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Modelled yield and water use efficiency of maize in response to crop management and Southern Oscillation Index in a soil-climate transect in Argentina

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ABSTRACT

Maize responses to individual management factors have been widely investigated but studies of higher-order interactions involving multiple factors are rare. This paper investigates the responses of grain yield and water use efficiency of rainfed maize to sowing date, stubble condition, hybrids of contrasting cycle length, soil depth and their interactions, and how these responses are affected by El Niño – Southern Oscillation (ENSO) phenomenon. Grain yield and water balance were modelled with CropSyst using 33 years of weather data for eight locations in an east–west transect in the Southern Pampas of Argentina. Modelled grain yield decreased westward, in parallel with decreasing rainfall. Southern Oscillation Index (SOI) discriminated crop season rainfall and grain yield, with lower rainfall and grain yield for SOI phase Consistently Positive (CP) and higher rainfall and grain yield for SOI phase Consistently Negative (CN). Differences in grain yield between stubble and bare soil were constant across location. High available water, as related to soil depth, increased grain yield across the transect. The effect of sowing date and stubble varied with SOI phase; for CN, highest grain yields were obtained with early sowing whereas for CP grain yield showed no correlation with sowing date. Yield differences between bare soil and stubble conditions were higher under CP than under CN, reflecting the positive effect of stubble in years with rainfall below average. Water use efficiency (WUE = yield per unit evapotranspiration) averaged 19.0 kg ha^{-1} mm^{-1} for soils with stubble and 16.5 kg ha^{-1} mm^{-1} for bare soil. We conclude that SOI provides an agronomically meaningful predictor of seasonal conditions that can be used to estimate crop production and manage risk by adjusting key management practices.

1. Introduction

Rainfed maize is grown in a wide range of climates and soils and depends on two sources of water: available soil water at sowing and rainfall during the cropping season. Available soil water at sowing depends on management practices, climate conditions and soil type during fallow (Calviño et al., 2003; Monzon et al., 2006). Low water availability during the growing season, as related to both low rainfall and shallow soils, is the major constraint for maize grain yield in the Southern Pampas of Argentina (Otegui et al., 1995; Sadras and Calviño, 2001; Calviño et al., 2003). Evaporative demand further modulates these responses as radiation, temperature and vapour pressure deficit vary considerably from year to year and from east to west in this area (Pascale and Damario, 2004). The individual effects of sowing date, stubble conditions as related to tillage practices, hybrid cycle length and maximum soil available water on the yield of maize have been investigated in this region (Cirilo and Andrade, 1994a,b; Calviño et al., 2003; Capristo et al., 2007). However, yield responses to the interactions among these factors are largely unknown.

El Niño – Southern Oscillation (ENSO) is a climate pattern that occurs across the tropical Pacific Ocean characterized by variations in the temperature of the surface of the eastern Pacific Ocean and in air surface pressure in the tropical western Pacific. The warm oceanic phase, El Niño, accompanies high air surface pressure while the cold phase, La Niña, accompanies low air surface pressure (NOAA: www.cpc.ncep.noaa.gov). Agronomically important aspects of the rainfall pattern of the Pampas and other cropping regions of the world are related to ENSO (Ferreyra et al., 2001; Podestá et al., 2002; Bert et al., 2006; Monzon et al., 2007; Tsubo and Walker, 2007). Stone et al. (1996) developed a rainfall probability forecast based on the phases of the Southern Oscillation Index

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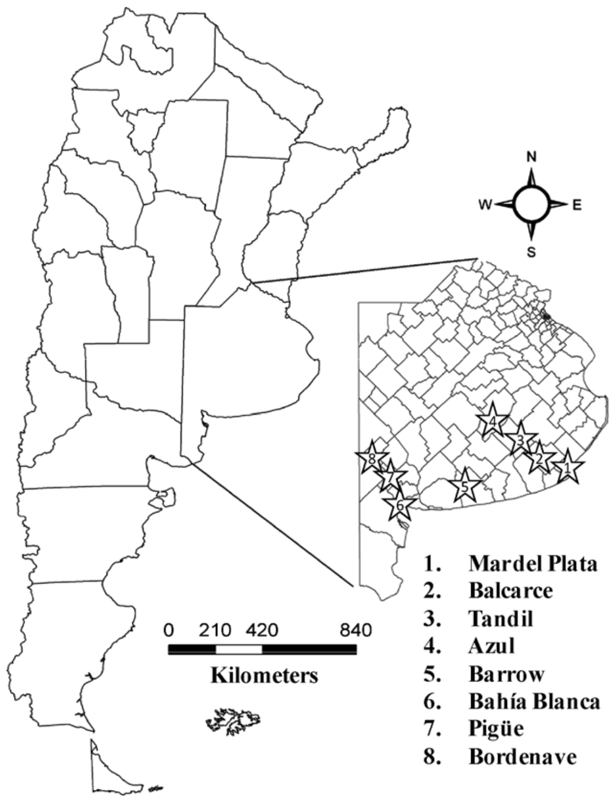

Fig. 1. Map showing analysed locations in an east–west transect in the Southern Pampas of Argentina.

(SOI), defined as the difference in atmospheric pressure anomalies between Tahiti and Darwin divided by the standard deviation of the difference, that proved relevant for risk management of cropping systems in Australia (Potgieter et al., 2002; Anwar et al., 2008). No attempts have been made to develop quantitative relationships accounting for the associations between SOI phases, rainfall and its implications for maize crop production in the Southern Pampas.

The primary aim of this study was to assess the long-term yield and water use efficiency of rainfed maize as affected by the combination of seasonal conditions, management practices including sowing date, stubble condition, the use of hybrids of contrasting cycle length, and soil depth. We hypothesize that: (i) the effects of management practices on maize grain yield and water use efficiency vary in an east–west transect for the Southern Pampa; and (ii) a SOI-based forecast can discriminate agronomically relevant seasonal conditions along a transect. A secondary aim was to compare the capacity of two models: CERES-Maize v4.0 (Jones and Kiniry, 1986), and CropSyst (Stöckle et al., 2003) to capture maize performance under these environmental and management conditions.

2. Methods

2.1. Overview of the region

This study focus on eight locations situated in an east–west transect in the Southern Pampas of Argentina, which were selected for their agronomic relevance and availability of weather data (Table 1 and Fig. 1). This region has a temperate climate with an isohygrous rainfall pattern, which shifts to slightly summer-dominant rainfall towards the west (Sadras and Hall, 1989; Pascale and Damario, 2004). Main soils for the region are Typic Argiudolls, Typic Haplustolls and Petrocalcic Paleustolls (both illitic, fine, thermic) with organic matter in the uppermost layer between 3 and 6.5%, and 1.3–1.5 mm maximum plant available water cm^{-1} soil (Hall et al., 1992; Travasso and Suero, 1994). Constraint to rooting depth by a widespread caliche layer is the main source of variation in maximum soil available water (Sadras and Calviño, 2001; Pazos and Mestelan, 2002). Typical farming systems include wheat as main winter crop and soybean, maize and sunflower as summer crops (Sadras and Calviño, 2001).

