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# THE ROLE OF ENSO IN DETERMINING CLIMATE AND MAIZE YIELD VARIABILITY IN THE U.S. CORNBELT

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## ABSTRACT

Recent advances in understanding the role of the El Niño–Southern Oscillation (ENSO) in climate variability present opportunities for improving efficiency in agricultural production. We investigated the relationships between ENSO, climate and maize yields in the U.S. cornbelt, using both observed data and crop simulations. Using a time-series of sea-surface temperature anomalies (SSTA) from the NINO3 region of the Pacific Ocean and historical records of temperature and precipitation spatially averaged across 51 mid-western climate divisions from 1950 to 1995, we ran linear correlation tests at three different lags. Northern hemisphere wintertime SSTAs were significantly correlated with air temperature at the 95% level of confidence in both the previous ($r = -0.32$) and following ($r = 0.41$) summer, but had opposite signs. Correlations with precipitation were significant only in the summer preceding the ENSO event ($r = 0.31$). Detrended maize yield for the same area and time period was also significantly related to SSTAs in the winter after harvest, with a correlation coefficient of 0.39, indicating that ENSO accounts for $\approx 15\%$ of interannual maize yield variability in the cornbelt. Crop growth simulations at seven sites across the region suggest that water stress in July and August is the primary cause of lowered corn yield in La Niña years, but shortened grainfill period due to higher temperatures is also important. The benefits of El Niño-related rainfall and cooler temperatures are less pronounced than the negative impacts of warmer and dryer La Niñas. However, advance warning of both ENSO phases may present opportunities for improved crop management in the cornbelt. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: ENSO; U.S. cornbelt; maize yield; regression analysis; crop simulation

## 1. INTRODUCTION

Interannual climate variability poses some of the greatest risk that farmers face, either directly through impacts on crop yields, or indirectly via impacts on pest dynamics, fertiliser efficiency or prices. Risk due to climate variations has been assumed to be unavoidable—farm management is generally based on long term mean expectations of climate and crop responses to local edaphic conditions, because seasonal climate forecasts have had negligible skill, and are therefore rarely taken into account by farmers when making management decisions. However, in the last decade, significant progress has been made in the skill of predicting seasonal to interannual climate, primarily because of new understanding about the teleconnections between ocean circulation and atmospheric processes, offering the potential for decreasing risk in crop management.

The El Niño–Southern Oscillation (ENSO), which refers to fluctuations in both sea-surface temperatures (SSTs) in the eastern equatorial Pacific and in sea-level pressures in the southern Pacific (Southern Oscillation Index, SOI), is one of the most important controlling factors in global interannual climate variability (Ropelewski and Halpert, 1987; Kiladis and Diaz, 1989; Nicholls, 1989; Hastenrath, 1995).

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Both the positive phase, when SST anomalies are significantly higher than normal (El Niño), and the negative phase, with below normal SSTs (La Niña), carry implications for climatic anomalies. Using coupled ocean–atmosphere circulation models, it is now possible to forecast Pacific SST anomalies (SSTA) up to 1 year in advance with reasonable skill (Latif *et al.*, 1994). Using correlations between SSTAs and historical climate anomalies, as well as coupled general circulation models, potential exists for developing seasonal climate forecasting tools which exhibit skill levels greater than chance. In some cases, when the season of interest follows the period of peak SSTAs, climate forecasts can be made directly, without having to rely on predictions of SSTAs, thereby improving forecast skill.

Analyses of the impacts of ENSO on climate and crop yields have been made in regions outside the U.S. for over a decade. In Australia, where serious long term drought during the early 1990s was strongly linked to a persistent El Niño event, heightened awareness of the value of climate prediction in reducing risk in farm production has speeded the development of approaches utilising long-term climate records, crop simulation models and farm-level economic analysis (Hammer *et al.*, 1987; Hammer and McCown, 1995; Hammer *et al.*, 1996; Meinke *et al.*, 1996). Hammer *et al.* (1996) used a wheat yield simulation model with 95-year records of daily precipitation and temperature for a representative location in Northern Australia. They performed a simple economic analysis using yields from simulations with varied nitrogen level and cultivar maturity group to test the value of existing and potential ENSO-forecasting methodologies. The results indicate that for the site tested, an increase in profits and/or decrease in risk in wheat production is realised by consideration of the seasonal forecast that employs the SOI.

