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Climatic constraints for the maize-soybean system in the humid subtropical region of Argentina

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Abstract The implementation of two summer crops in the same growing season is a possible alternative for land intensification in areas with a long frost-free period. The aim of this study was to analyse the strategy of land intensification through the implementation of the maize-soybean succession at two locations (Reconquista, 29°09′S 59°40′W and Las Breñas, 27°05′S 61°5′W) of the humid subtropical region of Argentina. CERES-Maize and CROPGRO-Soybean models were used to evaluate the impact of inter-annual variability of climate (36 years) of both locations on rain-fed grain yields of the following productive alternatives: (i) monoculture of maize, (ii) monoculture of soybean and (iii) the succession of a short-cycle maize followed by soybean as the second summer crop (maize-soybean system). The maize-soybean system was evaluated by the method of land equivalent ratio (LER), based on the sum of the relative grain yields of its components. The impact of the inter-annual variability of climate and of "El Niño" or "La Niña" episodes (El Niño Southern Oscillation phenomenon (ENSO)) on LER values was analysed. Simulated yields of maize monoculture (5687 kg ha^{-1}; CV = 49.7% and 5637 kg ha^{-1}; CV = 57.6% at Reconquista and Las Breñas, respectively) were higher than those of the short-cycle maize, especially at Las Breñas (5448 kg ha^{-1}; CV = 49.3% and 2322 kg ha^{-1}; CV = 33.9% at Reconquista and Las Breñas, respectively). Simulated yields of the soybean monoculture were higher (3588 kg ha^{-1}; CV = 26.1% and 2883 kg ha^{-1}; CV = 20.7% at Reconquista and Las Breñas, respectively) that those of the soybean as the second crop (2634 kg ha^{-1}; CV = 38.1% and 2456 kg ha^{-1}; CV = 32.9% at Reconquista and Las Breñas, respectively) at both locations. Average LERs were 1.69 (CV = 11.4%) at Reconquista and 1.41 (CV = 26.1%) at Las Breñas, and the inter-annual variability of LER was mainly determined by grain yields of (i) soybean as the second crop at Reconquista and (ii) maize monoculture at Las Breñas. Soil water content after maize harvest and rainfalls during reproductive period of soybean as the second crop conditioned LER values, but they were generally greater than 1. At Reconquista, LER values were not affected by the different episodes of ENSO phenomenon. By contrast, at Las Breñas, LER values were higher during La Niña episodes (1.48; CV = 26.6%) than during El Niño episodes (1.32; CV = 23.7%) mainly by their effects on grain yields of maize monoculture. Therefore, crop simulation models demonstrate the possibility to intensify land use (40–70%) at two locations of the humid subtropical region of Argentina, by the implementation of the maize-soybean system.

1 Introduction

The current rate of growth experienced by the global demand for agricultural products is one of the greatest challenges facing humanity. In this sense, different studies estimate that for the period 2005–2050 global demand for agricultural products will increase by 100% (e.g. Tilman et al. 2011). To meet this demand, it is necessary to increase agricultural production at an average annual rate of 2.4% (Ray et al. 2013). However, for the major global crops (maize, rice, wheat and soybean), their productions annually increase at a rate of 1.6% (maize), 1%

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(rice), 0.9% (wheat) and 1.3% (soybean) per year (Ray et al. 2013). Given this scenario, agricultural production would be increased at a faster rate, to reduce the gap between demand and supply of agricultural products. Two alternatives could be implemented to meet this objective; (i) the expansion of the agricultural frontier and (ii) the increasing productivity per unit area. From the 1960s, world area annually cultivated with major grain crops has slightly changed (FAO 2015). An exception to this trend was the case of soybean. Soybean area has increased significantly, and particularly in Argentina, it has expanded to the northern humid subtropical region at the expense of deforestation of native forests (Dirección de Bosques 2007). Furthermore, it is important to note that potential lands to be incorporated into global agricultural production has a large percentage of low productive capacity soils, which are highly dependent on inputs (Norse et al. 1992; Buringh and Dudal 1987). Hence, further expansions of agricultural frontier do not seem to be reasonable for the sustainability of agricultural systems.

The increasing productivity per unit area seems to be the most plausible alternative to increase global agricultural production. Higher grain yields per unit area could be achieved by improving crop attributes that increase the potential and yield stability (Russell 1986; Tollenaar et al. 1992). On the other hand, the increase in productivity per unit area can be achieved by intensifying land use. This latter strategy seeks to improve the efficiency in the capture and use of resources by crop production systems (Caviglia and Andrade 2010; Caviglia et al. 2004). In the temperate humid region of Argentine, one of the most adopted intensification system is the succession of winter crops with summer crops, as in the case of wheat-soybean double crop. Argentine wheat area, however, has recently been reduced and new alternatives of land intensification have been explored, as the cultivation of two summer crops in the same year (Monzón et al. 2014). For this double-crop system, an early sowing of a short-maize cycle would release the field as early as possible in order to minimise the negative impact of delayed sowing date on soybean grain yield (Monzón et al. 2014). This intensification of land use based on two summer crops has begun to be used in the humid subtropical region of Argentina, where the growing season is very long product of an extensive frost-free period and rainfalls generally exceed those of temperate regions. Information of climate impact on the productivity of the maize-soybean system is not available.

The analysis of production systems with crop succession should be allowed to establish whether the productivity of the system (e.g. maize-soybean) is higher than those of its components (i.e. monocultures of maize or soybean). One of the methods for the analysis of crop successions is the land equivalent ratio (LER; Connolly et al. 2001; Fukai 1993), an indicator of the land productivity for the evaluated system. The LER is obtained from the sum of the relative yields of each component (Silvertown 1982). So, for the maize-soybean system, LER = (grain yield of a maize as the first crop/grain yield of maize monoculture) + (grain yield of soybean as the second crop/grain yield of soybean monoculture). The LER values higher than 1, means that the intensified system is more productive, in relative terms, than the sum of both monocultures.

The evaluation of intensified systems can be done through field experiments (e.g. Monzón et al. 2014) and/or with the assistance of crop simulation models. These models are programs that use mathematical equations to reproduce the growth and development of different crops depending on soil characteristics, climate and crop husbandry (Boote et al. 1996; Hoogenboom et al. 2004). Outputs of crop simulation models include phenology, biomass production, grain yields, soil water balance and soil nitrogen dynamic (Jones et al. 2003). Their use is widespread because these models allow evaluating production strategies which combine many variables (Sadler et al. 1999). In this regard, one of the main advantages of these models is the ability to provide a probabilistic approach to simulated outputs, because these models work with time series of climate data, covering much of the existing inter-annual variability of meteorological conditions in a given region. A weak of these models is that they generally do not include the negative impact of biotic stresses (i.e. pest, diseases and weeds).

There is various crop simulation models, among the most used are the models included in the DSSAT (Decision Support System for Agrotechnology Transfer) package. Models of CERES family simulate the development and growth of cereal crops and have been validated by several authors, e.g. CERES-Maize (Mercau et al. 2001), CERES-Wheat (Calderini et al. 1994; Menéndez and Satorre 2007). Similarly, CROPGRO-Soybean model (Jones et al. 2003) has been validated for soybean crops (Mercau et al. 2007). However, few studies have combined these models to analyse the succession of summer crops and the productive results of land intensification in terms of LER.

In this work, we have used the CERES-Maize model and CROPGRO-Soybean model, coupled with long-term series (36 years) of daily climatic records (maximum and minimum air temperature, solar radiation and precipitation) of two locations of the humid subtropical region of Argentina to simulate the inter-annual variability of rain fed grain yields of (i) monoculture of maize, (ii) monoculture of soybean and (iii) the components of maize-soybean system (a maize followed by soybean as the second summer crop). The impact of climate (including the episodes of the El Niño Southern Oscillation phenomenon; (ENSO)) on the different productive strategies was also explored.

2 Material and methods

2.1 Locations

Simulations of the different productive strategies were performed for two locations of the humid subtropical region of Argentina. Climatic series provided by the National Weather Service are available for the locations of Reconquista (29°09′S 59°40′W) and Las Breñas (27°05′S 61°5′W) with 36 years (1971–2006) of daily records of maximum and minimum air temperature, solar radiation and rainfalls. The mean annual temperature at Reconquista is 20.1 °C (range 19.4–21.1 °C) with a mean frost-free period of 299 days which starts on August 17 (± 44.5 days) and finishes on June 13 (± 36.6 days). Mean annual photoperiod duration is 13 h (range 11–15 h) and mean daily solar radiation is 16.4 MJ m^{-2} d^{-1} (range 7.9–26 MJ m^{-2} d^{-1}). Annual rainfall totalizes ca. 1284 mm with the higher records from spring to autumn and the lower values during winter. The mean annual temperature at Las Breñas is 21.6 °C (range 20.6–23.0 °C) with a mean frost-free period of 285 days which starts on August 20 (± 46.6 days) and finishes on June 2 (± 36.0 days). Mean annual photoperiod duration is 13 h (range 11–15 h) and mean daily solar radiation is 16.9 MJ m^{-2} d^{-1} (range 8.1–27.2 MJ m^{-2} d^{-1}). Annual rainfall totalizes ca. 1006 mm with the higher records from spring to autumn and the lower values during winter.

