A Modeling Approach to Explore Water Management Strategies for Late-Sown Maize and Double-Cropped Wheat–Maize in the Rainfed Pampas Region of Argentina

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Abstract

Most of Argentine maize (*Zea mays* L.) production takes place under rainfed farming in the Pampas region, where water availability is the main limiting resource. Most crops are still sown early in spring to have the critical period of silking before the frequent mid-summer water deficit. Early sowing dates (September) have been also linked to the need for escaping the increased incidence of insect pests associated with late sowings, a restriction that has been drastically reduced with the introduction of Bt hybrids. Therefore, very late sowing dates (December) became an actual alternative that must be evaluated. We estimated the combined effect of late sowings, variable levels of plant available soil water (PASW) at sowing in single- and double-cropped crops, and variable levels of soil N supply on the interannual variation of maize yield in four sites of the region. For this purpose we used 41 yr of daily, measured weather data and the Crop Environment Resource Synthesis-Maize (CERES-Maize) simulation model. Rainfed yield was very stable across December sowings ($\geq$7.5 Mg ha^{-1}) for latitudes $\leq$36° S, provided PASW (1.8 m) at sowing was 100% and initial N availability reached approximately 130 kg ha^{-1} N. This strategy had almost no yield penalty as compared with potential yield. The response rate to mentioned N availability turned negative for PASW at sowing $\leq$35%. Because of the apparent yield stability across December sowings, farmers should be recommended to survey PASW rather than tie late sowing of maize to scattered rainfall events.

Abbreviations: AAPRESID, Argentine Association of No-Till Farmers; CERES-Maize, Crop Environment Resource Synthesis-Maize; DCM, double-cropped wheat–maize; ENSO, El Niño–Southern Oscillation; LSM, late-sown, single-cropped maize; PASW, plant available soil water; PET, potential evapotranspiration; RM, relative maturity; WUE, water use efficiency.

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doi:10.2134/advagricsystmodel5.c13

Practical Applications of Agricultural System Models to Optimize the Use of Limited Water
Lajpat R. Ahuja, Liwang Ma, and Robert J. Lascano, Editors
Advances in Agricultural Systems Modeling, Volume 5. Lajpat R. Ahuja, Series Editor

USDA-ARS

Since the advent of the second industrial era in the 1880s, agricultural production has been challenged by the steady increase of demand (Evans, 1997). Until the 1960s this increase was satisfied by the expansion of crops into new land, but since then we have depended predominantly on increasing yield (production per unit land area). At the end of the 20th century, however, some studies highlighted the need for intensifying cropping systems to ensure production keeps pace with demand, focusing on the annual yield per unit land area cropped to several crops rather than on the yield of individual crops (Evans, 1997, 1999). International concern about these issues grew during recent years, when gloomy reports provided warnings about the apparent incapacity of global yield gains to fulfill predicted demand trends (Fischer and Edmeades, 2010; Hall and Richards, 2013; Ray et al., 2013). Forecasts on yield gains were less critical for maize than for wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) (Ray et al., 2013), and the Pampas region of Argentina (ca. 30–39° S and 56–65° W) was identified as one of the world areas where maize had a steady and rapid yield increase (Ray et al., 2012). Commercial maize production in Argentina rose from 8.5 ± 1.6 million megagrams in the 1970s to 17.5 ± 3.8 million megagrams in the 2000s, with almost no change in the area cropped to this species (ca. 3 million hectares). The increase was due exclusively to enhanced yields, and gains for this trait were estimated at 120 kg ha^{-1} yr^{-1} (2.8% yr^{-1}) for the 1970 to 2010 period (based on public statistics; SAGPYA, 2013). This progress can be attributed to both genetics and management practices and has been reached without irrigation.

Most of Argentine maize production takes place under rainfed farming in the Pampas region of the country (Fig. 13–1), for which rainfall has a large interannual variability (Messina et al., 1999). Consequently, water availability is usually the most limiting resource to yield of this crop, and a strong association has been detected between maize yield and the occurrence of the extreme phases of the El Niño–Southern Oscillation (ENSO) phenomenon during the 20th century (Podestá et al., 1999). This trend held for the period with steady increase in maize yield (1969–1970 to 2010–2011). Years with below-expected values (30% of the series with a decrease of ≥10% of expected value, based on residuals analysis) usually corresponded (54%) to the cool La Niña phase, which brings below-normal spring and summer rainfall to Argentina. On the contrary, the warm El Niño phase (wetter than normal for Argentina) had a larger incidence (62%) among years with above-expected values (30% of the series with an increase ≥10% of

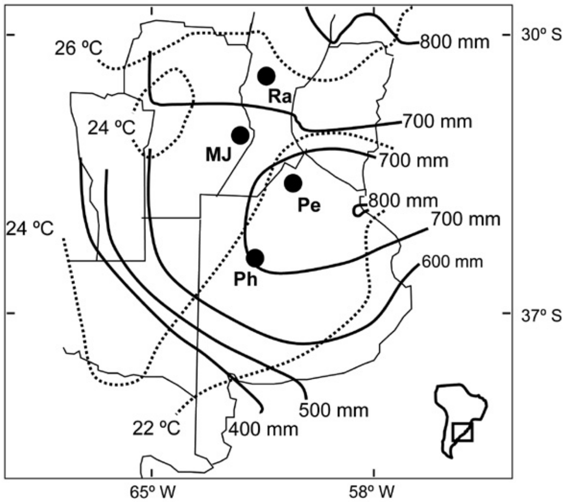

Fig. 13–1. The enlarged area represents the Pampas region of Argentina (ca. 30–39° S and 56–65° W), indicated with a square within South America in the inset. Solid and dotted lines indicate isohyets and mean temperature isotherms, respectively, during the warm season (21 September to 21 March). Solid circles correspond to the evaluated sites of Pergamino (Pe), Pehuajó (Ph), Marcos Juárez (MJ), and Rafaela (Ra).

expected value). These trends had no link to a bias of the phases along the studied period, which registered an even distribution of La Niña events in 33% of the years and of El Niño events in 35% of the years.