Early work on identifying regions of the world where ENSO figured significantly in interannual climate variability provided evidence of a climate signal in the U.S. In 1987, Ropelewski and Halpert reported that El Niño events were associated with increased precipitation in the southeastern U.S. and in the southern Rocky Mountain region. Handler (1984) found a strong relationship between yield data from the major cornbelt states since 1868 and years ranked using a classification scheme of ENSO event intensity, with El Niño years associated with positive maize yield anomalies and La Niña years with negative anomalies. Using reconstructions from white oak tree rings in Ohio going back to 1640, Cleveland and Duvick (1992) showed a strong correlation between tree ring width and the SOI. Their work indicates that El Niño events are associated with a higher probability of wet years in Ohio, and La Niña events with a higher probability of droughts. When testing monthly precipitation and the Palmer Drought Index from the current century for their site against the SOI, correlations were lower than with tree rings, implying that climate information that may not be detected by traditional analysis 'accumulates' in the perennial plant. More recent work by Carlson *et al.* (1996) inspects temperature and monthly precipitation for the main cornbelt states in ENSO years. Both precipitation and maximum temperature in August were significantly related to ENSO events in Iowa. Work by Piechota and Dracup (1996) on relationships between the Palmer Drought Index and ENSO in the US indicates that for the majority of regions effected by ENSO, the impact follows the peak wintertime SST anomalies, rather than preceding them, as the work mentioned above indicates. However, for the western cornbelt (which they call 'Central'), the timing of the signal appears to be in accordance with other work, with a significant signature in the late summer and autumn of the year leading up to the maximum SST anomalies.

The objectives of this study are: (i) to identify the correlations of sea-surface temperatures in the NINO3 region of the Pacific with maize yields and climate variables in the U.S. cornbelt; and (ii) to investigate the phenological effects of ENSO-related climate anomalies on maize yields using a simulation model. Both objectives contribute to the development of ENSO-based climate forecast applications in crop management.

## 2. METHODS

### *2.1. SST, yield and climate data*

Monthly mean SSTAs for the NINO3 region from 1950 to 1995 (Kaplan *et al.*, 1998) were used in linear correlation analysis. The NINO3 region lies between 5.0°S and 5.0°N in latitude and 90°W and 180°

 

W in longitude in the Pacific Ocean and is considered to be a primary indicator of ENSO. Mean SSTAs from November through February (NDJF) and March through June (MAMJ) were treated as independent variables. To classify years into ENSO categories, the 46-year record was grouped into years with NDJF mean SSTAs higher (El Niño years), or lower (La Niña years) than $\pm 0.7$ standard deviations from the mean anomaly for the period. Although there are other, more complex methods of defining ENSO events (Stone and Auliciems, 1992; Sittel, 1994), there appears to be little mechanistic basis for their complexity. The criterion we use, strength of the SSTA, is straightforward, commonly used, and is one predicted in ENSO-forecasting schemes. By this criterion, 11 years are classified as El Niños, 8 years are classified as La Niñas, and 27 years are considered neutral (Table I).

In order to spatially delineate the rainfed cornbelt, average maize production at the county-level (USDA/NASS Crops County Data) over the last 20 years was used to select the Agricultural Statistics Divisions (ASD) with production above an arbitrary limit (Figure 1). Maize yield data by ASD (Official Estimates, USDA/NASS) from 1950 to 1995 were then averaged by year across the region, weighting each value by the relative area of the respective ASD. The area-weighted average yield was then detrended by subtracting the best-fit line from yearly values to account for yield increases due to technology. Where ASD-level yield data are used in this analysis, the linear trend fit to the regional average yields was used to detrend the individual district yields.

Monthly climate data for the climate divisions (CD) corresponding to the selected ASDs were obtained from NOAA. For the study area, the only discrepancy in borders between ASDs and CDs occurs in the northern tier of Missouri, where ASDs 1, 2, and 3 correspond to CDs 1 and 2. Monthly mean precipitation, temperature and Palmer Drought Severity Index (PDSI) were spatially averaged for the region, likewise with maize yields. Justification for grouping all climate divisions in the currently defined cornbelt was based on climate-zone analysis across the US performed by Fovell and Fovell (1993). In their cluster analysis, all but 11 of the 50 CDs included in our defined region fall into a homogeneous group they term the 'East Central' region. The other 11 CDs we include in the cornbelt are located on the northern tier of Iowa and the southern edge of Minnesota and Wisconsin, which they define as the 'Northeast Tier'.