2.2 Simulations

We have used CERES-Maize model (v.3.5) and CROPGRO-Soybean model (v.3.5) for the simulations of phenology and grain yields of the different productive strategies: (i) maize monoculture, (ii) soybean monoculture and (iii) a short-cycle maize hybrid followed by soybean as the second summer crop (maize-soybean system). For maize simulations, hybrid NK960 was used for the monoculture (long-cycle hybrid) and NK840 (short-cycle hybrid) as the first crop of the maize-soybean system. At Reconquista, simulated sowing date of maize monoculture was August 15, which corresponds to the usual date of early maize sowing for the region under study. At Las Breñas, low rainfalls during July and August and high frequencies of air temperatures above 35 °C (i.e. extremely high temperatures, see section 2.4) at the end of the spring and early in the summer (Fig. 1) determine that maize monoculture is generally sowed at late December. Hence, at this location simulated sowing date of maize monoculture was December 20. For the maize-soybean system, sowing date of maize was August 15 at both locations. At Reconquista, the A6445 variety (maturity group VI) was used for simulations of the soybean monoculture (sowing date on November 20 if an event of rainfalls greater than 10 mm occurred from November 15 to 25; if not sowing date was delayed to December 20) and the maize-soybean system (sowing date ca. on December 26; 8 days after the simulated physiological maturity of maize NK840 hybrid). At Las Breñas, variety A8000 (maturity group VIII) was used for simulations of soybean monoculture (sowing date on December 20) and the maize-soybean system (sowing date ca. on December 14; 8 days after the simulated physiological maturity of maize NK840 hybrid). Maize hybrids are commercial cultivars of Syngenta Argentina and A6445 and A8000 are soybean varieties of Nidera Argentina. Genetic coefficients of maize hybrids (Giménez 2015) and soybean varieties (Mercau et al. 2007) were previously obtained and are detailed in Tables 1 and 2.

Soils used for crop simulations correspond to a Typical Argialboll (Soil Survey Stuff 2010) for Reconquista and Udic Argiustoll for Las Breñas. These soil types were chosen by its representativeness in the area of the selected locations. Briefly, typical Argialboll (soil depth 200 cm) has a 2% of organic matter and a bulk density of 1.2 g cm^{-3} in the first soil layer and maximum available soil water content (maximum ASW) of 235 mm at 0–200 cm soil depth. Udic Argiustoll (soil depth 250 cm) has a ca. 6% of organic matter and a bulk density of 1.09 g cm^{-3} in the first soil layer and maximum ASW of 285 mm at 0–250 cm soil depth.

A nitrogen availability of 60 kg N ha^{-1} (0–60 cm soil depth) was considered at simulated sowing dates of maize at Reconquista. At Las Breñas, nitrogen availability varied from 60 to 80 kg N ha^{-1} for the sowing dates of maize in the double cropping system and in the monoculture, respectively. These nitrogen contents are the usual values at these locations and sowing dates. For the simulations of soybean as a second crop, an initial nitrogen availability of 20 kg N ha^{-1} (0–60 cm soil depth) was used which corresponds with the common soil N content after the harvest of maize crops.

Simulated plant density for maize crops was 7 plants m^{-2} with a row spacing of 0.70 m. For soybean simulations, row spacing was 0.35 m and planting density was modified according to sowing date. For the soybean monoculture, plant density was 30 plants m^{-2} and for the soybean as the second crop, plant density was 40 plants m^{-2}. No-tillage system was used in all simulations.

The variability in soil water content at sowing of each crop was simulated with CERES-Maize model (v.3.5). For the monocultures, the fallow period started on March 31 with an initial ASW of 40% and finished the day before sowing. For the soybean as the second crop, the fallow period started with the ASW at the simulated date of maize physiological maturity and finished 8 days later. Hence in the maize-soybean system, sowing date of soybean varied in accordance with the simulated date of physiological maturity of the previous maize crop. Consequently, 36 initial soil water contents were simulated at the sowing date of each crop.

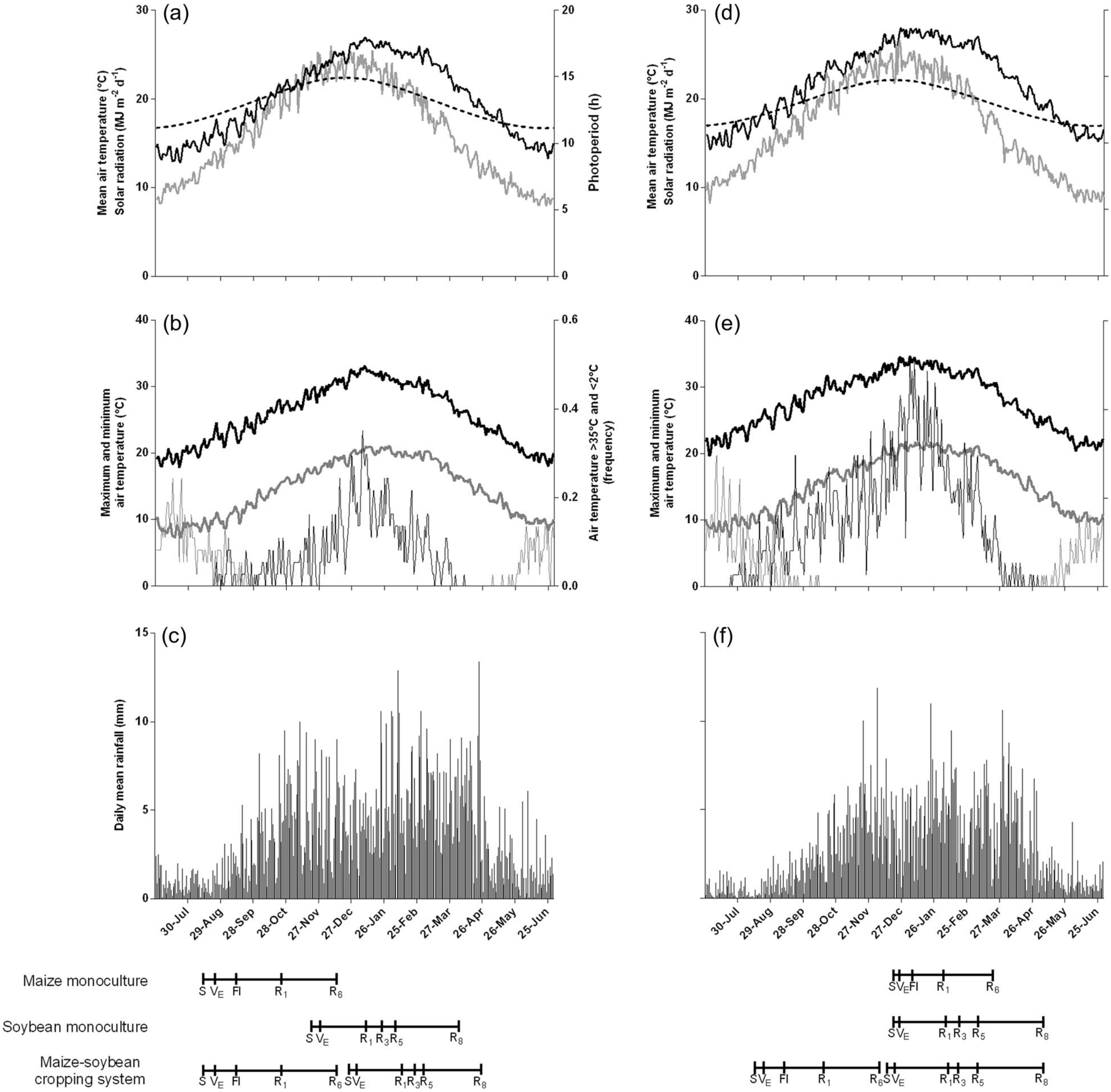


Fig. 1 Evolution of: (**a**, **d**) mean air temperature (black line), daily incident solar radiation (grey line) and photoperiod (dotted line); (**b**, **c**) maximum (black line) and minimum air temperature (grey line) and (**c**, **f**) daily rainfall at Reconquista (a, b, c) and Las Breñas (**d**, **e**, **f**). Values are the mean of daily records of 36 years of each location. Simulated phenology of maize and soybean crops is included at the bottom of figures. Frequencies of air temperatures < 2 °C (thin grey line) and maximum air temperature > 35 °C (thin black line) are also presented (**b**, **e**). For maize, the mean dates of the following stages were simulated with CERES-Maize model: sowing, seedling emergence (E), floral initiation (FI), female flowering (R_1) and physiological maturity (R_6). For soybean, dates of seedling emergence (E), first flower (R_1), first pod (R_3), first seed (R_5) and physiological maturity (R_8) were simulated with CROPGRO-Soybean model