In spite of the abovementioned evidence, the combined effect of management practices (soil water at sowing, sowing date, stand density, fertilization) that affect crop water use did not receive adequate attention until the end of the 20th century. This situation was due to some permanent restrictions, such as the increased incidence of important insect pests (e.g., European corn borer [*Ostrinia nubilalis* Hübner], fall armyworm [*Spodoptera frugiperda* J.E. Smith], corn earworm [*Helicoverpa zea* Boddie]) with delayed sowing, which made late-sown maize and double-cropped winter crop–maize (i.e., maize sown immediately after the harvest of any winter crop) nonvalid alternatives in areas where double-cropped wheat–soybean is widely spread since the 1980s (Hall et al., 1992; Messina et al., 1999). This constraint, together with the strong paradigm of the advantage of early sowing for maximizing maize yield in temperate regions (Cirilo and Andrade, 1994; Otegui et al., 1995), has limited late sowing of this species (December–January) to the subtropical, low-yielding non-Pampas areas of the northwest and northeast parts of the country, linked to their pronounced monsoonal regime and heat-shock risk during the summer. The insect problem began to decrease in 1998 with the appearance of the first transgenic maize in the Argentine market (Bt corn; Williams et al., 1997) and has been currently minimized with the inclusion of additional transgenic events ("stacked events") for enhanced crop protection against a wide insect spectrum. However, the lack of a thorough approach to the analysis of the interaction among management practices persisted for a few more years, because the necessary information for the correct use of integrative tools such as crop models was not available. Calibration of CERES-Maize (Jones and Kiniry, 1986) to the conditions of the Pampas region of Argentina commenced in the 1990s (Otegui et al., 1996; Guevara et al., 1999), but it was its adoption by AACREA (Argentine Association of Regional Agricultural Experimentation Consortia) that granted the rapid assembly of all needed information on soils and climate (Mercau et al., 2001) and boosted its use as a decision-making tool in the last decade (Bert et al., 2006, 2007).

In this new technological scenario, it is possible to revisit some recurrent questions raised by farmers along the extended sowing period for summer crops in the Pampas region, but now including its broad variation in soil types and interannual rainfall regimes (Hall et al., 1992). Examples of these types of questions include the following:

1. When early sowing (September–October) of maize is delayed and the time to start soybean sowing is reached (November), is it better to finish sowing maize or to postpone this activity until December, after all soybean has been sown?
2. When soil water availability during spring is usually scarce and early sowing promotes a large interannual variation in maize yield, as in many western areas of the Pampas region (Ferreyra et al., 2001), or a winter cover or forage crop does not allow to sow early enough to avoid silking to take place before the critical summer water deficit, what yield level could be expected of a delayed sowing?
3. When sowing of soybean in the double-cropped wheat–soybean sequence reaches mid-December and a significant yield decline is expected for each day delay in its sowing (Peltzer, 2007), is it better to continue with soybean or to start with maize?

In this chapter we will present several elements for assisting decision-making on these issues and will compare them with the few available data on late-sown, single-cropped maize (LSM) crops from on-farm research organized in recent years by the Argentine Association of No-Till Farmers (AAPRESID). Our results are based on a previous study (Otegui et al., 2002) developed for a technological meeting on maize management. This study was synthesized in an assistant tool (Mercau et al., 2002) that is periodically updated. Different production levels will be analyzed (van Ittersum and Rabbinge, 1997), from conditions with no stress (i.e., potential yields) to water-limited and water- + N-limited crops (i.e., attainable yields). All results (observed and simulated) correspond to crops grown free of biotic constraints (insects, diseases, and weeds) and not influenced by the soil water table (Nosetto et al., 2009), because their effects are not included in crop simulation models used in this study.

Late-sown Maize and Double-cropped Wheat–Maize in the Central Area of the Pampas Region

The few records of potential on-farm maize yields (i.e., harvested in areas >1 ha) in the Pampas region indicate that they range between 13.9 and 17.8 Mg ha^{-1} (dry weight). They have been obtained with transgenic, single-cross maize hybrids of relative maturity (RM) 116 to 125 (FAO 500–650; Otegui et al., 1995, 1996), sown early in September and grown under irrigation and high N fertilizer rates near Teodelina (34° S, 61° W), Santa Fe (Otegui et al., 2007). These yields were close to values registered during the previous decade (1990s) in experimental plots cropped in the same area under September sowings (Otegui et al., 1995) and 80,000 plants ha^{-1}, but with nontransgenic, single-cross hybrids of RM 110 (12.8–15.4 Mg ha^{-1}) and three-way cross hybrids of RM 125 (15.7–17.7 Mg ha^{-1}). On the basis of these studies and a series of 24 yr of weather records (1970–1971 to 1993–1994) of the region, it was estimated that potential yield of maize hybrids (RM 125) grown at the mentioned stand density in the area ranged between 15.3 ± 3.4 and 15.2 ± 1.0 Mg ha^{-1} for September and October sowings, respectively, and declined to 14.2 ± 1.1 Mg ha^{-1} for November sowings (Otegui et al., 1996). These trends have been recently confirmed by another model-based study (Maddonni, 2012), which expanded the analysis to other sites of the Pampas region (31°10′–35°48′ S, 61°30′–64°21′ W) but did not include sowing dates beyond 1 December. Evidently, the sowing delay along November does not represent a strong penalty to potential yield for latitudes ≤36° S. The trend, however, cannot be extrapolated to later sowings, because several aspects may lie beyond the limits of the models used for estimation (e.g., reduced air temperature that causes a reduction in radiation use efficiency; Otegui et al., 1996), yielding wrong predictions (Jones and Kiniry, 1986). Moreover, there is evidence of a strong yield decline for sowing dates ≥November at latitudes ≥37°45′ S (Cirilo and Andrade, 1994), but no evidence of the ability of models such as CERES-Maize for predicting them in the environment of interest. For these reasons, the first step was the evaluation of errors when a model is used for comparison with observed data from very late sowings.

Model Goodness of Fit for Predicting Crop Performance in Very Late Sowing Dates

The evaluated model was a modified version of MZCER980, included in the Decision Support System for Agrotechnology Transfer (DSSAT)-CERES-Maize V3.5 (Jones et al., 1998). Four changes were introduced to the original version: (i) the optimum temperature that affects maximum grain-filling rate was set at 26°C as in a previous version (Jones and Kiniry, 1986), (ii) the use efficiency of carbon remobilized to grain filling was set at 0.3 after Kiniry et al. (1997), (iii) the response of the kernel number per plant to plant growth during the critical period of silking + 170°C day was modified to account for positive effects of low temperatures on the duration of the period (Otegui and Bonhomme, 1998), which may affect the total assimilate production through extended light interception as well as through daily plant growth rate (Ritchie and Alagarswamy, 2003), and (iv) the effect of the soil root growth factor on root depth capacity, introduced in MZGECER980, was removed and limited to root density, as in a previous version (Jones and Kiniry, 1986). This modified model has been used satisfactorily for describing the performance of rainfed maize crops grown under different N rates and conventional sowing dates in the area of interest (Mercau et al., 2001). Water and N routines, therefore, were assumed to work properly for the Pampas region environment. Data for model evaluation in late sowing dates were provided by A. Cirilo (personal communication) and corresponded to 48 experimental plots, grown free of abiotic and biotic stress between 1996–1997 and 2000–2001 at the Pergamino experimental unit (33°56′ S, 60°33′ W; Buenos Aires province) of the National Institute of Agricultural Technology. Plots were cropped on soils of silty clay loam type (Typic Argiudoll; USDA taxonomy), and sowing dates ranged between 31 October and 25 January. Five hybrids of RM between 113 and 125 were used (DK639, DK664, DK752, DK757, DK765, and C280), for which the necessary genetic coefficients were available. Stand densities ranged between 50,000 and 80,000 plants ha^{-1}. Observed yields varied between 1.9 and 9.9 Mg ha^{-1} (all the yield values are presented on a dry basis) and were adequately predicted by the model with an RMSE of 18% of observed values (Fig. 13–2). This trend did not vary among yield components (RMSE of 18% for grain number m^{-2} and RMSE of 14% for individual grain weight), suggesting the model weighs all factors that affect crop growth along the cycle evenly. No trend in yield was detected across stand densities for late sowings under no water or N stress. Accordingly, simulations indicated an almost null effect of evaluated stand densities on yield, and there was a good agreement between observed and predicted results for this trait (RMSE for yield of 16, 20, and 17% at low, medium, and high stand densities).

