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ENSO, seasonal rainfall patterns and simulated maize yield variability in Zimbabwe

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ENSO, seasonal rainfall patterns and simulated maize yield variability in Zimbabwe

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Abstract

A correlation between ENSO (El Niño/Southern Oscillation) and rainfall in southern Africa has been recognized for at least a decade. This recognition has led to the expectation that ENSO-based climate predictions will have significant applications in agricultural management. This study is an analysis of the potential for using ENSO predictions to reduce risk in agricultural production associated with rainfall variability at the site level. Records of sea-surface temperatures in the equatorial Pacific during November, December and January were used to define El Niño, La Niña and neutral years. Climate data from four sites in four of the five agroecological zones (AEZ) in Zimbabwe were analyzed with respect to ENSO phases and used to drive a maize growth simulation model parameterized for soil conditions typical of each area, using two nitrogen fertilizer treatments and three planting dates. The four sites (Karoi, AEZ II; Gweru, AEZ III; Masvingo, AEZ IV; and Beitbridge, AEZ V) all showed a decrease in seasonal precipitation associated with the El Niño phase, compared to both neutral and La Niña years. At sites in zones II and III, within-season rainfall variability increased for both El Niño and La Niña years relative to neutral years. While average simulated maize yields were generally lowest in El Niño years, variability in rainfall pattern and standard deviation of yields at the site level was high within each ENSO phase, indicating that more precise seasonal climate predictions would be necessary for forecasts to be valuable in crop management decisions in Zimbabwe. However, simulation results point towards the relative importance of predicting favorable cropping seasons as opposed to poor ones with respect to better nitrogen management and yield improvement for the more marginal sites.

Keywords: Climate variability; El Niño; Zimbabwe; Maize

1. Introduction

Agriculture in Zimbabwe is spread across a variety of agroecological zones (AEZ) ranging from high rainfall/high productivity sites (annual precipitation > 1000 mm, AEZ I) to areas of extremely low productivity where rainfall is sparse and variable (annual precipitation < 500 mm, AEZ V) (Fig. 1 and Table 1). Zimbabwe has a single rainy season, occurring in the southern hemisphere summer. In zones I and II, precipitation is evenly distributed within the rainy season, and shows little variability from year to year. As annual rainfall decreases moving from zones III to V, both within-season and

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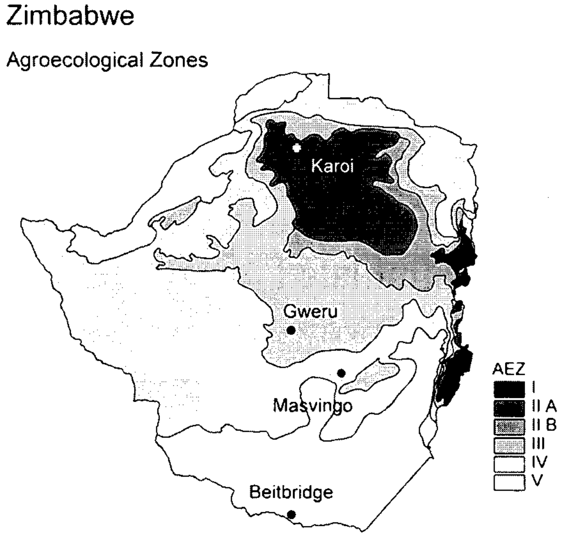

Fig. 1. Agroecological Zones in Zimbabwe and location of sites modeled.

interannual variability increase. Rainfall variability is critical in determining agricultural yields. In more stable environments, even if rainfall is relatively low, farmers can tune their cropping systems to optimize resources. But if the pattern of precipitation from the time of planting onward is unknown, farm management is likely to be aimed at minimizing risk, which often means settling for low inputs and low but stable yields.

Maize is the most important cereal in Zimbabwe, both in terms of diet and farm production. Approximately half of the maize production in Zimbabwe is grown in 'communal areas' (Masters, 1994; Shumba, 1994), land that was once defined as a distinct political unit set aside for the native population. Although communal area borders are no longer recognized as a political division, the term is still used to make the distinction from the commercial farming sector, and refers to land worked using semi-traditional methods wherein farm operations and resources are shared. Ninety percent of communal land is located in AEZs III, IV and V (Mataruka, 1985; Huchu and Sithole, 1994). Yields from the communal areas for maize are approximately one quarter the average of that on large commercial farms (Masters, 1994). This yield discrepancy is the result of both agroecological and socioeconomic factors. In addition to climate variability and less productive soils found in the communal areas, the application rate of inputs such as fertilizer and level of mechanization are extremely constrained (Kumwenda et al., 1996). These factors are related: the riskiness of agriculture in the more variable environments makes high economic investment unattractive. Climate variability has been identified as the premier constraint to agricultural productivity in southern Africa (Waddington, 1994). This strongly suggests that reducing the risk associated with climate variability has a high potential for increasing productivity in Zimbabwe.

A strong relationship is now known to exist between the El Niño/Southern Oscillation (ENSO) and annual precipitation in southern Africa (Ropelewski and Halpert, 1987; Janowiak, 1988; Kiladis and Diaz, 1989; Matarira, 1990). The El Niño component of ENSO refers to temperature fluctuations in the eastern equatorial Pacific surface waters, and the Southern Oscillation is the associated change in sea-level pressure in the southern Pacific. Sea-surface temperatures and pressures in the Atlantic (Nicholson and Entekhabi, 1987) and the Indian Ocean (Jury et al., 1996) have also been found to correlate to varying degrees with precipitation patterns in Africa but are not as yet predictable in advance.