2.3 Crops phenology

The inter-annual variability of maize and soybean phenology was simulated by CERES-Maize model (v.3.5) and CROPGRO-Soybean model (v.3.5), respectively. For maize hybrids, dates of seedling emergence (V_E), floral initiation, female flowering (R_1) and physiological maturity (R_6) were simulated (Ritchie et al. 1993). For soybean cultivars, simulated dates were those of the following stages (Fehr and Caviness 1977): seedling emergence (V_E), beginning bloom, i.e. first flower (R_1), beginning pod, i.e. first pod (R_3), beginning seed, i.e. first seed (R_5) and full maturity (R_8). The occurrence of maize critical period (30 days centred on R_1) for kernel set was estimated from simulated date of R_1 (Otegui and Bonhomme 1998). For soybean, duration of the critical period for pod set was estimated from simulate dates of R_3 and R_5 (Board and Tan 1995).

Table 1 Genetic coefficient values for the NK840 and NK960 maize hybrids

Cultivar trait and units	Acronym	Genetic coefficient	
		NK840	NK960
Thermal time from seedling emergence to the end of juvenile phase (°Cd)	P1	156.8	164.5
Photoperiod sensitivity coefficient (d h^{-1})	P2	0.67	0.39
Thermal time from anthesis to physiological maturity (°Cd)	P5	802.8	789.3
Maximum possible number of kernels per plant (number per plant)	G2	926.8	848.6
Kernel filling rate during the linear grain filling stage under optimum conditions (mg d^{-1})	G3	7.56	8.26
Phyllochron (thermal time between successive leaf tip appearances) (°Cd $leaf^{-1}$)	PHINT	44	40

2.4 Characterisation of climatic variables during crops cycles

Simulated phenology of crops was coupled with daily climate variables to analyse mean air temperature, accumulated incident solar radiation and accumulated rainfalls during crops cycles, and the occurrence of frost damage and temperatures extremely high during the most sensitive stages of crops to these constraints. Probability of frost damage was estimated from simulations of crop phenology and minimum daily air temperatures (*T*min) of each year of the climatic series. The occurrence of *T*min below 2 °C from seedling emergence in soybean, and from floral initiation in maize was considered detrimental for these crops (De Fina and Ravelo 1979). Maximum daily air temperatures (*T*max) of each of the years of climatic series were used to quantify the probability of extremely high temperatures (*T*max > 35 °C) of each day of the critical periods of both species (Berry and Bjorkman 1980; Commuri and Jones 2001).

2.5 Data analysis

Inter-annual variability of the different stages of crops was described by the mean date of each stage and the standard deviation (SD). The inter-annual variability of grain yields of the different crops was presented by the cumulative frequencies of these records. For this purpose, simulated grain yields for each year of the climatic series were ranked in ascending order and the cumulative frequency was calculated for each value. The inter-annual variability of grain yields was

Table 2 Genetic coefficient values for the A6445 and A8000 soybean cultivars

Cultivar trait and units	Acronym	Genetic coefficient	
		A6445	A8000
Critical short day length below which reproductive development progress with no day length effect (h)	CSDL	12.45	12.00
Slope of the relative response of development to photoperiod with time (d h^{-1})	PPSEN	0.305	0.340
Time between plant emergence and first flower (R_1) (photo thermal days)	EM-FL	23.5	19.0
Time between first flower and first pod (R_3) (photo thermal days)	FL-SH	6.0	4.0
Time between firs flower and first seed (R_5) (photo thermal days)	FL-SD	12.0	13.0
Time between first seed and physiological maturity (R_8) (photo thermal days)	SD-PM	41.50	41.00
Time between first flower and end of leaf expansion (photo thermal days)	FL-LF	19.0	19.00
Maximum leaf photosynthesis rate at 30 °C, 350 vpm $C0_2$ and high light (mg CO_2 $m^{-2}S^{-1}$)	LFMAX	0.85	0.800
Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	SLAVR	375	375
Maximum size of full leaf (three leaflets) (cm^2)	SIZLF	180.0	180
Maximum fraction of daily growth that is partitioned to seed and shell	XFRT	1.00	1.00
Maximum weight per seed (g)	WTPSD	0.155	0.165
Seed filling duration for pod cohort at standard growth conditions (photo thermal days)	SFDUR	27.5	24.0
Average seed per pod under standard growing conditions (numbers per pod)	SDPDV	2.05	1.95
Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	PODUR	9.0	11.0

quantified by the coefficient variation (CV) of the mean grain yield. Correlations between yields of maize crops and between soybean crops were explored, and linear regression were fitted.

For the maize-soybean system, the LER was obtained from the sum of the relative yield of each component of the system and the inter-annual variability of LER was presented by the CV of the mean LER and by the cumulative frequencies of this variable. Correlations among LERs and its components were explored. The impact of "El Niño" or "La Niña" episodes on LER was also determined. Each year of the climatic records was classified as El Niño (warm), La Niña (cold) or neutral based on events in the Tropical Pacific. Events were defined as five consecutive overlapping 3-month periods at or above the + 0.5 °C anomaly for warm (El Niño) events and at or below the − 0.5 °C anomaly for cold (La Niña) events (Climate Prediction Centre; http://www.cpc.noaa.gov/). At each location, mean LERs for the El Niño, La Niña and neutral episodes were calculated. Similarly accumulated rainfalls during the cycle and during the critical period of crops of each year of climatic series were grouped based on classification of the different episodes of ENSO.

Frequencies of water stress index during reproductive period of soybean as the second crop were obtained with CROPGRO-Soybean model and relationships between soybean grain yields and water stress indexes during the reproductive periods were explored in order to fit penalty functions of soybean grain yield by water stress.

3 Results

3.1 Phenology of crops and climatic variables

At Reconquista and for mid-August sowing, the simulated duration of the cycle of both maize hybrids was ca. 124 days (Table 3), exploring equivalent air mean temperatures along the cycle (ca. 20.4 °C range 19.3 to 21.3 °C) and during the critical period (ca. 21.0 °C range 19.4 to 22.4 °C) (Fig. 1a). Likewise, incident solar radiation accumulated along the cycles (ca. 2206 MJ m^{-2} for NK840 and 2264.5 MJ m^{-2} for NK960) and during the critical periods (ca. 618.7 MJ m^{-2} for NK840 and 617.4 MJ m^{-2} for NK960) of both hybrids was similar. The effect of inter-annual variability of air temperature on the phenology of both hybrids was reflected in the SD of the simulated dates of the ontogenic stages (Table 3). For both hybrids, mean photoperiod from emergency to floral initiation was 12.5 h. For the soybean cultivar A6445, the delay in sowing date from mid-November (monoculture) to late December (second summer crop) determined a shortening (11.6%) of the cycle (138 vs 122 days) (Table 3). Mean air temperature during the cycle of soybean monoculture was 24.7 °C (range 23.7–26 °C), with an average of 25.5 °C (range 23.3 to 27.2 °C) during the critical period (Fig. 1a). Photoperiod during the cycle of soybean monoculture was ca. 14.1 h (range 13.7 to 14.2 h), with an average of 13.5 h (range 13 to 14.3 h) during the grain filling period (Fig. 1a). For soybean cultivar A6445 as the second crop after maize, mean air temperature during the cycle was 24 °C (range 22.6 to 25.5 °C) with an average of 24.7 °C (range 23 to 28.1 °C) during the critical period (Fig. 1a) and a mean photoperiod of 13.5 h (range 13.3–13.7 h) and 12.8 h (range 12.6 to 13 h) during the cycle and the grain filling period, respectively (Fig. 1a). Soybean as the second crop exhibited higher inter-annual variability of simulated phenological stages than soybean monoculture (Table 3). Additionally, soybean after maize not only had the shortest cycle but also explored decreased daily values of incident solar radiation especially during reproductive periods (Fig. 1a). Hence, the incident solar radiation accumulated during the cycle of soybean monoculture (ca. 2773 MJ m^{-2}) was on average 24.5% higher than that of the soybean as the second crop (ca. 2228.1 MJ m^{-2}). During the critical period the incident solar radiation accumulated was on average 564.8 vs. 476.3 MJ m^{-2} for soybean monoculture and soybean as the second crop, respectively.