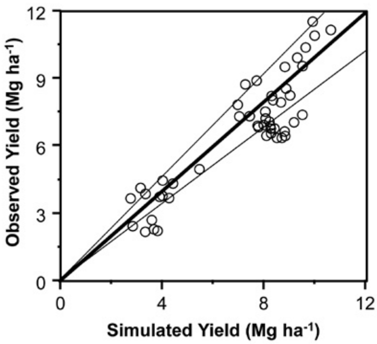

Fig. 13–2. Relationship between observed and predicted maize yields. Data (*n* = 48) correspond to late-sown (between 31 October and 25 January) experimental plots cropped at the Pergamino site (Fig. 13–1). The thick solid line represents the 1:1 relationship, and the thin lines represent a model prediction of 1.15 (bottommost) and 0.85 (uppermost) of observed yields.

Water-Limited Yields with No Nitrogen Limitation

The scenario of analysis included 41 growing seasons (1971–1972 to 2011–2012), with sowing dates evaluated at 10-d intervals between 10 December and 10 January. Simulated conditions included standard soils of the region (Typic Argiudols with 2.5% organic matter and 256 mm of available soil water up to 1.8-m depth), two single-cross maize hybrids (DK 752 of RM 125, and DK 664 of RM 116), and a stand density of 65,000 plants ha^{-1}. Three levels of soil water at sowing were tested: one representative of LSM and the other two representative of the most expected conditions at physiological maturity of a wheat crop, immediately before sowing of maize in a double-cropped wheat–maize sequence (DCM). The whole soil profile was set at field capacity for the LSM. For the DCM, one condition was defined as dry (DCM_{DRY}) and the other as wet (DCM_{WET}). For DCM_{DRY}, soil water content was (i) set at 30% PASW up to 1.2-m depth and (ii) increased to 40% of PASW for the 1.2- to 1.5-m layer and to 50% PASW for the 1.5- to 1.8-m layer (mean PASW of 35% for the whole profile). For DCM_{WET}, soil water was set at field capacity up to 0.6-m depth, and the rest of the layers were at the same PASW of the DCM_{DRY} condition (mean PASW of 58% for the whole profile). Soil water in the DCM_{DRY} condition is representative of years when wheat crops end with low water content and farmers start sowing the summer species in the double-cropped sequence with any rainfall event of small intensity (i.e., low recharge). Soil water in the DCM_{WET} condition is representative of wheat crops that received a rainfall recharge after physiological maturity and/or farmers that wait for it to reduce the risk of crop failure due to poor seedling establishment. To ensure crop germination, a rainfall of 8 mm was simulated by adding irrigation of that amount immediately after each simulated sowing date. The nitrogen routine was turned off to ensure no N limitation to crop growth.

Results for the described scenarios are summarized in Table 13–1. Estimated yields with no N limitation were highest for fully irrigated crops at the earliest evaluated sowing date (10 December) and lowest for the driest option (DCM_{DRY}) and most delayed sowing (10 January). As expected, yield declined with reduced soil water content at sowing (Table 13–1). Nevertheless, while rainfed late-sown maize crops (LSM_{RAIN}) had yield levels slightly lower than the potential expected with no water limitation along the cycle (LSM_{POT}), both double-cropped strategies (DCM_{WET} and DCM_{DRY}) had higher risk of yield reduction. This reduction was chiefly linked to reductions in kernel number m^{-2} (Fig. 13–3a), which were associated with a low maximum light interception efficiency at silking (Fig. 13–3b). Differences between DCM_{WET} and DCM_{DRY} were linked to water-stress conditions that affect leaf expansion, which led to reduced (<85%) or markedly reduced (<65%) ground cover in 39 and 10% of the years, respectively, among DCM_{DRY} crops. These negative conditions were negligible among DCM_{WET} crops (Fig. 13–3b).

Potential yield of a single-cropped maize declined with a delayed sowing date from 10 December to 10 January, in agreement with previous reports for early sown maize in the same area (Otegui et al., 1995, 1996). Interestingly, this

Table 13–1. Sowing date effects on estimated yield of maize crops grown under contrasting water regimes and no N limitation at the Pergamino site of the Pampas region.

		Sowing date			
Water regime†	Quantile	10 December	20 December	30 December	10 January
	%	kg ha^{-1}			
LSM_{POT}	25	10,442	10,024	7,858	6,212
	50	11,154	11,121	9,169	7,510
	75	12,301	11,859	10,622	8,294
LSM_{RAIN}	25	9,548	9,285	7,849	6,212
	50	10,526	10,800	8,872	7,492
	75	11,924	11,831	10,502	8,294
DCM_{WET}	25	7,204	8,429	6,200	5,343
	50	9,842	9,805	8,181	7,021
	75	11,135	11,143	9,492	8,086
DCM_{DRY}	25	5,378	7,102	5,900	4,720
	50	8,320	8,558	7,602	6,486
	75	10,056	9,496	8,700	7,210

† Water regimes included (i) single-cropped, late-sown maize crops (LSM) with no water restriction along the cycle (LSM_{POT}) or rainfed farming with the soil at field capacity at sowing (LSM_{RAIN}) and (ii) rainfed farming of double-cropped maize crops (DCM). For the latter, levels of plant available soil water (PASW) at sowing were as follows: (i) high, at field capacity in the uppermost 60-cm soil layer and 30% PASW between 60 and 120 cm (DCM_{WET}), and (ii) low, at 30% PASW in the uppermost 120-cm soil layer (DCM_{DRY}). The rest of the profile was between 40% (120–150 cm) and 50% (150–180 cm) PASW for DCM crops.

