvest index plateaued at the maximum value (Muchow, 1989b). The maximum harvest index was set at 0.5 to reflect the genetic potential of most current commercial maize hybrids. Consequently throughout grain filling, grain yield was calculated as the product of accumulated biomass and the harvest index.

Since the positive relationship between the reciprocal of the duration of grain filling and mean temperature was linear from 8 to 32 °C with a base temperature of 0.2 °C (Muchow, 1989b), thermal units from silking to maturity were calculated with a base temperature of 0 °C and no maximum temperature. The thermal units from silking to physiological maturity was fixed at 1150 (Muchow, 1989b) for all simulations presented here. However, there is evidence

Table 1. Observed and simulated oven-dry maize grain yield, duration (D), mean daily temperature (T) and incident radiation (R) from simulated emergence to maturity.

Sowing date	Cultivar	Grain yield Observed	Simulated	D	T	R
		g m^{-2}		d	°C	MJ m^{-2} d^{-1}
Katherine, AUS.						
25 Nov. 83	Dekalb XL82	832	796	88	28.2	24.0
7 Feb. 84	Dekalb XL82	809	837	93	26.7	22.0
10 Oct. 84	Dekalb XL82	817	833	85	28.9	25.5
6 Feb. 85	Dekalb XL82	809	810	95	26.3	22.2
20 Aug. 85	Dekalb XL82	763	884	90	27.3	26.0
29 Jan. 86	Dekalb XL82	854	828	89	27.6	23.8
30 Aug. 86	Dekalb XL82	820	832	84	28.7	25.5
1 Feb. 88	Dekalb XL82	823	819	89	27.6	23.5
Gainesville, FL						
26 Feb. 82	McCurdy 84AA	1038	976	115	23.3	19.2
23 Apr. 83	Pioneer 3192	867	840	98	26.0	20.9
Quincy, FL						
24 Mar. 77	Pioneer 3369A	1073† 1225‡	1121 1349	112	23.6	25.8
30 Mar. 78	Pioneer 3368A	879† 828‡,§	849 1027	112	23.6	21.0
Champaign, IL						
4 May 82	Agway 849X	1101	1115	126	21.5	19.9
12 May 83	Pioneer 3378	1080	1123	109	24.0	22.8
Grand Junction, CO						
22 Apr. 82	NK PX74	1734	1573	146	19.2	26.7
5 May 83	SX 5509	1516	1606	141	19.3	26.2
7 May 84	Funk G4507	1647	1672	138	19.8	28.3
5 May 85	Dekalb 656	1521	1799	143	18.9	28.2
28 Apr. 86	Dekalb 656	1483	1479	153	18.0	22.4

† 6 plants m^{-2}.
‡ 9 plants m^{-2}.
§ 30% barren plants.

that genetic variation in this parameter exists (e.g., Daynard and Kannenberg, 1976; McGarrahan and Dale, 1984) and this parameter could be adjusted.

Simulation Studies

Experimental yield data and meteorological data from eight sowings at Katherine (14°28′S) in tropical Australia, from two sowings each at Gainesville (29°40′N) and Quincy (30°34′N), FL, and Champaign, IL (40°7′N), and from five sowings at Grand Junction, CO (39°4′N) were used (Table 1). All crops were fully irrigated and grown under high fertility conditions. All crops at Katherine were grown under identical cultural conditions and these are detailed in Muchow (1988a,1989a). The experimental details of the crops at Gainesville are given by Bennett et al. (1989) and Lorens et al. (1987); those at Quincy by Rhoads and Stanley (1984); and those at Champaign by Ottman and Welch (1988).