Considering climatic constrains for summer crops production at Reconquista, frequency of frost damage after floral initiation of NK840 and NK960 would be 0.056 (Fig. 1b). For soybean monoculture or soybean as the second summer crop, frosts would never occur at any time of the cycle (Fig. 1b). Maize hybrids would be exposed to mean maximum temperature of ca. 26 °C and 26.7 °C during the cycle and the critical period, respectively (Fig. 1b). Mean frequency of extremely high temperatures during the critical period of both maize hybrids would be 0.045 (CV = 6.6%) for the NK840 and 0.045 (CV = 7.6%) for the NK960. For soybean monoculture, the mean maximum temperature during the cycle and the critical period would be ca. 30 °C. For soybean as the second crop, the average maximum temperature in the cycle would be 29.3 and 29.8 °C during the critical period (Fig. 1b). Mean frequency of extremely high temperatures during the critical period would be 0.137 (CV = 8.6%) and 0.083 (CV = 11.5%) for soybean monoculture and soybean as the second crop, respectively.

At Las Breñas, the simulated duration of maize hybrid NK960 sown on December was 18.6% shorter (ca. 92 days) than that of NK840 sown on mid-August (ca. 113 days) (Table 3). For the latter hybrid, mean air temperature explored along the cycle was lower (ca. 22.1 °C range 20.8 to 23.7 °C), than that explored by the former (ca. 26.6 °C range 24.5 to 28.3 °C) (Fig. 1d). Similarly, mean air temperature during the critical period of the NK840 was lower (ca. 22.8 °C range 20.4 to 25.1 °C) than that explored by the NK960 (ca. 26.6 °C range 29.8–24.3 °C). In the same way, the different sowing dates were reflected in values of accumulated incident solar radiation along the cycle (ca. 2053 and 1921.3 MJ m^{-2} for

Table 3 Simulated dates and days after sowing of ontogenic stages of NK960 and NK840 maize hybrids and A6445 and A8000 soybean cultivars sown at Reconquista and Las Breñas. Values in brackets are the standard deviation (in days) of the mean simulated dates

Location	Crop	Cultivar	Phenology	Date	Days after sowing
Reconquista	Maize	NK960	Sowing	August 15	
			Emergency	August 25 (3.0)	10
			Floral initiation	September 17 (4.5)	33
			R_1	October 25 (4.4)	71
			R_6	December 17 (4.4)	124
		NK840	Sowing	August 15	
			Emergency	August 25 (2.9)	10
			Floral initiation	September 16 (4.3)	32
			R_1	October 25 (4.2)	71
			R_6	December 18 (4.2)	125
	Soybean	A6445	Sowing	November 20	
			Emergency	November 26 (0.8)	6
			R_1	January 13 (2.0)	55
			R_3	January 25 (2.2)	67
			R_5	February 6 (2.9)	78
			R_8	April 6 (2.2)	138
		A6445	Sowing	December 26 (4.3)	
			Emergency	January 1 (4.3)	6
			R_1	February 12 (3.9)	48
			R_3	February 22 (3.9)	58
			R_5	March 3 (3.8)	67
			R_8	April 27 (3.8)	122
Las Breñas	Maize	NK960	Sowing	December 20	
			Emergency	December 25 (0.6)	5
			Floral initiation	January 7 (0.8)	18
			R_1	Febraury 4 (2.0)	47
			R_6	March 21 (4.0)	92
		NK840	Sowing	August 15	
			Emergency	August 23 (2.2)	8
			Floral initiation	September 11 (3.7)	27
			R_1	October 17 (4.7)	63
			R_6	December 6 (5.4)	113
	Soybean	A8000	Sowing	December 20	
			Emergency	December 26 (0.5)	6
			R_1	Febraury 9 (1.8)	51
			R_3	Febraury 18 (2.0)	60
			R_5	March 8 (2.0)	78
			R_8	May 6 (2.0)	137
		A8000	Sowing	December 14 (5.4)	
			Emergency	December 21 (5.5)	7
			R_1	Febraury 8 (4.8)	56
			R_3	Febraury 17 (4.3)	65
			R_5	March 7 (3.5)	83
			R_8	May 6 (3.0)	143

NK840 and NK960, respectively) (Fig. 1d). However, during their critical periods, the differences in this climate variable were negligible (ca. 611.9 and 671.2 MJ m^{-2} for NK840 and NK960, respectively). Mean photoperiod for the period emergency-floral initiation was 12.4 and 14.7 h for NK840 and NK960, respectively. As the sowing dates of both soybean crops were similar, the difference in the cycle duration was small (ca. 137 vs. 143 days, for soybean monoculture and soybean as the second crop, respectively) (Table 3). Mean air temperature during the cycle of the soybean monoculture was 24.8 °C (range 23.8 to 26.5 °C), with an average of 25.5 °C (range 23.2 to 28.2 °C) during the critical period (Fig. 1d). In average, photoperiod during the cycle of soybean monoculture was 13.4 h (range 13.3 to 13.5 h), with an average of 12.7 h (range 12.5 to 13.2 h) during grain filling period. For the soybean as the second crop, mean air temperature during the cycle was 25 °C (range 23.7 to 26.6 °C) with an average of 25.5 °C (range 23.2 to 28.2 °C) during the critical period (Fig. 1d). Photoperiod during the cycle of soybean as the second crop was 13.5 h (range 13.3 to 13.6 h) with a photoperiod of 12.7 h (range 12.4 to 12.8 h) during the grain filling period (Fig. 1d). In the same way, the incident solar radiation accumulated during the cycle was similar for both soybean crops. In average, incident solar radiation accumulated during the cycle was ca. 2534.9 and 2647.3 MJ m^{-2} for soybean monoculture and soybean as the second crop, respectively. The incident solar radiation accumulated during the critical period was ca. 705 MJ m^{-2} for the soybean monoculture and ca. 723.7 MJ m^{-2} for soybean as the second crop.

Considering climatic constrains for summer crops production at Las Beñas, the frequency of frost damage after floral initiation of NK840 would be 0.28 and frosts would never occur after floral initiation of NK960 (Fig. 1e). Both for soybean monoculture and soybean as the second crop, the frequency of frost damage during grain filling period (after R_5) would be 0.028. Maize hybrid NK840 sown on mid-August would be exposed to mean maximum temperature of 29 and 29.7 °C during the cycle and the critical period, respectively (Fig. 1e). For NK960 sown on late-December the average maximum temperature would be ca. 32.6 and 32.5 °C during the cycle and the critical period. Mean frequency of extremely high temperatures during the critical period would be 0.274 (CV = 4.2%) and 0.159 (CV = 5.9%) for NK960 and NK840, respectively. For soybean monoculture, the average maximum temperature would be 30.6 °C during the cycle and 31.2 °C during the critical period. For soybean as the second crop, the average maximum temperature would be 30.8 °C during the cycle and 31.2 °C during the critical period (Fig. 1e). Frequencies of extremely high temperatures during the critical period would be 0.167 (CV = 4.2%) for soybean monoculture and 0.168 (CV = 8.6%) for soybean as the second crop.

3.2 Water availability for rain fed summer crops

At Reconquista, accumulated rainfalls during the fallow period of maize (from March 31 to August 15) and soybean monocultures (from March 31 to November 20) totalized ca. 231 and 632 mm (frequency = 0.50), respectively (Fig. 2a). Hence, the simulated average ASW at sowing of soybean (236 mm, i.e. 100% of maximum ASW) would be greater than that of maize (161.4 mm, i.e. 68.6% of maximum ASW) (Fig. 2b). By contrast, mean accumulated rainfalls (frequency = 0.50) from physiological maturity of the NK840 to the sowing of soybean as the second crop was close to 22 mm (Fig. 2a) and simulated ASW at sowing would be ca. 79 mm, i.e. 33.6% of maximum ASW (Fig. 2b). The inter-annual variability of ASW at sowing of the soybean as a second crop (CV = 74.8%) was higher than those of the monocultures (CV = 24.7 and 15.5% for maize and soybean monoculture, respectively). Therefore, simulations of soybean grain yield after maize were performed for three possible scenarios of initial soil water content: (i) 20% of maximum ASW (i.e. 47 mm), corresponding to the lower third of the frequencies, (ii) 40% of maximum ASW (i.e. 94 mm) corresponding to the average frequency and (iii) 50% of maximum ASW (i.e. 117.5 mm) corresponding to the top third of the frequencies.