2.2. Modelling crop responses to management, soil and climate

2.2.1. Models

We compared two crop models: CERES-Maize and CropSyst. CERES-Maize (v4.0) simulates grain yield estimating: (i) grain number as a function of crop growth rate per plant around silking and (ii) grain weight as a function of crop growth rate during grain filling. CropSyst (v3.04.08) simulates grain yield as the product of aboveground dry matter and harvest index, which varies according to crop growth rate during flowering and grain filling. For the objectives of our study, each model has some disadvantages. CERES-Maize does not account for the effect of stubble mulch on the crop water balance; no tillage and stubble retention is common in more than 80% of the farms in the Southern Pampas (Gonzalez Montaner, 2004; www.aapresid.org.ar). CropSyst does not considered plant density, a major factor influencing maize growth and yield (Andrade et al., 1999).

2.2.2. Model evaluation

Both models were evaluated by comparison of model estimates and actual data collected from field experiments summarised in Table 2. In all experiments management practices were prescribed to achieve high yields, with the assumption of no nutrient limitation. Sources of variation in maize growth and yield in these studies include location and soil type, seasonal conditions, sowing date, tillage system and hybrid cycle length. Available data were split into calibration and validation sets; the most detailed experiments were used to calibrate the models, leaving the rest for validation (Table 2). Daily weather data required to run models were obtained from the nearest weather station; variables included maximum and minimum temperature, solar radiation, precipitation, dew point temperature and wind speed. All weather data, used for model evaluation and simulations (Section 2.2.3), were provided and previously passed through a quality control check by the National Institute of Agricultural Technology – Castelar (INTA–Castelar). Typical soils for each experiment were identified from soil surveys (SAGyP-INTA, 1989). Since field slopes are low for most of this region, run off was assumed to be negligible. CropSyst was run with the finite difference option for water balance. Model performance was assessed with regression analysis of simulated and measured variables, Student test to compare intercept and slopes values to zero and one, respectively, and root mean square error (RMSE) using IRENE software (Fila et al., 2003).

2.2.3. Simulation of maize responses to climate, soil and management practices

We modelled the factorial combination of eight locations (Table 1, Fig. 1), 33 years (1971–2003), three maximum soil water holding capacities (100, 150 and 200 mm; Table 3), four sowing dates (16 September, 1 October, 16 October and 31 October), two soil stubble conditions (stubble, bare soil), and four maize hybrids with different cycle length (extremely short season, 1286 °C d from sowing to physiological maturity; short season, 1466 °C d; mid season, 1534 °C d; and full season, 1666 °C d). Hybrid parameters were calibrated with data from Capristo et al. (2007). Since soybean is a typical crop predecessor for maize in the region; we simulated a two year soybean-maize rotation to account for initial maize crop

Table 1
Total rainfall, reference evapotranspiration (ETo), and water deficit (ETo – rainfall) for the maize crop season (sowing to physiological maturity) at eight locations in an east–west transect in the Southern Pampas. ETo was calculated with the Priestley and Taylor (1972) method included in CropSyst model. Values represent means from 33-years (1971–2003).

Location	Latitude (°)	Longitude (°)	Rainfall (mm)	ETo (mm)	Water deficit (mm)
Mar del Plata	−37.92	−57.57	463	707	244
Balcarce	−37.77	−58.30	500	673	173
Tandil	−37.32	−59.15	480	767	287
Azul	−36.77	−59.87	474	669	195
Barrow	−38.35	−60.27	391	822	431
Bahía Blanca	−38.67	−62.25	279	969	690
Pigüe	−37.60	−62.40	405	716	311
Bordenave	−37.80	−63.02	374	720	346

Table 2
Description of sources of data used in calibration and validation of the models.

Experiment	Sources of variation				Number of data	
	Locations, water and tillage conditions	Sowing dates and seasons	Maize yield range ($kg\,ha^{-1}$)	Crop variables	Calibration	Validation
Cirilo and Andrade (1994a,b)	Balcarce, irrigated, tillage	September to mid October. 1989, 1991	9959–11,926	Dry matter accumulation ($kg\,ha^{-1}$), grain yield ($kg\,ha^{-1}$), grain weight ($mg\,grain^{-1}$) and grain number ($grains\,m^{-2}$), intercepted radiation ($MJ\,m^{-2}\,day^{-1}$), silking and maturity date (days)	4	
Gardiol et al. (2001)	Balcarce, irrigated, tillage	Mid October 1993		Dry matter accumulation ($kg\,ha^{-1}$), water consumption (mm)	3	
Valentinuz (1996)	Balcarce, irrigated, tillage	Mid October 1994, 1995	10,790, 11,730	Dry matter accumulation ($kg\,ha^{-1}$), grain yield ($kg\,ha^{-1}$), intercepted radiation ($MJ\,m^{-2}\,day^{-1}$), silking and maturity date (days), leaf area index ($m^2\,m^{-2}$)	2	
Capristo et al. (2007)	Balcarce, irrigated, tillage	Mid October 2000, 2001	6880–12,900	Dry matter accumulation ($kg\,ha^{-1}$), grain yield ($kg\,ha^{-1}$), grain weight ($mg\,grain^{-1}$) and grain number ($grains\,m^{-2}$), silking and maturity date (days)	8	
ROET (www.intabalcarce.org)	Balcarce, Barrow and Bellocq, rainfed, tillage	October 1988–1994	593–13,667	Grain yield ($kg\,ha^{-1}$), flowering and maturity date (days)		15
Andrade, unpublished	Balcarce, irrigated and rainfed, tillage	Mid October 1989–1996	4205–12,797	Grain yield ($kg\,ha^{-1}$)		16
Rizzalli (1998)	Balcarce, rainfed, tillage and no tillage	Mid October, 1995, 1996, 1998	1698–7353	Dry matter accumulation ($kg\,ha^{-1}$), grain yield ($kg\,ha^{-1}$), intercepted radiation ($MJ\,m^{-2}\,day^{-1}$), silking and maturity date (days), water consumption (mm)		16–24
Caviglia and Della Maggiora, unpublished	Balcarce, irrigated and rainfed, tillage	October, 2000		Water consumption (mm)		6

conditions. This method was used to estimate initial soil water separately for each combination of management practices. Soybean (maturity group IV) was sown on 1 November and simulations started in 1971 and 1972, to generate inputs for each year of the maize simulations. Available soil water at sowing for soybean in year 1971 and 1972 was set at maximum soil available water. Maize grain yield and aboveground dry matter in this work were expressed at 0% moisture content.

