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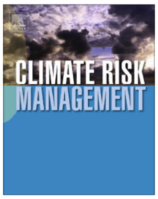

Tailoring wheat management to ENSO phases for increased wheat production in Paraguay

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ABSTRACT

Reported regional wheat yields in Paraguay vary from 1 to 3 t/ha from year to year, but appear not to be correlated with El Niño-Southern Oscillation (ENSO) phases. Historical weather data from two locations in representative wheat-growing regions of Paraguay, Encarnación-Itapúa and Ciudad del Este-Alto Paraná combined with crop modeling, were analyzed to optimize nitrogen (N) fertilizer application rates according to the ENSO phase of a growing season. The ENSO phase of a growing season was defined based on the average of the sea surface temperature (SST) anomalies in the Eastern Equatorial Pacific region for the period June–October using the El Niño region 3.0 index (Niño 3.0). Simulated average yields in Alto Paraná were higher in the drier and cooler La Niña wheat-growing seasons (average of 3.5 t/ha) compared to the other phases (average of 3.2 t/ha) and in Itapúa, in Neutral seasons (average of 3.8 t/ha) compared to the other phases (average of 3.7 t/ha). Accordingly, optimal N fertilizer applications ranged between 20 and 60 kg N/ha between phases depending on the sowing date, soil type and initial amount of soil water content. Applying an ENSO or General Circulation Model (GCM)-based forecast for ENSO-season-type specific N fertilizer applications resulted in benefits of >100 US$/ha when compared with current farmers' practice of consistently low N fertilizer applications in Paraguay. When N management based on forecasts was compared with optimized N application without forecast, the benefits of the forecast was only up to 8 US$/ha. The ENSO-persistence-based forecast showed higher values than the GCM-based forecasts with two lead-times but lower skill. Using climate information can significantly increase current wheat yields and gross margins in Paraguay by tailoring N fertilizer applications to the Niño 3.0-defined ENSO phases, which can be forecasted with moderate skill at the beginning of the growing season.

Introduction

Wheat is one of the most important food crops covering about 22% of the worlds cultivated land (Licker et al., 2010). It is grown in a wide range of growing conditions, and yields often vary from year to year due to seasonal climate variability in

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rainfall and temperature (Lobell et al., 2009). Wheat is sown in Paraguay during autumn and early winter between May and June, following soybean grown over the summer. In Paraguay, 65% of wheat production is concentrated in two regions, Alto Paraná (37%) and Itapúa (28%). In 2008, wheat production reached 800,000 t with an average yield of 2.1 t/ha (Cardozo et al., 2010).

Most studies on El Niño-Southern Oscillation (ENSO) anomalies in southeastern South America have focused on precipitation as the main cause for seasonal yield variability (Barreiro, 2010; Grimm and Tedeschi, 2009; Barros et al., 2008; Silvestri, 2005). But, some correlation between ENSO and seasonal temperature anomalies has been suggested for Paraguay (Barreiro, 2010; Barros et al., 2002), but this has not been considered in analyzing seasonal yield variability in this country. Hence, understanding seasonal rainfall and temperature variability and its association with ENSO phases in Paraguay would allow farmers to develop management practices tailored to anticipated climate conditions and yield potential (Podesta et al., 2002).

The application of ENSO phases as a planning tool in agriculture has been reported for different parts of the world (Jones et al., 2000; Hammer et al., 2001; Potgieter et al., 2002; Mauget et al., 2009), showing that tailoring management practices to anticipated rainfall can increase farmerś profits (Asseng et al., 2012; Hansen et al., 2009; Moeller et al., 2008). The planning tool's profitability, however, varies between regions and crops (Meza et al., 2008). In South America, studies on the interaction between ENSO phases and wheat yields have led to contradicting results. For example, in Argentina, studies on the impact of ENSO on wheat yield found no interaction between ENSO and yields (Podesta et al., 1999). In contrast, in Santa María, Rio Grande do Sur in Brazil, La Niña seasons were more favorable for high wheat yields (Alberto et al., 2006). A study of summer-grown soybeans in Paraguay showed lower precipitation patterns during the early (sowing–blooming) and late (seed-podding to maturity) developmental stages of the crop during La Niña seasons compared to El Niño seasons (Fraisse et al., 2008). However, no such analysis has been carried out for wheat growing over winter in Paraguay. Hence, the objectives of this study were (1) to explore differences in wheat yields due to seasonal ENSO phases in the main wheat-growing region of Paraguay and (2) to evaluate ENSO- and GCM-based forecasts for managing seasonal variability to increase farmerś gross margins.

Methods and materials

Experiment

Historic climate data records of two weather stations were used in the simulation: Encarnación-Itapúa, with sixty seasons (1951–2010) and Ciudad del Este-Alto Paraná, with forty seasons (1967–2006). The same weather data records were previously used in a soybean study in Paraguay (Fraisse et al., 2008). Longer historic weather data was not available for any of the locations in Paraguay. The treatments in the experiment were: (1) two clay soils with different field capacity per location: in Alto Paraná, a soil with lower plant available water holding capacity (LWH) of 240 mm and a soil with higher plant available water holding capacity (HWH) of 290 mm; in Itapúa, a soil with LWH of 200 mm and with HWH of 300 mm; (2) four different sowing dates: May 10, May 20, May 30 and June 10; (3) six different nitrogen (N) applications: 0, 20, 40, 60, 80 and 100 kg N/ha as ammonium nitrate fertilizer applied in one application at sowing; and, (4) two different initial soil water contents: wet (soil water content at drained upper limit) and dry (soil water content at plant lower limit). Soil input values were obtained from a previous soil characterization (Lopez-Gorostiaga et al., 1993). The selected wheat cultivar br23 is a medium maturity cultivar developed in Brazil and widely used in Paraguay (Anonymous, 2002). The timing of wheat developmental stages in Paraguay was parameterized in the simulation using expert information from an extension group in Paraguay.

ENSO classification

The ENSO is a coupled ocean–atmosphere interaction driven by the anomalously warm (El Niño phase) or cold (La Niña phase) sea surface temperatures (SST) in the Eastern Equatorial Pacific. Typically, the ENSO phase is established in austral summer and persists for a number of months thereafter (Rasmusson and Carpenter, 1983). The atmospheric (teleconnection) response to a given ENSO phase can be seen in the precipitation and temperature patterns at numerous locations around the globe, including South America (Halpert and Ropelewski, 1992; Ropelewski and Halpert, 1987). The remote atmospheric response to ENSO is typically delayed by 1–3 months (Kumar and Hoerling, 2003).

There is no consensus in the scientific community on which ENSO index defines better the ENSO phase (Hanley et al., 2003). The Southern Oscillation Index (SOI) (Hammer et al., 1996), the Multivariate ENSO Index (MEI) (Ganguli and Reddy, 2013), the El Niño region 3.0 index (Niño 3.0) (Baawain et al., 2005) and the Japan Meteorological Agency Index (JMA) (Hanley et al., 2003; Fraisse et al., 2006; Gimeno et al., 2002; Hansen et al., 1999; Izaurralde et al., 1999) have been used in categorizing seasons among others. The weather data for this study were categorized into ENSO phases using the Niño 3.0 information (Baawain et al., 2005; Trenberth, 1997). The average of the Niño 3.0 index monthly anomalies for June–October was used to classify the wheat growing-season into El Niño seasons (>0.5 °C), La Niña seasons (<−0.5 °C) and Neutral seasons. Continuously updated monthly Niño 3.0 anomalies are available on the Internet (COAPS, 2014).