At Las Breñas, accumulated rainfalls during the fallow periods of both monocultures (from March 31 to December 20) totalized ca. 549 mm (frequency = 0.50) (Fig. 2c). For the double cropping system, mean accumulated rainfalls during the fallow periods totalized ca. 205 mm for maize (from March 31 to August 15) and 23 mm for soybean (from physiological maturity of the NK840 to the sowing of soybean) (Fig. 2c). Hence, soil water content at sowing of these cropping systems would be ca. 186 mm for both monocultures (76.2% of maximum ASW), and 113 mm (46.3% of maximum ASW) and 123 mm (50.4% of maximum ASW) for maize and soybean of the double-cropping system, respectively (Fig. 2d). Simulations of soybean grain yield as the second crop were performed for three scenarios of initial soil water content: (i) 54% of maximum ASW (i.e. 154 mm), corresponding to the lower third of the frequencies, (ii) 58% of maximum ASW (i.e. 165 mm) corresponding to the average frequency and (iii) 60% of maximum ASW (i.e. 171 mm) corresponding to the top third of the frequencies.

Maize crops sown on mid-August at Reconquista (maize in monoculture and maize of the double-cropping system) during neutral years would be exposed to higher accumulated rainfalls in the cycle than at Las Breñas (maize of the double-cropping system) (Table 4). Accumulated rainfalls during the cycle of maize or soybean monocultures during neutral years would be slightly higher at Reconquista than at Las Breñas due to the higher concentration of rainfalls during the summer season at Las Breñas (Table 4 and Fig. 1c, f). By contrast, accumulated rainfalls during the cycle of soybean as the second crop would be similar at both locations during neutral years. Considering the different episodes of the ENSO phenomenon, crops sown on mid-August at both locations would be exposed to lower accumulated rainfalls during La Niña than during El Niño or Neutral years (Table 4). The opposite trend was estimated for crops sown on December at Las Breñas. At Reconquista, the positive impact of El Niño episodes on accumulated rainfalls during the cycle of soybean monoculture would be similar for soybean as the second crop.

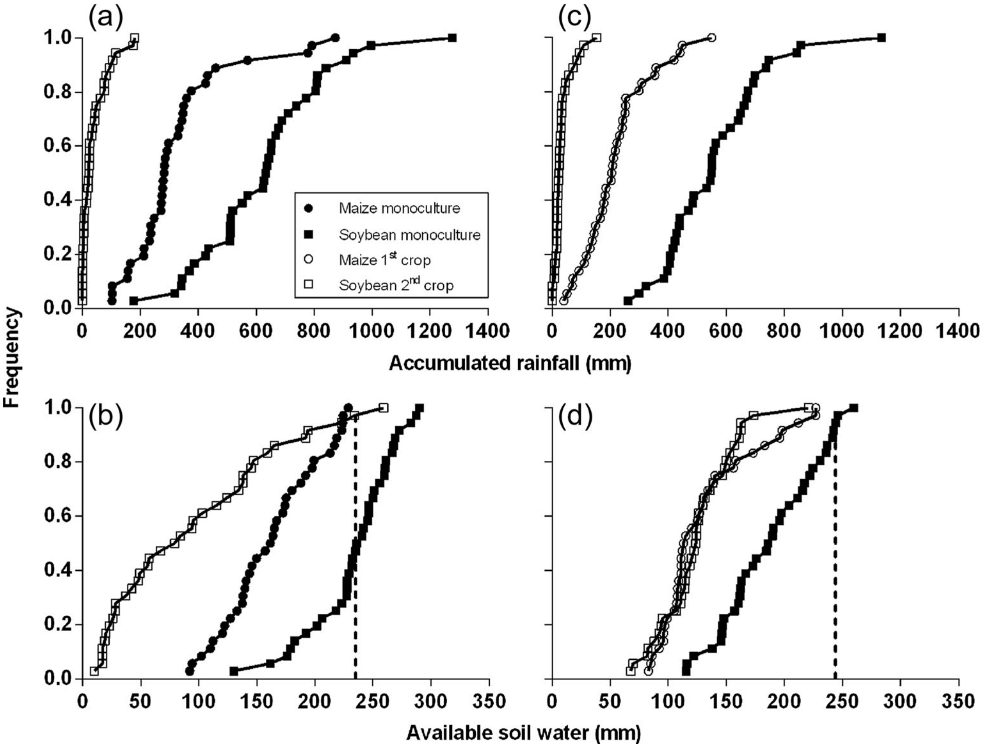


Fig. 2 Cumulative frequencies of total rainfalls during fallow period (**a**, **c**) and available soil water content at sowing of maize and soybean in monocultures and as the first or second crop of the maize-soybean system (**b**, **d**) at Reconquista (**a**, **b**) and Las Breñas (**c**, **d**). The analyses were performed with CERES-Maize model and daily rainfall records of 36 years of each location. The vertical dotted line indicates available soil water content at field capacity. In **a**, **b**, symbols of maize monoculture and those of maize as the first crop of maize-soybean system are overlapped. In **c**, **d**, symbols of maize and soybean monocultures are overlapped

These trends resulted similar for accumulated rainfalls during the critical period of all crops (Table 4).

3.3 Grain yields of productive strategies

At Reconquista, simulated grain yields of maize sown on mid-August were not greatly affected by the genotype (Fig. 3a). The average simulated yield of NK840 was 4.2% lower (ca. 5448; 2467–13,222 kg ha^{-1}) than that of NK960 (ca. 5687; 2800–14,068 kg ha^{-1}). Inter-annual variability of grain yield was similar for both hybrids (CV = 49.3 and 49.8% for NK840 and NK960, respectively). For soybean simulations (Fig. 3b), mean grain yield of soybean as the second crop (ca. 2634; 344–4064 kg ha^{-1}) was ca. 26.6% lower than that of soybean monoculture (ca. 3588; 2198–5226 kg ha^{-1}), but inter-annual variability of grain yield of the former (CV = 38%) was higher that of the latter (CV = 26%). Water availability at sowing of soybean as the second crop affected simulated grain yields (Fig. 3c). Higher ASW determined higher grain yields (ca. 2174, 2569 and 2953 kg ha^{-1}, for 20, 40 and 50% of maximum ASW, respectively) and markedly reduced the inter-annual variability of these yields (CV = 47, 38 and 28% for 20, 40 and 50% of maximum ASW, respectively).

At Las Breñas, grain yields of the late sown maize hybrid (NK960) of the monoculture (ca. 5637; 2207–12,368 kg ha^{-1}; CV = 57.6%) greatly exceeded grain yields of the early sown maize hybrid (NK840) (ca. 2322; 1302–3951 kg ha^{-1}; CV = 33.9%) of the double-cropping system but exhibited a higher inter-annual variability (Fig. 3d). For soybean simulations (Fig. 3e), mean grain yield of soybean as the second crop (ca. 2457; 196–3773 kg ha^{-1} CV = 32.9%) was ca. 14.8% lower than that of soybean monoculture (ca. 2883; 1731–4065 kg ha^{-1}; CV = 20.7%). Soil water content at sowing of soybean as the second crop did not affect simulated grain yields (Fig. 3f).

At both locations, grain yield of soybean as the second crop was negatively related to water stress index during reproductive periods (Fig. 4a, c). At Reconquista, this index decreased as soil water content at sowing was close to 50% of maximum ASW (Fig. 4b). At Las Breñas, water stress index during reproductive periods was not affected by soil water content at sowing greater than 54% of maximum ASW (Fig. 4d).

At Reconquista, the historical records of climate variables during the cycles of both maize hybrids were similarly reflected in simulated grain yields, most points were close to the 1:1 relationship and the linear function fitted to data set of both hybrids had a determination coefficient of 0.98 and a slope slightly lower than 1 (Fig. 5a). A positive relationship was also observed for the comparison of simulated soybean grain yields at both cropping systems (soybean as the second crop vs soybean monoculture) but with a larger negative ordinate value because most points were placed below the 1:1 relationship (Fig. 5b). Hence, relative grain yields of maize were close to 1 for most simulated years (Fig. 5a), and those of soybean were mostly lower than 1 (Fig. 5b). At Las Breñas, no trend was observed for the comparison of maize grain yields at both cropping systems (maize of the double-cropping system

Table 4 Accumulated rainfalls (mm) during the cycle and the critical period of maize and soybean in monocultures and in the maize-soybean cropping system (maize first crop and soybean second crop) at two locations (Reconquista and Las Breñas) during La Niña (11 years), El Niño (12 years) and neutral (13 years) episodes of the ENSO phenomenon. For each episode, accumulated rainfalls are detailed for the upper percentile 90 (P90), the mean value and the percentile 10 (P10)

