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Capture and use of water and radiation in summer intercrops in the south-east Pampas of Argentina

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ABSTRACT

Intercrops are an alternative to intensify and diversify the agricultural systems in the south-east Pampas of Argentina. The aim of this study was to evaluate resource capture and resource use efficiency in maize–soybean and sunflower–soybean intercrops and in their respective sole crops. Water and radiation capture, biomass and grain production were measured for sole crops and intercrops. Water and radiation productivities were estimated as the energy produced per unit of annual available resource. Comparisons of intercrops with soybean sole crops were emphasized because current soybean expansion in the region represents a threat to agricultural system sustainability.

Intercrops showed an increase in crop duration when compared to their sole counterparts. Maize–soybean intercrop resulted in an improved radiation and water productivities compared with soybean sole crops. Maize cultivated as sole crop attained the highest resource productivity. On the other hand, resource productivity of sunflower–soybean intercrop was higher than or similar to its corresponding sole crops.

The improvement in water productivity for intercrop compared with soybean sole crop was accounted for by an increase in water capture efficiency and, also, by an increase in water use efficiency in the case of maize–soybean intercrop.

The increase in radiation productivity for maize–soybean intercrop compared with soybean sole crop was the result of an increase in radiation use efficiency and of a minor but significant increase in radiation capture efficiency. Contrarily, the improvement in radiation productivity of sunflower–soybean intercrop compared with sunflower or soybean sole crops was null or small.

Grain yield of intercropped sunflower and maize was 20% lower than yield of sole crops. Therefore, yield attained by intercropping was mainly limited by a poor production of the soybean component. This work provides eco-physiological basis to improve management practices of summer intercrops.

1. Introduction

The increasing world population, income per capita and biofuel requirements will drive food and fiber demand during the next years (Andrade, 2011; FAO, 2009). Since possibilities to add new arable land to cropping are limited, future food needs will be fulfilled by increasing production per unit of cultivated land (Andrade, 2011; Sadras and Roget, 2004). Increased efficiency in the capture and use of available resources remains a key challenge to achieve this goal (Calviño et al., 2003; Caviglia et al., 2004; Caviglia and Andrade, 2010). More intense use of suitable land could also help to alleviate the pressure to produce grain in less productive and environmentally fragile agroecosystems (Borlaug and Dowswell, 1997; Brentrup et al., 2004a,b; Cassman, 1999; Gregory et al., 2002).

The south-east Pampas region is situated at the south-east of the Buenos Aires province, Argentina. The current cultivated area in this region is almost two million hectares, from which one million are assigned to summer crops. Soybean is the dominant summer crop, with 67% of the sown area, followed by sunflower (27%) and maize (6%) (www.minagri.gov.ar).

A single crop per year uses only a small proportion of potentially available resources. Calculations based on local measurements (Abbate et al., 1995; Andrade, 1995; Andrade et al., 2002; Della Magiora et al., 2000) indicate that sole crops of wheat, maize and soybean can capture only 20–36% of annual incident photosynthetically active radiation (PAR). These studies also indicate that the potential evapotranspiration during the crop season of single crops ranges from 400 to 600 mm, which accounts for 44–71% of annual rainfall. Farming systems with an increased ability to capture resources and to use them more efficiently are necessary (Caviglia and Andrade, 2010).

Resource capture could be increased by the use of higher maturity group genotypes. However, this strategy is limited by

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the displacement of reproductive stages to times of low incident radiation and low temperature (Capristo et al., 2007). The increase in resources capture by sequential summer double crop (e.g. sunflower–soybean, maize–soybean, maize–sunflower) is also not feasible in the south-east Pampas due to the limited frost-free period that characterizes this region. Intercrops, i.e. two or more simultaneous crops in the same area (Andrews and Kassam, 1976), often increase resource productivity (capture and use efficiency) compared to their sole counterparts (Caviglia et al., 2004; Keating and Carberry, 1993; Midmore, 1993). Wheat–soybean intercropping increased water and radiation productivity in the south-east Pampas of Argentina (Caviglia et al., 2004).