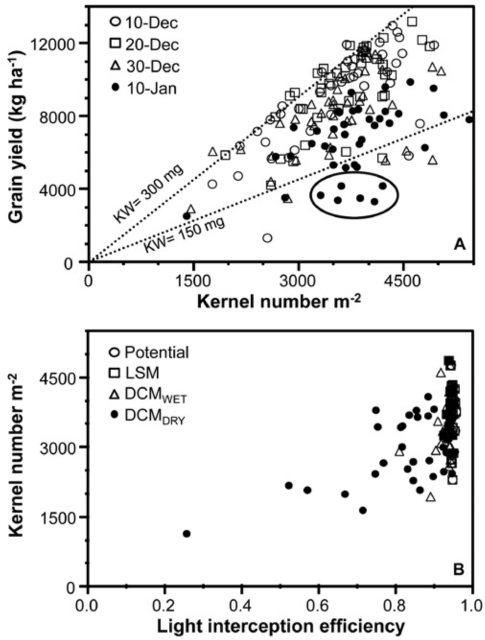

Fig. 13–3. Estimated response of (a) yield to kernel number m^{-2} and (b) kernel number m^{-2} to maximum light interception efficiency. Data in Fig. 13–3a correspond to DCM$_{WET}$ crops grown at four sowing dates at the Pergamino site. Dotted lines represent isoquants of constant individual kernel weight (KW), and encircled symbols correspond to crops that experienced early termination of grain filling due to low temperatures. Data in Fig. 13–3b correspond to different cropping strategies (LSM$_{POT}$, with no water restriction; LSM$_{RAIN}$, rainfed farming with 100% soil water at sowing up to 1.8-m depth; DCM$_{WET}$, double-cropped wheat–maize with high soil water at maize sowing in the uppermost 60-cm soil layer and low water availability in deeper layers; DCM$_{DRY}$, same as DCM$_{WET}$ but with low soil water at maize sowing in the uppermost soil layer) for a 20 December sowing date at the Pergamino site. All data in Fig. 13–3a and 13–3b are with no N restriction.

trend was slightly different under rainfed farming (LSM$_{RAIN}$ and DCM), and the highest yields were obtained with sowing dates on 10 December as well as 20 December (Table 13–1, Fig. 13–4). A delayed sowing date pushed the estimated silking date from 13 February ± 4 d for the 10 December sowing to 18 March ± 4 d for the 10 January sowing. For the central area of the Pampas region, this delay in silking time is accompanied by a decline in air temperature and solar radiation and an increase in rainfall (Hall et al., 1992; Maddonni, 2012), which causes (i) a reduction in evaporative demand and an improved soil water condition and (ii) a less favorable photothermal quotient (Cantagallo et al., 1997). Consequently, the crop water balance tends to improve in the transition from summer to fall, whereas the opposite occurs in the photothermal environment (Coll et al., 2011). The relative importance of these trends affected estimated final yield

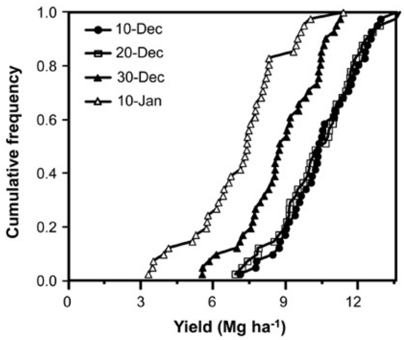

Fig. 13–4. Estimated frequency of attainable yield (LSM_{RAIN}, rainfed farming and 100% plant available soil water at sowing) across four sowing dates with no N limitation at the Pergamino site.

and its components, kernel number m^{-2} and individual kernel weight. Multiple regression analysis indicated that final yield was always significantly ($P < 0.001$) affected by both yield components, but its variations were mainly driven by variations in kernel number m^{-2} for December sowings and by variations in kernel weight afterward. These results highlight the importance given by the model to the grain-filling period and source–sink relations for late-sown maize crops, in agreement with physiological studies on this topic that included a wide range of sowing dates (Cirilo and Andrade, 1996; Borrás et al., 2004). For the area under study, it was estimated that early frosts had no terminal effect among December sowings; but this constraint, together with long periods of low temperatures, caused the anticipated termination of grain filling in 25% of the years among January sowings (Fig. 13–3a).

On the basis of the negative effect of low soil water at sowing due to poor rainfall recharge on yield, as well as on the apparent yield stability across December sowings, farmers should be recommended to survey soil water content rather than to tie maize sowing dates to the first rainfall events after the harvest of winter crops. Estimated trends among maize crops in a DCM sequence set an important difference with soybean crops in the double-cropped wheat–soybean sequence. Similar analyses made for the latter with CROPGRO-soybean (Hoogenboom et al., 1999) suggested a marked decline in yield with delayed sowing after 15 December for the nearby site of Paraná, located at 32° S and 60° W (Peltzer, 2007; Coll et al., 2011).

Water-Limited Yields: Response to Nitrogen

We simulated a range of N availability at sowing (soil $N\text{-}NO_3$ + soil $N\text{-}NH_4$ + N-fertilizer) between 40 and 190 kg ha^{-1} N. This was performed by adding different amounts of N-fertilizer to a fixed amount of N-soil (40 kg ha^{-1} N in the uppermost 0.6-m soil layer and 15 kg ha^{-1} N in the rest of the profile). The response of estimated maize yield to N availability at sowing increased with improved soil water availability ($LSM_{RAIN} > DCM_{WET} > DCM_{DRY}$) and decreased with sowing date delay after 20 December (Table 13–2). Considering 70 kg ha^{-1} N as a common soil N supply for maize crops in this area (Alvarez and Steinbach, 2009), the response rate to N fertilization in the 20 December sowing rose from 9 kg grain ha^{-1} kg N^{-1} for DCM_{DRY} to 24 kg grain ha^{-1} kg N^{-1} for DCM_{WET} and 27 kg grain ha^{-1} kg N^{-1} for LSM_{RAIN} when N availability increased from 70 to 100 units N ha^{-1}. This response declined to (i) 2.1, 16.3, and 21.5 kg grain ha^{-1} kg N^{-1}, respectively, when N availability increased from 100 to 130 kg ha^{-1} N and (ii) −0.23, 5.6, and 12.4 kg grain ha^{-1} kg N^{-1}, respectively, when N availability increased from 130 to 160 kg ha^{-1} N. These figures are in agreement with recent studies on site-specific N management that set a limit at 130 kg ha^{-1} N for Typic Haplustol soils in the western area of the Pampas region (Gregoret et al., 2011). However, the estimated response of yield to N availability among the bottommost 25% of the years (discussed in a next section) indicated that it (i) began to decrease at relatively low N levels for the