		Reconquista			Las Breñas		
		La Niña	Neutral	El Niño	La Niña	Neutral	El Niño
Accumulated rainfalls during the cycle (mm)							
Maize monoculture	P(90)	565	600	612	608	504	480
	Mean	314	436	477	446	354	384
	P(10)	172	238	283	297	257	215
Soybean monoculture	P(90)	809	784	1037	869	705	707
	Mean	657	560	809	651	531	532
	P(10)	506	370	577	419	350	340
Maize first crop	P(90)	386	600	612	300	455	451
	Mean	291	436	485	221	309	300
	P(10)	172	238	283	112	219	163
Soybean second crop	P(90)	746	758	1145	871	717	710
	Mean	625	547	747	676	560	553
	P(10)	534	256	426	491	350	340
Accumulated rainfalls during the critical period (mm)							
Maize monoculture	P(90)	94	246	170	369	269	224
	Mean	88	169	153	200	140	166
	P(10)	35	93	109	78	35	70
Soybean monoculture	P(90)	265	260	277	295	192	237
	Mean	139	149	170	167	122	147
	P(10)	44	77	59	49	57	49
Maize first crop	P(90)	94	234	170	94	155	146
	Mean	88	160	152	61	92	95
	P(10)	35	93	94	22	39	59
Soybean second crop	P(90)	182	236	311	308	192	255
	Mean	132	123	189	167	126	168
	P(10)	61	14	86	49	57	80

sown on mid-August vs maize monoculture sown on late-December), yielding lower relative yields as grain yield of maize monoculture increased (Fig. 5c). The similar environmental conditions during soybean cycles were reflected in the fitted relationship among grain yields of this crop at both cropping systems (Fig. 5d).

At both locations, simulated LERs were always greater than 1 (Fig. 6a, c), with maximum values of 2.11–2.3 and a minimum values of 1.09–0.99 at Reconquista and Las Breñas, respectively. At Reconquista, ca. LER was 1.68 (CV = 11%) with a frequency of 0.86 to be equal or greater than 1.5. At Las Breñas, ca. LER was 1.4 (CV = 26%) and only exceed LERs > 1.5 with a frequency of 0.31.

At Reconquista, LERs variability promoted by environmental conditions was closely associated with the relative grain yields of soybean (R^2 = 0.87, $P < 0.05$), but not with those of maize (R^2 = 0.01). Soil water condition at sowing of the soybean as the second crop affected LER values (Fig. 6b). For the three analysed scenarios of initial ASW, LER values were 1.55 (1.09 to 2.09), 1.66 (1.28 to 2.15) and 1.79 (1.49 to 2.17) for 20, 40 and 50% of maximum ASW, respectively. The different episodes of ENSO phenomenon did not affect LER values (Fig. 6a). By contrast, at Las Breñas, inter-annual variability of LER was promoted by the relative grain yields of maize (R^2 = 0.74) and LER values did not vary for the three scenarios of ASW at sowing of soybean as the second crop (Fig. 6d). LERs were higher during La Niña episodes (ca. 1.48, CV = 26.6%) than during El Niño episodes (ca. 1.32, CV = 23.7%) (Fig. 6c) mainly by the negative effect of La Niña on grain yields of maize monoculture (ca. 4227, 6182 and 6294 kg ha^{-1} for La Niña, neutral and El Niño episodes).

4 Discussion

The intensification of land use emerges as one of the alternatives to address the growing global demand for food. For example, intensive production systems that include two or more crops growing at the same time on the same area (i.e. polycultures; Vandermeer 1989) are adopted in environments limited by the short frost-free period (Coll et al. 2012). In areas with a long frost-free period, the strategy of land

Fig. 3 Cumulative frequencies of simulated grain yields of maize monoculture and maize as the first crop of maize-soybean system (**a**, **d**), soybean in monoculture and soybean as the second crop of the maize-soybean system (**b**, **e**) and soybean as the second crop of the maize-soybean system at three soil water contents at sowing (**c**, **f**) at Reconquista (**a**, **b**, **c**) and Las Breñas (**d**, **e**, **f**). Simulations were performed with a CERES-Maize model and CROPGRO-Soybean model and daily climatic records of 36 years of each location

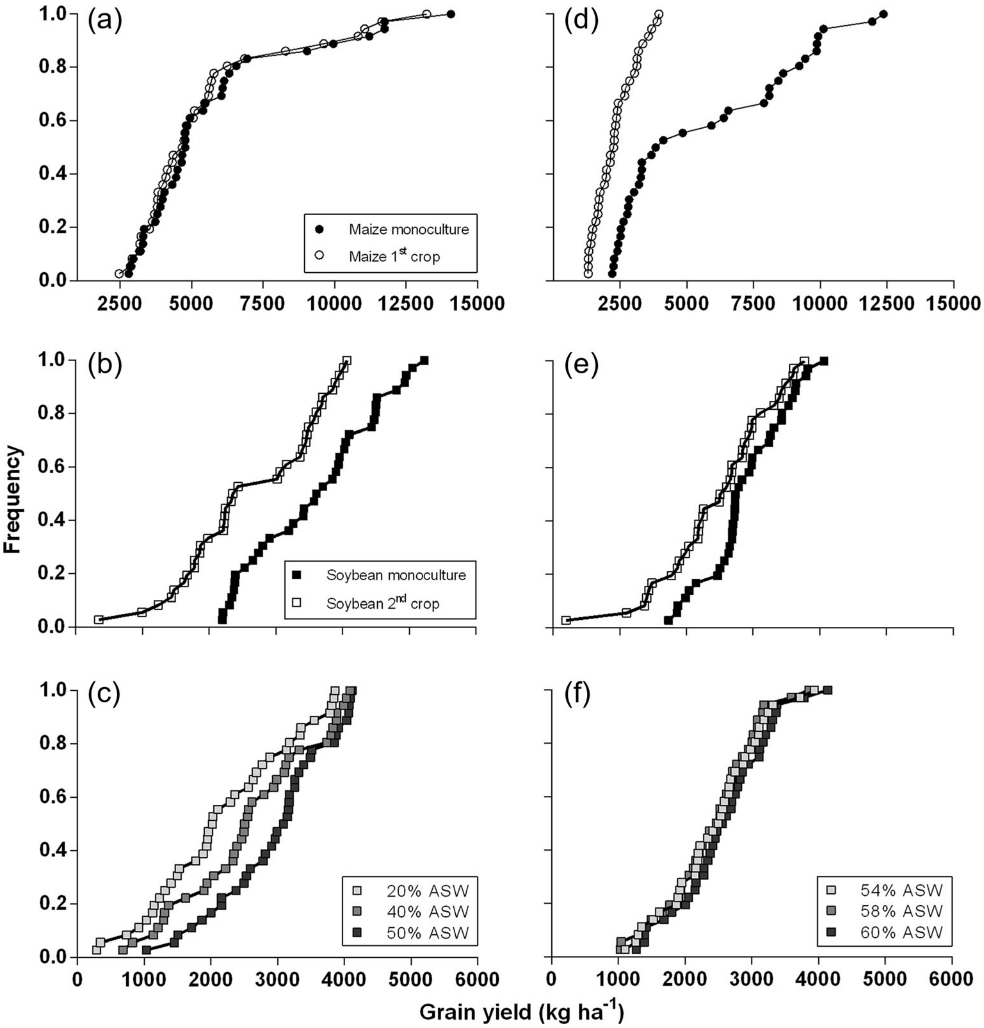
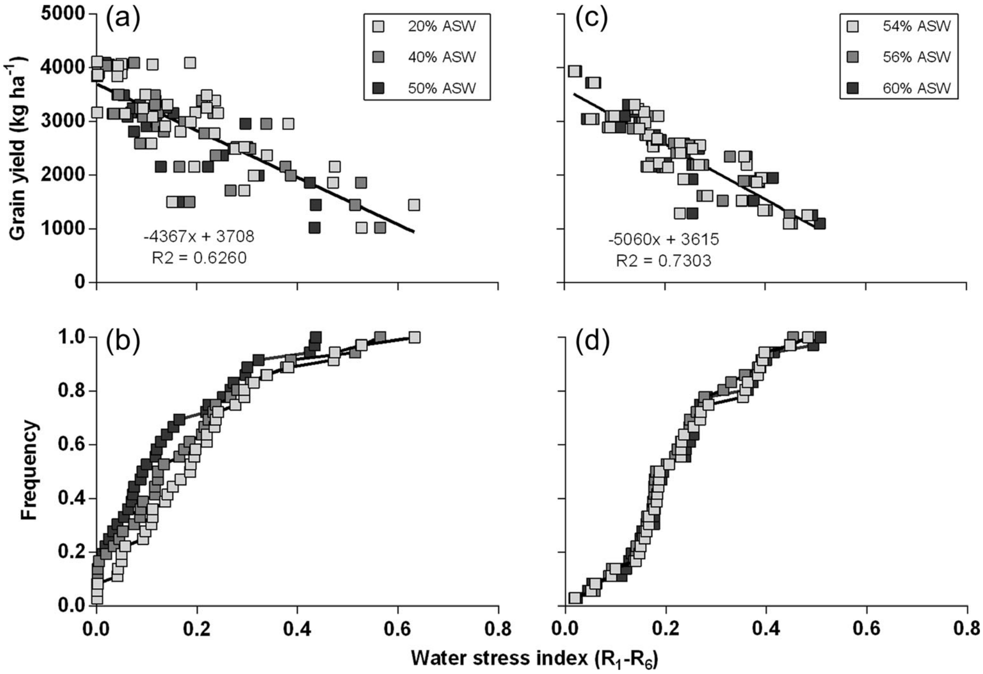