Sunflower–soybean and maize–soybean intercrops are other options to increase the capture of available resources (Echarte et al., 2011). Extended crop duration would be consequence of maize and sunflower relatively early sowing and soybean relatively late physiological maturity. Other contribution to productivity is likely to come from the increased resource use efficiency (Rao, 1986; Willey, 1979). These increases would be generated as a consequence of spatial and temporal complementarities between component crops (Francis, 1989; Willey, 1990).

Annual crops have a typical period of maximum environmental stress susceptibility matching with key processes of grain number determination (Andrade, 1995; Andrade and Ferreiro, 1996; Cantagallo et al., 2004; Egli and Bruening, 2005; Otegui and Andrade, 1998). When crops are sown at near optimal dates, the time of the year in which these critical periods take place in the south-east Pampas differ between soybean and maize, and between soybean and sunflower constituting the main ecophysiological base supporting the proposed intercropping systems.

Soybean crop has been expanding markedly in Argentina (Navarrete et al., 2009; Satorre, 2005) representing a threat to agricultural system sustainability (Wright and Hons, 2004). In this context, sunflower–soybean and maize–soybean intercrops constitute other alternatives to soybean monocrop and means for sustainable intensification 0in the south-east Pampas.

The local performance of maize–soybean and sunflower–soybean intercropping has been previously assessed by Echarte et al. (2011). They studied the effect of plant density of intercropped maize and sunflower on the land equivalent ratio index. Nevertheless, no attempt has been made to estimate the capture and use efficiency of resources of these intercropping systems.

The aim of this study was to assess productivity, resource capture and resource use efficiency of maize–soybean and sunflower–soybean intercrops, compared to sole crops in the south-east Pampas of Argentina.

2. Materials and methods

2.1. Site

Field experiments were carried out during cropping seasons 2005–2006 (Year 1) and 2006–2007 (Year 2) at the INTA Research Station, Balcarce (37.58S, 58.28W, 130 m above sea level). Experiments were established on a silty loam soil (Class I, Typic Argiudoll, USDA taxonomy) with an effective depth of 1.60 m determined by a petrocalcic horizon (caliche layer) that restrict root development. Daily mean air temperature, rainfall and incident global radiation were obtained from a weather station situated 400 m from the experimental site.

2.2. Experiment design and crop management

Experiments consisted of a randomized complete block design with three replicates. The treatments were: (i) maize, (ii) sunflower and (iii) soybean as sole crops and, (iv) maize–soybean and (v) sunflower–soybean as intercrops. Row spacing for all sole crops was 0.52 m. Intercrops arrangement consisted of two rows of soybean per row of maize or sunflower, with a row spacing of 0.52 m (Fig. 1). Rows followed a north-south orientation. For intercrops and sole crops, maize hybrid (relative maturity 118; DK682 RR) and sunflower hybrid (intermediate cycle; DK3880 Cl) were sown on early October (1 October Year 1 and 12 October Year 2), and soybean (maturity group IV; SPS4500 RR) was sown on late November (18 November in Year 1 and 27 November in Year 2). The availability of specific traits for herbicide tolerance allowed successful weed management based on glyphosate in maize–soybean intercrop and on imidazolinones in sunflower–soybean intercrop.

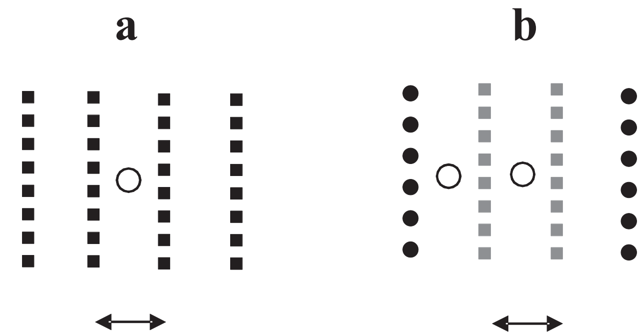

Fig. 1. Schematic representation of sole crops (a) and intercrops (b), empty circle indicates placement of tubes for neutron probe measurements. In the intercrops, soybean lines are represented by gray squares and the former crops by black circles. Distance between adjacent rows was 0.52 m (arrows). In the intercrops, row distance between maize or sunflower was 1.56 m.