At Grand Junction, crops were sown on the dates shown in Table 1 at the Colorado State University Agricultural Research Center (S.R. Olsen and D.F. Champion, 1988, personal communication). Crops were sown in 0.61-m rows at a rate of 10.6 seeds m^{-2}. At least five replicate plots consisting of four rows each 15 m in length were sown. At sowing, 18 g N m^{-2} of ammonium nitrate was applied, and an additional 18 g N m^{-2} of anhydrous ammonia was applied when the crop height was approximately 1 m. The crops were furrow irrigated regularly throughout the growing season to prevent water deficits. At maturity, the center two rows were machine harvested; the area sampled was 21 m^2.

Grain yield was simulated using the daily maximum and minimum temperature and incident solar radiation for each sowing. The plant population was set to that used in the experimental crops, i.e., 7 plants m^{-2} for Katherine, 7.2 plants m^{-2} for Gainesville, and 6 and 9 plants m^{-2} for Quincy. At Champaign, there was no response to the three plant populations used in 1982 and an average plant population of 8 plants m^{-2} was used; in 1983 the plant population was 8.9 plants m^{-2}. No plant population data were recorded at Grand Junction; it was assumed that 80% of sown seeds established giving a plant population of 8.5 plants m^{-2}.

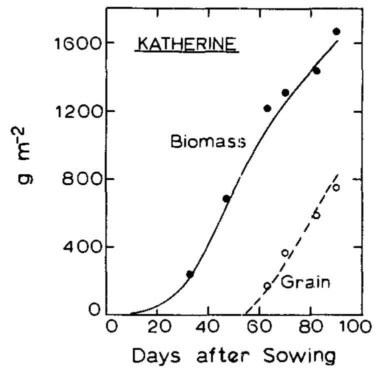

Fig. 2. Predicted (lines) and observed biomass (●) and grain (○) accumulation for the 29 Jan. 1986 sowing at Katherine.

The total number of developed leaves is closely related to the thermal units for silking and is an indicator of the maturity rating of a hybrid (Allen et al., 1973). For three sowings at Katherine, mean leaf number varied from 17.5 to 19.2, with an average value of 18.3 (Muchow and Carberry, 1989). A total leaf number of 18.3 was used in all simulations at all locations. Leaf numbers ranging from 17 to 20 were observed for the hybrids used at Gainesville (Bennett and Hammond, 1983; Bennett et al., 1989). Furthermore, the simulated days from sowing to silking in the 1982 and 1983 sowings at Gainesville were 68 and 53 d, respectively, compared with observed values of 65 and 52. Similarly at Champaign, the simulated days from sowing to silking were 77 and 72 in 1982 and 1983, respectively, compared with observed values of 77 and 69 d. No silking date data were available from Quincy or Grand Junction.

For three sowings at Katherine, Muchow and Carberry (1989) reported the mean area of the largest leaf as 596 cm^2 for 'DeKalb XL82,' and this value was used for all simulations at Katherine. No data on the area of the largest leaf were available from any of the locations in the USA. Jones and Kiniry (1986) used a value of 595 cm^2 in the CERES-Maize model; but Thiagarajah and Hunt (1982) recorded a maximum leaf size of 842 cm^2, Dwyer and Stewart (1986) recorded 768 cm^2, and Wolfe et al. (1988) recorded 800 cm^2. When a value of 596 cm^2 was used for the Gainesville data, the simulated maximum green leaf area index was 3.5 compared with the observed maximum green leaf area index of 4.4 (Bennett et al., 1989). Using a value of 750 cm^2 for the area of the largest leaf produced a green leaf area index that more closely simulated the observed index, and this value was used as the area of the largest leaf in all simulations for locations in the USA.

For each location and sowing, the simulated grain yield was compared with the observed grain yield. The coefficients used in the model described above were obtained from data from the sowings at Katherine on 10 Oct. 1984, 6 Feb. 1985, 20 Aug. 1985, and 29 Jan. 1986. The remaining Katherine sowings and all the sowings from the USA are independent data sets. Differences among sowings and locations were examined only in terms of the temperature and radiation regime.