Using a model of Pacific ocean circulation coupled to a simple atmospheric circulation model, sea-

Table 1
Characteristics of agroecological zones

Zone	Characteristics
1	1050 mm or more rainfall per annum with some rain in all months of the year and relatively low temperatures
2	700–1500 mm rainfall per annum with rainfall confined to summer
3	500–700 mm rainfall per annum with relatively high temperatures, infrequent, heavy showers, and subject to seasonal drought
4	450–600 mm rainfall per annum and subject to frequent seasonal drought
5	Less than 500 mm rainfall per annum, erratically distributed

After Vincent and Thomas, 1960.

surface temperature (SST) patterns in the eastern equatorial region can be forecast with correlations between 0.70 and 0.85, depending on the lead time (Chen et al., 1995; Zebiak and Cane, 1995). Temperatures in the region of the equatorial Pacific called the 'NINO3' region (5°N to 5°S; 90°W to 150°W) are commonly used as a primary indicator of ENSO events. Thus, given the high skill in predicting ENSO phases at lead times of up to a year and correlations of ENSO with seasonal precipitation in southern Africa, there exists an opportunity for applications of forecasts to agricultural and water resources management.

Indication of the potential impacts of ENSO on agriculture in Zimbabwe was shown in the study by Cane et al. (1994) in which it was found that SSTs in the NINO3 region were a good predictor of national-level Zimbabwean maize yields. Years in which the SST anomaly was strongly positive (El Niño years) were associated with lower than average precipitation and maize yields; years with negative SST anomalies (called here 'La Niña' years) were associated with higher than average rainfall and maize yields. They found the correlation between SSTs and maize yields to be slightly higher than SSTs and annual precipitation, indicating that the influence of ENSO on climate and crop yields may be more complex than simple annual precipitation averages reveal.

The objectives of this study are to identify the aspects of climate, particularly rainfall, in Zimbabwe that are associated with the ENSO signal, and to test the usefulness of predictions for maize crop management at the site level. Climate data from sites in each of AEZs II through V are grouped into El Niño, La Niña, and neutral years and used to drive a crop simulation model parameterized for field conditions at each site. Alternative cropping strategies are tested for each ENSO phase and resulting simulated yields are compared as an indicator of potential usefulness of ENSO predictions.

2. Methods

2.1. Climate data

Daily climate data (maximum and minimum temperature and rainfall) were obtained from the Zimbabwe Ministry of Agriculture for four sites for the years 1951 to 1991 (Makadho, 1996). The four sites range across four of the five AEZs: Karoi (16.82°S, 29.83°E) in the north within AEZ II; Gweru (19.45°S, 29.81°E) in the central highlands, AEZ III; Masvingo (20.07°S, 30.83°E) further south in AEZ IV; and Beitbridge (22.21°S, 29.98°E) on the southernmost border of Zimbabwe in the harshest zone, AEZ V (Fig. 1). Maize production is highest in Karoi, where it is grown primarily on large commercial farms. At Beitbridge, maize cropping is extremely marginal and is practiced primarily to supplement income from cattle farming and off-farm activities.

Years between 1951 and 1991 were divided into each of the two ENSO phases, El Niño, La Niña, and neutral years, according to the November–December–January mean of the NINO3 sea-surface temperature anomaly for each year. ENSO classes were defined by adding or subtracting one half the standard deviation of the NDJ mean SST anomalies from the mean for the period between 1945 and 1990. Years with anomalies lower than one half a standard deviation from the mean were defined as La Niña years, and above one half a standard deviation defined as El Niño years. By this classification, warm SST events, or El Niño years, occurred during the cropping seasons beginning in 1951, 57, 63, 65, 68, 69, 72, 76, 82, 86 and 87 (11 events). Cold events or La Niñas, occurred in 1954, 55, 56, 62, 64, 67, 70, 71, 73, 74, 75, 83, 84, and 88 (14 events). The 15 remaining cropping seasons between 1951 and 1991 were classified as neutral ENSO events. Because crops are planted at the beginning of the rainy season in October or November, and harvest occurs during the following calendar year, there were 40 harvest years during this 41-year climate record.

2.2. Simulations

Crop simulations were performed using CERES-Maize (Jones and Kiniry, 1986), a dynamic process growth model which quantifies interactions among weather variables, soil water and nitrogen fluxes, and plant physiological response at a daily time-step. Weeds and insect pests are not modeled. Soil input parameters were obtained from the Department of Agricultural, Technical and Extension Services of the Zimbabwe Ministry of Agriculture. Soil texture parameters represented a deep, fine loam at Karoi, a shallow clay at Gweru, a moderately deep, coarse loam at Masvingo, and a shallow clay loam at Beitbridge. In simulations at all sites, two levels of nitrogen fertilizer were used, an 'optimum' level according to a definition by CIMMYT-Zimbabwe (CIMMYT-Zimbabwe, 1993) and a lower level more representative of communal farmer practices. The optimum (hereafter referred to as 'High N') was defined as 80 kg ha^{-1} ammonium nitrate incorporated at planting and a top dress of 30 kg ha^{-1} applied six weeks later. The other N treatment was defined as 30 kg ha^{-1} applied planting and 15 kg ha^{-1} at six weeks after planting. Actual nitrogen usage in the communal areas is often much lower than even the 'Low N' treatment here due to financial risk (Bratton and Truscott, 1985; Masters, 1994; Huchu and Sithole, 1994). These simulations thus represent the upper bound of yields at each site. Maize cultivar coefficients, i.e., parameters controlling the crop phenological response to the environment, were obtained for R201, an early-maturing maize hybrid which was released in Zimbabwe in the 1970s (Ngara, 1985; Masters, 1994) and is still widely used.