CropSyst was run with the finite difference option for water balance, assuming no run off and non-limiting nutrient availability based on current fertilization rates and favourable mineralization during the growing season (Echeverría et al., 1994). To account for variations in vapour pressure deficits across the east–west transect, the Priestley–Taylor constant and aridity factor in CropSyst were modified for each location to match local estimates of reference evapotranspiration based on FAO-56 method (Allen et al., 1998). We identified major soil series from the soil survey map of the Buenos Aires province for each location (Table 3, SAGyP-INTA, 1989). We used texture data from each horizon to estimate maximum soil available water with CERES-Maize and CropSyst.

A CropSyst water stress index, [1 − (actual transpiration/potential transpiration)] was used to quantify the crop water status. Daily indexes were averaged from emergence to maturity.

The average grain yield for a given location is a convenient measure of the environmental condition for that location (Finlay and Wilkinson, 1963). We thus plotted simulated maize grain yield under different management practices as a function of the

Table 3
Soil profile description and soil depth used to achieve target maximum soil available water for eight locations in an east–west transect in the Southern Pampas.

Location	Soil type	Soil depth (cm)	Lower limit (cm/cm)	Upper limit (cm/cm)	Sand (%, >0.05 mm)	Clay (%, <0.002 mm)
Mar del Plata – Balcarce – Tandil – Azul	Fine typic Argiudoll	0–15	0.144	0.284	36.2	24.6
		15–30	0.147	0.287	35.8	25.5
		30–40	0.160	0.307	30.9	28.4
		40–70	0.176	0.311	35.6	31.5
		70–100	0.143	0.277	39.3	24.3
		100–148	0.121	0.252	43.6	18.7
Barrow, Bordenave and Pigüe shallow soils (<1 m)	Fine typic shallow Argiudoll	0–20	0.173	0.303	38.4	30.8
		20–50	0.230	0.345	40.6	41.9
		50–71	0.149	0.282	39.4	25.7
Barrow, Bordenave and Pigüe deep soils (>1 m)	Fine typic Argiudoll	0–20	0.150	0.276	42.8	25.7
		20–30	0.164	0.296	37.9	28.9
		30–42	0.172	0.307	35.6	30.6
		42–65	0.227	0.361	31.3	40.9
		65–90	0.141	0.273	40.5	23.7
		90–150	0.119	0.254	42.7	18.3
Bahía Blanca	Fine typic Haplustoll	0–20	0.195	0.343	26.5	35.1
		20–38	0.221	0.367	25.2	39.6
		38–60	0.222	0.354	32.8	40.1
		60–150	0.184	0.324	32.0	33.0

	Soil depth (cm)		
Maximum soil available water (mm)	Mar del Plata, Balcarce, Tandil, Azul	Barrow, Bordenave, Pigüe	Bahía Blanca
100	72	80	71
150	110	113	106
200	148	150	142

average simulated grain yield for each location to account for interactions.

Water use efficiency (WUE) was calculated as the ratio between modelled crop grain yield and crop evapotranspiration. Then, we focused on how management practices affect the water footprint of maize production, i.e. water needed to produce a tonne of maize (Water Footprint Manual, www.waterfootprint.org). We compared water footprint of maize calculated from crop models with reported water footprint on a country scale (www.waterfootprint.org; http://faostat.fao.org). Regression analysis, Student *t*-test, and ANOVA, were used to assess the relationships between maize grain yield, management practices and SOI across locations. LSD test was used to compared means. All analyses were performed using R software (v 2.12.1, R development Core Team, 2008).

2.3. Climate data analysis

Using the same time series (1971–2003) as in the simulations described in Section 2.2.3, we characterized the rainfall pattern of each location. Rainfall was quantified for the crop growing season and for the phenostages: (i) sowing to 15 before silking, (ii) the critical period from 15 days before to 15 days after silking, and (iii) grain filling.

The relationship between rainfall for these maize phenostages and SOI phases during the preceding months was investigated. We select a SOI system with five phases because it proved to be relevant for risk management of cropping systems in Australia (Potgieter et al., 2002; Anwar et al., 2008) and Argentina (Monzon et al., 2007). The phases are Consistently Negative (CN), Consistently Positive (CP), Rapidly Falling (RF), Rapidly Rising (RR) and Consistently near Zero (CNZ), using the bounds for each class reported by Stone et al. (1996). SOI phases were determined by the Department of Primary Industries of Queensland (www.longpaddock.qld.gov.au).

Percent consistency of SOI was assessed by cross validation using the Climate Variability Analyser software (De Li Liu, DPI Australia, personal communication). This analysis requires longer series (>70 years) than the period used in simulations (see Section 2.2.3). Time series for two locations (Mar del Plata and Azul) were not long enough to be used in the SOI percent consistency analysis. For each time series of 70 years, median rainfall was calculated with data from 67 years (training set) leaving the first 3 years (test set) to evaluate consistency, and then repeating the procedure until we completed the data set. Percent consistency was calculated as the number of consistent forecasts for a category (e.g. above median), divided by the total number of forecasts made for that category, as explained in Anwar et al. (2008).

3. Results

3.1. Model performance

Models were evaluated across locations for the management variables under study (Table 4). For the calibration data set, CERES-Maize and CropSyst predicted the date of silking with RMSE = 2.7 and 3.1 days, respectively; and maturity with RMSE = 7.4 and 5.8 days, respectively. Difference between simulated and measured aboveground dry matter was around 0.7% for CropSyst (RMSE = 1202 kg ha^{-1}). CERES-Maize v4.0 underestimated aboveground dry matter by 8% (RMSE = 2532 kg ha^{-1}). Table 4a and Fig. 2a presented the model validation and Table 5 crop parameter used for simulations. For both models intercepts were not statistically different from 0 and slopes were not statistically different from 1. Based on performance and the need to account for stubble effects, CropSyst was the selected model for our study. CropSyst was also tested for crop grain yield and crop season evapotranspiration under different tillage conditions for extremely short to full season hybrids (Table 4b and Fig. 2b). Intercepts were not statistically different from 0 and slopes were not statically different from 1. Root mean square error for grain yield was 1432 kg ha^{-1} and for crop seasonal evapotranspiration RMSE was 53.9 mm (Fig. 2b). CropSyst adequately simulated crop evapotranspiration during crop cycle (Fig. 3).