The achieved plant densities were 6.5 plants m^{-2} for maize, 4 plants m^{-2} for sunflower and 27 plants m^{-2} for soybean. These densities were maintained for the three species in both cropping systems (i.e., sole crops and intercrops). Plots were 12 m long and 10 rows wide. Complementary irrigation was applied with a splinker irrigation system to alleviate the effect of drought (Table 1). Water supplied by irrigation was estimated using nine water gauges distributed across the experimental area.

2.3. Measurements

Crop development was recorded weekly using the scales of Ritchie and Hanway (1982) for maize, Schneiter and Miller (1981) for sunflower and Fehr and Caviness (1977) for soybean. The date of a phenological stage for each experimental unit was determined when 50% of the plants reached that stage.

Soil water content from 0.2 m up to the petrocalcic horizon (1.6 m) was measured at least weekly during the cropping season using a neutron probe (Troxler, USA) and was complemented with gravimetric sample for the topsoil (0–0.2 m). Soil water content in the intercropping systems was obtained as the sum of a third of the water content estimated between soybean rows plus two thirds of the water content estimated between soybean and maize or sunflower rows (Fig. 1). Seasonal evapotranspiration was estimated using a water balance, based on measured changes in soil water content and rainfall plus irrigation (Allen et al., 2006; Della Magiora et al., 2000), including data from emergence to physiological maturity in sole crops and from maize or sunflower emergence to soybean physiological maturity in intercrops.

Fraction of intercepted photosynthetically active radiation (FiPAR) was calculated for each plot 3:00 h before solar zenith and at zenith as $[1-(I/I_0)]$, where I represents the incident photosynthetically active radiation immediately above senesced leaves and I_0 represents the incident PAR at the top of the canopy. Measurements

Table 1
Monthly average temperature, photosynthetic active radiation and rainfall plus irrigation during Year 1 (2005/2006) and Year 2 (2006/2007) and historical averages (1975–2007) for Balcarce, Argentina. Irrigation values are shown between brackets.

Month	Temperature (°C)			Photosynthetic active radiation ($MJ\,m^{-2}\,day^{-1}$)			Rainfall + irrigation (mm)		
	Year 1	Year 2	Historical	Year 1	Year 2	Historical	Year 1	Year 2	Historical
May	11.7	10.6	11.1	3.6	3.8	3.6	17	1	65
June	9.5	9.2	8.3	2.4	2.4	2.8	70	79	49
July	8.4	9.9	7.5	2.8	2.3	3.3	51	56	50
August	9.0	8.9	8.9	3.8	4.2	4.5	109	11	42
September	10.6	10.8	10.5	5.8	5.9	6.0	59	45	54
October	12.6	14.4	13.4	9.0	7.7	8.2	60	77	98
November	17.0	16.0	15.9	9.5	10.5	9.8	85	39 (12)	84
December	16.8	21.0	18.8	10.8	10.9	11.6	103	113	112
January	19.4	20.8	20.5	10.9	10.4	10.7	148 (12)	114 (78)	109
February	19.6	21.2	19.8	9.1	8.9	9.6	125	149 (26)	84
March	17.5	18.3	17.9	7.7	6.9	7.3	21	212	82
April	15.5	14.9	14.4	5.1	5.3	5.3	52	238	85

were made at least fortnightly on sunny days using a line quantum sensor 1.0 m long (Model 191 SB, Li-Cor, Lincoln, NE). For sole crop plots, sensor placement followed the technique described by Gallo and Daughtry (1986). Maize or sunflower inter-row distance in intercrop was wider than the sensor length (i.e. 1.56 m vs. 1.0 m). The effective sensor length was reduced to 0.78 m (by covering 0.22 m of the sensor with a zero-transparency plastic) and the average of two contiguous measurements across the inter-row space (simulating a 1.56 m sensor) assembled an estimation of PAR transmitted through the canopy. The fraction of PAR intercepted for each plot and day moment was calculated as the average of four estimations.