NINO3 SSTAs were averaged into three periods: winter previous (NDJF-1); spring previous (MAMJ-1); and winter following (NDJF + 1) the crop season. Because the ENSO climate signal is thought to be manifest on a time-scale of seasons rather than at a resolution of months, means for three agronomically-relevant periods were created for each climate variable: March–April–May (MAM, germination and establishment); June–July–August (JJA, tasseling and grainfill); and the total combined mean (labelled

Table I. Classification of years (1950–1995) into ENSO phases, based on NDJF-average SSTA in the NINO3 region, see text for more details

| El Niño | Neutral | | La Niña |
|---|---|---|---|
| 1951 | 1950 | 1971 | 1955 |
| 1957 | 1952 | 1974 | 1964 |
| 1965 | 1953 | 1977 | 1967 |
| 1969 | 1954 | 1978 | 1970 |
| 1972 | 1956 | 1979 | 1973 |
| 1976 | 1958 | 1980 | 1975 |
| 1982 | 1959 | 1981 | 1984 |
| 1986 | 1960 | 1983 | 1988 |
| 1987 | 1961 | 1985 | |
| 1991 | 1962 | 1989 | |
| 1994 | 1963 | 1990 | |
| | 1966 | 1992 | |
| | 1968 | 1993 | |
| | | 1995 | |

 

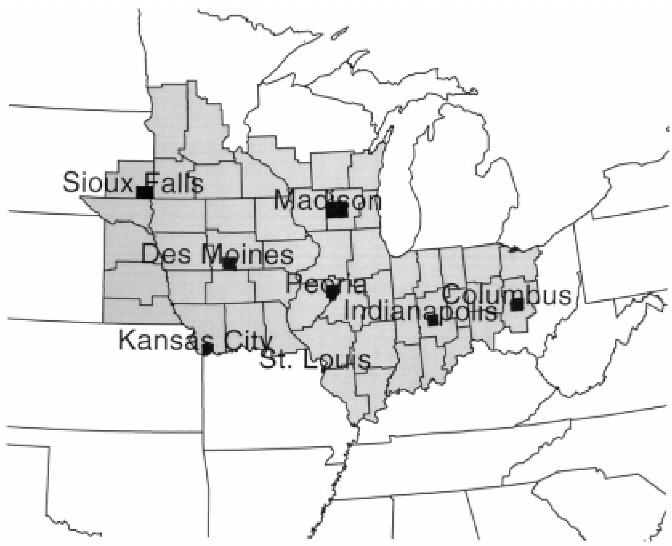


Figure 1. Agricultural Statistics Districts included in study. Counties for which maize simulations were run are labelled

'All'). Correlations between the three lag periods of SSTA, the three climatological mean periods, and maize yields were calculated.

### *2.2. Crop simulations*

Simulations of maize growth and yield were performed with the DSSAT3 simulation environment which uses CERES-Maize (Jones and Kiniry, 1986) to model crop development and interactions with site-specific weather and soils data. Daily weather records (maximum and minimum temperature, solar radiation, and precipitation) for years spanning 1951–1994 were obtained for eight sites in the cornbelt (Figure 1). Three generic soil types representative of the region were used in these simulations: a silt loam; a sandy loam; and a clay loam; with plant-available water decreasing in the order presented. Root growth was described as decreasing exponentially with depth down to 120 cm. The minimum planting date was set to the earliest date common to each location, but could be delayed until simulated soil temperature reached 12°C or higher. Each year was simulated independently, and runs were initiated on January 1 to allow for soil moisture equilibration.

Maize cultivar was defined as a mid-season-maturing variety (Pioneer 3394) for all sites except Sioux Falls, SD, and Madison, WI, which used coefficients for an earlier maturing maize variety (Pioneer 3720). Nitrogen levels used in the simulations are based on state-wide average nitrogen usage per unit area of fertiliser applied, reported by the ERS-NASS. Simulated application of fertiliser was set for the total being applied at the planting date. Site-specific simulation inputs are listed in Table II.

## 3. RESULTS

### *3.1. Climate indicators*

Correlations between seasonal temperature, precipitation, PDSI, maize yields and NINO3 SSTAs at the three lag periods are shown in Table III. A correlation $> \pm 0.29$ is significant at the 95% level of confidence. Mid-summer (JJA) temperature has significant positive correlation with the previous winter NINO3 index (NDJF-1), and is negatively correlated with the succeeding winter index (NDJF + 1). Temperature in the spring months appears unrelated to the NINO3 index.