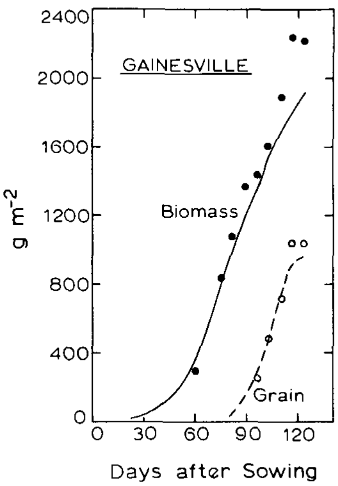

Fig. 3. Predicted (lines) and observed biomass (●) and grain (○) accumulation for the 26 Feb. 1982 sowing at Gainesville.

Two approaches were used to examine the sensitivity of maize yield to temperature and solar radiation. The effect of temperature change on grain yield at each of the five locations was assessed in the first approach. Here, simulations were done using the actual weather data except that daily mean temperature was changed by −4, −2, +2 or +4 °C. The ratio of grain yield for the altered temperature environment to that for the actual temperature regime was computed. The second approach allowed the influences of both temperature and solar radiation to be compared by inputting constant conditions for the entire crop season. Simulations were done by varying daily mean temperature among 20, 25 and 30 °C, and by varying solar radiation among 16, 20, 24 and 28 MJ m^{-2} d^{-1}, respectively.

RESULTS

Simulations

Experimental data for above-ground biomass and grain accumulation throughout the growing season were available for the 29 Jan. 1986 sowing at Katherine (Muchow, 1988b; Muchow and Davis, 1988) and for the 26 Feb. 1982 sowing at Gainesville (Bennett et al., 1989). Comparison of observed and simulated data showed close agreement for both biomass and grain yield throughout growth (Fig. 2 and 3). Similarly, for all locations there was close agreement between observed and simulated grain yield (Table 1).

Across all sowings there was little variation in grain yield at Katherine (Table 1). The duration of growth was reduced in sowings under higher temperature, but since the daily incident solar radiation was also higher in these sowings, final grain yield was hardly affected (Table 1). Comparisons of the two sowings at Gainesville also highlight the temperature effect (Table 1). The lower temperature during the 26 Feb. 1982 sowing lengthened the growth duration and produced a grain yield greater than the 1983 sowing even though incident solar radiation was greater in 1983. In contrast, comparison between the two sowings at Quincy where the temperature was similar in both sowings, shows grain yield was higher in the 24 Mar. 1977 sowing consistent with the higher incident solar radiation in 1977 (Table 1). Consequently, grain yield did vary between sowings at both Gainesville and Quincy, in one case associated with temperature differences and in the other instance with radiation differences.

Table 2. Simulated effect of increase and decrease by 2 and 4 °C from observed daily mean temperature on maize grain yield expressed as a ratio of that predicted for the actual temperature regime at each location.

Sowing date	Temperature change (°C)			
	−4	−2	+2	+4
Katherine, AUS.				
10 Oct. 84	1.15	1.07	0.90	0.81
6 Feb. 85	1.27	1.11	0.92	0.84
Gainesville, FL				
26 Feb. 82	1.10	1.06	0.93	0.85
23 Apr. 83	1.17	1.08	0.95	0.91
Quincy, FL				
24 Mar. 77	1.07	1.04	0.95	0.91
30 Mar. 78	1.08	1.05	0.97	0.92
Champaign, IL				
4 May 82	†	†	0.92	0.86
12 May 83	†	1.08	0.95	0.91
Grand Junction, CO				
7 May 84	†	†	0.91	0.85
28 Apr. 86	†	†	0.90	0.84

† Length of growing season insufficient for crop maturity using 18 leaf cultivar.