Following this classification, in Alto Paraná the climate data from 1967 to 2006 were grouped into 10 El Niño seasons, 9 La Niña seasons and 21 Neutral seasons. In Itapúa the climate data from 1951 to 2010 were grouped into 16 El Niño seasons, 16 La Niña seasons, and 28 Neutral seasons (Table 1).

Seasonal forecast

Three seasonal forecast systems were evaluated. For the first seasonal forecast system the Niño 3.0 index for May was assumed to be consistent with the Niño 3.0 of the following wheat growing-season (June–October). The ENSO-persistence-based forecast included 60 hindcast seasons (1951–2010). In the second forecast system, a General Circulation Model (GCM)-based forecast (Climate Forecast System version 2 (CFS-V2) from NOAÁs National Center for Environmental Prediction (NCEP) Saha et al., 2006; http://iridl.ldeo.columbia.edu/), predicting in April of each year (2-month lead time) the SST anomalies for the wheat growing season was used. In a third forecasting system, the same GCM-based forecast was employed by using the predictions made in May (1-month lead time) for the following wheat growing season.

The GCM-based forecast included 28 hindcast seasons (1982–2009). GCM-based hindcasts were initialized every month, with a 4 times-daily integration and up to 9 months lead time (Saha et al., 2010; Yuan et al., 2011). The latitude and longitude point extracted from the hindcast data was the El Niño region 3.0 (5S–5N, 150–90W). The average SST anomalies of the hindcast during the period June–October were used to classify the seasons into ENSO phases and compared with the classification obtained using the historical SST anomalies.

APSIM

The widely tested and adopted wheat model, the Agricultural Production System Simulator (APSIM) (Keating et al., 2003) N-Wheat model (Asseng et al., 1998; Asseng et al., 2001a,b; Asseng and Milroy, 2006), was used in this study. This crop model was developed by the Agricultural Production System Research Unit (APSRU) in Australia to analyze the biophysical processes involved in a farming system. It includes modules that simulated growth, development and yield of crops, soil water balance, mineralization and immobilization of soil nitrogen. The crop module accounts for the development and growth, water and nitrogen uptake, and the different stress factors of the wheat crop (Keating et al., 2003). The model calculates a potential yield for a specific environment, limited by temperature, solar radiation and rainfall (Lobell et al., 2009; Asseng, 2004). The APSIM N-Wheat model was used to simulate 40 crop seasons for Alto Paraná and 60 crop seasons for Itapúa. Ninety-six management practice combinations were tested for each year, and the resulting impacts on yield were evaluated for each ENSO phase.

Crop economics

Gross margin (GM) was calculated for each treatment:

$$\mathrm{GM} = Y * P_y - C_d - F * P_f$$

with Y as the grain yield, P_y as the price of wheat, C_d as the direct costs including all inputs required, except for N fertilizer costs, F as the amount of fertilizer and P_f as the cost per kg N fertilizer. The direct cost was 119 US$/ha (Cañete, 2005) and fertilizer cost was 0.88 US$/kg (Asseng et al., 2012; Moeller et al., 2008). A wheat price of 195 US$/t was assumed considering the price variability of wheat during the period 2005–2010 (FAOSTAT, 0000).

Marginal gross margins were calculated for changes in nitrogen application to evaluate the net return of investment of each dollar invested in fertilizer in each ENSO phase. The management practices tested were those combinations between management and ENSO phases that resulted in a statistical significant increase in GM. The assumption was made that for a farmer to invest in additional N fertilizer (in additional 20 kg N/ha units), the marginal gross margin had to be twice as much the original investment for the additional N fertilizer application (i.e., 2 US$ for each dollar invested in additional N fertilizer) (Asseng et al., 2012). This conservative approach accounts for a farmeŕs risk-averse behavior in dry land agriculture.

Statistical analysis

A statistical analysis was carried out to determine differences in practices in each phase. Analysis of Variance (ANOVA) was computed using the SAS 9.2.3 program. The model response variable was yield (t/ha) (Y) and gross margin (GM). The

Table 1
ENSO monthly mean for (June–October) classification following the El Niño region 3.0 index anomalies (1951–2010).

El Niño	1951, 1957, 1963, 1965, 1969, 1972, 1976, 1982, 1983, 1987, 1991, 1997, 2002, 2006, 2008, 2009
La Niña	1954, 1955, 1956, 1961, 1964, 1967, 1970,1971, 1973, 1975, 1978, 1985, 1988, 1999, 2007, 2010
Neutral	1952, 1953, 1958, 1959, 1960, 1962, 1966, 1968, 1974, 1977, 1979, 1980, 1981, 1984, 1986, 1989, 1990, 1992, 1993, 1994, 1995, 1996, 1998, 2000, 2001, 2003, 2004, 2005

main factors were soil (S), fertilizer (F), sowing date (P), initial water content (IC) and ENSO phase (E). Interaction effects were calculated between the main factors. Mean comparisons between significant interactions ($\alpha = 0.05$) were also computed using the Fisher's test.

The skill of each forecast system was computed using the Accuracy (ACC), Heidke Skill Score (HSS) (data not shown) and S% verification measurement tests (Table 2) (Jolliffe and Stephenson, 2003).

Results

Weather conditions

Differences in precipitation pattern were observed between ENSO phases during the wheat-growing-season in Paraguay (Fig. 1). However, the average monthly rainfall in Paraguay during the wheat growing season remained on average above 70 mm at both locations. Despite relative high rainfall in each month, La Niña seasons were drier during the months of August–October in Alto Paraná compared to the other two phases; La Niña seasons were also dryer in June, August and October in Itapúa and this variation in rainfall contributed to the variation in simulated yield among the ENSO phases.

Average maximum and minimum temperature anomaly differences were observed between ENSO phases during the wheat-growing-season in Paraguay (Fig. 2). The highest negative average maximum temperature anomalies occurred in July during La Niña phases in Alto Paraná (−0.5 °C) and in Itapúa (−1.1 °C). The highest positive anomaly of 0.6 °C occurred in July during El Niño phases in both locations. The highest negative average minimum temperature anomaly in Alto Paraná occurred in June during La Niña phase (−1.1 °C) and in Itapúa in July during La Niña phase (−0.6 °C). The highest positive anomaly in Alto Paraná occurred in July during El Niño phase (0.6 °C) and in Itapúa in September during La Niña phase (1.0 °C).

Observed and simulated yields

Observed regional wheat yields for Itapúa and Alto Paraná for the period 1991–2009 ranged between 1 and 3 t/ha (Fig. 3). The observed mean yield in Itapúa was 1.9 t/ha with a standard deviation of 0.6 t/ha, while in Alto Paraná the observed average yield was 2.1 t/ha with a standard deviation of 0.4 t/ha. Categorizing the observed yield data by seasonal ENSO phases showed that high and low yields occurred in El Niño and also La Niña seasons, suggesting no correlation of observed yields with ENSO phases.