As rows orientation was north-south and assuming canopy east-west symmetry around the zenith (Gilbert et al., 2003; Tsubo and Walker, 2002), daily weighed fraction of intercepted radiation (FiPAR) was calculated as:

$$\mathrm{FiPAR} = 2R_{\mathrm{zenith}-3\mathrm{h}} \times \mathrm{FR}_{\mathrm{Zenith}-3\mathrm{h}} + R_{\mathrm{zenith}} \times \mathrm{FR}_{\mathrm{Zenith}} \quad (1)$$

where FR is the fraction of intercepted PAR measured at each time of the day and R is the fraction of incident daily cumulative PAR of the period represented by each moment.

FiPAR between measurements were obtained by lineal interpolation. Daily intercepted PAR was obtained multiplying daily FiPAR by daily incident PAR, which was calculated as measured solar radiation affected by 0.48. Total intercepted PAR (IPAR) was calculated as cumulative daily intercepted PAR from emergence to physiological maturity in sole crops and from maize or sunflower emergence to soybean physiological maturity in intercrops.

At soybean flowering, soybean aboveground biomass was estimated by sampling plants from a 0.5 m^2 area and was expressed on a dry basis. Aboveground biomass and grain production were estimated at physiological maturity of each crop and expressed on a dry weight basis. After manual harvest, the remaining stubble of sunflower and maize was lodged in the direction of the row, simulating the effect of the combine. The final harvest area for each crop was 8 m^2. Land equivalent ratio (LER) was estimated as the sum of the relative yield of the component crops (i.e., ratio between yield in the intercrop and yield as sole crop). Total biomass and grain production were also expressed on energy units (MJ) to consider differences in chemical composition. Grain oil and protein concentration were determined by Soxhlet and Kjeldahl methods, respectively. Stubble chemical composition was expressed according to local information for maize, soybean and sunflower generated by Andrade (1995). Glucose equivalents were calculated according to Penning de Vries (1974). In Year 1, *Sclerotinea* spp. and *Canchrus* spp. affected growth and yield of soybean sole crops; consequently, biomass and grain yield data were obtained from areas with no visual symptoms of disease.

2.4. Calculations and data analysis

Resources use and use efficiency were calculated (i) annually, including data from 1 May to 30 April, and (ii) seasonally, including data from emergence to physiological maturity in sole crops and from maize or sunflower emergence to soybean physiological maturity in intercrops. Annual water availability was based on annual rainfall and irrigation and seasonal water availability included rainfall and irrigation plus soil available water at sowing up to 1.6 m soil depth. Radiation availability was calculated as the sum of daily incident PAR at annual or seasonal basis.

Water and radiation capture efficiencies (C_{WATER} and C_{RAD}, respectively) were calculated as the ratio between cumulative crop evapotranspiration (ET) and IPAR and water or radiation availability on seasonal (s) and annual (a) basis.

Water use efficiency for biomass or grain production ($\mathrm{WUE_B}$ and $\mathrm{WUE_Y}$, respectively) was estimated as the ratio between total aboveground biomass or grain yield and seasonal ET. Radiation use efficiency was estimated as the ratio between total aboveground biomass or grain yield and IPAR ($\mathrm{RUE_B}$ and $\mathrm{RUE_Y}$, respectively).

Table 2
Aboveground biomass production expressed as dry matter and as energy equivalents for maize, sunflower and soybean sole crops, and for maize–soybean and sunflower–soybean intercrops in Year 1 and Year 2. Means followed by the same letter within a column are not statistically different ($P < 0.05$).