Planting date was used as the main experimental treatment and tested for differences in yields between ENSO phases. Agricultural extension specialists generally encourage early planting (mid October to early November), as experiments have repeatedly shown a yield advantage (Waddington, 1994). However, farmers in the communal areas often plant as late as December due to labor shortages, lack of draft power, and the need for some assurance that the rainy season is well underway, thus reducing the risk associated with planting (Mombeshora and Mudhara, 1994; Masters, 1994). However, if a great enough yield advantage could be shown by early planting, we considered it a realistic alternative strategy.

3. Results

3.1. Climate analysis

Total annual precipitation, averaged by ENSO phase for the four sites studied (Table 2), shows the expected trend of decreases in El Niño years and increases in La Niña years, relative to neutral years, for all sites except Beitbridge. The trend is the same when considering only the period from October through April, relevant to the cropping season (Table 2). At Beitbridge, both El Niño and La Niña years have slightly lower rainfall than neutral years for both annual and seasonal sums.

Monthly precipitation by ENSO phase at Karoi (Fig. 2a) is distributed smoothly during the rainy season for all three ENSO phases. The lower annual rainfall at this site during El Niño years appears to be related to a slightly shortened rainy season. In El Niño years, by March average rainfall has already decreased to just over 50 mm compared to approximately 125 mm in March in La Niñas. Gweru and Masvingo, in AEZs III and IV, respectively, display rainfall patterns which are more distinct between ENSO phases (Fig. 2b and c). At both sites, precipitation in neutral years is roughly unimodal, with the peak rainy month occurring in January. In La Niña years, the month of maximum rainfall occurs in December, followed by a sharp decline in January, but with a generally normal to late end of season. Rainfall in El Niño years also appears to peak earlier than in neutral years, but the most distinctive feature

Table 2
Mean annual (July 1–June 30) and seasonal (October 1–April 30) precipitation (mm) by ENSO phase, 1951–1991

	Site							
	Karoi (AEZ II)		Gweru (AEZ III)		Masvingo (AEZ IV)		Beitbridge (AEZ V)	
	Annual	Seasonal	Annual	Seasonal	Annual	Seasonal	Annual	Seasonal
La Niña	740	719	750	726	725	692	332	301
Neutral	689	677	680	659	652	610	371	341
El Niño	615	608	619	591	565	526	302	278

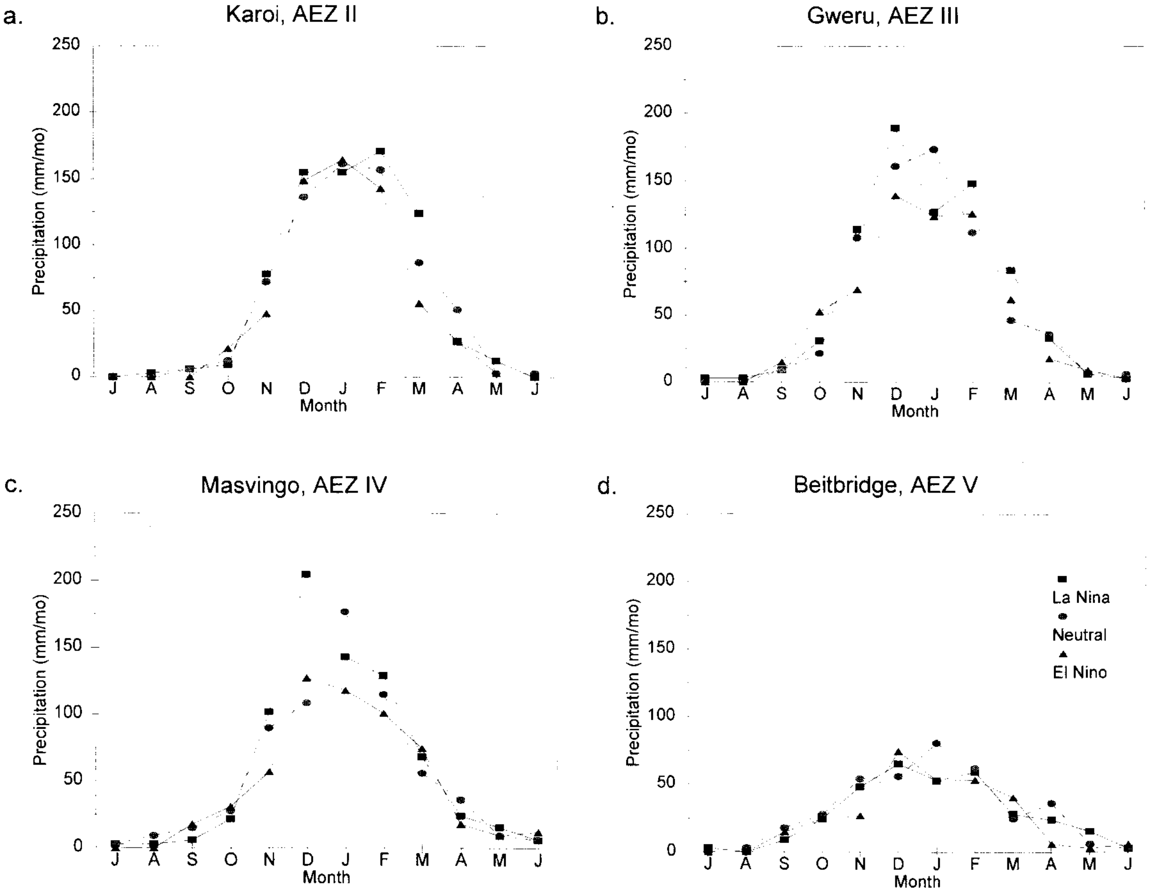

Fig. 2. a–d. Monthly precipitation by ENSO phase at four sites in Zimbabwe, 1951–1991.