Simulated yields for different management combinations resulted in a high variability of yields within and between ENSO phases. For instance, in Alto Paraná in La Niña seasons, first and third quartile yields varied between 2.6 and 3.9 t/ha. In El Niño seasons, yields ranged from 2.0 to 3.4 t/ha, and in Neutral seasons the variability in yield was between 2.3 and 3.7 t/ha. In Itapúa in La Niña seasons, first and third quartile yields varied similarly between 2.3 and 3.9 t/ha. In El Niño seasons, yields were in the range of 2.1 to 3.8 t/ha, and in Neutral seasons yields ranged between 2.5 and 4.1 t/ha. On average, higher simulated yields occurred during La Niña seasons in Alto Paraná, 3.2 t/ha compared to El Niño, 2.7 t/ha and Neutral seasons, 3.0 t/ha and during Neutral in Itapúa, 3.3 t/ha followed by La Niña and El Niño seasons 3.0 t/ha.

Farmers in Paraguay currently use approximately 20 kg N/ha of fertilizer applied at sowing. Fig. 4 shows the simulated wheat yield obtained with this practice and grouping the simulated yields by ENSO phase. Similar to the observed regional yields in Fig. 3, there appeared to be no correlation of simulated yields with 20 kg N/ha of fertilizer and ENSO phases, except for a tendency for slightly higher yields in La Niña seasons compared to the other phases in Alto Paraná and in Neutral seasons compared to the other phases in Itapúa.

Simulated management practices

The ANOVA on the impact of soil types, crop management, ENSO phases on simulated grain yields is shown in Table 3. In Alto Paraná, sowing date and initial amount of water at sowing were the two management practices interacting with the ENSO phases that were statistically significant at an $\alpha = 0.05$. In addition to the initial amount of water at sowing, soil type also had a statistically significant interaction with the ENSO phases in Itapúa.

Table 2
ENSO and GCM-based seasonal forecast skill for ENSO phases during the period June–October using the S% skill measurement.

Forecast	Enso	S% skill	
		GCM April	GCM May
Neutral	0.38[a]	0.00	0.29
El Niño	0.64[a]	0.43	0.64[a]
La Niña	0.67[a]	0.57	0.64[a]

[a] Statistical significance at 95% confidence level.

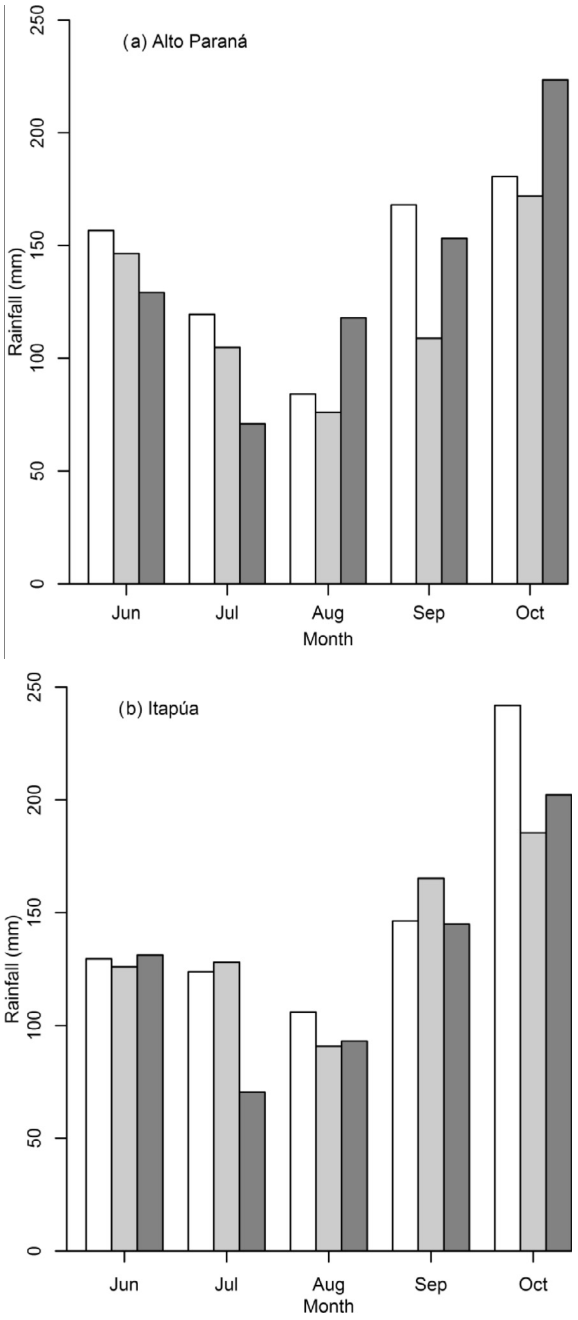

Fig. 1. Monthly mean precipitation (mm) for (a) Alto Paraná (1966–2006) and (b) Itapúa (1951–2010), Paraguay, for each ENSO phase. Precipitation is shown as bars: for El Niño phase (open bar), La Niña phase (light gray bar) and Neutral phase (dark gray bar).

Table 4 presents the mean yield differences for changes in management practices including fertilizer application, sowing date, initial soil water content and soil type, and mean yield differences for changes between the ENSO phases using the Fisher's mean comparison to test for significance.

N fertilizer

In Alto Paraná, increases in simulated yields with increased applied N fertilizer were statistically significant ($\alpha = 0.05$) up to 40 kg N/ha in La Niña and El Niño seasons and up to 60 kg N/ha in Neutral seasons as shown in Table 4a. In Itapúa, the increase in simulated yield with increased N fertilizer was significant at higher fertilizer levels. For instance, increases in

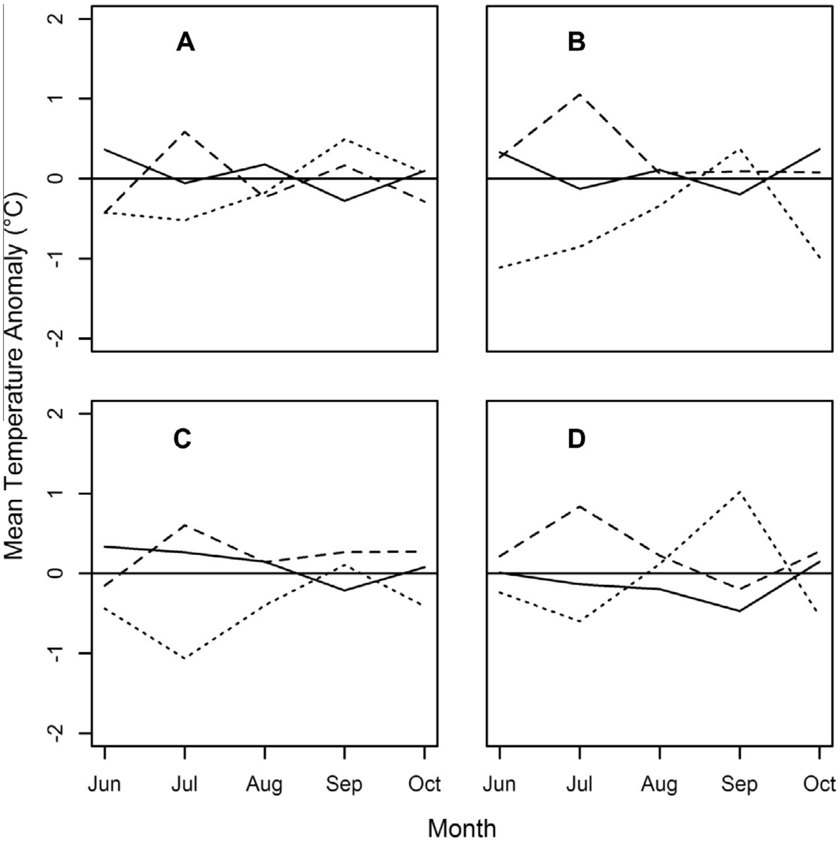

Fig. 2. Monthly mean temperature anomalies (°C) for Alto Paraná (1966–2006) (a) average maximum temperature and (b) average minimum temperature and Itapúa (1951–2010), Paraguay, (c) average maximum temperature and (d) average minimum temperature for each ENSO phase: El Niño phase (dashed line), La Niña phase (dotted line) and Neutral phase (full line).