At Quincy, both observed and simulated grain yields for the 24 Mar. 1977 sowing were higher at 9 plants m^{-2} compared with the lower population (Table 1) due to higher leaf area index and consequently higher radiation interception (1494 compared with 1817 MJ m^{-2} simulated from emergence to maturity). However, observed grain yield did not respond to plant population in 1978 but simulated grain yield did (Table 1). Rhoads and Stanley (1984) reported that both plant populations had one ear per plant in 1977, but in 1978 there were almost 30% fewer ears at 9 plants m^{-2}. Barreness is not accounted for in the model, but a 30% decrease in the simulated yield gives an estimate of 719 g m^{-2} compared with the observed yield of 828 g m^{-2}.

At Champaign, there was no difference in grain yield between sowings due to higher daily incident radiation compensating for the shorter growth duration at higher temperature (Table 1). This is similar to the finding at Katherine. However, grain yield was much higher at Champaign compared with Katherine, due to the lower temperature at Champaign. The highest grain yields were obtained at Grand Junction and were associated with the highest level of solar radiation and the lowest temperature for any of the locations studied (Table 1).

Sensitivity Analysis

Examination of the effect of increasing or decreasing temperature on grain yield in the sensitivity analysis using the actual meteorological data during the growing season shows that the magnitude of the effect does vary across locations and years (Table 2). Decreasing temperature increased simulated grain yield by lengthening the season except at Champaign, IL and Grand Junction, CO where the decreased temperatures caused the crops to be subjected to a freeze. Increasing

Table 3. Simulated effects of daily mean temperature and incident radiation on oven-dry maize grain yield. Daily mean temperature and incident radiation were held constant throughout growth for each simulation. A plant population of 7 plants m^{-2} and area of the largest leaf of 750 cm^{-2} was used.

Radiation	Temperature 20	25	30
MJ m^{-2} d^{-1}	g m^{-2}		
16	955	717	577
20	1194	896	721
24	1432	1075	865
28	1671	1254	1010

temperature decreased yield due to a simulated shortening of the season as expected. Across locations, the change in yield as a result of temperature change was greatest at Katherine and least at Quincy. The short growing season and lower yields at Katherine caused the percentage change in yield to be the greatest among locations.

The simulations where temperature and solar radiation were kept constant throughout the growing season showed large differences in grain yield (Table 3). The lowest yield (577 g m^{-2}) resulted from the environment with the highest temperature and least solar radiation. The highest simulated yield (1671 g m^{-2}) was nearly three times larger, and occurred under low temperature and high solar radiation. The yield response to temperature is associated with variation in the predicted length of the growing season. The simulated duration of growth was 148, 109 and 88 d for constant mean temperature of 20, 25 and 30 °C, respectively. The yield response to incident solar radiation was linearly related to the increase in the total amount of radiation intercepted by the crop.

DISCUSSION

This study indicates that both temperature and incident solar radiation quantitatively influence the variation in potential maize yield across environments. The primary influence of temperature is on growth duration. Lower temperature increases the length of time that the crop can intercept radiation. Under favorable growing conditions, biomass accumulation is directly proportional to the amount of radiation intercepted, and for a given harvest index, grain yield is directly proportional to biomass. Consequently, high maize yield is associated with low temperature and high solar radiation.

These conclusions are in basic agreement with those of Duncan et al. (1973). They observed higher maize grain yields at Davis, CA than at Greenfield, KY and Lexington, KY. Davis received the highest solar radiation and Lexington had the highest temperature. They attributed the yield depression at high temperature to both decreased rate of photosynthesis and decreased duration of photosynthesis. No account was taken in our simulations of temperature effects on the rate of photosynthesis (i.e., radiation was use efficiency), and several studies (e.g., Brown and Wilson, 1983) have shown that the response of leaf photosynthesis to temperature in C_4 plants is negligible over the range of temperatures observed in these field studies.