 

Table II. Sites chosen for maize simulations and associated model inputs

| Site | Site code | Nitrogen applied (kg ha$^{-1}$) | Earliest planting | Cultivar |
|---|---|---|---|---|
| Sioux Falls, SD | SFSD | 62 | May 15 | Pio 3720 |
| Madison, WI | MAWI | 71 | May 5 | Pio 3720 |
| Des Moines, IA | DMIA | 105 | May 5 | Pio 3394 |
| Peoria, IL | PEIL | 135 | May 1 | Pio 3394 |
| Indianapolis, IL | ININ | 114 | May 1 | Pio 3394 |
| Columbus, OH | COOH | 124 | May 5 | Pio 3394 |
| Kansas City, MO | KCMO | 115 | April 26 | Pio 3394 |
| St. Louis, MO | SLMO | 115 | April 26 | Pio 3394 |

Precipitation in mid-summer (JJA) has a significant positive correlation with succeeding winter index (NDJF + 1), but neither the preceding winter index nor the spring index show a relationship with precipitation (Table III). The PDSI represents an integration of both temperature and precipitation variables given soil moisture storage capacity, and is therefore potentially more relevant to climate–crop interactions. This integration results in correlations with the NINO3 index that show less extreme levels (Table III), none of which are significant in any of our pre-defined periods. This may be related to a lag in drought effect, which would peak in the end of summer.

### *3.2. Observed maize yields*

The correlation coefficient determined for the relationship between average annual observed cornbelt maize yields and NINO3 SSTs from the winter following harvest, 0.39, is significant at the 99% level of confidence (Table III). This indicates that conditions developing in late summer leading up the peak of an ENSO event (NDJF + 1) account for slightly more than 15% of yield variability in the cornbelt. The sign of the correlation is in agreement with other work (Handler, 1984; Carlson *et al*., 1996), positive

Table III. Correlation between NINO3 SSTA and temperature, precipitation, and Palmer Drought Severity Index (PDSI) averaged over March, April, and May (MAM), June, July, and August (JJA), and March through October (All), and seasonal maize yields

| SSTA lag period | Correlation coefficient *r* | | | |
|---|---|---|---|---|
| | Temperature | Precipitation | PDSI | Maize yield |
| (a) Previous winter | | | | −0.17 |
| MAM | 0.09 | 0.15 | 0.22 | |
| JJA | 0.41** | 0.03 | 0.10 | |
| All | 0.24 | 0.14 | 0.16 | |
| (b) Current spring | | | | 0.04 |
| MAM | 0.03 | 0.23 | 0.28 | |
| JJA | 0.20 | 0.09 | 0.25 | |
| All | 0.05 | 0.20 | 0.28 | |
| (c) Following winter | | | | 0.39** |
| MAM | 0.10 | 0.12 | 0.03 | |
| JJA | −0.32* | 0.31* | 0.25 | |
| All | −0.17 | 0.26 | 0.21 | |

SSTAs used in correlations are from: (a) the previous winter; (b) spring months; and (c) the following winter.
* Indicates significance at the 95% level of confidence.
** Indicates significance at the 99% level of confidence.

 

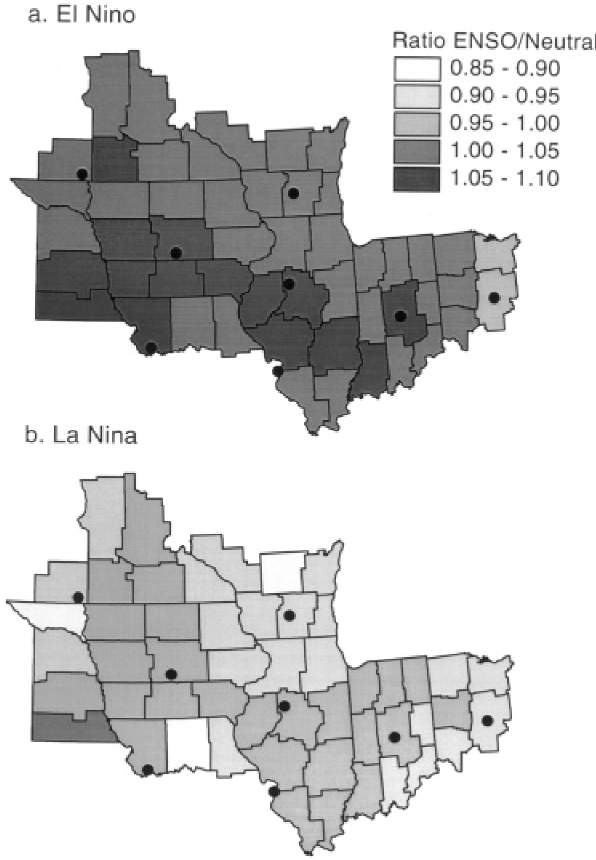


Figure 2. Ratio of detrended maize yields by Agricultural Statistics District in El Niño years to neutral years (a) and La Niña years to neutral years (b), 1950–1995

anomalies in SST (El Niños) are associated with higher yields and negative anomalies (La Niñas) with lower yields.