	Soybean		Maize or sunflower		Total			
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
	Dry matter ($g\,m^{-2}$)						Energy ($MJ\,m^{-2}$)	
Maize	–	–	2685 a	2269 a	2685 a	2269 a	59.6 a	49.1 a
Sunflower	–	–	1028 c	967 c	1028 d	967 c	27.2 d	25.5 c
Soybean	1118 a	927 a	–	–	1118 d	927 c	27.1 d	24.2 c
Maize–soybean	225 c	260 b	2113 b	1558 b	2338 b	1818 b	52.6 b	40.6 b
Sunflower–soybean	321 b	210 b	982 c	758 c	1302 c	968 c	34.1 c	26.0 c

Table 3
Grain yield expressed as dry matter and as energy equivalents for maize, sunflower and soybean sole crops, and for maize–soybean and sunflower–soybean intercrops and their components in Year 1 and Year 2. Means followed by the same letter within a column are not statistically different ($P < 0.05$).

	Soybean		Maize or sunflower		Total			
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
	Dry matter (g m^{-2})						Energy (MJ m^{-2})	
Maize	–	–	1450 a	1028 a	1450 a	1028 a	32.18 a	26.16 a
Sunflower	–	–	315 c	315 c	315 d	315 c	11.44 d	11.77 b
Soybean	348 a	392 a	–	–	348 d	392 c	11.40 d	12.75 b
Maize–soybean	73 c	112 b	1184 b	790 b	1256 b	902 b	28.66 b	22.34 a
Sunflower–soybean	127 b	95 b	275 c	229 d	403 c	325 c	14.24 c	13.36 b

Table 4
Evapotranspiration and water capture efficiency on seasonal ($C_{WATER(s)}$) and annual ($C_{WATER(a)}$) basis, for sole crops and maize–soybean and sunflower–soybean intercrops in Year 1 and Year 2. Means followed by the same letter within a column are not statistically different ($P < 0.05$).

	Evapotranspiration (mm)		$C_{WATER(s)}$		$C_{WATER(a)}$	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Maize	544 b	501 b	0.80 b	0.80 b	0.61 b	0.44 b
Sunflower	470 c	405 c	0.80 b	0.94 a	0.52 c	0.36 c
Soybean	495 c	524 b	0.92 a	0.90 ab	0.55 c	0.46 b
Maize–soybean	603 a	643 a	0.89 a	0.85 ab	0.67 a	0.57 a
Sunflower–soybean	581 ab	616 a	0.91 a	0.85 ab	0.65 ab	0.54 a

These efficiency indicators were also expressed on an energy basis taking into account the chemical composition of grain and residues (i.e., WUE_{eB}, WUE_{eY}, RUE_{eB} and RUE_{eY}).

Productivity of water (WP) and radiation (RP) expressed as energy produced in aboveground biomass at maturity and grain yield per unit of annual available water or radiation were estimated as the product of capture and efficiency factors (Caviglia et al., 2004) according to equations:

$$WP = C_{WATER(a)} \times WUE_{eB} \quad (2)$$

$$RP = C_{RAD(a)} \times RUE_{eB} \quad (3)$$

The effects of treatments were tested by analysis of variance (ANOVA). Analyses were performed using R software (v 2.12.1, R Development Core Team, 2008).

3. Results

3.1. Climate variables

Table 1 summarizes climatic data for Year 1 and Year 2. Monthly averages for daily incident PAR and daily mean temperature for the two seasons were similar to the historical average. Water input during Year 1 was similar to the historical average until February and below it afterwards. Water input during Year 2 (1134 mm) was lower than the historical average from sowing to November and markedly higher than the historical average after January.

Table 5
Intercepted photosynthetically active radiation (IPAR) and radiation capture efficiency on seasonal ($C_{RAD(s)}$) and annual ($C_{RAD(a)}$) basis, for sole crops and maize–soybean and sunflower–soybean intercrops in Year 1 and Year 2. Means followed by the same letter within a column are not statistically different ($P < 0.05$).