is of lower mid-season precipitation than in either neutral or La Niña years. Seasonal precipitation at Beitbridge in AEZ V is very low in all three ENSO phases. The shift from a seasonal maximum in January during neutral years to a maximum in December during both ENSO phases is similar to that seen at Gweru and Masvingo. Variability in monthly precipitation between ENSO phases was very high and at none of the sites were differences significant.

3.2. Yield simulations

3.2.1. Simulated ENSO impacts on yield

Simulated maize yields varied approximately seven-fold between Beitbridge and Karoi. Average yield across all years and all planting dates with low N at Beitbridge was just under 1 t ha^{-1}. Average yield reported for the 1980s by USAID (Eilerts and Vhurumuku, 1997) for the communal area of Beitbridge was only 0.3 t ha^{-1}, compared to the simulated average yield for the 1980s of 0.5 t ha^{-1}. Simulated yields at Masvingo, in AEZ IV on a fairly good soil with low N, averaged 2.4 t ha^{-1}, while at Gweru on a shallow soil in AEZ III, the average yield for the low N treatment was 2.3 t ha^{-1}. These yields compare with the average reported by Shumba (1994) of 1.0 t ha^{-1} in the communal area of Chivi, which is in the AEZ IV, and communal area yields for the 1980s of 0.7 t ha^{-1} (Masvingo) and 1.6 t ha^{-1} (Gweru) (Eilerts and Vhurumuku, 1997). At Karoi, average simulated yield was 4.1 t ha^{-1} for the low N treatment and 7.6 t ha^{-1} for high N inputs.

The average observed yield for commercial farmers at the national level for 1988–90 was 4.7 t ha^{-1}, as reported by Masters (1994), considerably lower than our simulations indicate. Although higher simulated yields are expected because of not taking weeds and insect pests into account, the results reported here are to be taken as general indicators rather than precise values.

Probability distributions for simulated yields averaged across the three planting dates and N-levels are shown by ENSO phase in Fig. 3a–d. Little difference in distribution between phases is seen at Karoi and Beitbridge although probability of a low yield is greater in El Niño years. An interesting feature of the probability distributions at these two sites is that in the more favorable site of Karoi, El Niño years tend to be more distinctive at the lower end of the yield spectrum, while at Beitbridge, where most years show very poor yields, ENSO phases are most distinguishable in the high end of the yield spectrum. At both Gweru and Masvingo, under this range of planting dates, yields are always highest in neutral years. However, the range of yields within all three ENSO phases in these simulations is wide and strongly overlapping, indicating that interannual climate variability within ENSO phases at the site level is high.

3.2.2. ENSO impacts by nitrogen-level

The pattern of changes in yield by ENSO phase at each site was similar for the two N treatments (Fig. 4). At both the high and low N levels, simulated yields averaged across planting date were highest in neutral years in all sites except Karoi. Simulated nitrogen losses from the soil profile were always highest in La Niña years due to the higher rainfall during the growing season, regardless of the level of nitrogen inputs. For example, at Masvingo, on average in La Niña years, 37 kg ha^{-1} of nitrogen was