CropSyst showed good performance to simulate grain yield and crop season evapotranspiration under a wide range of management

Table 4
Root mean square error (RMSE) and linear regression statistics for the validation set. (a) Simulated and observed values for maize grain yield (kg ha^{-1}) for CERES-Maize and CropSyst models, data from ROET and Andrade (Table 2); and (b) simulated and observed values for maize grain yield (kg ha^{-1}) and measured and simulated crop season evapotranspiration (mm) with CropSyst model, data from ROET, Andrade, Rizzalli and Caviglia and Della Maggiora (Table 2). Statistics correspond to Fig. 2a and b. Student-*t* test was used to test intercept = 0 and slope = 1.

Model	*n*	R^2	Intercept (*I*)		Slope (*S*)		RMSE
			Value	$P(I=0)$	Value	$P(S=1)$	
(a) Maize grain yield							
CERES-Maize	31	0.57	−1512	0.82	1.247	0.10	2219
CropSyst	31	0.72	−833	0.86	1.102	0.34	1543
(b) Maize grain yield and crop season evapotranspiration							
CropSyst (maize grain yield)	47	0.78	−648	0.86	1.09	0.25	1432
CropSyst (crop season evapotranspiration)	30	0.74	61.9	0.69	0.859	0.08	53.9

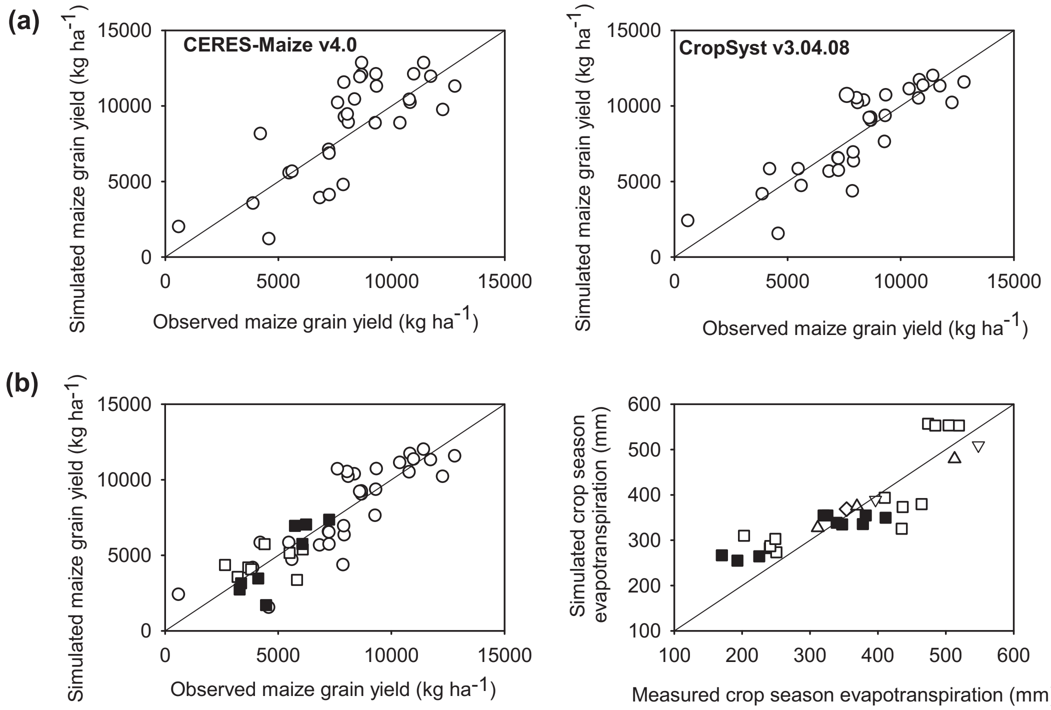

Fig. 2. (a) Observed and simulated maize grain yield (kg ha^{-1}) for validation data set (n = 31). Simulated data where obtained with CERES-Maize, and CropSyst models. See Table 4 for fitting details. Line represents $y = x$ relationship. (b) Observed and simulated maize grain yield (kg ha^{-1}, n = 47) and measured and simulated crop season evapotranspiration (n = 30) with CropSyst. Empty symbols are conventional tillage conditions and closed symbols are no tillage conditions. Circles are maize hybrid Dk 636, squares hybrid Ax 777, triangles down hybrid Dk 688, diamond hybrid Romario and triangles up hybrid Pioneer 37P73.

Table 5
Crop parameters used for simulations in CERES-Maize and CropSyst models.

Maize hybrid	CERES-Maize					
	P1[a]	P2	P5	G2	G3	PHINT
Dekalb 636	235	0.3	790	730	6.6	38.9

Maize hybrid	CropSyst[b]				
	Degree days from sowing to peak leaf area index	Degree days from sowing to begin anthesis	Degree days from sowing to begin grain filling	Degree days from sowing to physiological maturity	Unstressed harvest index
Dekalb 636	799	846	1016	1666	0.45
Nidera Ax 777	769	816	986	1618	0.40
Dekalb 688	787	834	1004	1660	0.51
Pionner 37P73	623	670	840	1466	0.51
Extremely short season	555	602	772	1286	0.50
Short season	623	670	840	1466	0.50
Mid season	723	770	940	1534	0.50
Full season	799	846	1016	1666	0.50

[a] P1 = degree days (base 8 °C) from emergence to end of juvenile phase, P2 = photoperiod sensitivity coefficient (0–1.0), P5 = degree days (base 8 °C) from silking to physiological maturity, G2 = potential kernel number, G3 = potential kernel growth rate mg/(kernel d), and PHINT = degree days required for a leaf tip to emerge (phyllochron interval) (°C d).

[b] The following parameters were the same for all hybrids: (i) light to above ground biomass conversion = 4.9 g MJ^{-1}, (ii) maximum expected leaf are index = 5.5 m^2 m^{-2}, (iii) leaf duration = 900 °C day, (iv) extinction coefficient for solar radiation = 0.4, (v) degree days from sowing to physiological maturity = 65 °C day, (vi) base temperature = 8 °C, (vii) cut off temperature = 30 °C. For the rest of the parameters we used default values for maize.