The ratio of detrended ASD-level yields in El Niño or La Niña years to those classified as neutral years is shown by ASD in Figure 2(a) and (b), respectively. The spatial pattern of ENSO influence is not homogeneous. In El Niño years, the districts that tend to have the highest long-term yields, such as in central Iowa and Illinois, show most benefit from ENSO-related climate patterns. Similarly, in La Niña years, the areas with the best overall conditions for growing appear to be the least negatively affected. Only three ASDs experienced yield ratios of La Niña-to-neutral years lower than 0.9. The region as a whole experienced a 4% increase in maize yields on average over the 11 El Niños considered here, and a 5% decrease below neutral years during La Niña years (Table IV).

Table IV. Observed average regional maize yields (1951–1995) detrended to 1995 levels, grouped by ENSO phase

| ENSO phase | Yield (std, kg $ha^{-1}$) | Yield ratio (event years/neutral years) |
|---|---|---|
| El Niño | 8340 (627) | 1.04 |
| La Niña | 7611 (770) | 0.95 |
| Neutral | 8000 (655) | |

 

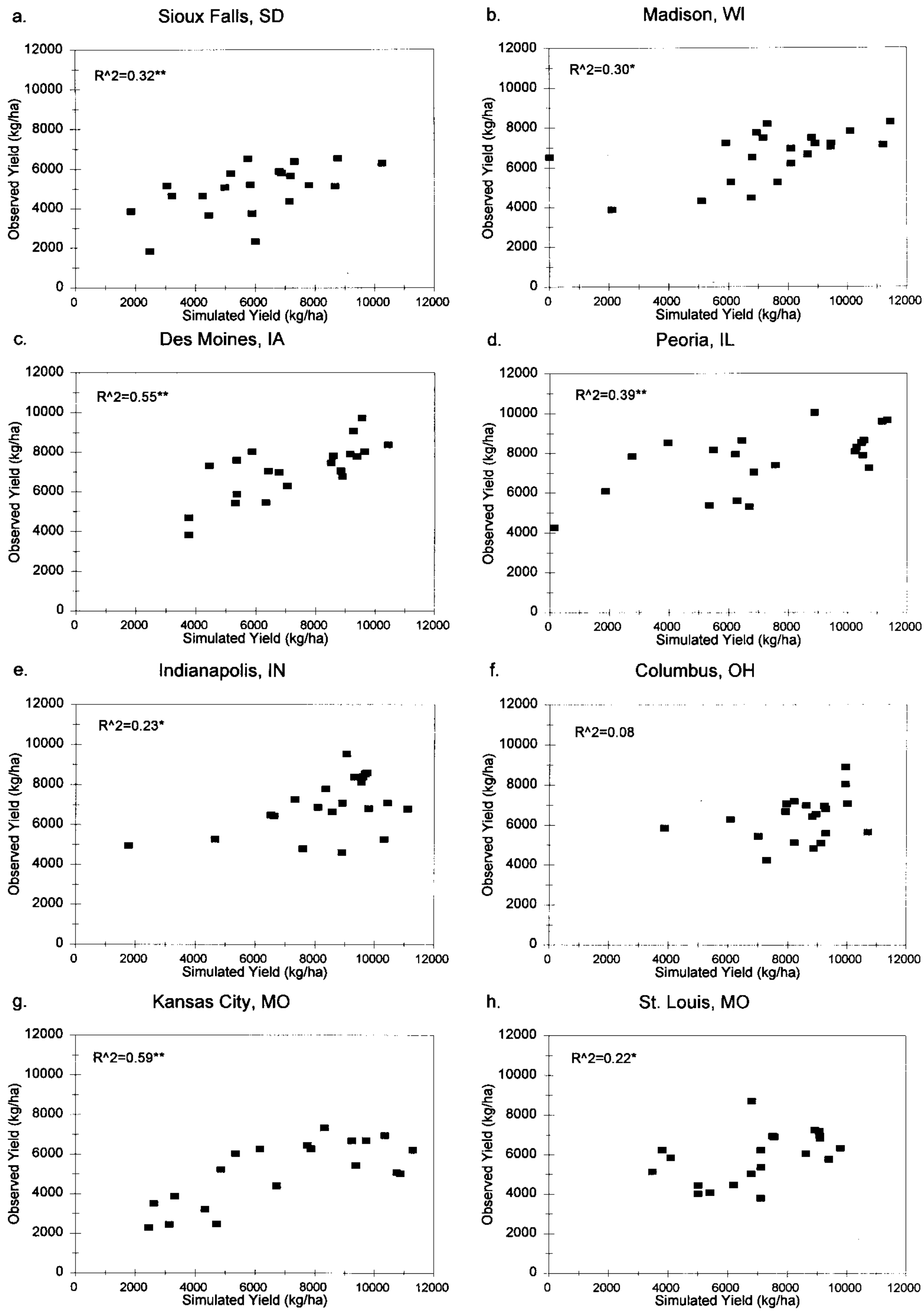


Figure 3a–h. Simulated maize yields resulting from the average of simulations using three soil types (silt loam, sand loam, and clay loam) versus observed county-level maize yields at eight sites in the U.S. cornbelt, 1972–1992. * and ** indicate significance at the 95 and 99% levels of confidence, respectively