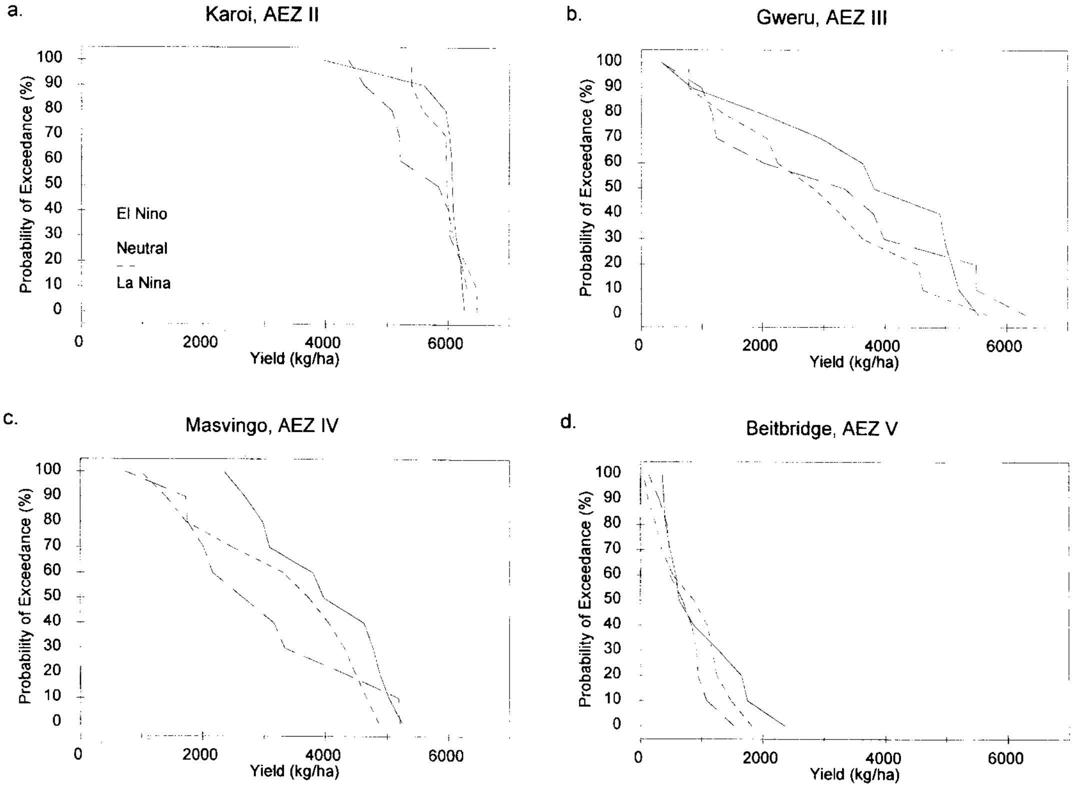

Fig. 3. a–d. Simulated maize yield probabilities by ENSO phase at four sites in Zimbabwe.

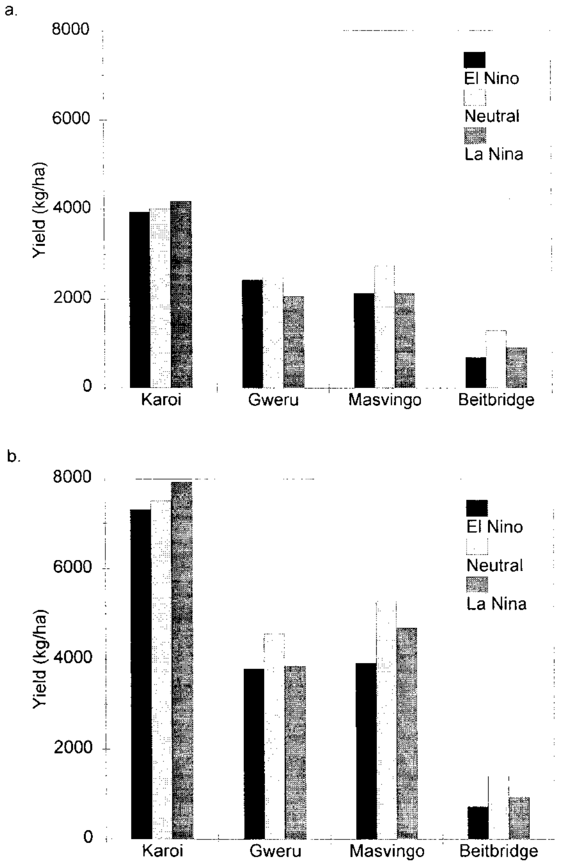

Fig. 4. Simulated mean maize yield by ENSO phase and nitrogen level at four sites in Zimbabwe: a) low N treatment (30 kg ha^{-1} at planting and 15 kg ha^{-1} top dress at six weeks), b) high N treatment (80 kg ha^{-1} at planting and 30 kg ha^{-1} top dress at six weeks.

leached from the profile during the growing season, while the average loss for each neutral and El Niño years was 24 kg ha^{-1}. Nitrogen stress may therefore account to some degree for the fact that yield levels do not follow the order of seasonal precipitation by ENSO phase, in which La Nina years should show the highest yields. This effect requires further investigation by comparison with field data.

3.2.3. *ENSO impacts by planting date*

Differences in yield by ENSO phase and planting date (Table 3) suggest that forecasts of ENSO phases might possibly be used to make planting date decisions at Gweru and Masvingo, but not necessarily in the more stable zone at Karoi or the poor site of Beitbridge. A summary by ENSO phase and planting date, averaged across N treatments, is shown in Fig. 5. At Karoi, within any of the three ENSO phases, there is little difference in simulated yield between planting dates and the standard early November planting date is probably close to the optimum (Fig. 5). At Beitbridge, the higher average precipitation during neutral years noted in Table 2 translated into somewhat higher yields in neutral years compared to both El Niño and La Niña years.

During El Niño years, only Gweru showed any advantage to change in planting date. There, simulated yields using the late planting averaged 27% higher than the mid planting date. In neutral years, the mid planting date, reflecting currently advised practices, is likely to be appropriate at all four sites, though the small differences in yield between planting dates implies that there is some leeway in timing. During La Niña years, early planting resulted in approximately 22% higher average simulated yields at both Gweru and Masvingo compared to the mid planting date.

However, in all cases and at all sites, the standard deviation in simulated yield associated with each planting date is very high (Table 3). As a percentage of yield, the deviation is highest at Beitbridge, where climate conditions are least favorable for maize production, and lowest at Karoi, where stable climate is common to all three ENSO phases. In all sets, the maximum yield in the group of El Niño years is higher than the minimum yield in La Niña or neutral years (Fig. 3). Some of this overlap may be due to the simple definition of ENSO phase used here—in application to real farmer's livelihoods, perhaps only more extreme anomalies in SST should be used, or other indicators, such as conditions in the previous year, should be taken into account to define ENSO events (e.g., Kiladis and Diaz, 1989).

3.2.4. *Inspection of single ENSO events at Masvingo*

To gain a clearer understanding of the dynamics of climate and crop growth leading the average yields presented in Table 3, three representative years, one for each ENSO phase, were chosen from the simulations at Masvingo for closer inspection.