Table 13–2. Yield response to sowing date and N availability at sowing (soil N-NO_3 + soil N-NH_4 + N-fertilizer) for rainfed crops at the Pergamino site.†

Sowing date	N	LSM_{RAIN}		DCM_{WET}		DCM_{DRY}	
		Mean	SD	Mean	SD	Mean	SD
		kg ha^{-1}					
10 December	70	8,137	± 815	7,268	±1,377	6,129	±1,937
	100	8,981	± 916	7,927	±1,609	6,449	±2,238
	130	9,653	±1,041	8,345	±1,995	6,536	±2,512
	160	10,008	±1,299	8,549	±2,232	6,451	±2,675
20 December	70	8,118	± 924	7,470	±1,248	6,399	±1,630
	100	8,925	±1,056	8,193	±1,433	6,670	±1,908
	130	9,570	±1,202	8,682	±1,655	6,732	±2,108
	160	9,941	±1,355	8,849	±1,830	6,725	±2,229
30 December	70	7,260	±1,104	6,674	±1,361	5,917	±1,523
	100	7,924	±1,252	7,274	±1,528	6,164	±1,813
	130	8,455	±1,374	7,655	±1,706	6,194	±1,962
	160	8,707	±1,468	7,714	±1,905	6,063	±1,911
10 January	70	6,070	±1,367	5,666	±1,428	5,045	±1,369
	100	6,589	±1,534	6,136	±1,564	5,251	±1,563
	130	6,939	±1,676	6,386	±1,659	5,210	±1,641
	160	7,075	±1,761	6,381	±1,689	5,066	±1,593

† Water regimes included (i) single-cropped, late-sown maize crops (LSM) with no water restriction along the cycle (LSM_{POT}) or rainfed farming with the soil at field capacity at sowing (LSM_{RAIN}) and (ii) rainfed farming of double-cropped maize crops (DCM). For the latter, levels of plant available soil water (PASW) at sowing were as follows: (i) high, at field capacity in the uppermost 60-cm soil layer and 30% PASW between 60 and 120 cm (DCM_{WET}), and (ii) low, at 30% PASW in the uppermost 120-cm soil layer (DCM_{DRY}). The rest of the profile was between 40% (120–150 cm) and 50% (150–180 cm) PASW for DCM crops.

LSM_{RAIN} and DCM_{WET} strategies or (ii) remained very low and almost invariable for the DCM_{DRY} strategy. This variation highlights the importance of long-term weather forecasts together with the survey of PASW at sowing for minimizing the economic risk linked to management decisions (Messina et al., 1999).

Late-sown maize and double-cropped wheat–maize across the Pampas region

Currently, most of maize production comes from an area located between 30 and 35° S and 60 and 65° W of the Pampas region (Fig. 13–1). Within this area, three additional sites were selected for the analysis of the strategies (LSM_{RAIN}, DCM_{WET}, and DCM_{DRY}) previously evaluated for the Pergamino site. The new environments were considered representative of the regional variation in soil and climate conditions and with a long enough frost-free period for the development of late-sown maize. The new sites (Fig. 13–1) were Rafaela (31°12′ S, 61°30′ W; Santa Fe province), Marcos Juárez (32°36′ S, 62°33′ W; Córdoba province), and Pehuajó (35°54′ S, 61°54′ W; Buenos Aires province). The most remarkable differences among them have been described by Maddonni (2012) and are summarized in Table 13–3 for all evaluated combinations of sites and sowing dates. We highlight (i) the strong differences in rainfall among sites (Rafaela > Pehuajó > Pergamino > Marcos Juárez) as compared with the slight differences in potential evapotranspiration (PET), but the clear improvement in water balance (rainfall–PET) with delayed sowing for all sites, (ii) a latitude gradient in mean maximum and mean minimum temperatures (Rafaela > Marcos Juárez > Pergamino > Pehuajó), (iii) differences in incident solar radiation (Pergamino > Pehuajó > Marcos Juárez > Rafaela), but particularly an abrupt decline during late summer and early autumn for the site at highest latitude (Pehuajó), and (iv) Typic Hapludol soils in Pehuajó (no argillic horizon) as compared with Typic Argiudol soils (with an argillic horizon) in all the other sites.

Water-Limited Yields with No Nitrogen Limitation

Mentioned differences in temperature caused a gradient in the length of phenological phases across the different combinations of sites and sowing dates (Table 13–4), which was not affected across strategies related to PASW at sowing (data not shown). The dates of silking and physiological maturity were delayed with increased latitude (Pehuajó > Pergamino > Marcos Juárez > Rafaela) and sowing date. These differences, however, were much smaller for the pre-silking stage than for the post-silking one (Table 13–4), because the former matched the period of high and stable temperatures of early and mid-summer whereas the latter took place during the period of highest rate of decline in this variable (Hall et al., 1992; Borrás et al., 2004). On the contrary, low temperatures during grain filling are

Table 13–3. Detail of climatic characteristics during the cycle for maize crops sown at different sites and dates.

Site	Sowing date	Temperature†		Cumulative values		
		Maximum	Minimum	Incident PAR‡	Rainfall	PET§
		——— °C ———		MJ	——— mm ———	
Pergamino	10 December	27.5 ± 1.3	14.7 ± 1.1	1175 ± 73	405 ± 11	651 ± 33
	20 December	26.3 ± 1.3	13.7 ± 1.1	1160 ± 66	432 ± 7	630 ± 32
	30 December	25.2 ± 1.2	12.8 ± 1.1	1115 ± 73	458 ± 7	596 ± 38
	10 January	24.5 ± 1.1	12.2 ± 1.0	1023 ± 91	483 ± 6	545 ± 45
Pehuajó	10 December	26.2 ± 1.7	13.3 ± 1.3	1189 ± 81	511 ± 11	643 ± 33
	20 December	25.2 ± 1.7	12.7 ± 1.2	1136 ± 75	545 ± 8	607 ± 30
	30 December	24.5 ± 1.6	12.1 ± 1.2	1053 ± 76	568 ± 8	559 ± 31
	10 January	24.0 ± 1.4	11.8 ± 1.2	949 ± 78	612 ± 14	506 ± 35
Marcos Juárez	10 December	28.6 ± 1.3	16.4 ± 0.9	1098 ± 72	229 ± 39	624 ± 39
	20 December	27.7 ± 1.3	15.6 ± 1.0	1085 ± 61	301 ± 16	609 ± 33
	30 December	26.3 ± 1.5	14.3 ± 1.1	1081 ± 54	348 ± 10	592 ± 29
	10 January	25.2 ± 1.5	13.4 ± 1.2	1022 ± 62	383 ± 6	554 ± 32
Rafaela	10 December	29.5 ± 1.2	16.9 ± 0.8	1085 ± 47	655 ± 13	627 ± 27
	20 December	28.8 ± 1.3	16.4 ± 0.9	1063 ± 52	707 ± 19	611 ± 28
	30 December	27.5 ± 1.3	15.4 ± 1.0	1057 ± 50	783 ± 20	595 ± 24
	10 January	26.0 ± 1.4	14.1 ± 1.0	1033 ± 52	932 ± 101	568 ± 26

† Mean ± SD of daily records.