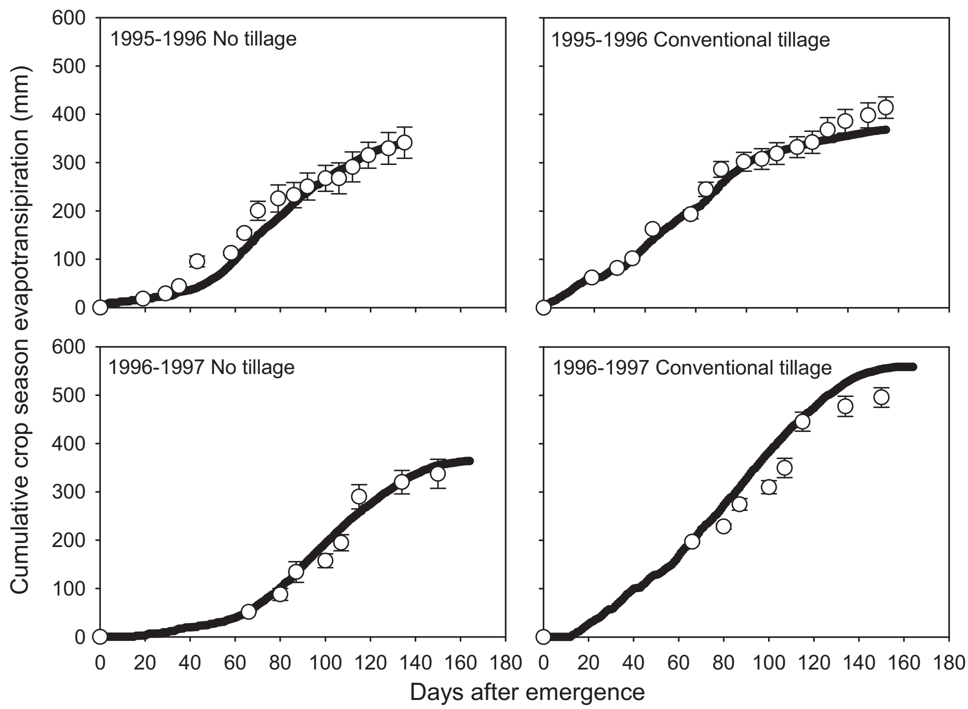

Fig. 3. Measured and simulated maize crop season evapotranspiration for selected experiments under no tillage and conventional tillage. All experiments from Rizzalli (1998). Continuous line showed simulated data and empty circles are measured data. Simulated data using CropSyst. Bars show standard deviation.

conditions and commonly used plant densities (from 5 to 9 pl m^{-2}). Further evaluations for water budget during fallow periods under different stubble conditions for these environments can be found in Monzon et al. (2006).

3.2. Climate and SOI phases

Table 1 shows the variation of crop season rainfall, reference evapotranspiration and water deficit in the east–west transect. Rainfall during the maize cropping cycle increases eastwards, as reflected in a significant rainfall-longitude correlation ($r = 0.77$, $P < 0.05$). Water supply and demand varied considerably across locations, i.e. seasonal rainfall varies from 29% of evaporative demand at Bahía Blanca to 74% at Balcarce (Table 1). ETo and water deficit, however, showed no correlation with longitude.

Rainfall from sowing to 15 days before silking (October to December) varied with SOI phase in September for all locations except for Barrow (Fig. 4). Greater rainfall discrimination capacity was observed for the Consistently Negative (CN) and Consistently Positive (CP) phases. October to December rainfall represents approximately 64% of total crop season rainfall across the transect. However, the SOI phase system between July and January did not discriminate rainfall during the critical period for grain set and grain filling (January to March).

The overall cross-validated ability of the five SOI phase system for October–December rainfall in all locations varied between 52–73% (data not shown). However, the skill of some individual phases was high. In 73–91% of the years, rainfall was higher than the average for phase CN. Moreover, in 62–85% of the years rainfall was below average for phase CP, as tested independently with cross validation (numbers inside Fig. 4). Based on cross-validation results, rainfall discrimination capacity and plausible agronomical applications, hereon SOI phases were split into three groups: (i) phase Consistently Negative (CN), (ii) phase Consistently Positive (CP) and (iii) the average of phases Rapidly Falling, Rapidly Rising and Consistently near Zero (RF-RR-CNZ).

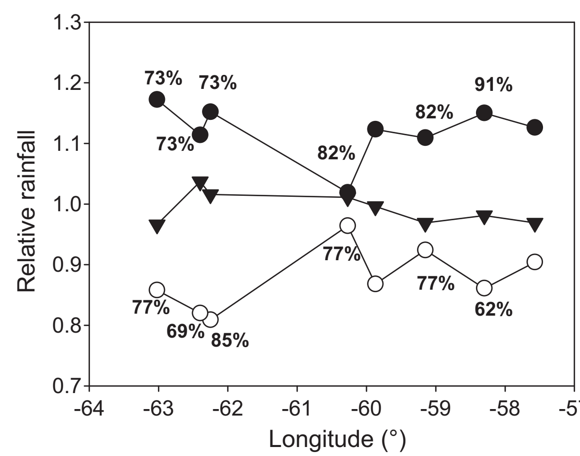

Fig. 4. Relative rainfall between October to December (sowing to 15 days before silking) as a function of longitude and Southern Oscillation Index (SOI) for September. To account for differences between locations, rainfall was expressed relative to the mean for each location. Symbols represent SOI phases: closed circles are Consistently Negative, empty circles are Consistently Positive and triangles are average of phases Rapidly Falling, Rapidly Rising and Consistently near Zero. Numbers inside figure indicate percentage consistency for SOI phases, for Mar del Plata and Azul data is not available because time series were not long enough.

3.3. Main effects of SOI and management variables on modelled maize grain yield

Main effects of SOI, location, sowing date, stubble condition, hybrid cycle and maximum soil available water on maize grain yield were highly significant ($P < 0.001$). Crop grain yield decreased