### *3.3. Simulations*

The average of simulated maize yields using three soil types at each of the eight sites is shown plotted against observed county-level yields for the period from 1972 to 1992 (Figure 3). At all sites, the simulated yields under-predict observed yields in poor years and over-predict yields in better years. This is partially due to the effect of spatially-averaging observed yields. The range of observed county-level yields is from slightly over 2 t $ha^{-1}$ (at Sioux Falls, ND and Kansas City, MO), to just over 10 t $ha^{-1}$ (at Peoria, IL). Simulated yields range from complete crop failures to just over 11 t $ha^{-1}$. Simulated maize yields predict observations most closely at Des Moines, IA ($r^2 = 0.55$) and Kansas City, MO ($r^2 = 0.59$). Simulated yields at Columbus, OH were not significantly correlated with observations, and were therefore dropped from the analysis. Predictions at other sites, though statistically significant at the 95% level of confidence, range from fair to poor. Factors important in determining final yield unaccounted for in simulations, such as pests and excess water, may be responsible for the poor predictive ability of the model at some sites. Better agreement would be desirable, but the model simulations are adequate for the limited purpose of the present investigation.

Table V. Simulated maize yield ratios, ENSO years/neutral years, by site and soil type

| Site | Soil | Percentage change from neutral years | |
|---|---|---|---|
| | | El Niño | La Niña |
| Sioux Falls, SD | Clay loam | 3 | −38 |
| | Sand loam | 3 | −31 |
| | Silt loam | 5 | −19 |
| | Mean | 4 | −30 |
| Madison, WI | Clay loam | −5 | −28 |
| | Sand loam | −9 | −25 |
| | Silt loam | −12 | −17 |
| | Mean | −9 | −23 |
| Des Moines, IA | Clay loam | 13 | −24 |
| | Sand loam | 16 | −20 |
| | Silt loam | 10 | −17 |
| | Mean | 13 | −21 |
| Peoria, IL | Clay loam | −6 | −25 |
| | Sand loam | 0 | −14 |
| | Silt loam | 0 | −13 |
| | Mean | −2 | −17 |
| Indianapolis, IN | Clay loam | 9 | −20 |
| | Sand loam | 7 | −19 |
| | Silt loam | 3 | −17 |
| | Mean | 6 | −19 |
| Kansas City, MO | Clay loam | −18 | −22 |
| | Sand loam | −15 | −23 |
| | Silt loam | −9 | −18 |
| | Mean | −10 | −21 |
| St. Louis, MO | Clay loam | 11 | −4 |
| | Sand loam | 8 | 8 |
| | Silt loam | 8 | 7 |
| | Mean | 9 | 4 |
| Mean by soil type | Clay loam | 2 | −23 |
| | Sand loam | 1 | −18 |
| | Silt loam | 1 | −14 |
| Mean all sites and soils | | 2 | −18 |

 

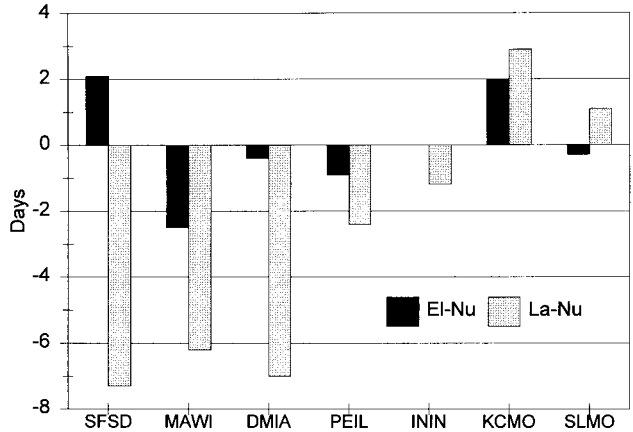


Figure 4. Mean difference in simulated number of days from maize flowering to the end of grain fill in maize between El Niño and neutral years, and La Niña and neutral years at seven sites in the U.S. cornbelt