‡ Photosynthetically active radiation.

§ Potential evapotranspiration.

expected to cause the early termination of the cycle and consequently to reduce the extension of the post-silking period for sowings beyond December at the site of highest latitude (Pehuajó) evaluated in this research (Table 13–4).

As described for the Pergamino site, estimated potential yields (LSM_{POT}) were generally highest ($\geq$9.9 ± 1.03 Mg ha^{-1}) for the earliest sowing date (10 December) and declined with delayed sowing (Table 13–5). There was, however, a sowing date $\times$ site interaction response (Table 13–5). The negative effects of low temperature with delayed sowing were more pronounced at the highest latitude site (Pehuajó) than at the intermediate latitudes of Pergamino (Table 13–1) and Marcos Juárez (Table 13–5), and no trend was detected in potential yield for the site located at the lowest evaluated latitude (Rafaela, Table 13–5). The response to sowing date was very similar for attainable yields with LSM crops (Fig. 13–4). Interestingly, estimated yield losses (i.e., attainable as compared with potential for each evaluated condition) were very low (0–6%) for LSM_{RAIN} crops in all evaluated sites (Table

Table 13–4. Estimated occurrence of phenological events for maize crops sown at different sites and dates.

Site	Sowing date	Date†		Period	
		Silking	Physiological maturity	Sowing to silking	Silking to physiological maturity
				d	
Pergamino	10 December	6–22 Feb.	22 Mar. to 2 June	65 ± 4	80 ± 12
	20 December	15 Feb. to 3 Mar.	30 Apr. to 18 June	65 ± 3	89 ± 11
	30 December	26 Feb. to 15 Mar.	2 May to 15 July	66 ± 3	90 ± 16
	10 January	12–25 Mar.	4 May to 15 Aug.	67 ± 4	85 ± 18
Pehuajó	10 December	9 Feb. to 1 Mar.	11 Mar. to 3 June	69 ± 4	81 ± 26
	20 December	18 Feb. to 7 Mar.	23 Mar. to 16 June	69 ± 4	84 ± 27
	30 December	2–21 Mar.	1 Apr. to 20 June	70 ± 4	82 ± 25
	10 January	21 Mar. to 2 Apr.	12 Apr. to 20 June	72 ± 4	72 ± 22
Marcos Juárez	10 December	3–20 Feb.	13 Mar. to 4 May	64 ± 4	66 ± 13
	20 December	15 Feb. to 1 Mar.	11 Mar. to 24 May	65 ± 4	73 ± 16
	30 December	25 Feb. to 13 Mar.	28 Mar. to 12 June	65 ± 4	83 ± 20
	10 January	8 Mar. to 20 Apr.	7 Apr. to 3 July	66 ± 3	86 ± 20
Rafaela	10 December	4–17 Feb.	26 Mar. to 9 May	62 ± 4	65 ± 7
	20 December	13–25 Feb.	28 Mar. to 27 May	62 ± 3	70 ± 10
	30 December	22 Feb. to 9 Mar.	13 Apr. to 3 July	62 ± 3	80 ± 10
	10 January	6–20 Mar.	27 Apr. to 18 July	63 ± 3	89 ± 14

† Maximum range.

Table 13–5. Estimated potential yields of late-sown, single-cropped maize crops grown at different sites and sowing dates with no N restriction.

Site	Quantile	Sowing date			
		10 December	20 December	30 December	10 January
	%	kg ha^{-1}			
Pehuajó	25	10,756	9,039	6,453	4,268
	50	11,540	10,037	7,474	5,309
	75	12,093	10,914	9,009	6,422
Marcos Juarez	25	9,237	9,166	8,790	7,533
	50	10,411	10,374	10,204	8,743
	75	11,083	10,914	10,713	9,869
Rafaela	25	9,118	8,658	8,615	8,404
	50	9,831	9,507	9,921	9,853
	75	10,868	10,515	10,601	10,361

13–6). This result contrasts markedly with estimated losses from early sown (15–20 September) maize crops in the region, which are expected to reach ~32% when the computation is based on mean values of potential (Otegui et al., 1996) and attainable (rainfed farming with no N restriction and 100% PASW at sowing) yields (Mercau, 2002). However, an important penalty to yield is expected among late-sown maize crops with reduced water availability at sowing (Fig. 13–5 and Table 13–6). This penalty reached 6.5 to 22% for DCM_{WET} and increased pronouncedly for DCM_{DRY} (14–47%). These trends in yield had a concomitant effect on water use efficiency (WUE, in kilograms of grain per millimeter of crop evapotranspiration; Table 13–7), which declined with reduced water availability at sowing (LSM_{RAIN} > DCM_{WET} > DCM_{DRY}). A delayed sowing date led to a decline in yield losses, as compared with potential yield among DCMs (Table 13–6), because the critical periods of silking and grain filling (Table 13–4) are expected to take place after the occurrence of maximum evaporative demand that takes place during January (Totis de Zeljkovich and Rebella, 1980; Hall et al., 1992). For crops at high N availability, however, these effects of sowing date did not have a uniform effect on WUE (Table 13–7). This trait tended to increase with delayed sowing for the Marcos Juárez and Rafaela sites, whereas it tended to decline with delayed sowing at Pehuajó (steadily)

Table 13–6. Estimated grain yield loss of rainfed maize as single-cropped late-sown crops and in the double-cropped wheat–maize sequence.†

Site	Strategy‡	Sowing date			
		10 December	20 December	30 December	10 January
		%			
Pergamino	LSM_{RAIN}	6	3	3	0
	DCM_{WET}	12	12	11	7
	DCM_{DRY}	25	23	17	14
Pehuajó	LSM_{RAIN}	5	5	1	0
	DCM_{WET}	16	14	9	9
	DCM_{DRY}	30	22	17	15
Marcos Juarez	LSM_{RAIN}	2	1	5	2
	DCM_{WET}	17	12	17	11
	DCM_{DRY}	31	26	31	25
Rafaela	LSM_{RAIN}	4	2	4	0
	DCM_{WET}	21	18	22	15
	DCM_{DRY}	47	38	34	32

† For each site × sowing date, loss (%) = (1 − attainable GY/potential GY) × 100. Median values were used for computation. GY, grain yield.