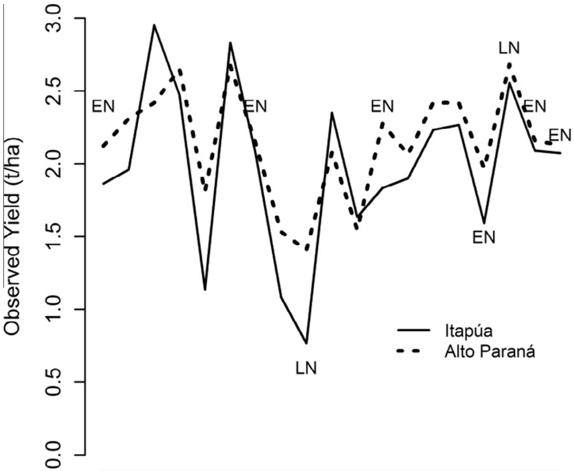

Fig. 3. Observed yield (t/ha) for Alto Paraná (dashed line) and Itapúa, Paraguay (full line); El Niño (EN), La Niña (LN) seasons.

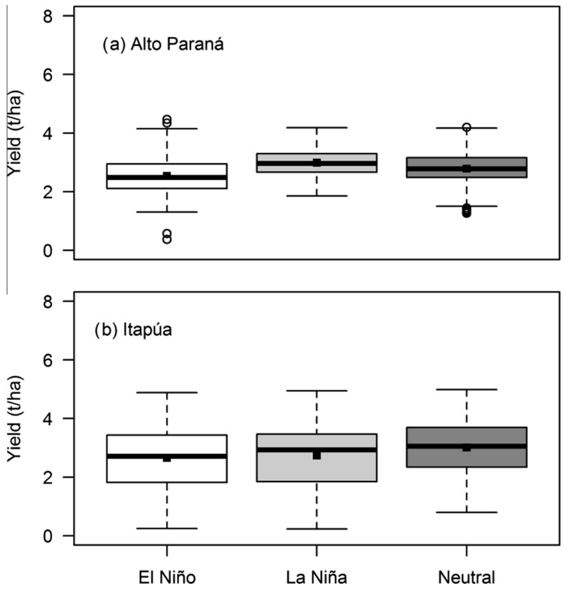

Fig. 4. Simulated yield (t/ha) for (a) Alto Paraná and (b) Itapúa, Paraguay for El Niño (open box), La Niña (light gray box) and Neutral (dark gray box) with current N application of 20 kg N/ha. Horizontal lines show median; black squares show average; upper box shows third quartile data; lower box shows second quartile data; upper error bar shows fourth quartile data; lower error bar shows the first quartile data and open circles show the outliers.

Table 3
Analysis of ANOVA results of soil type, initial soil water, crop, management practices and ENSO phases for Alto Paraná and Itapúa, Paraguay.

Location	Alto Paraná			Itapúa		
Source	DF	*F* value	Pr > *F*	DF	*F* value	Pr > *F*
Soil type (ST)	1	101.00	<.0001[a]	1	825.54	<.0001[a]
Fertilizer (F)	5	371.06	<.0001[a]	5	444.33	<.0001[a]
Sowing date (PD)	3	5.73	0.0007[a]	3	4.20	0.0056[a]
Soil water content (SWC)	1	18.82	<.0001[a]	1	111.31	<.0001[a]
Enso	2	76.83	<.0001[a]	2	78.50	<.0001[a]
ST*F	5	19.76	<.0001[a]	5	46.76	<.0001[a]
ST*PD	3	1.12	0.3407	3	5.28	0.0012[a]
ST*SWC	1	2.64	0.1043	1	33.44	<.0001[a]
ST*Enso	2	1.39	0.2482	2	6.91	0.0010[a]
F*PD	15	0.13	1.0000	15	0.64	0.8479
F*SWC	5	0.93	0.4634	5	1.48	0.1923
F*Enso	10	0.59	0.8230	10	0.31	0.9800
PD*SWC	3	0.59	0.6238	3	0.74	0.5256
PD*Enso	6	2.76	0.0112[a]	6	0.97	0.4442
SWC*Enso	2	8.44	0.0002[a]	2	5.76	0.0032[a]
F*PD*SWC	15	0.02	1.0000	15	0.01	1.0000
F*SWC*Enso	10	0.10	0.9998	10	0.01	1.0000
F*PD*Enso	30	0.20	1.0000	30	0.06	1.0000
PD*SWC*Enso	6	0.13	0.9928	6	0.14	0.9918
F*PD*SWC*Enso	30	0.01	1.0000	30	0.00	1.0000

[a] Statistical significance at 95% confidence level.

simulated yield with higher applied N fertilizer were statistically significant ($\alpha = 0.05$) up to 60 kg N/ha in El Niño and up to 80 kg N/ha in La Niña ($\alpha = 0.10$) and Neutral seasons ($\alpha = 0.10$).

Sowing date

The sowing date affected simulated yields differently in each ENSO phase as shown in Table 4a. It had no effect on simulated yield during La Niña seasons in Alto Paraná and during El Niño and Neutral seasons in Itapúa. In El Niño seasons, sowing later in the growing season affected the simulated yields in Alto Paraná. For instance, a shift in sowing date from May 10 to 20 resulted in significant increases in yield at $\alpha = 0.05$ and a change in sowing date from May 30 to June 10 also resulted in significant increase in yield at $\alpha = 0.10$. In the Neutral seasons in Alto Paraná a change from May 30 to June 10 resulted in a

Table 4
Mean wheat grain yield changes (t/ha) in management practices, soil types, initial soil water contents and ENSO phases at Alto Paraná and Itapúa, Paraguay using fisher's test.

a) For changes in management practices

Location	Phases	N fertilizer				
		0–20 kg	20–40 kg	40–60 kg	60–80 kg	80–100 kg
Alto Paraná						
	El Niño	1.0803^{b}	0.4347^{b}	0.1751^{a}	0.0442	0.0083
	La Niña	1.1227^{b}	0.5208^{b}	0.1745^{a}	0.0184	0.0034
	Neutral	0.9881^{b}	0.4118^{b}	0.1840^{b}	0.0758	0.0138
Itapúa						
	El Niño	0.8443^{b}	0.4274^{b}	0.2294^{b}	0.1256	0.0686
	La Niña	0.9022^{b}	0.4579^{b}	0.2747^{b}	0.1461^{a}	0.0744
	Neutral	0.8839^{b}	0.4537^{b}	0.2374^{b}	0.1192^{a}	0.0582