	IPAR (MJ m^{-2})		$C_{RAD(s)}$		$C_{RAD(a)}$	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Maize	962 a	877 a	0.62 b	0.61 a	0.39 a	0.37 a
Sunflower	809 c	731 b	0.63 b	0.63 a	0.33 c	0.30 b
Soybean	890 b	726 b	0.71 a	0.66 a	0.37 b	0.30 b
Maize–soybean	979 a	841 a	0.58 b	0.54 b	0.40 a	0.35 a
Sunflower–soybean	941 a	686 b	0.55 b	0.44 c	0.39 a	0.29 b

3.2. Crop development, growth and LER

The length of the growing cycles was similar for sunflower–soybean and maize–soybean intercrops, and lasted 180 and 166 days for Year 1 and Year 2 respectively. The intercrop growing cycle was extended by an average of 20, 56 and 46 days compared with those of maize, sunflower and soybean sole crops, respectively (Fig. 2).

The major phenological events of maize, sunflower and soybean occurred simultaneously on sole crops and intercrops. Critical periods for grain set in maize and sunflower began when intercropped soybean was at vegetative stages. At the beginning of soybean flowering, biomass production of the intercropped soybean was severely affected compared with that of soybean sole crop (74 and 67% reduction, two year average for sunflower–soybean and maize–soybean intercrops respectively). The overlapping period between component crops was longer for maize–soybean intercrop than for sunflower–soybean intercrop (Fig. 2).

Maize sole crop produced the highest biomass (Table 2). Biomass production of maize–soybean intercrop was lower than maize sole crop biomass and higher than soybean sole crop biomass. Biomass production of sunflower–soybean intercrop was higher than (Year 1) or similar to (Year 2) those of sunflower and soybean sole crops (Table 2).

As occurred for total biomass production, grain production was affected by crop and cropping system (Table 3). Maize sole crop attained the highest grain yield. Maize–soybean intercrop grain yield was between those of maize and soybean sole crop (Table 3) Sunflower–soybean intercrop grain yield was higher than (Year 1) or similar to (Year 2) those of sunflower and soybean sole crops (Table 3). In Year 1, soybean sole crop grain yield estimated from areas with no visual symptoms of *Sclerotinea* spp. and *Canchrus* spp. was 348 g m^{-2}; without this correction, soybean sole crop yield was 247 g m^{-2}.

Biomass and grain production of intercropped maize and sunflower (i.e., former species) were slightly below those of their respective sole crop (Tables 2 and 3). Contrarily, biomass and grain production of intercropped soybean compared with soybean sole crop decreased between 71 and 80% and between 64 and 77% when it was intercropped with maize and sunflower respectively (Table 3). LER values for maize–soybean were 1.03 and 1.05 for Year

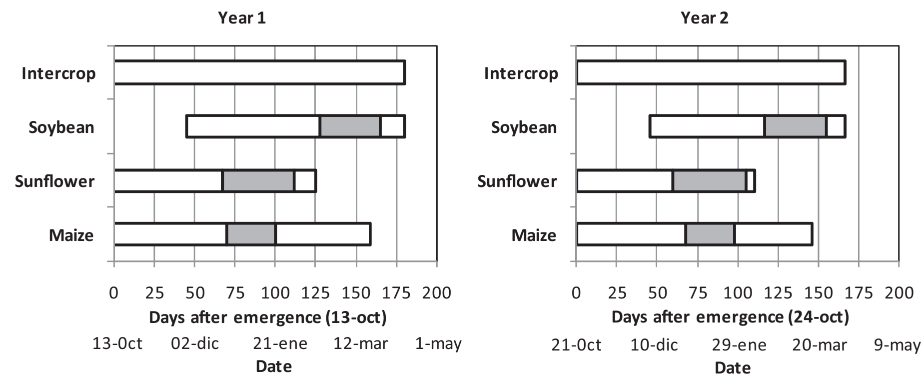

Fig. 2. Growing cycle for the sole crops and for the intercrops expressed in days. Zero in the *X*-axis indicates the emergence of maize and sunflower sole crops and of the former crop in the intercrop. Duration of maize–soybean and sunflower–soybean intercrops was similar. Grey horizontal bars indicate the critical periods for grain yield determination in maize (from 15 days before to 15 days after flowering), sunflower (from 20 days before to 30 days after flowering) and soybean (from R4 to R6).

1 and 2, respectively. LER values for sunflower–soybean were 1.24 and 0.97 for Year 1 and 2, respectively.