Both temperature and radiation vary during the growing season, and since these factors interact in determining grain yield, it is difficult to assess the impact of temperature and solar radiation on grain yield using mean seasonal values. The simple model framework developed here allows such an examination of the consequences of environmental variation on maize productivity. The model describes three key activities of crop growth: phenology and leaf growth as a function of temperature and leaf number; biomass accumulation as a function of radiation intercepted; and grain growth according to a linear increase in harvest index. The functions were developed from data collected in a tropical environment and were adequate in simulating growth in a number of locations across the USA. Furthermore, the growth of a number of different cultivars was simulated at different locations in the USA without any adjustments in parameters to account for the range of cultivars studied. These results highlight the great influence of environment in determining potential grain yield.

A number of generalizations on the effect of location on potential maize yields can be made. The yield potential of maize cultivars with 18 leaves growing in tropical environments is lower than in temperate environments, despite high levels of solar radiation. In the tropics, high temperature is the dominant influence markedly decreasing the duration of crop growth. Maize grown in the midwest USA does not necessarily have a higher yield potential than that grown in the southern USA, as highlighted by the comparison between Quincy and Champaign. Only at locations with low temperature and a predominance of clear days with consequent high solar radiation, were simulated maize yields greater than 1600 g m^{-2} (300 bushels per acre at 15.5% moisture). Grand Junction, CO, with an elevation of 1350 m and a long growing season, is a location with such an environment.

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REFERENCES

Allen, J.R., G.W. McKee, and J.H. McGahen. 1973. Leaf number and maturity in hybrid corn. Agron. J. 65:233–235.

Allison, J.C.S., and T.B. Daynard. 1979. Effect of change in time of flowering, induced by altering photoperiod or temperature, on attributes related to yield in maize. Crop Sci. 19:1–4.

Badu-Apraku, B., R.B. Hunter, and M. Tollenaar. 1983. Effect of temperature during grain filling on whole plant and grain yield in maize (*Zea mays* L.). Can. J. Plant Sci. 63:357–363.

Bennett, J.M., and L.C. Hammond. 1983. Grain yields of several corn hybrids in response to water stresses imposed during vegetative growth stages. Proc. Soil Crop Sci. Soc. Fla. 42:107–111.

Bennett, J.M., L.S.M. Muitti, P.S.C. Rao, and J.W. Jones. 1989. Interactive effects of nitrogen and water stresses on biomass accumulation, nitrogen uptake, and seed yield of maize. Field Crop Res. 19:297–311.

Brown, R.H., and J.R. Wilson. 1983. Nitrogen response of Panicum species differing in CO_2 fixation pathways. II. CO_2 exchange characteristics. Crop Sci. 23:1154–1159.

Daynard, T.B., and L.W. Kannenberg. 1976. Relationships between length of the actual and effective grain filling periods and the grain