Table 3
Simulated maize yields by ENSO phase and planting date 1952–1991

			Mean yield and standard deviation (t ha^{-1})					
			Early (Oct. 25)		Mid (Nov. 7)		Late (Nov. 21)	
Karoi	Hi N	La Niña	7.8	0.6	8.0	0.9	8.0	0.9
AEZ II		Neutral	7.3	1.6	7.9	0.6	7.4	1.5
		El Niño	7.2	1.3	7.4	0.6	7.3	0.7
	Lo N	La Niña	4.2	0.5	4.2	0.6	4.2	0.6
		Neutral	4.1	0.6	4.3	0.4	3.7	1.5
		El Niño	3.9	0.8	4.0	0.6	3.9	0.6
Gweru	Hi N	La Niña	4.6	2.7	3.6	2.3	3.3	2.3
AEZ III		Neutral	4.8	2.1	4.9	2.5	4.0	2.5
		El Niño	3.7	2.6	3.5	2.3	4.2	2.5
	Lo N	La Niña	2.2	1.5	1.9	2.3	2.1	1.4
		Neutral	2.9	1.1	2.6	2.5	2.0	1.3
		El Niño	2.3	1.4	2.1	2.3	2.9	1.5
Masvingo	Hi N	La Niña	5.6	2.0	4.7	2.2	3.8	2.1
AEZ IV		Neutral	5.0	1.9	5.4	1.7	5.5	2.1
		El Niño	4.0	2.4	4.0	2.0	3.8	2.2
	Lo N	La Niña	2.7	0.8	2.0	0.9	1.7	1.0
		Neutral	2.8	0.9	3.0	0.9	2.4	0.8
		El Niño	2.3	1.1	2.2	0.7	2.0	1.1
Beitbridge	Hi N	La Niña	0.9	0.8	0.9	0.3	0.9	0.6
AEZ V		Neutral	1.2	0.9	1.4	1.3	1.6	1.2
		El Niño	0.8	0.8	0.6	1.0	0.8	0.8
	Lo N	La Niña	0.9	0.8	0.9	0.3	0.9	0.6
		Neutral	1.1	0.9	1.4	1.2	1.5	1.3
		El Niño	0.8	0.8	0.5	0.9	0.7	0.8

High N simulations were used for these examples. The 1973–74 cropping season was a La Niña year with simulated yields slightly higher than the mean for all La Niñas. 1989–90 was chosen as the neutral year, and 1987–88 to represent an El Niño year.

Precipitation during the growing season of 1973–74 (Fig. 6a) shows the December peak and January lull in rainfall seen in the La Niña summary for Masvingo. Crop development (Fig. 6b) proceeds at roughly the same pace for the three different planting dates, but staggered at 2 week intervals. Leaf area development also proceeded similarly in all three simulations (Fig. 6c) indicating a lack of water stress. Although there was almost no water stress during any of the three runs, nitrogen stress during grainfill increased from early to late planting. On a scale of 0 to 1, with 1 representing maximum stress, simulations indicated an average nitrogen stress index of 0.42, 0.51, and 0.52 in early, mid, and late plantings. Nitrogen stress during silking also increased with planting date such that total grain number per m^2 of ground area decreased from 2420 to 1321 between early and late plantings. Early planting resulted in a simulated yield of 7.4 t ha^{-1} compared to late planting yield of 4.2 t ha^{-1}. N uptake by the crop was inversely related to the amount leached, with uptake at 84 kg ha^{-1} in the early planting versus 48 kg ha^{-1} in the late planting. In this year, the advantage of early planting was to allow for biomass development and N uptake before the heavy mid-season rainfall event occurred.

During the neutral 1989–90 season, total precipitation was somewhat lower than the neutral year mean shown in Fig. 2 for Masvingo (Fig. 7a). The peak period is in late January and early February. Under these conditions, water stress had developed during late silking and early grainfill of the early planting (Fig. 7b). Leaf area index also exhibits an early decline due to water stress (Fig. 7c). For the late planting, there was no water stress until the end

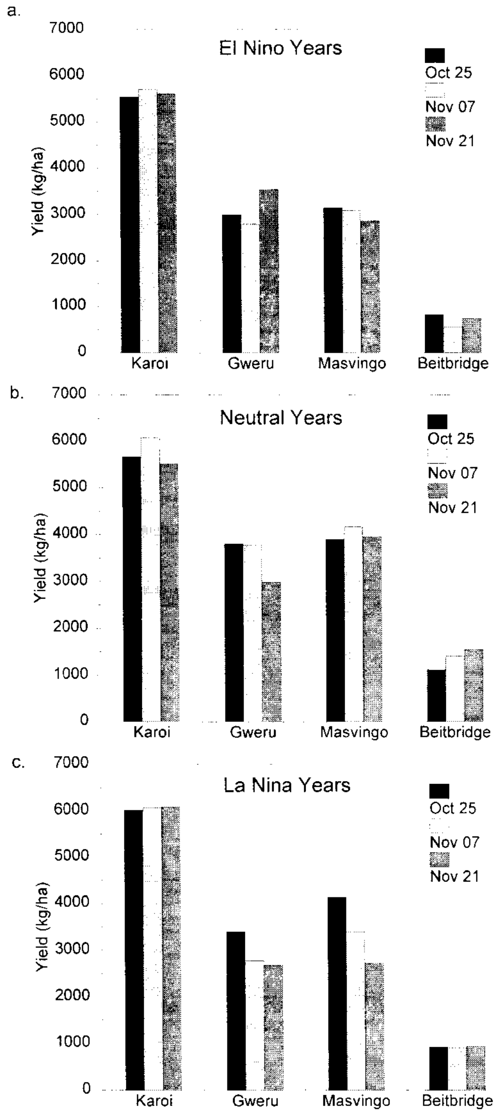

Fig. 5. Simulated maize yield by planting date and ENSO phase at four sites in Zimbabwe: a) El Niño years, b) neutral years, c) La Niña years. See text for definition of ENSO phases.

of grainfill and yields were the highest. Nitrogen stress was similar for both early and late plantings.