3.3. Resource capture

Intercrops used more water than their respective sole crops (Table 4, Fig. 3). Increase in evapotranspiration compared to the average of sole crops was 27% for sunflower–soybean intercrop and 21% for maize–soybean intercrop. Unlike this, the fraction of seasonal available water used by crops was little affected by the cropping system (Table 4). Differences in total water consumption among copping systems were related to the extension of the growing cycle. On the other hand, the dynamic of water consumption followed a similar pattern for single crops and intercrops alternatives when they coexisted (Fig. 3).

Differences in IPAR between intercrops and their respective sole crops were relatively smaller than differences in evapotranspiration (Table 5). Maize–soybean intercrop and maize sole

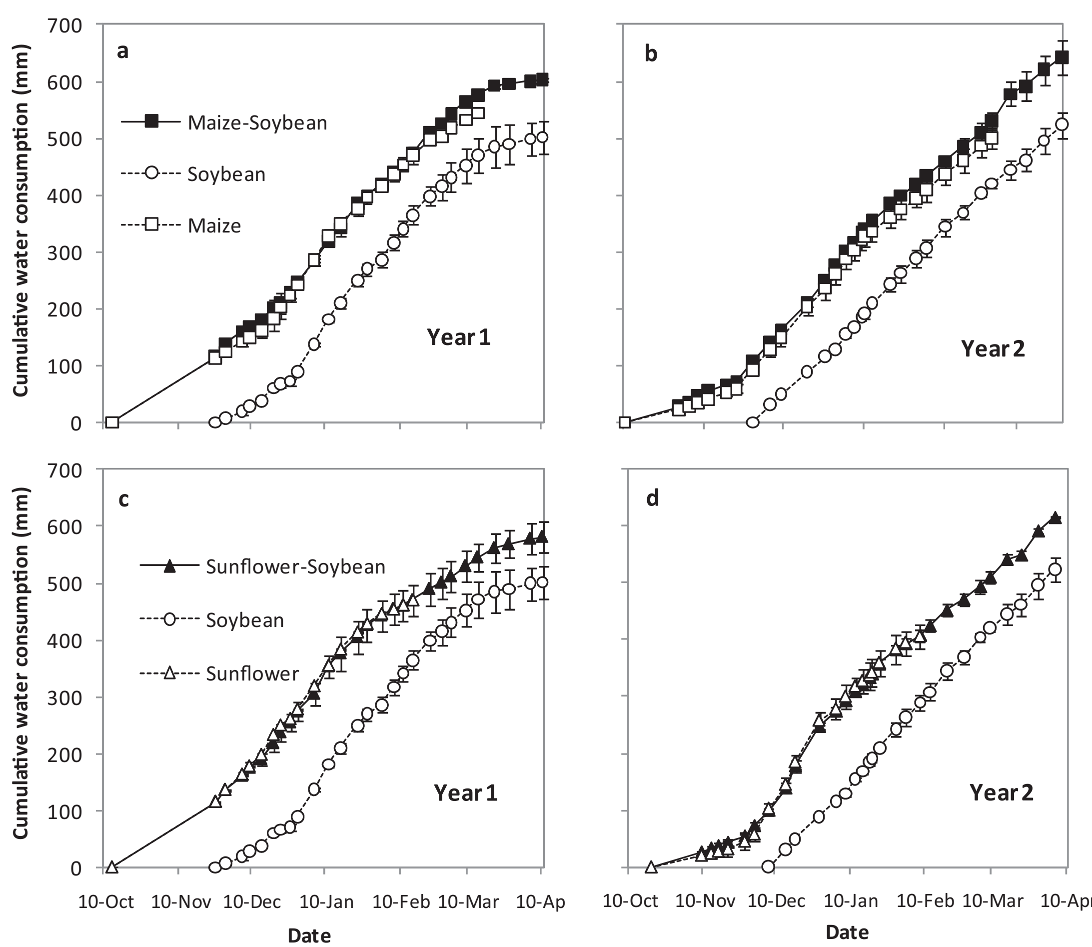

Fig. 3. Cumulative water consumption (mm) during two growing seasons (Year 1 and Year 2) comparing maize–soybean intercrop with their respective sole crops (a and b) and sunflower–soybean intercrop with their respective sole crops (c and d). Vertical bars indicate ±SE.