Fig. 4 (**a**, **c**) Grain yield response of soybean as the second crop of maize-soybean system to mean water stress index during reproductive periods (R_1–R_6) and (**b**, **d**) cumulative frequencies of mean water stress index during reproductive periods of soybean as the second crop of maize-soybean system for three soil water contents (ASW) at sowing at Reconquista (**a**, **b**) and Las Breñas (**c**, **d**). The analyses were performed with CROPGRO-Soybean model and daily climatic records of the 36 years of each location



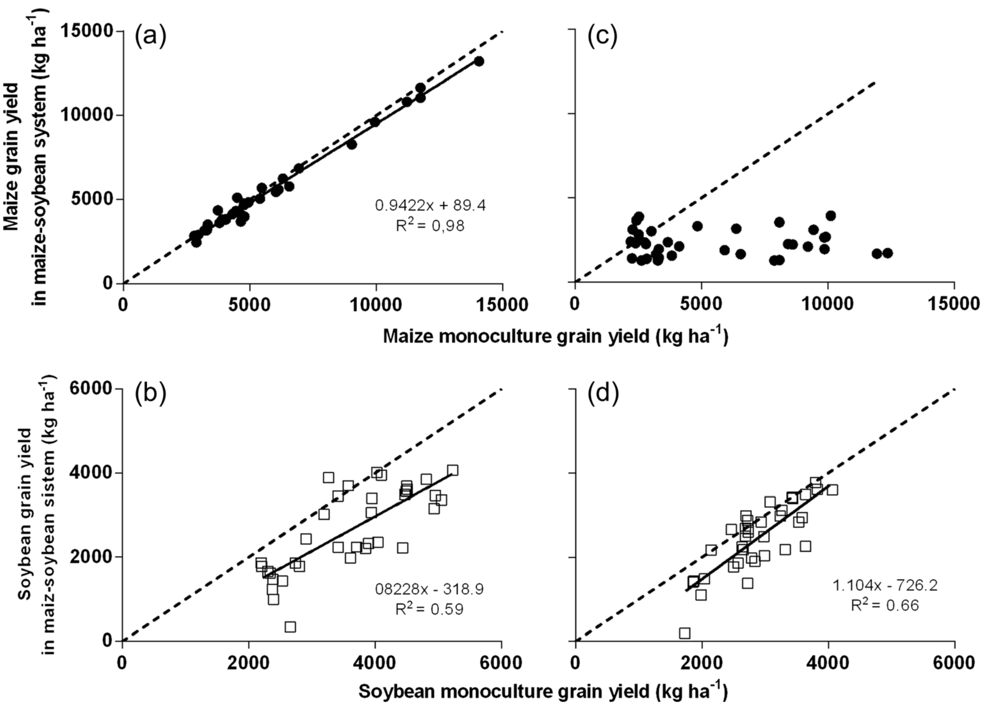


Fig. 5 Simulated grain yields of maize in the maize-soybean system vs maize in monoculture (**a**, **b**) and simulated grain yields of soybean in the maize-soybean system vs soybean in monoculture (**c**, **d**) at Reconquista (**a**, **b**) and Las Breñas (**c**, **d**). Simulations were performed with CERES-Maize model and CROPGRO-Soybean model and daily climatic records of 36 years of each location. Linear regressions fitted to data sets are included. Dotted lines represent the 1:1 relationship between variables

intensification is based on the succession of two crops (e.g. wheat-soybean system, maize-soybean system) whose implementation is simpler than that of polycultures. However, few studies have analysed the productivity of the double-cropping system from a probabilistic approach. In this study, we have simulated the productivity of the maize-soybean system and of the monocultures of its integrant species, at two locations of the humid subtropical region of Argentina. We have chosen these locations due to (i) the availability of long series of daily climatic records, and (ii) differences between locations of some climatic records (frost-free period, maximum temperatures and rainfalls distribution). At each location, the maize-soybean system and monocultures were simulated according to the commonest husbandry of crops (i.e. sowing dates, genotypes, plant densities). In order to give a probabilistic approach to these analyses, rain-fed yields were simulated with CERES-Maize and CROPGRO-Soybean models and the 1971–2006 climatic series of each location. The productivity

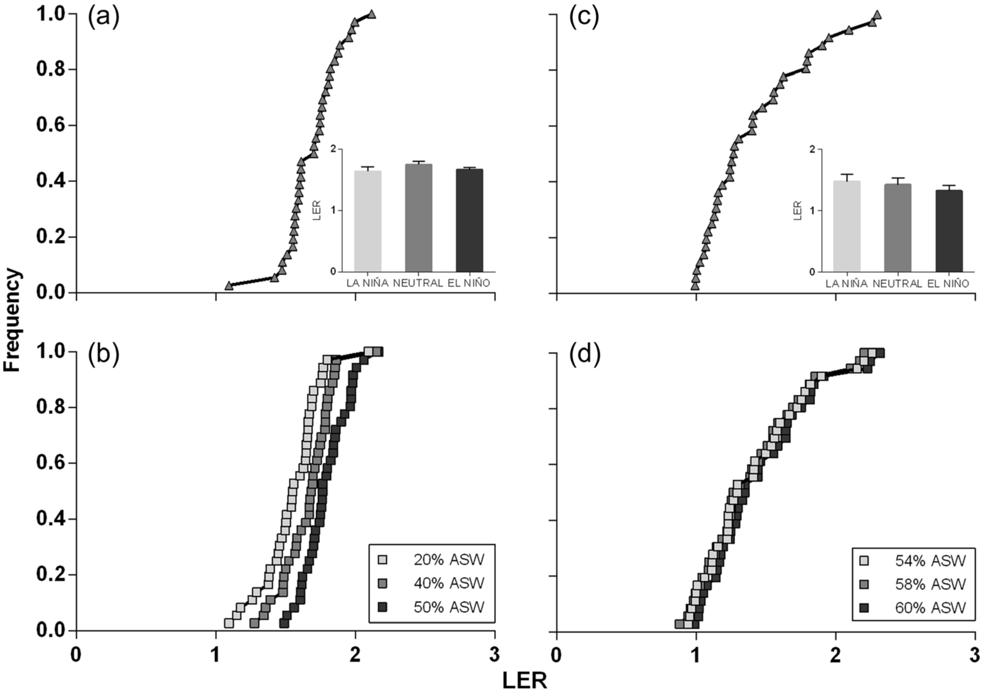


Fig. 6 Cumulative frequencies of simulated land equivalent ratio (LER) for the maize-soybean system (**a**, **c**) and of the same system with different initial soil water content (ASW) at sowing of soybean as the second crop (**b**, **d**) at Reconquista (**a**, **b**) and Las Breñas (**c**, **d**). Simulations were performed with CERES-Maize model and CROPGRO-Soybean model and daily climatic records of 36 years of each location. Inset presents mean LER during La Niña, El Niño and neutral episodes of ENSO phenomenon. Vertical bars represent standard error of the means

of the maize-soybean system was evaluated by the LER index (Silvertown 1982), which emerges from the sum of the simulated relative grain yields of its components (grain yields in the double-cropping system/grain yields in monoculture).