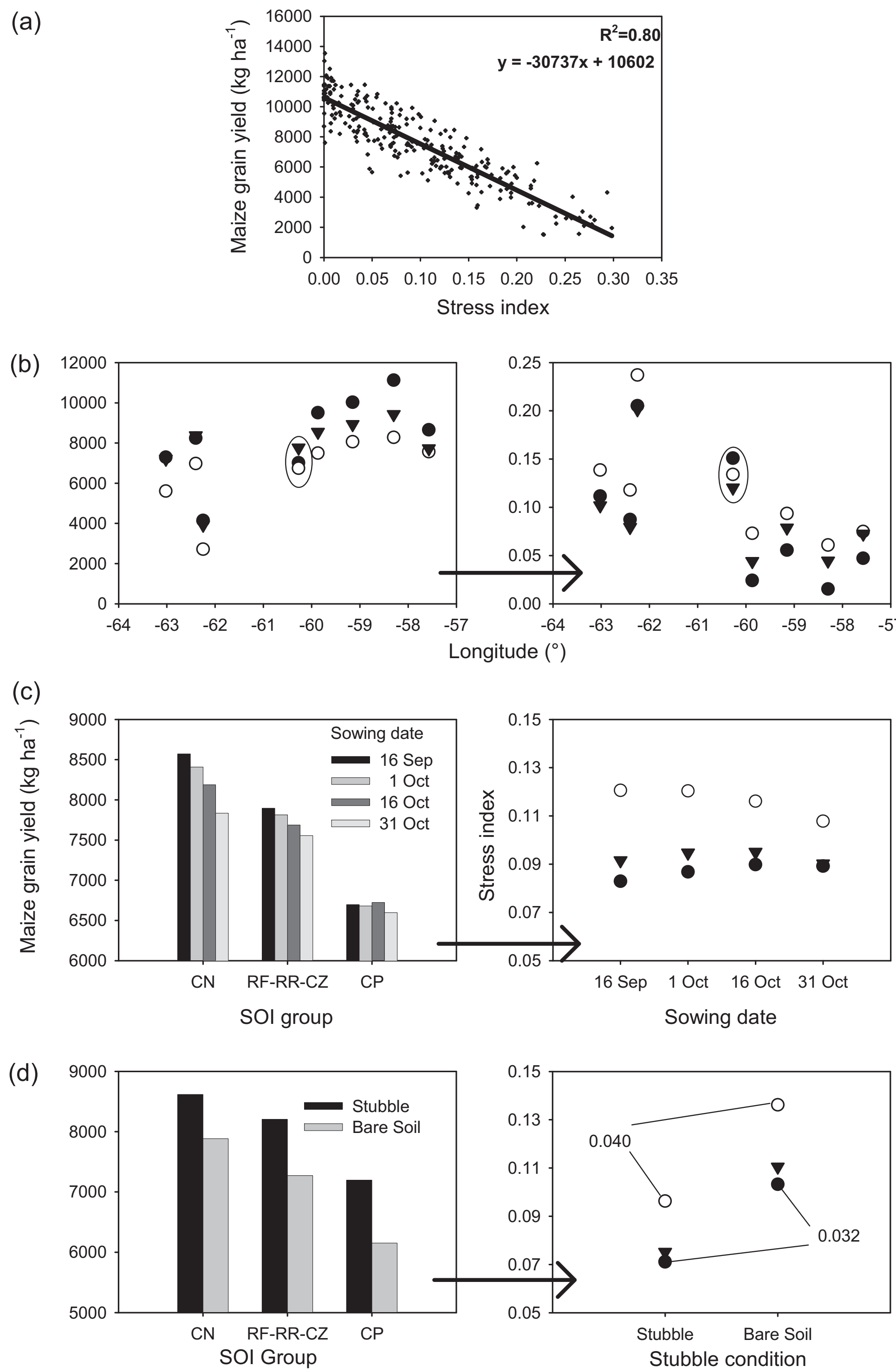

Fig. 5. (a) Maize grain yield (kg ha^{-1}) as a function of average stress index (data show location * year values); and maize grain yield and stress index as a function of (b) location and SOI groups, (c) sowing date and SOI groups and (d) stubble condition and SOI groups. SOI groups are represented with closed circles for phase Consistently Negative (CN), empty circles for phase Consistently Positive (CP) and triangles are average of phases Rapidly Falling, Rapidly Rising and Consistently near Zero (RF-RR-CZ). Simulated data using CropSyst.

westward (Fig. 5b), in parallel with decreasing rainfall (Table 1). Highest yields were obtained at Balcarce (9637 kg ha^{-1}) and lowest at Bahía Blanca (3653 kg ha^{-1}), in agreement with climatic conditions for both locations (Table 1). SOI groups were associated with crop season rainfall (Fig. 4) and grain yield (Fig. 5b). Low rainfall and low grain yield corresponded with SOI CP and high rainfall and high grain yield with SOI CN; the only exception was Barrow as described in Section 3.4.1. Yield across locations was highest for early sowing (Fig. 5c).

On average, yield increased from 7152 kg ha^{-1} under bare soil to 8054 kg ha^{-1} under stubble (Fig. 5d). Yield increased with increased hybrid cycle length (Fig. 6c) and with increasing maximum soil available water (Fig. 6d). These factors, however, interacted with SOI and location.