‡ Water regimes included (i) single-cropped, late-sown maize crops (LSM) with no water restriction along the cycle (LSM_{POT}) or rainfed farming with the soil at field capacity at sowing (LSM_{RAIN}) and (ii) rainfed farming of double-cropped maize crops (DCM). For the latter, levels of plant available soil water (PASW) at sowing were as follows: (i) high, at field capacity in the uppermost 60-cm soil layer and 30% PASW between 60 and 120 cm (DCM_{WET}), and (ii) low, at 30% PASW in the uppermost 120-cm soil layer (DCM_{DRY}). The rest of the profile was between 40% (120–150 cm) and 50% (150–180 cm) PASW for DCM crops.

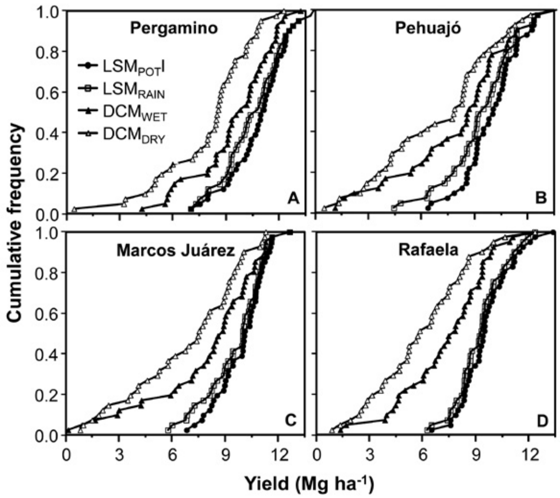

Fig. 13–5. Estimated frequency of maize yield for different cropping strategies (described in Fig. 13–3) in a 20 December sowing date and with no N restriction at four sites of the Pampas region.

and Pergamino (from 20 December onward). This difference among sites is chiefly linked to the effect of this management practice on yield (Tables 13–1, 13–5, and 13–6), because crop evapotranspiration follows PET (Table 13–3) and always declined with delayed sowing.

Water-Limited Yield: Response to Nitrogen

Nitrogen use efficiency (in kilograms of grain per kilogram of N absorbed by the crop at maturity) usually declined with reduced PASW at sowing, delayed sowing date, and enhanced N availability (Table 13–7). There was, however, a clear site × PASW at sowing interaction in yield response to N availability (Fig. 13–6). For all evaluated conditions in a 20 December sowing date, the response rate (first derivate of the quadratic model adjusted to 41 simulated years along 6 levels of N supply at sowing) was always high (19–34 kg grain ha^{-1} kg N^{-1}) when soil N (soil N-NO_3 + soil N-NH_4 + N-fertilizer) was low (≤40 kg ha^{-1} N) and soil water was high (LSM$_{RAIN}$ and DCM$_{WET}$), and it declined with reduced water availability and/or enhanced soil N. The expected response for an initial soil N level of 70 kg ha^{-1} N would be always ≥25 kg grain ha^{-1} kg N^{-1} (Table 13–8) among late-sown maize crops that start growing with the whole profile at field capacity (LSM$_{RAIN}$ strategy) in a 20 December sowing. On the contrary, the response declined to almost null or even negative values for the worst water-limited scenario (DCM$_{DRY}$).

Estimated mean yield across all sowing date × PASW × soil N combinations ranged between 5.1 and 10 Mg ha^{-1} for Pergamino, 3.9 and 10.4 Mg ha^{-1} for

Table 13–7. Mean values of water and N use efficiencies for different sites, cropping strategies and sowing dates.†

Site	Strategy	N level	Sowing date							
			10 December		20 December		30 December		10 January	
			WUE	NUE	WUE	NUE	WUE	NUE	WUE	NUE
		kg ha^{-1}	kg mm^{-1}	kg kg^{-1}	kg mm^{-1}	kg kg^{-1}	kg mm^{-1}	kg kg^{-1}	kg mm^{-1}	kg kg^{-1}
Pergamino	LSM_{RAIN}	70	15	74	16	71	15	61	14	52
		130	18	60	19	57	17	49	16	41
	DCM_{WET}	70	14	68	15	68	14	59	13	50
		130	16	53	18	53	16	46	15	39
	DCM_{DRY}	70	13	60	14	60	14	54	13	47
		130	14	47	15	47	15	43	13	38
Pehuajó	LSM_{RAIN}	70	17	67	16	59	15	49	12	37
		130	19	54	18	48	16	40	13	31
	DCM_{WET}	70	15	60	15	55	14	46	11	35
		130	17	49	17	45	15	38	12	29
	DCM_{DRY}	70	14	56	15	52	14	45	11	33
		130	16	46	16	44	14	38	11	29
Marcos Juárez	LSM_{RAIN}	70	14	70	15	67	16	65	16	59
		130	17	56	17	54	18	52	18	48
	DCM_{WET}	70	13	63	14	62	14	61	15	56
		130	15	50	16	49	17	48	17	45
	DCM_{DRY}	70	13	58	13	58	14	57	14	52
		130	13	45	14	46	15	45	15	42
Rafaela	LSM_{RAIN}	70	17	70	15	67	15	65	16	62
		130	13	56	17	54	18	52	19	51
	DCM_{WET}	70	14	59	13	57	14	59	15	58
		130	11	46	14	45	16	45	17	46
	DCM_{DRY}	70	11	50	12	51	13	51	14	52
		130	15	41	12	42	13	43	14	44

† Water regimes included (i) single-cropped, late-sown maize crops (LSM) with no water restriction along the cycle (LSM_{POT}) or rainfed farming with the soil at field capacity at sowing (LSM_{RAIN}) and (ii) rainfed farming of double-cropped maize crops (DCM). For the latter, levels of plant available soil water (PASW) at sowing were as follows: (i) high, at field capacity in the uppermost 60-cm soil layer and 30% PASW between 60 and 120 cm (DCM_{WET}), and (ii) low, at 30% PASW in the uppermost 120-cm soil layer (DCM_{DRY}). The rest of the profile was between 40% (120–150 cm) and 50% (150–180 cm) PASW for DCM crops. WUE, water use efficiency (kilograms of grain per millimeter of crop evapotranspiration); NUE, N use efficiency (kilograms of grain per kilogram of N absorbed by the crop at maturity).