		Sowing date			Soil water content	Soil type
Alto Paraná		May 10–20	May 20–30	May 30–June 10	Empty–Full	LWH–HWH
	El Niño	0.1787^{b}	0.0293	0.1439^{a}	0.1090^{b}	0.2662^{b}
	La Niña	−0.0798	0.0226	−0.0150	0.0018	0.3613^{b}
	Neutral	0.0094	0.0722	0.1239^{b}	0.2674^{b}	0.2488^{b}
Itapúa						
	El Niño	0.0423	0.0747	0.0286	0.3493^{b}	0.6988^{b}
	La Niña	−0.0981	0.0790	0.1152^{a}	0.1452^{b}	0.8864^{b}
	Neutral	0.0606	−0.0151	0.0542	0.3315^{b}	0.6642^{b}

b) For changes in ENSO phases

Management Practices	Alto Paraná			Itapúa		
	EN-LN	EN-N	N-LN	EN-LN	EN-N	N-LN
N fertilizer						
0 kg	0.4062^{b}	0.3384^{b}	0.0678	0.0195	0.3130^{b}	−0.2935^{b}
20 kg	0.4486^{b}	0.2462^{b}	0.2025^{b}	0.0773	0.3526^{b}	−0.2752^{b}
40 kg	0.5347^{b}	0.2233^{b}	0.3114^{b}	0.1079	0.3790^{b}	−0.2711^{b}
60 kg	0.5341^{b}	0.2322^{b}	0.3018^{b}	0.1532^{a}	0.3870^{b}	−0.2338^{b}
80 kg	0.5083^{b}	0.2639^{b}	0.2445^{b}	0.1737^{b}	0.3806^{b}	−0.2069^{b}
100 kg	0.4966^{b}	0.2693^{b}	0.2272^{b}	0.1795^{b}	0.3703^{b}	−0.1908^{b}
Sowing date						
May 10	0.7251^{b}	0.3727^{b}	0.3524^{b}	0.2002^{b}	0.3887^{b}	−0.1885^{b}
May 20	0.4665^{b}	0.2034^{b}	0.2631^{b}	0.0596	0.4069^{b}	−0.3472^{b}
May 30	0.4598^{b}	0.2464^{b}	0.2134^{b}	0.0639	0.3169^{b}	−0.2530^{b}
June 10	0.3009^{b}	0.2264^{b}	0.0745	0.1504^{b}	0.3425^{b}	−0.1921^{b}
Soil water content						
Dry	0.5416^{b}	0.1830^{b}	0.3586^{b}	0.2206^{b}	0.3727^{b}	−0.1521^{b}
Wet	0.4345^{b}	0.3414^{b}	0.0931^{a}	0.0164^{a}	0.3548^{b}	−0.3383^{b}
Soil type						
LWH	0.4405^{b}	0.2709^{b}	0.1696^{b}	0.0247	0.3811^{b}	−0.3563^{b}
HWH	0.5356^{b}	0.2535^{b}	0.2821^{b}	0.2123^{b}	0.3465^{b}	−0.1341^{b}

[a] Statistical significance at 90% confidence level. N Neutral, EN El Niño, LN La Niña, LWH soil with lower plant available water holding capacity. HWH soil with higher plant available water holding capacity.

[b] Statistical significance at 95% confidence level.

significant increase in yields at $\alpha = 0.05$. In La Niña seasons, the sowing date in Itapúa had a positive effect on yield if the sowing date was shifted from May 30 to June 10 at $\alpha = 0.10$.

Initial soil water content and soil type

Table 4a shows the mean yield gains of having a full profile at sowing. Simulations under a full profile compared to an empty profile increased yields in the range of 0.1–0.3 t/ha at $\alpha = 0.05$ during El Niño and Neutral phases, but with no effect during a La Niña phase in Alto Paraná and at $\alpha = 0.05$ during all three ENSO phases in Itapúa. Crops during a Neutral phase had the greatest potential to benefit from soil water content at sowing at Alto Paraná and during an El Niño phase in Itapúa. Soils with higher plant available water holding capacity had a positive effect on yields in all ENSO phases. In Alto Paraná, the increase in yields due to soil type ranged between 0.2 and 0.4 t/ha. In Itapúa, the increase in yields ranged between 0.6 and 0.9 t/ha.

Crop development

In addition to yield, anthesis date, maturity date and biomass accumulation were analyzed in the simulations suggesting differences in crop development, as a consequence of differences in temperatures among ENSO phases. In Alto Paraná, the anthesis and maturity date was delayed by an average of 3 days in La Niña seasons compared to an El Niño phase and by an average of 1.4 days for anthesis and maturity date compared to a Neutral phase. The delay in the anthesis date resulted in higher biomass accumulation in La Niña seasons (total average of 6.6 t/ha) compared to Neutral seasons (total average of 6.1 t/ha) and El Niño seasons (average of 5.4 t/ha).

In Itapúa, the anthesis date was delayed by an average of 3.6 days and maturity by 2.7 days in La Niña seasons compared to an El Niño phase and by an average of 2.8 days for anthesis and 1.1 days for maturity compared to a Neutral phase. The delay in the anthesis date resulted in higher biomass accumulation in La Niña seasons (total average of 6.2 t/ha) compared to El Niño seasons (total average of 6.0 t/ha), but crops in Neutral seasons accumulated on average the highest biomass (average of 6.6 t/ha).

Differences between ENSO phases

Applying a common management practice and evaluating the simulated impact on yields by ENSO phase made it possible to determine the differences in yields attributable to ENSO-related climate variability. In Alto Paraná, simulated yield comparison among ENSO phases resulted in statistically significant differences for all the management practices in this study (Table 4b), except when no N fertilizer was applied and at sowing date of June 30, where no statistical difference between Neutral and La Niña phase yields were simulated. In Itapúa, simulated yield differences between El Niño and La Niña phases were not found for some of the management practices. Yield differences between these two phases were only apparent with more than 60 kg N/ha applied at sowing and no difference between phases occurred at sowing date May 20 and 30 and when there was no initial soil water content at sowing.

Net gross margins

Fig. 5 presents the net gross margins for Alto Paraná for changes in N fertilizer application and sowing date for different initial soil water contents and soil types for each ENSO phase. On soil types with HWH, a change in N fertilizer application from 20 to 40 kg N/ha regardless of the initial soil water content at sowing resulted in higher returns during all three ENSO phases. The optimal sowing date for a HWH soil at Alto Paraná was June 10 for El Niño and Neutral seasons regardless of the initial soil water content at sowing, and during La Niña, June 10 was the optimal sowing date for a dry soil at sowing and May 10, for a wet soil at sowing.

During El Niño, La Niña and Neutral seasons, a change in fertilizer application from 20 to 40 kg N/ha was economical on soil types with LWH and dry soils at sowing, and a change in fertilizer from 40 to 60 kg N/ha for wet soils at sowing. An additional increase in fertilizer did not meet the required profit threshold for each dollar invested in N fertilizer. Under dry soil at sowing the optimal sowing dates on soil types with LWH soils occurred later in the sowing window: June 10 for El Niño and Neutral seasons and May 30 for La Niña seasons. The optimal sowing dates under wet soils at sowing was May 20 for El Niño seasons, May 10 for La Niña seasons and June 30 for Neutral seasons.