Climatic constraints for the different cropping systems were explored at each location. At Reconquista, simulated sowing date of maize (August 15) of both cropping systems was placed close to the date of the last frost (August 17 ± 44.5 days) to maximise the growing season explored by maize monoculture and the double-cropping system within the frost-free period. For this sowing date, simulated frequency of damage by late frost in maize would be very low (< 0.06). For soybean monoculture (sowing date November 20) or soybean as the second summer crop (sowing date on late-December), frosts would never occur at any time of their cycles. Similarly, the frequencies of extremely high temperatures around the critical period of maize (ca. frequency = 0.045 for maize in monoculture and of the double-cropping system) or soybean (ca. frequency = 0.137 and 0.083 for soybean monoculture and soybean as the second crop, respectively) would be very low, and these frequencies would increase (Fig. 1b) if sowing date of monocultures would be delayed (Maddonni 2012). Additionally, the simulated fallow period for both monocultures and for the maize of the double-cropping system would allow (frequency > 0.50) water reloading of soil profiles before sowings (Fig. 2b). Hence, the early sowing date of maize (mid-August) and the November sowing of soybean seem to have few climatic constrains for these crops at this location of the humid subtropical region of Argentina. At Las Breñas, the estimated frost-free period (258 days) is slightly shorter than at Reconquista (299 days), but the low rainfall at the end of the winter season (less than 20 mm during July and August; Fig. 1f) and the high maximum air temperatures during the summer (Fig. 1e) promote the delayed sowing dates (mid or late December) of summer crops. Hence, soil water content at sowing of maize and soybean in monocultures would be ca. 76.2% of maximum ASW (Fig. 2d) and frequencies of extremely high temperatures would be moderate (ca. 0.274) and low (0.167) during the critical periods of maize and soybean monocultures, respectively (Fig. 1e). For the double-cropping system, however, we simulated an early sowing date of maize (mid-August), despite of the low ASW at sowing (ca. 46.3% of maximum ASW; Fig. 2d), in order to place both crops within the shorter frost-free period (frequency of frost damage during the grain filling period of soybean would be very low) and to reduce the frequency of extremely high temperatures specially during the critical period of maize (ca. frequency = 0.159) (Fig. 1e), which penalty grain yields (Rattalino Edreira et al. 2011). Hence, at this location, the early-sown maize crop of the double-cropping system would be more limited by initial ASW and the risk of late-frost than the late-sown maize monocultures, but would be exposed to low frequency of extremely high temperatures during the critical period.

The analysis at Reconquista revealed slight differences between simulated grain yields of maize in monoculture and in the double-cropping system but larger differences of soybean grain yields in the same productive systems (Fig. 3a, b). Despite of hybrids were classified as short- (NK840) or long- (NK960) cycle, when sown at mid-August were exposed during the inductive phase to a mean photoperiod close to the critical value (ca. 12.5 h) at which differences among hybrids in cycle duration are reduced (Kiniry et al. 1983). Hence, both hybrids maize would be exposed to similar incident solar radiation accumulated throughout the cycle, which would determine similar biomass production and, therefore, similar grain yields (Muchow et al. 1990; Andrade 1995; Capristo et al. 2007). Simulated grain yields of soybean in the double-cropping system were sharply lower than those in monoculture (Fig. 3b). The delayed sowing date of soybean as the second crop would expose the critical period to low incident solar radiation values (Andrade 1995; Calviño et al. 2003a) and declining photoperiods (Fig. 1a) reducing the duration of the critical period and grain yield (Major et al. 1975). Our analysis revealed that unlike what happens for early-sown monocultures of summer crops after a long fallow period, it would be likely that soil water contents at sowing of soybean would limit the growth of this second crop (Fig. 2b). Simulations with different soil water contents at sowing of soybean (20, 40 and 50% of maximum ASW) after maize suggest that at this location initial ASW would affect soybean grain yield and also would have an impact on inter-annual variability of grain yields (Fig. 3c). These results are similar to those obtained by other authors for the wheat-soybean system in colder regions of South America (Calviño et al. 2003b; Ernst and Bianculli 2013). Similarly, field experiments in the humid temperate region of Argentina (Monzón et al. 2014) and simulations for the cold temperate region of Argentina (Caviglia et al. 2013) described the high variability of soybean grain yields in the double-cropping system. Our results also suggest for Reconquista the great dependency of soybean in the double-cropping system on rainfalls during the cycle, as was depicted by the negative relationship between simulated grain yields and water stress index during reproductive stages of this crop (Fig. 4a). Therefore, water content of soils at maize harvest would be critical to the behaviour of late soybean, because it is unlikely (frequency < 0.05; Fig. 2b) the occurrence of rains able to recharge the soil profile during the short fallow period (8 days) before soybean sowing. Hence, our simulations suggest that at Reconquista, (i) inter-annual variability of grain yield of soybean as the second crop would explain variations of LER and (ii) ASW at sowing of soybean after maize would condition LER values (Fig. 6b). The different episodes of ENSO phenomenon, however, would not affect LER values (Fig. 6a).

Differences in simulated grain yields of soybean in monoculture and in the double-cropping system at Las Breñas were lower than those at Reconquista (Fig. 3b, e), because at the former location, simulations of sowing dates did not greatly differ between cropping systems (Table 3). By contrast, grain yields of the late-sown maize hybrid in monoculture at Las Breñas greatly exceeded than those of the early-sown hybrid of the double-cropping system (Fig. 3d), despite of the shorter cycle of the former (Table 3). The restrictive initial ASW at the early-sown maize would condition its performance (Fig. 2d). Hence, at Las Breñas, inter-annual variability of LER was promoted by relative grain yields of maize and LER values did not vary for the three scenarios of ASW at sowing of soybean as the second crop (Fig. 6d). At this location, La Niña episodes of ENSO phenomenon increased LER values due to its negative impact on grain yield of maize monoculture (ca. 4227 vs 6182 kg ha^{-1} for La Niña and neutral years, respectively). Similar negative impact of La Niña on maize monocultures was documented for actual maize grain yields at different regions of Argentina (Aramburu et al. 2015). Consequently at this location of the humid subtropical region of Argentina, framers would consider early forecast (July–August) of episodes of ENSO for the implementation of the double-cropping system vs maize or soybean monocultures in order to mitigate negative effects of La Niña episodes.

Despite these differences between locations, simulated LER values of the maize-soybean system were higher than 1 (ca. 1.4, CV = 26% and 1.68, CV = 11% at Las Breñas and Reconquista, respectively).

Similar results were found for the maize-soybean system, as well as for other double-cropping systems (e.g. wheat-soybean, sunflower-soybean), in the humid temperate region of Argentina (Caviglia et al. 2004; Coll et al. 2012; Andrade et al. 2012; Monzón et al. 2014). The simulated LER values suggest the feasibility of intensifying land use from the maize-soybean system at these locations of the humid subtropical region of Argentina by a higher capture of resources over monocultures (Caviglia et al. 2004; Coll et al. 2012; Caviglia and Andrade 2010; Caviglia et al. 2013). Hence, at these locations monocultures of soybean or maize would require about 40–70% more surface area to match the production of the maize-soybean system. It is important to emphasise the need to conduct an economic analysis of these results to determine the feasibility of carrying out the alternative of the maize-soybean system to commercial production. In the humid temperate region of Argentina, production costs of maize in the double-cropping system are similar to those of the maize monoculture (Monzón et al. 2014). On the other hand, the cost of soybean in the double-cropping system accounts for 70% of that in monoculture, which makes gross margins of soybean in the double-cropping system similar to that in monoculture. However, the analysis of historical data of commodities-prices and on-farm costs showed that gross margin of maize-soybean system was higher than that of soybean in monoculture when the price ratio between soybean and maize was lower than 2.2 (Monzón et al. 2014). Therefore, the commercial feasibility of the maize-soybean system is highly dependent on the price of soybean. However, the productive systems with maize in the rotations are more efficient in the use of resources (Caviglia et al. 2013) by the efficient photosynthetic carbon metabolism (C_4) of this species and the low energy content of maize kernels (high starch content) compared with those of soybean (C_3 species with high protein content of grains) (Andrade 1995). Furthermore, the inclusion of C_4 species like maize, increases biomass production per unit of resource used favouring the carbon balance of rotations (Miranda et al. 2012). Therefore, maize-soybean system would be an alternative that promotes the sustainability of production systems in humid subtropical regions, without neglecting the possibility to obtain a high return given by the inclusion of soybean in the rotation.

5 Conclusions

This paper proposes a probabilistic analysis of the maize-soybean system at two locations of the humid subtropical region of Argentina based on crop simulation models (CERES-Maize and CROPGRO-Soybean) and long series of daily climatic records. Models simulated a potential increased of land use intensity (40–70%), in terms of the sum of relative grain yields of each component (LER) by the implementation of the maize-soybean system at both locations. At Reconquista, the simulated inter-annual variability of LERs was mainly related to grain yields of soybean as the second crop, which were affected by initial soil water content at sowing. Hence, soil water content after maize harvest would have a marked effect on grain yield of the succession crop. By contrast, at Las Breñas, the simulated inter-annual variability of LERs was determined by the impact of climate on grain yield of the maize monoculture, and initial soil water content at sowing of soybean after maize did not markedly affect LER values. The simulated impact of ENSO on the performance of the maize-soybean system was only recorded at Las Breñas, where La Niña episodes increased LERs due to its negative impact on grain yield of maize monoculture. It is important to highlight the need to evaluate this productive alternative with actual grain yields and to analyse this system with an economic approach in order to determine the feasibility of this practice.

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