Pehuajó, 5.4 and 9.3 Mg ha^{-1} for Marcos Juárez, and 4.7 and 9.2 Mg ha^{-1} for Rafaela. These estimates are within the range of observed results obtained by AAPRESID farmers with only 2 yr of evaluation in sites close to those included in our analysis (Gambin and Borrás, 2013). They obtained approximately 8.2 to 10.8 Mg ha^{-1} for

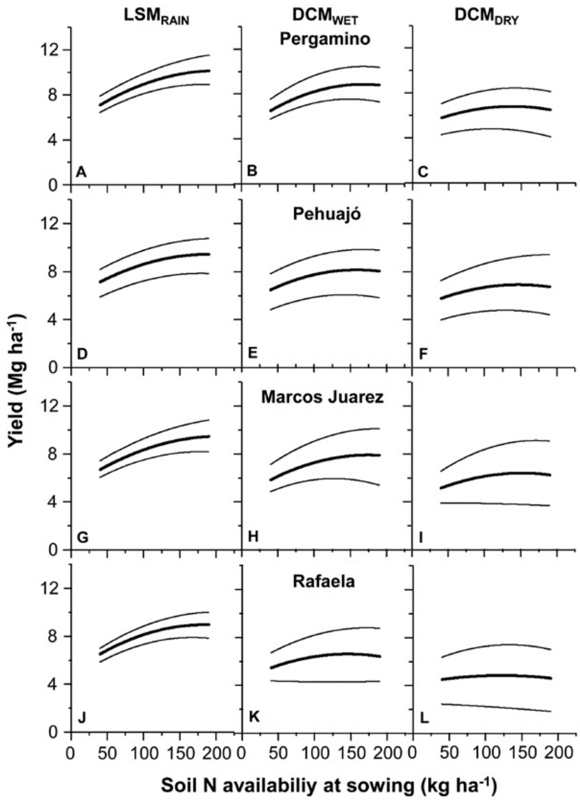

Fig. 13–6. Estimated response of yield to soil N supply at sowing (soil N-NO_3 + soil N-NH_4 + N-fertilizer) for three cropping strategies (described in Fig. 13–3) and four sites of the Pampas region. The thick solid line represents the quadratic model adjusted to 41 simulated years along 6 levels of N supply at sowing for median yield values, and thin lines represent the models adjusted to 20% (bottommost) and 80% (uppermost) quantiles.

the dry 2011–2012 growing season (classified as La Niña) and approximately 4.3 to 11.8 kg ha^{-1} for the typical 2012–2013 growing season (classified as neutral). They highlighted the sowing date and N fertilization as important management practices behind observed variations in yield. For all combinations of site × sowing date × PASW, our analysis indicated that the response rate to N supply varied in agreement with expected yield under no N limitation (Table 13–8); that is, the response rate is expected to decline with reduced PASW at sowing (LSM_{RAIN} > DCM_{WET} > DCM_{DRY}) and delayed sowing (Table 13–8). Considering that 8 to 15 kg of grain are necessary to pay for 1 kg of N applied as fertilizer (Mercau et al., 2002), the fertilizer rate to be recommended to farmers will vary considerably among evaluated sites and N levels. The continuous functions fitted in this research are expected to assist agronomists in this task.

Table 13–8. Estimated marginal yield response to two levels of nitrogen availability at sowing (soil N-NO_3 + soil N-NH_4 + N-fertilizer) evaluated for different sites, cropping strategies, and sowing dates. Data correspond to median values as those described in Fig. 13–6 for the 20 December sowing.†

Site	Strategy	N level	Sowing date			
			10 December	20 December	30 December	10 January
		kg ha^{-1}	kg grain ha^{-1} kg N^{-1}			
Pergamino	LSM_{RAIN}	70	32	31	26	20
		130	17	17	13	8
	DCM_{WET}	70	26	28	23	18
		130	10	11	7	5
	DCM_{DRY}	70	16	15	13	10
		130	1	2	1	-1
Pehuajó	LSM_{RAIN}	70	29	25	18	11
		130	16	12	7	4
	DCM_{WET}	70	23	21	16	9
		130	8	7	4	2
	DCM_{DRY}	70	17	16	11	6
		130	4	3	2	1
Marcos Juárez	LSM_{RAIN}	70	29	28	27	25
		130	16	15	15	11
	DCM_{WET}	70	23	24	24	21
		130	9	10	9	7
	DCM_{DRY}	70	15	16	17	14
		130	3	4	3	3
Rafaela	LSM_{RAIN}	70	29	27	27	26
		130	14	13	13	13
	DCM_{WET}	70	18	16	17	18
		130	4	3	3	5
	DCM_{DRY}	70	6	5	5	8
		130	–1	–1	0	2

† The estimated marginal yield response was obtained from the first derivative of the mean quadratic function fitted in Fig. 13–6. Water regimes included (i) single-cropped, late-sown maize crops (LSM) with no water restriction along the cycle (LSM_{POT}) or rainfed farming with the soil at field capacity at sowing (LSM_{RAIN}) and (ii) rainfed farming of double-cropped maize crops (DCM). For the latter, levels of plant available soil water (PASW) at sowing were as follows: (i) high, at field capacity in the uppermost 60-cm soil layer and 30% PASW between 60 and 120 cm (DCM_{WET}), and (ii) low, at 30% PASW in the uppermost 120-cm soil layer (DCM_{DRY}). The rest of the profile was between 40% (120–150 cm) and 50% (150–180 cm) PASW for DCM crops.

Conclusions

Late sowing can be an avenue to increase maize production in the Pampas region. Yield potential for this alternative is lower than for early sowings (Otegui et al., 1995, 1996), but interannual variation among attainable yields (i.e., rainfed farming) is expected to be substantially reduced for LSM_{RAIN} and DCM_{WET} as compared with early sowings, particularly in areas where soil water recharge is not expected to take place until late in spring. Late sowing, therefore, would allow an increase in the land cropped to maize when soil water at sowing usually affects adequate crop establishment in early sowings. It would also be a good alternative when soil temperature is low early in spring, which is a common restriction for latitudes >36° S (not evaluated in this study). Results from our modeling approach suggest that the survey of soil water at sowing is critical for the correct planning of a late-sown maize crop, particularly those scheduled as double crops (DCM) after any winter crop (wheat, barley [*Hordeum vulgare* L.], pea [*Pisum sativum* L.], rapeseed [*Brassica napus* L.]). Adequate soil water recharge becomes more critical than the sowing date for reducing yield losses among late sown crops, particularly to the north of the region (i.e., lower latitudes). The analysis of complementary irrigation at sowing will be necessary in areas where this recharge may limit early crop establishment. Occurrence of a shallow water table requires its monitoring because it may introduce a large variation in expected maize yield in the region (Nosetto et al., 2009) and is not considered by models used in this study. Finally, our approach produced a tool for assisting farmers and their advisors on N fertilization decisions, taking into account the simultaneous modification of management practices (e.g., sowing date) and growing conditions (e.g., soil water and soil N content at sowing) in contrasting environments. This tool leads to improved fertilizer use efficiency, a key issue for reducing the negative impact of cropping systems in the context of forecasted climate change scenarios (Intergovernmental Panel on Climate Change, 2007).

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