Net gross margins in Itapúa were also calculated for changes in fertilizer application considering soil type, sowing date and initial soil water content for each ENSO phase. For soils with HWH in El Niño and Neutral seasons, the current fertilizer application of 20 kg N/ha resulted on average in a net gross margin return of 2 US$ for each dollar invested in N for dry soils at sowing and a change from 20 to 40 kg N/ha for wet soils at sowing. In La Niña seasons, in soils with HWH, a change in fertilizer application from 20 to 40 kg N/ha was economical, regardless of the initial soil water content at sowing. The optimal sowing date for the soil with HWH was June 30 in the three ENSO phases, regardless of the soil water at sowing. For soils with LWH, an increase in fertilizer application from 20 to 60 kg N/ha resulted on average in a net gross margin return above 2 US$, regardless of the initial soil water content at sowing in the three ENSO phases. The optimal sowing date on soils with LWH in all the phases was June 30 with the exception of El Niño (May 30) and Neutral seasons (May 10) for wet soils at sowing.

Evaluating optimal practices

Considering the optimal amount of fertilizer for each ENSO phase to guarantee an average net return of 2 US$ for each dollar invested in N fertilizer, Fig. 5 shows the potential benefits of changing the amount of fertilizer and sowing dates to the optimal levels in different ENSO phases compared to the current farmer practice of applying 20 kg N/ha and sowing at May 20.

The mean gross margins achieved by applying 20 kg N/ha in Alto Paraná on a HWH soil were 384 US$/ha in El Niño, 483 US$/ha in La Niña and 433 US$/ha in Neutral seasons. By applying 40 kg N/ha regardless of the initial soil water content at sowing and sowing in the optimal dates, the gross margins increased by 31% in El Niño, by 20% in Neutral seasons and by 17% in La Niña seasons compared to current farmer's practice of applying 20 kg N/ha. The standard deviation for the optimal N fertilizer practices was 206 US$/ha in El Niño, 179 US$/ha in Neutral seasons and 114 US$/ha in La Niña seasons compared to a standard deviation of 113, 125 and 64 US$/ha for El Niño, Neutral and La Niña phases, respectively, under the current farmer's practice.

The mean gross margins achieved by applying 20 kg N/ha in Alto Paraná on a LWH soil were 322 US$/ha in El Niño, 391 US$/ha in La Niña and 365 US$/ha in Neutral seasons. By applying 40–60 kg N/ha depending on the initial soil water content

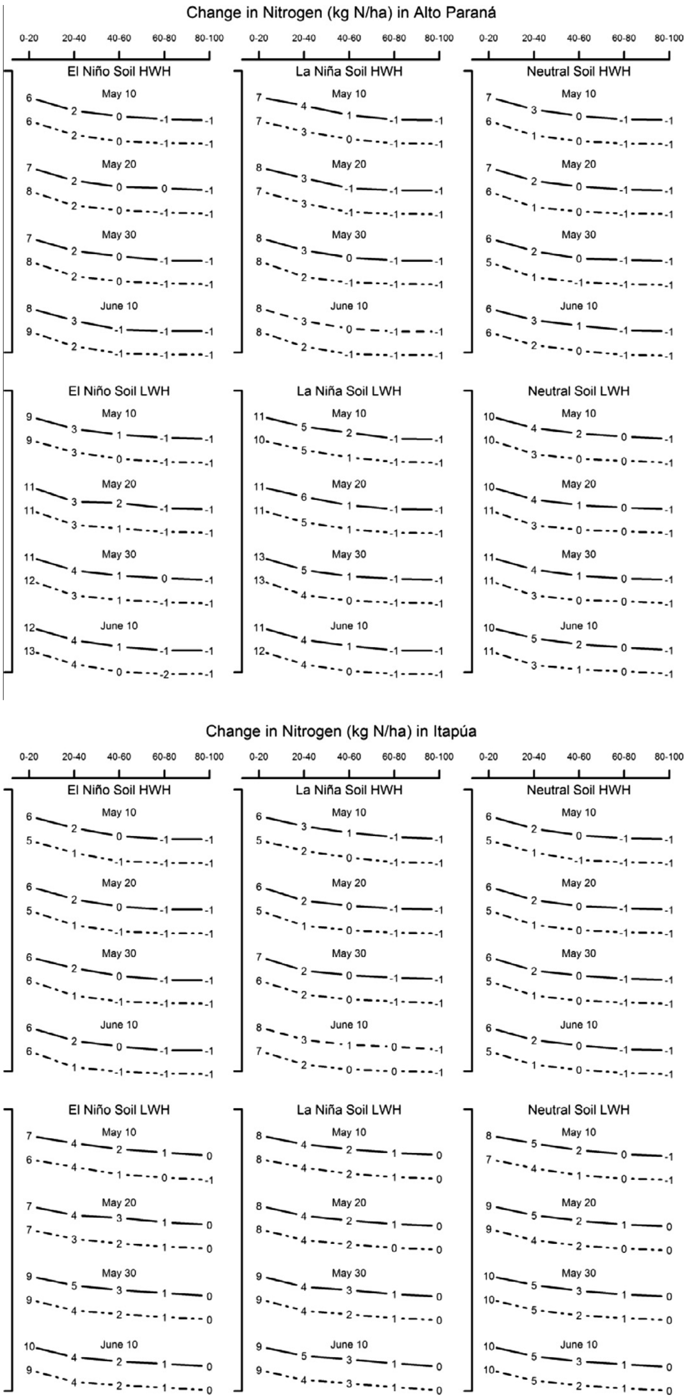

Fig. 5. Simulated gross margin net returns expressed in dollars (US$) for changes in the level of nitrogen applied (kg N/ha) at (a) Alto Paraná and (b) Itapúa, Paraguay for four different sowing dates with initial soil water in the profile at drained upper limit (full line) and a dry soil profile (dot with line) for a soil with high plant available water holding capacity (HWH) and a soil with low plant available water holding capacity (LWH) for the three ENSO phases.

at sowing and sowing at optimal sowing dates, the gross margins increased by 38% in El Niño, by 33% in Neutral and by 35% in La Niña seasons compared to current farmer's practice. The standard deviation for the optimal N fertilizer application was 174 US$/ha in El Niño, 159 US$/ha in Neutral and 115 US$/ha in La Niña seasons compared to a standard deviation of 85, 86 and 61 US$/ha for El Niño, Neutral and La Niña phases respectively, under the current farmer's practice (Fig. 6).

In Itapúa, the gross margins under the normal practices on a soil with HWH were 481 US$/ha in El Niño, 500 US$/ha in La Niña and 549 US$/ha in Neutral seasons. For the optimal scenario, gross margins increased by 10% in an El Niño, by 8% in