Precipitation in the moderate El Niño in 1987–88 (Fig. 8a) displays the December peak and January dry spell typical of an El Niño year, although total rainfall for the season was not particularly low (602 mm between planting and harvest). Simulated leaf area index shown in Fig. 8c might imply that crop vigor was highest in the mid planting. However, water stress during grainfill due to the January drought led to decreased photosynthesis and lower yields compared to the early planting. For the late planted treatment, water stress during silking averaged 0.59 with 1 representing maximum stress. Nitrogen stress during silking was also high in the late treatment, with combined effects leading to a yield

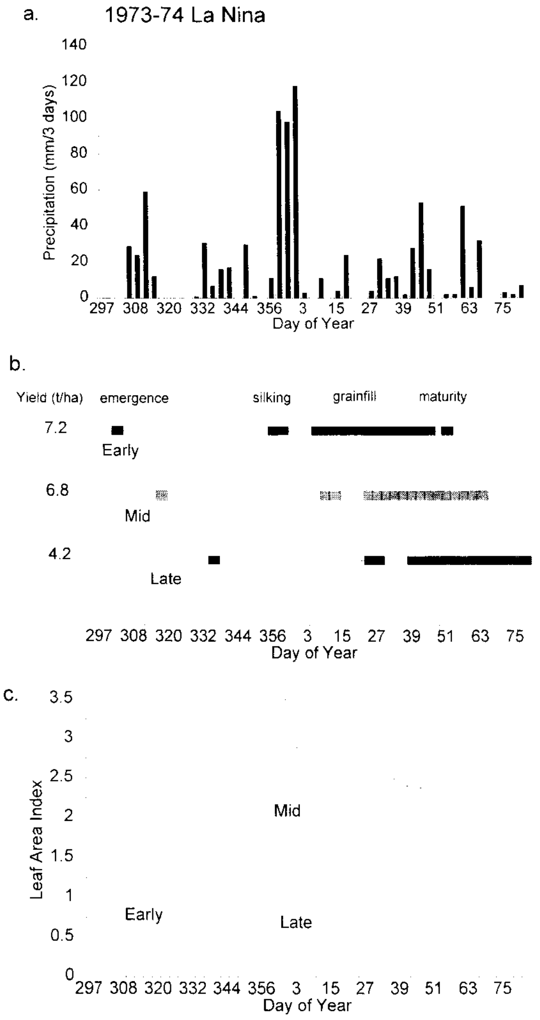

Fig. 6. Detail from the 1973–74 La Niña cropping season at Masvingo: a) growing season precipitation at 3-day intervals; b) calendar of simulated maize phenology for three planting dates; c) simulated crop leaf area index for three planting dates.

of 2.6 t ha^{-1}. The highest yields, 5.3 and 5.2 t ha^{-1}, were achieved with the early and mid planting which avoided the drought during the most sensitive periods.

Based on long-term ENSO patterns in both rainfall and simulated maize yields, no clear advice on planting date had emerged for El Niño and neutral years at Masvingo, although there was evidence that early planting in La Niña years might lead to improved yield. In these individual examples, planting at the currently advised period of early November would have led to near-optimum yields in the 1987–88 mild El Niño and the 1989–90 neutral year. In the La Niña year of 1973–74, early planting was warranted. However, these cases indicate the importance of within-season rainfall distribution in determining stresses and final yield.

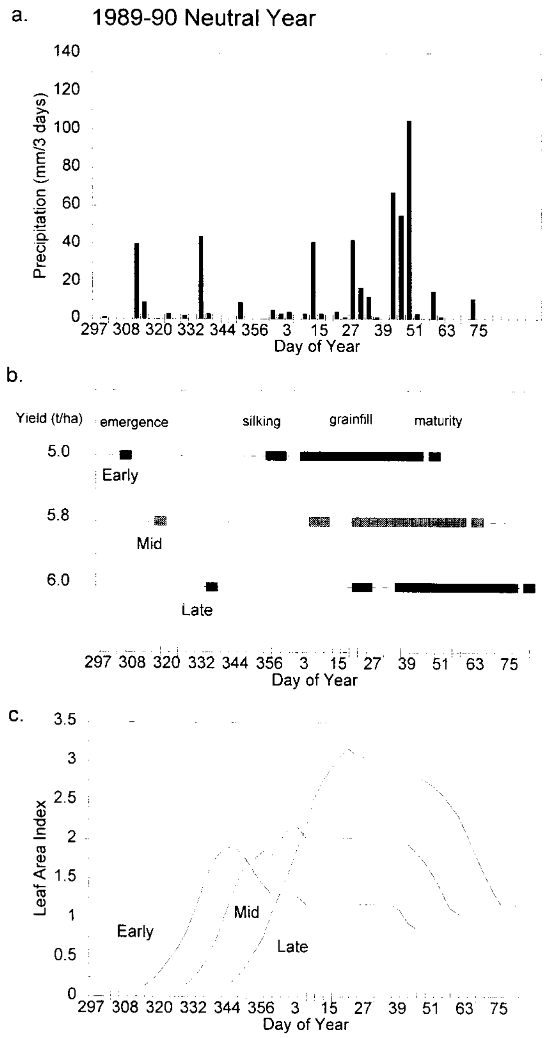

Fig. 7. Detail from the 1989–90 Neutral cropping season at Masvingo: a) growing season precipitation at 3-day intervals; b) calendar of simulated maize phenology for three planting dates; c) simulated crop leaf area index for three planting dates.