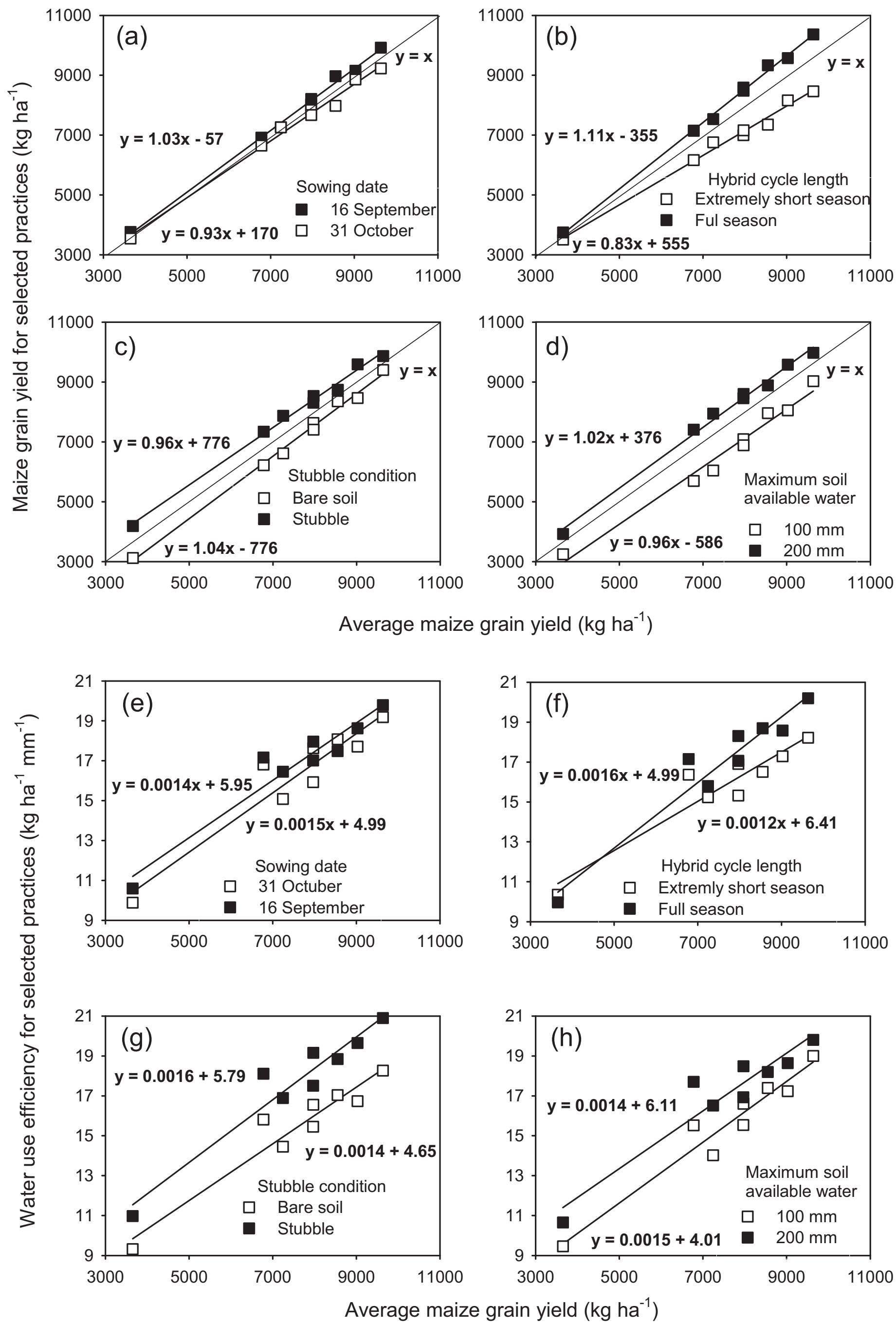

Fig. 6. Maize grain yield (kg ha^{-1}) and water use efficiency (WUE = grain yield/actual evopotranspiration) for selected practices as a function of location. Selected management practices are: (a) and (e), sowing date; (b) and (f), hybrid cycle length; (c) and (g), stubble condition; and (d) and (h), maximum soil available water. Locations are represented by the average yield for all evaluated management practices. Simulated data using CropSyst.

3.4. Interactions

3.4.1. Interactions with SOI

The ANOVA for maize grain yield showed significant SOI × location, SOI × sowing date and SOI × stubble condition interactions ($P < 0.001$). Modelled grain yield was negatively correlated to the average water stress index from emergence to maturity (Fig. 5a). For every 0.1 unit increase in stress index grain yield decreased by 3074 kg ha^{-1} ($R^2 = 0.80$). SOI groups were clearly related to maize grain yield and average stress index; i.e. grain yields were higher for CN and lowest for CP. The only exception was Barrow (location × SOI interaction for grain yield) as shown by encircled data in Fig. 5b. In Barrow rainfall did not vary significantly with SOI.

Optimum sowing date varied with SOI. Best grain yields for CN were obtained with early sowing whereas, grain yield showed no correlation with sowing date for CP. Stress index for CN was lower for earlier sowing dates and the opposite was observed for CP (Fig. 5c).

The effects of stubble condition on grain yield and stress index were greater under CP than under CN (Fig. 5d).

3.4.2. Interactions with location

The ANOVA for maize grain yield showed significant location × sowing date, location × stubble condition, location × hybrid cycle and location × maximum soil available water interactions ($P < 0.001$). Differences between maize grain yield for the earliest and latest sowing date (16 September vs. 31 October) did not show significant trends across locations (Fig. 6a). Positive effects of full season hybrids were greatest in high yielding locations and smallest in low yielding locations, as shown by statistically different slopes in Fig. 6b ($P < 0.01$). The benefits of stubble on grain yield were observed at high and low yielding locations, as showed by similar slopes but significantly different intercepts (Fig. 6c, $P < 0.01$). The significant interaction between stubble condition and location was explained by the lowest yield difference at Azul between stubble and bare soil. The presence of stubble increased yield by 26% in the lowest yielding location and 5% in the highest yielding location. Differences between low and high maximum soil available water (100 and 200 mm) were stable across locations as showed by non significant difference for slopes ($P = 0.44$, Fig. 6d), but showed significant differences for intercepts ($P < 0.01$, Fig. 6d).

3.5. Water use efficiency: impact of management practices

Water use efficiency (WUE) was highest in high yield location and varied with management practices (Fig. 6e–h). Differences in WUE between sowing dates were small (from 16.5 to 17.1 kg ha^{-1} mm^{-1}, Fig. 6e) and remained constant across locations. Hybrid cycle length affected WUE (from 17.3 to 19.1 kg ha^{-1} mm^{-1}, Fig. 6f) but the effect was largest in high yield locations as showed by statically significant slopes ($P < 0.01$).

Averaged WUE was higher for soils with stubble (19.0 kg ha^{-1} mm^{-1}) than for bare soil (16.5 kg ha^{-1} mm^{-1}, Fig. 6g). WUE under stubble remained constant for the different sowing dates (19.0 kg ha^{-1} mm^{-1}) but under bare soil WUE increased with delayed sowing (from 15.9 to 17.1 kg ha^{-1} mm^{-1}, data not shown).

Water use efficiency was higher in soils with high maximum available water and remained fairly constant across locations as shown by different intercepts in Fig. 6h ($P < 0.01$).

Water footprint of maize was clearly related to maize grain yield and was affected by management practices, particularly by stubble condition (Fig. 7). In Barrow for instance, the water needed to produce a tonne of maize was 591 m^3 under stubble and 700 m^3 under bare soil (Fig. 7a). Averaged across locations in the east–west transect, yield was 13% higher and water footprint was 14% lower under stubble than under bare soil. Functions derived from our simulations closely matched actual data at country level for countries with more than 1 million hectares of maize for the period 1997–2001 (Fig. 7b). These results further reinforce the accuracy of CropSyst model to simulate the water balance.

4. Discussion

4.1. Model performance

CropSyst outperformed CERES for our range of conditions and was used to explore high-level interactions between climate, soil and management practices in an east–west transect in the Southern Pampas. CropSyst simulated phenology, aboveground dry matter, water consumption during crop cycle and grain yield with errors which are commensurate with our aims of exploring interactions between agronomic practices, soil and climate (López-Cedrón et al., 2008; Grassini et al., 2009). CropSyst simulated particularly well the cumulative crop season evapotranspiration (Fig. 3). Fitted boundary functions for water use efficiency (estimated as described in Grassini et al., 2009), had slopes of 53 and 28 kg ha^{-1} mm^{-1} for aboveground dry matter and grain yield, respectively. These were very close to the slopes of 54 kg ha^{-1} mm^{-1} for aboveground dry matter and 31 kg ha^{-1} mm^{-1} for grain yield derived from measurements in the western Corn Belt of USA (Grassini et al., 2009). Data used for validation, mostly grain yield and water consumption, were within the range of values simulated for the whole transect (Figs. 2, 5 and 6). Furthermore, there was a close agreement for the water footprint-maize grain yield relationship between modelled values and large scale observations (Fig. 7b).