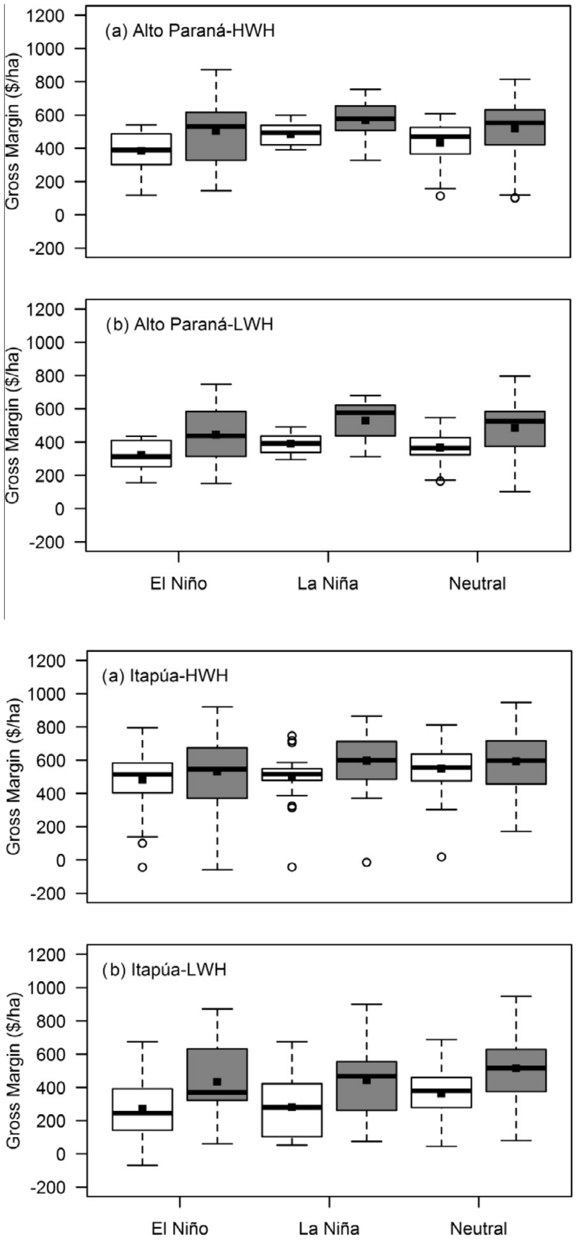

Fig. 6. Simulated gross margins for (a) Alto Paraná and (b) Itapúa, Paraguay, for three ENSO phases with current N application of 20 kg N/ha and sowing date May 20 in the three phases (open boxes) and the economical management practices for El Niño, Neutral and La Niña (gray boxes). Horizontal lines report median; black squares show average; upper box shows the third quartile data; lower box shows the second quartile data; upper error bar shows the fourth quartile data; lower error bar shows the first quartile data and open circles show the outliers.

Neutral and by 20% in La Niña seasons compared to the returns obtained under the current practice. The associated standard deviation was 203 US$/ha in El Niño, 193 US$/ha in Neutral and 180 US$/ha in La Niña seasons compared to a standard deviation of 191, 138 and 136 US$/ha in El Niño, Neutral and La Niña phases respectively, under the current farmer's practice.

The mean gross margins achieved by applying 20 kg N/ha in Itapúa on a LWH soil were 269 US$/ha in El Niño, 281 US$/ha in La Niña and 363 US$/ha in Neutral seasons. By applying 60 kg N/ha regardless of the initial soil water content at sowing and sowing at the optimal dates, the gross margins increased by 61% in El Niño, by 41% in Neutral seasons and by 58% in La Niña seasons compared to current practice. The standard deviation for optimal N fertilizer application rates was 189 US$/ha in El Niño, 168 US$/ha in Neutral seasons and 212 US$/ha in La Niña seasons compared to a standard deviation of 161, 131 and 175 US$/ha in El Niño, Neutral and La Niña phases respectively, under the current farmer's practice.

Evaluating seasonal forecasts

An ENSO-persistence-based and two GCM-based forecast systems were used to predict an ENSO phase season with the aim to alter N fertilizer rates tailored to the predicted season type.

The ENSO-persistence-based forecast resulted in higher net returns compared to the GCM-based forecasts for both locations (Fig. 7). The value of the ENSO-persistence-based forecast for Alto Paraná on a soil with HWH was of 88 US$/ha for dry soils at sowing and of 101 US$/ha for wet soils at sowing compared to the current farmers N practice of 20 kg N/ha and a sowing date of May 20. On a soil with LWH, the ENSO-persistence-based forecast value was 96 US$/ha for dry soils at sowing and 133 US$/ha for wet soils at sowing.

The value of the GCM-based forecast with 1-month and 2-month lead time for Alto Paraná on a soil with HWH was of 63 US$/ha for dry soils at sowing and of 62 and 55 US$/ha, respectively for wet soils at sowing compared to the current farmers N practice. On a soil with LWH, the GCM-based forecast value was of 76 US$/ha for dry soils at sowing and of 110 and 101 US$/ha, respectively for wet soils at sowing.

The value of the ENSO-persistence-based forecast for Itapúa in a soil with HWH was of 43 US$/ha for dry soils at sowing and of 75 US$/ha for wet soils at sowing compared to the current N practice. In a soil with LWH, the ENSO-persistence-based forecast value was 145 US$/ha for dry soils at sowing and of 178 US$/ha for wet soils at sowing.

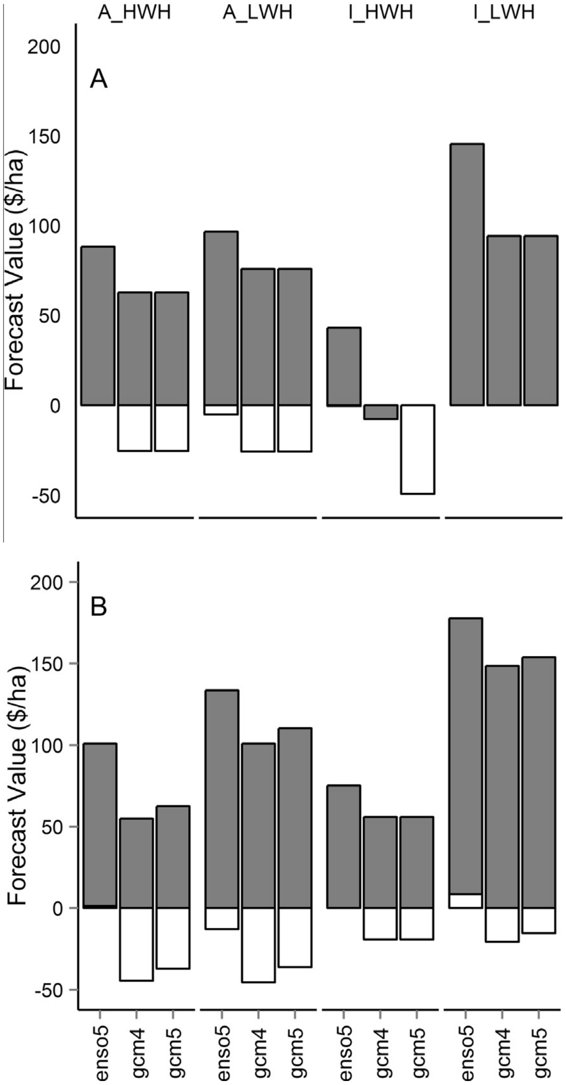

Fig. 7. Seasonal forecast value for Alto Paraná (A) and Itapúa (I), Paraguay, in a soil with high plant available water holding capacity (HWH) and a soil with low plant available water holding capacity (LWH) under (A) dry soil profile and (B) full soil profile. The seasonal forecast value was compared to using current management practices (gray bars) and optimal management practices (white bars) for an ENSO May forecast (enso5), a GCM forecast made in May (gcm5) and a GCM forecast made in April for the period May–October (gcm4).

The value of the GCM-based forecast for Itapúa in a soil with HWH was of -6 and -8 US$/ha, respectively for dry soils at sowing and of 56 US$/ha for wet soils at sowing compared to the current N practice. In a soil with LWH, the GCM-based forecast value was 94 US$/ha for dry soils at sowing and of 154 and 149 US$/ha, respectively for wet soils at sowing.