Simulation output was divided into ENSO events using the criteria defined above. In Table V, the percentage change in simulated yields in El Niño and La Niña years from neutral years is shown by site and soil type. The percentage change in La Niña years from neutral years is negative at all sites except St. Louis, MO. The average decrease in simulated maize yield across all seven sites is just under 18% in La Niña years, while in El Niño years, simulated yield is essentially unchanged from neutral years. The ranking of sites with respect to simulated yield decreases in La Niña years is roughly in agreement with the ASD categorisations shown in Figure 2(b). Sioux Falls and Madison are the most negatively affected sites, while Des Moines, Indianapolis and Peoria rank third, fourth and fifth with respect to decreases in yields in La Niña years relative to neutral years, although the absolute decrease in yield is exaggerated in the simulations.

At most sites, the negative impact of climate during La Niña years is modified by soil type. Decreases in yield become smaller as the plant-available water increases (clay loam to silt loam), indicating that water is a limiting factor. This trend is not as evident in the El Niño-to-neutral ratios, emphasising the likelihood that other factors, such as temperature, are more significant limitations than water availability during El Niño years. Only Des Moines shows a strong positive response in simulated yield to El Niño years. At most other sites, the change from neutral-year yields is very small, and at Madison and Kansas City, yields in El Niño years, as in La Niña years, are lower than in neutral years.

In order to assess the impact of changes in temperature, simulated development rates were averaged by phenological stage for each ENSO phase. There was no change by ENSO phase in the early growth stages, with phenology in all subsets of years advancing at approximately the same rate. In the later period of growth, five out of seven sites showed faster development from flowering through grainfill in La Niña years than in neutral years (Figure 4). At Sioux Falls, Madison, and Des Moines, grainfill was shortened by an average of 7 days. At Madison, WI, development in both El Niño and La Niña years was shortened relative to neutral years, which may explain the decrease in yield found in both phases at that site (Table V). At both Missouri sites in the south, a minor slowing of development rates between ENSO phases were found in these simulations.

The effect of the combination of temperature and water stress on growth was assessed for each ENSO phase by summarising the decrease in simulated transpiration below the potential. In the period between flowering and the beginning of grainfill, only at Sioux Falls was there any noticeable difference in water stress between ENSO phases. At that site, simulations indicated an average of $\approx 25\%$ reduction in photosynthesis due to water stress in La Niña years compared to about 6% in El Niños (Figure 5(a)). This development period generally takes place during early- to mid-July. During grainfill in mid-July through August, simulations resulted in greater water-stress-related reductions in photosynthesis in La Niña years compared to El Niño years at all seven sites (Figure 5(b)). An approximate twofold increase in stress level occurs at each site, so that sites with the lowest stress in El Niño years also have the lowest stress in La Niñas. Madison and Indianapolis are examples of sites showing relatively low water stress in these simulations. Sioux Falls and Des Moines, alternatively, show an almost 50% reduction in photosynthesis during grainfill in La Niña years, compared to $\approx 25\%$ in El Niño years in these simulations.

## 4. DISCUSSION AND CONCLUSIONS

La Niña years tend to be warmer and drier in summer than neutral years in the cornbelt. We found evidence for this both in correlations between wintertime Pacific SSTAs and seasonal climate data for the region, and in decreased observed and simulated maize yields. NDJF SSTAs from the winter preceding planting are strongly correlated with summer temperatures, but not with summer precipitation. NDJF SSTAs from the following winter, however, are well correlated both with temperature and precipitation in June, July and August. Correlations of temperature with SSTAs in the preceding and succeeding winters have opposite signs, possibly indicating that a rapid change from one ENSO phase to the other is an important component of climate predictability, as frequently noted (Stone *et al.*, 1996). The combination of high temperatures and low precipitation leads to a poor moisture balance. Crop model simulations show a greater degree of plant-water stress and possibly faster development (five out of seven sites) in the later phenological stages in La Niña years compared to neutral years. No significant relationship between SSTAs and springtime temperature or precipitation was found, even using simulta-