4.2. Tailoring management to SOI phase

Associations among rainfall, yield and SOI were strong, as shown in other regions of Argentina (Podestá et al., 2002; Bert et al., 2006) and Australia (Potgieter et al., 2002; Anwar et al., 2008). Grain yield difference between phases CN and CP across the whole set of data was 1576 kg ha^{-1}. Phases CN and CP occurred in approximately 50% of the years. An important feature of the SOI system in our region is that significant skill is apparent in September, previous to the maize growing season. SOI based forecast is therefore agronomically meaningful, in contrast to other regions where the SOI skill is out-of-phase with the timing of agronomical decisions. Of the practices evaluated in this paper, sowing date can be easily modified from year to year to account for predicted type of season. Fertilizer rate could also be manipulated to match yield expectations in association with SOI phases (Bert et al., 2006). Furthermore, the demonstrated skill of SOI phases in September, prior to sowing, would allow farmers to grow low input crops instead of maize to reduce the economic risk in a dry year as anticipated by a CP phase in September (Fig. 5d). Other practices like stubble condition are associated with a cropping system (no-tillage) and are not easily modified from year to year.

4.3. Impact of management practices

The presence of stubble increased average grain yield by 902 kg ha^{-1} compared to bare soil. The positive effect of stubble retention on the control of soil erosion is well documented, but the actual contribution to grain yield mediated by improved soil water storage is strongly dependent on soil and climate, and remains unclear for many environments (Cantero-Martínez et al., 1995; Gregory et al., 2000; Triplett and Dick, 2008). Soil water storage at sowing, for the selected crop rotation, was close to its maximum capacity for the different stubble conditions across the transect (data not shown); though yield differences can be mainly attributed to conditions during crop cycle. Larger effects of stubble on yield were observed in phase CP (Fig. 5d) and low yielding locations (Fig. 6c). Likewise, Monzon et al. (2006) showed that stubble contributions to soil water storage were highest under intermediate rainfall and lowest under high or very low rainfall.

Early sowing showed high yield potential in association with a higher photothermal coefficient at the critical period for grain number determination and grain filling (Cirilo and Andrade, 1996; Andrade et al., 2002). This higher yield potential can be expressed when water is not limiting; during CN phase, better water conditions allow for a significant response to early sowing (Fig. 5c). Full season hybrid has higher yield potential than the extremely short season counterpart but this advantage was only expressed at high yielding locations. Capristo et al. (2007) found similar yield differences at high yielding environments. In their work, extremely short season hybrids reached silking earlier but with low canopy cover because of smaller number of leaves compared to full season hybrids. Yield reduction in short season hybrids was mainly explained by reduced intercepted radiation at silking and short grain filling period. This disadvantage of short season hybrids can be counterbalanced with increase crop density in order to achieve full

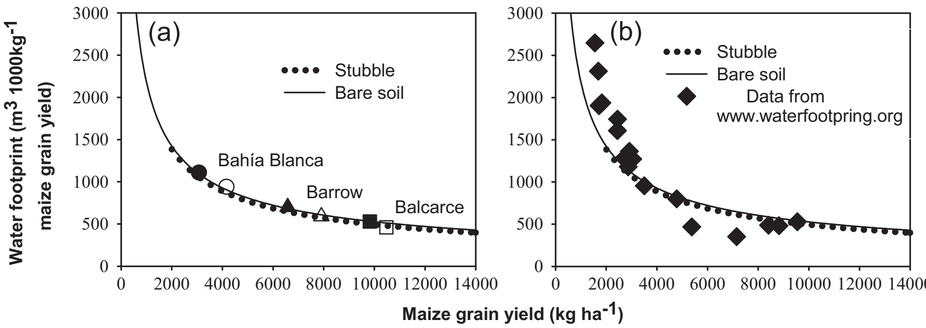

Fig. 7. (a) Water footprint of maize as a function of maize grain yield (kg ha^{-1}) under different stubble conditions; simulated data using CropSyst. Function derived from location * year values. Symbols show selected locations, empty symbols are stubble and closed symbols bare soil conditions. Data from countries with more than 1 million. Data from countries with more than 1 million hectares of maize (period 1997–2001, FAO statistics) where included in Fig 7b.

canopy cover earlier, hence reducing soil evaporation and increasing transpiration and capture of radiation (Sarlangue et al., 2007).

High available water, as related to soil depth, increased grain yield with no trend across locations (Fig. 6d). The geospatial distribution of the caliche layer that affects soil depth and consequently maximum soil available water can easily be measured with a GPS device and a penetrometer (Sadras and Calviño, 2001; Pazos and Mestelan, 2002). Using this information and local derived functions farmers have redefined crop allocation to soils (Sadras and Calviño, 2001). This simple practice considerably improved farm income in this region during the last decade (Calviño, AACREA personal communication).

4.4. Water use efficiency and water footprint

Water use efficiency was higher for full season hybrids than for their extremely short season counterparts, as related to differences in transpiration (273 mm for extremely short vs. 329 mm for full season hybrid) and soil evaporation. An extremely short cycle implies lower maximal radiation interception and shorter relative period under maximal canopy cover conditions (Capristo et al., 2007). Then a higher proportion of water is lost as soil evaporation in extremely short hybrids (35% in extremely short cycle vs. 29% in full season) reducing overall WUE. On the other side, WUE responded to the interaction between stubble condition and sowing date. As sowing was delayed, maize achieved maximal canopy cover earlier diminishing soil evaporation under bared soil conditions (from 219 to 181 mm). Soil evaporation however remained constant for the different sowing dates under stubble conditions (~134 mm). WUE was low in shallow soils because less water was transpired compared to deep soil. Soil evaporation was similar for both soil depths.

Considering that agricultural production accounts for 70% of the worldwide usage of fresh water, the water used to produce a given amount of grain is increasingly important. Even though we compared water footprint from simulated experiments only considering the primary water used (green water) at a local basis with calculated data at a country level, similarities are surprising, i.e. low grain yields are related with high water footprint (Fig. 7b). Countries or regions with low adoption of appropriate crop management practices or relative high water deficit are those with the highest water footprint. Soil evaporation is a major unproductive component of evapotranspiration (Cooper et al., 1987; Sadras and Baldock, 2003; Sadras and Rodriguez, 2007), then practices that increase transpiration in detriment of soil evaporation will reduce the water footprint. The presence of stubble may contribute to reduce soil evaporation in some combinations of soils, climates and cropping systems hence increasing yield per unit of available water.

5. Conclusion

This study has quantified the effect of climate and management practices on maize yield and water use efficiency across a transect in the Southern Pampa of Argentina using a crop simulation model and long term weather and research data. We found that SOI provided an early, agronomically meaningful prediction of seasonal conditions and showed how it can be used to adjust management practices. This work reinforces the conclusion that improvement of crop models and weather forecasts would have a positive impact on economic and environmental aspects of crop production (Passioura, 1996; Calviño and Monzon, 2009).

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