The forecasts were also evaluated by comparing them to a simulated optimal N management practices. In such comparison, the GCM-based forecasts had negative values at both locations, due to predicting too many seasons wrongly. The value of the ENSO-persistence-based forecast was only 1 US$/ha at Alto Paraná on a soil with HWH with initial soil water at sowing and 8 US$/ha at Itapúa on a soil with LWH with initial soil water at sowing.

Discussion

The Niño 3.0 classification used in this study to categorize the wheat growing-seasons into ENSO phases showed a relationship between ENSO phases and seasonal weather conditions during the wheat growing-season in Paraguay. This allowed a season-specific N management according season types to optimize N fertilizer application to rainfall and temperature conditions. The seasonal forecasts analyzed in this study highlighted the potential use of the Niño 3.0 index for May monthly anomaly as an indicator of the prevailing ENSO phase during the growing-season to manage N fertilizer accordingly, particularly when compared to current farmer's N management. The GCM-based forecasts showed consistently less value than the ENSO-persistence-based forecast due to low predictive skill in this region. Previous works have used the Niño 3.0 index to predict the ENSO phases (Baawain et al., 2005; Trenberth, 1997), but have not considered the potential use of this information as a seasonal planning tool. In this study, we used the ENSO-persistence-based seasonal forecast as a seasonal planning tool because information about the ENSO phase is available before farmers have to choose their wheat N management practice (COAPS, 2014). With information about the ENSO season, farmers know if a season will be less favorable (i.e., wet and warmer (El Niño)) or more favorable (i.e., dry and colder (La Niña)) at the start of the wheat-growing season (May/June), and can adjust their fertilizer rates and sowing dates to each season according to the anticipated crop production potential.

Recent advances of coupled ocean–atmospheric modeling made more skillful predictions of the ENSO phase possible (Tippett et al., 2012); however, the GCM-based forecasts used in this study for SST prediction were not as skillful as the ENSO-persistence-based forecast. Using the ENSO-persistence-based forecast allowed the information of the ENSO phase to be available at the time wheat is sown in Paraguay. By having on-time information for the next season's climate conditions, farmers will be able to better cope with future climate uncertainties by adopting different management practices to specific season types. A limitation in using the Niño 3.0 May monthly anomalies to predict the ENSO phase of the following growing season is that May is still close to the ENSO transition phase of March/April, when SST often drastically change resulting in a ENSO phase change (Torrence and Webster, 1998).

This analysis showed that higher yields are achievable in Paraguay by applying N fertilizer above the current common farmer's practice of 20 kg N/ha in most of the seasons. By differentiating between ENSO phases and managing fertilizer application and sowing dates according to ENSO phases, farmerś gross margins can be significantly increased. Tailoring agronomic practices to season types has increased yields in other regions of the world (Podesta et al., 2002; Bert et al., 2006). The value of the ENSO-persistence-based-forecast was up to 178 US$/ha when compared to current farmer's practice, but only up to 8 US$/ha when compared to a simulated optimized N fertilizer rate based on climatology. This is similar to the value of the seasonal forecast found in Australia (Moeller et al., 2008; Wang et al., 2008), but less than reported for using a GCM-based seasonal forecasts for wheat production in the southern region of Western Australia (Asseng et al., 2012).

The results obtained in this study show higher wheat yields during the La Niña phase in Alto Paraná, correlating with a previous study for wheat in South Brazil (Alberto et al., 2006) and higher wheat yields during Neutral phase in Itapúa. However, the difference in yields between ENSO phases in that study was not attributed to in-season rainfall or temperature variability. Other reports have suggested differences in temperature between ENSO phases (Barreiro, 2010; Barros et al., 2002), but seasonal yield forecasts have previously concentrated on rainfall variability only (Hansen et al., 2009; Moeller et al., 2008; Fraisse et al., 2008). Our results show that during the winter growing season in Paraguay, temperature and rainfall drive seasonal yield variability, with temperature being the main variable leading to differences in wheat yield between phases. The cooler temperatures found during La Niña seasons in Alto Paraná and during Neutral seasons in Itapúa delays anthesis and maturity, which allows more biomass accumulation and consequently higher yields in this environment. As shown in Itapúa, warm temperatures after anthesis in La Niña seasons can lead to a reduction in biomass accumulation and yield.

The soil water content at sowing can be an important factor in rain-fed environments (Moeller et al., 2009; Asseng et al., 2008) depending on the in-season rainfall and the soil water-holding capacity (Asseng et al., 1998). In our study, the amount of water in the soil at sowing had a large impact on the simulated yield depending on the location and ENSO phase. The optimum sowing date in some of the ENSO phases was conditional to the amount of water in the soil at sowing. In a La Niña phase in Alto Paraná, the amount of water in the soil at sowing was especially important, as also found in Australia for variable rainfall seasons, indicating insufficient rainfall in such seasons (Moeller et al., 2009).

Measuring and managing risk in farmers' decision making processes has been a continuous challenge (Roetter and Van Keulen, 1997; Roetter et al., 1997). Farmers are exposed to a variety of risks and uncertainties and have their own goal-seeking maximization objectives, which cause a range of behaviors (Greiner et al., 2009). The optimal agronomic practices here focused on the common risk-averse farmers assuming a net premium return of 200% for each additional unit invested in N fertilizer (Asseng et al., 2012). However, the risk attitude of farmers might vary with different perceptions of risk, allocating different resources (Jones et al., 2000); however, comparison between farmers sharing the same risk profile is possible. For instance, studies have found N fertilizer application is a risk-increasing asset such that risk-averse farmers use less N fertilizer than risk-neutral farmers (Gandorfer et al., 2011). Not incorporating the risk-aversion factor into the analysis could lead to misleading recommendations (Groom et al., 2008). The results found here suggest that differentiating between N management practices for each ENSO phase allows farmers to increase their gross margin while keeping a net gross margin return of 2 US$ per dollar invested in fertilizer input.

El Niño seasons resulted in lower yields with higher variability compared to the other two phases in Paraguay. At Alto Paraná, Neutral seasons and at Itapúa, La Niña seasons resulted in medium yields with moderate variability. At Alto Paraná, la Niña seasons showed the highest gross margins with less dispersion while in Itapúa, Neutral seasons showed the highest gross margins with moderate variability. Neutral seasons also resulted in high variability in wheat (Alberto et al., 2006) and other crops (Berlato et al., 2005) in Brazil. Considering most of the seasons are Neutral seasons, identifying the favorable crop growing seasons becomes critical to farmers. Applying low N fertilizer inputs in favorable seasons will produce low yields, as shown in the historical observed yield records. Observed yield records on its own are therefore not a good indicator of potential yield variability as potential high-yielding seasons are usually under-fertilized and hence less suitable to uncover a seasonal climate signal. Using simulated yield data correlations with an ENSO signal showed that applying high N inputs in favorable seasons increases the potential of achieving significant higher yields, without risking over-fertilization of crops in poor seasons. Identifying the good seasons and applying higher N input during these seasons become critical for farmers attempting to increase yield and gross margins.

Conclusion

Seasonal climate variability quantified by ENSO phases showed that temperature differences in addition to rainfall differences among seasons is a main driver for wheat yield variability in Paraguay. Grain yields are higher during La Niña and Neutral phase if crop management is adapted accordingly (i.e., using higher inputs). Soil types, initial amount of soil water at sowing and sowing dates can affect the value of a forecast. N fertilizer management can increase wheat yields and gross margins in Paraguay by tailoring N fertilizer applications to season types by applying seasonal forecasts.

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