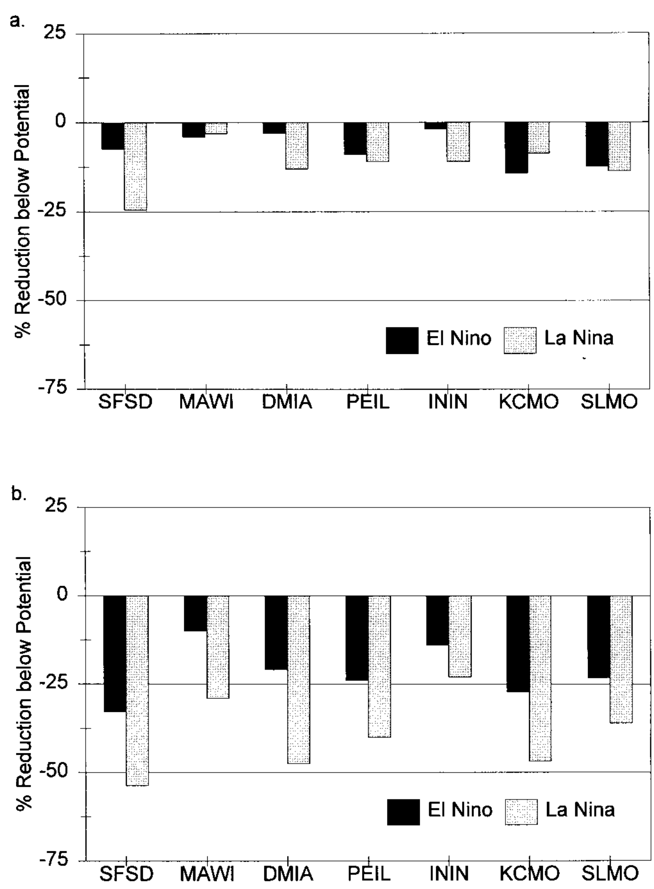


Figure 5. Mean percent reduction in simulated actual transpiration relative to potential transpiration in El Niño and La Niña years in two phenological stages: (a) flowering to the beginning of grain fill; and (b) during grainfill, at seven sites in the U.S. cornbelt

 

neous SSTAs in the test. This lack of a springtime effect was reflected in crop simulations, as no differences in early stage development between ENSO phases were observed.

El Niños, with cooler temperatures and better rainfall, lead to some yield improvement, but the positive impact of El Niños is less pronounced than the negative impact of La Niñas. At the ASD-level, observed yield ratios were never higher than 1.10 for the El Niño-to-neutral comparison, while the minimum La Niña-to-neutral ratio reached 0.85. Observed US maize yields for 1997, the summer preceding the El Niño of 1997/98, are reported by the USDA/NASS as the third highest on record, thereby easily falling into the category of above normal yields as defined here. However, although temperatures remained cool in typical El Niño fashion, an anomalous dry spell during August threatened crops but was relieved by the return of rains late in the season.

Simulations, which reflect field-level soil–plant–climate interactions, indicate average losses in La Niña years of almost 18% across all sites and soil types, while the average improvement in simulated yield associated with El Niños was only 2%. Rainfall is thought to be the primary limiting factor in maize yields in the cornbelt, but cool temperatures lead to slow development, increasing the possibility of losses to freezing if the crop is not mature before harvest. Additionally, factors not represented in the simulations, such as pest and disease problems, are exacerbated by cool, wet conditions, potentially limiting the benefits of El Nino-type climate in the cornbelt.

Farmers in the Midwest may take advantage of ENSO-based seasonal forecasts by selecting maturity class of maize hybrids, altering planting date, or changing nitrogen management scheme. In cooler and wetter El Niño years, tuning the crop maturity class and increasing planting density may be possible to take advantage of the soil moisture later into the season, although extra attention is likely to be required for pest management. In La Niña years, with high probability of late-season drought, faster maturing or drought-resistant maize hybrids are likely to reduce losses, and decreased need for pesticides may lead to environmental benefits. In choosing the maturity class of maize hybrid, altered development rate due to changes in summer temperatures should be considered.

The greatest impact of an ENSO event in the U.S. cornbelt is felt in the summer preceding the peak SSTA. The NINO3 SSTA is merely an index of ENSO, one with maximum variation at the end of the calendar year. The ENSO is a cycle, and is well underway by the summer of an ENSO year. However, there is no prior winter, spring or summer season index that identifies the ENSO state as clearly as the NDJF NINO3. Hence, timely seasonal climate predictions will necessarily have to rely on skilful forecasts of ENSO. Farmers in this region are planting in April, thus requiring seed and input purchases as early as February or March. ENSO-forecasts made at a 9–10-month lead will have to be skilful enough so that, when utilized in a climate prediction scheme with its own associated errors, overall forecast quality still warrants consideration in crop management decisions.

Our analysis indicates that there are regional differences in climate response to ENSO events across the cornbelt. Further work detailing the sub-regional climatic influence of ENSO events, as well as tests using hindcasts of SSTAs, are needed to better define benefits to U.S. corn farmers of using ENSO-based seasonal climate predictions.

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