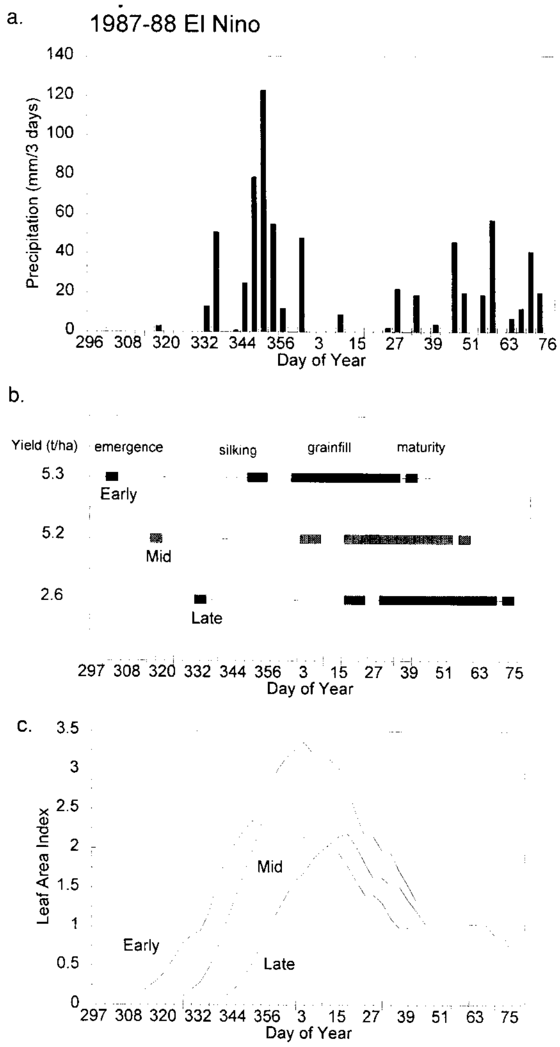

Fig. 8. Detail from the 1987–88 El Niño cropping season at Masvingo: a) growing season precipitation at 3-day intervals; b) calendar of simulated maize phenology for three planting dates; c) simulated crop leaf area index for three planting dates.

4. Conclusions

Crop simulations with stratified ENSO climate scenarios at specific sites in Zimbabwe imply that, although long-term mean precipitation and yield values vary by ENSO phase, the degree of variability within phases may limit the usefulness of this simple approach to forecast application. Analysis at the national level (Cane et al., 1994) has shown that there are significant differences in annual precipitation and maize yields between ENSO phases in Zimbabwe. However, the application of this approach at the site level may require more precise definition of ENSO phases, or the use of climate forecasts specific to each individual year based on numerical models which take into consideration large scale phenomena other than Pacific sea surface temperatures.

The value of this analysis lies in the implications for the usefulness of type of forecasts, and regional distribution. Based on the yield distributions shown in Fig. 3, the primary range of yield distinctions between ENSO phases varies depending on the AEZ. For sites operating near the yield potential such as Karoi in AEZ II, forecasts of a poor growing season may be more useful than those of good years. Similarly, for marginal sites like Beitbridge in AEZ V, where long term mean yields are extremely low and crop failures common, accurate forecasts of favorable years may be used as a basis to increase inputs. For the sites in the moderate yield range such as Gweru and Masvingo, these simulations imply that, similar to Beitbridge, forecasts of La Niña years which tend to be associated with greater seasonal precipitation, lead to management opportunities providing the greatest benefit. In El Niño years, varying time of planting was of little consequence in improving yields.

Although we detected a dry period in January relative to December and February in AEZs III and IV associated with La Niña events, simulations imply that the overall season is wet enough so that crops do not generally suffer from drought stress during this phase. Alternatively, excessively heavy rainfall in December may lead to decreased crop yields resulting from nitrogen losses from the soil profile. The common practice of splitting nitrogen fertilizer applications may help to avoid losses. Advance knowledge of a high-rainfall growing season may help improve fertilizer management, which is critical to resource-poor farmers.

This work investigates the implications of regional ENSO-related climate impacts at the site-level in Zimbabwe. This effort is directed at the development a methodology for applying seasonal climate forecasts to agricultural management at the farm level to reduce risks in production associated with climate variability. Our results indicate that, although ENSO is a strong determinant of inter-annual climate variability at these sites in Zimbabwe, forecasts based simply on ENSO categories are not likely to provide high enough quality information for maize management decision-making. However, current state-of-the-art climate forecasting methods go beyond this simple approach and are likely to result in more precise predictions upon which management decisions can be formulated in the near future. Using the conceptual framework outlined here, with improvements in both climate forecasts and crop simulation models, there is potential for identifying management strategies that reduce agricultural risk associated with climate in Zimbabwe and other ENSO-affected regions.

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