yield of corn. Can. J. Plant Sci. 556:237–242.
de Wit, C.T. 1965. Photosynthesis of leaf canopies. Agric. Res. Rep. no. 663, Inst. for Biol. and Chem. Res. on Field Crops and Herb., Wageningen, The Netherlands.
Duncan, W.G., D.L. Shaver, and W.A. Williams. 1973. Insolation and temperature effects on maize growth and yield. Crop Sci. 13:187–191.
Dwyer, L.M., and D.W. Stewart. 1986. Leaf area development in field grown maize. Agron. J. 78:334–343.
Gilmore, E.C., and J.S. Rogers. 1958. Heat units as a method of measuring maturity in corn. Agron. J. 50:611–615.
Hunter, R.B., M. Tollenaar, and C.M. Breuer. 1977. Effects of photoperiod and temperature on vegetative and reproductive growth of a maize (Zea mays) hybrid. Can. J. Plant Sci. 57:1127–1133.
Jones, C.A., and J.R. Kiniry. 1986. CERES-maize: A simulation model of maize growth and development. Texas A&M Univ. Press, College Station, TX.
Kiniry, J.R., C.A. Jones, J.C. O'Toole, R. Blanchet, M. Cabelguenne, and D.A. Spanel. 1989. Radiation use efficiency in biomass accumulation prior to grain filling for five grain-crop species. Field Crop Res. 20:51–64.
Loomis, R.S., and W.A. Williams. 1963. Maximum crop productivity: An estimate. Crop Sci. 3:67–72.
Lorens, G.F., J.M. Bennett, and L.B. Logalle. 1987. Differences in drought resistance between two corn hybrids. I. Water relations and root length density. Agron. J. 79:802–807.
McGarrahan, J.P., and R.F. Dale. 1984. A trend toward a longer grain-filling period for corn: A case study in Indiana. Agron. J. 76:518–522.
Monteith, J.L., and R.K. Scott. 1982. Weather and yield variation of crops. p. 127–149. *In* K. Blaxter and L. Fowden (ed.), Food, nutrition and climate. Applied Sci. Publ., Englewood, NJ.
Muchow, R.C. 1988a. Effect of nitrogen supply on the comparative productivity of maize and sorghum in a semi-arid tropical environment. I. Leaf growth and leaf nitrogen. Field Crop Res. 18:1–16.
Muchow, R.C. 1988b. Effect of nitrogen supply on the comparative productivity of maize and sorghum in a semi-arid tropical environment. III. Grain yield and nitrogen accumulation. Field Crop Res. 18:31–44.
Muchow, R.C. 1989a. Comparative productivity of maize, sorghum, and pearl millet in a semi-arid tropical environment. I. Yield potential. Field Crop Res. 20:191–205.
Muchow, R.C. 1989b. Effect of high temperature on grain growth in field grown maize. Field Crop Res. (in review).
Muchow, R.C., and P.S. Carberry. 1989. Environmental control of phenology and leaf growth in a tropically-adapted maize. Field Crop Res. 20:221–236.
Muchow, R.C., and R. Davis. 1988. Effect of nitrogen supply on the comparative productivity of maize and sorghum in a semi-arid tropical environment. II. Radiation interception and biomass accumulation. Field Crop Res. 18:17–30.
Ottman, M.J., and L.F. Welch. 1988. Supplemental radiation effects on senescence, plant nutrients, and yield of field-grown corn. Agron. J. 80:619–626.
Rhoads, F.M., and R.L. Stanley. 1984. Yield and nutrient utilization efficiency of irrigated corn. Agron. J. 76:219–223.
Runge, E.C.A. 1968. Effect of rainfall and temperature interactions during the growing season on corn yield. Agron. J. 60:503–507.
Sivakumar, M.V.K., and S.M. Virmani. 1984. Crop productivity in relation to interception of photosynthetically active radiation. Agric. For. Meteorol. 31:131–141.
Spaeth, S.C., T.R. Sinclair, T. Ohnuma, and S. Konno. 1987. Temperature, radiation, and duration dependence of high soybean yields: Measurement and simulation. Field Crop Res. 16:297–307.
Stapper, M., and G.F. Arkin. 1980. CORNF: A dynamic growth and development model for maize (*Zea mays* L.). Texas Agric. Exp. Stn. Rep. no. 80-2.
Thiagarajah, M.R., and L.A. Hunt. 1982. Effects of temperature on leaf growth in corn (*Zea mays*). Can. J. Bot. 60:1647–1652.
Thompson, L.M. 1986. Climatic change, weather variability, and corn production. Agron. J. 78:649–653.
Tollenaar, M., and T.W. Bruulsema. 1988. Efficiency of maize dry matter production during periods of complete leaf area expansion. Agron. J. 80:580–585.
Williams, W.A., R.S. Loomis, and C.R. Lepley. 1965. Vegetative growth of corn as affected by population density. I. Productivity in relation to interception of solar radiation. Crop Sci. 5:211–215.
Wolfe, D.W., D.W. Henderson, T.C. Hsiao, and A. Alvino. 1988. Interactive water and nitrogen effects on senescence of maize. II. Photosynthetic decline and longevity of individual leaves. Agron. J. 80:865–870.