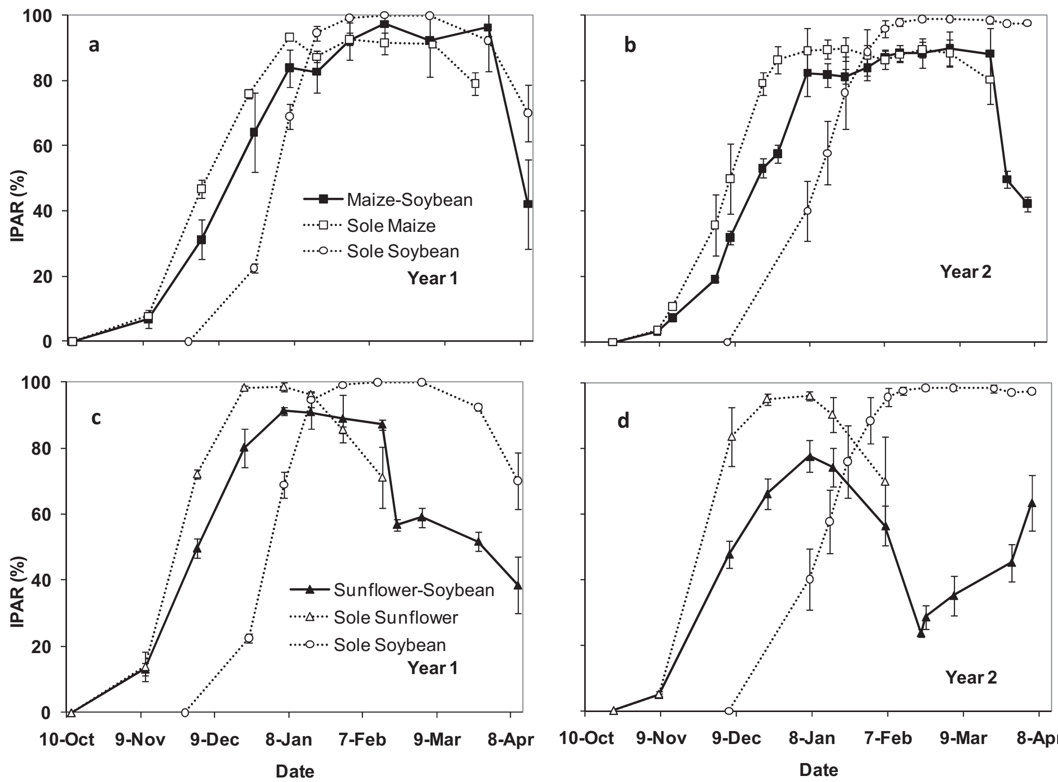

Fig. 4. Radiation intercepted by the crop, expressed as a percentage of incident radiation (IPAR %), during two growing seasons (Year 1 and Year 2) comparing maize–soybean intercrop with their respective sole crops (a and b) and sunflower–soybean intercrop with their respective sole crops (c and d). Vertical bars indicate ±SE.

crop intercepted the highest amount of PAR. Intercepted PAR of sunflower–soybean intercrop was higher than (Year 1) or similar to (Year 2) the average of sunflower and soybean sole crops (Table 5).

PAR intercepted by all treatments was lower in Year 2 than in Year 1 (Fig. 4). This was consequence of unfavorable conditions for canopy growth in Year 2 due to scarce water input during the crop vegetative stages (Table 1).

3.4. Resource use efficiency

Water and radiation use efficiencies for biomass and grain production of maize–soybean intercrop were between those of the respective sole crops (Tables 6 and 7). Resource use efficiencies in biomass and grain production of sunflower–soybean intercrop were similar to those of its respective sole crops, except for water use efficiency in Year 2. Water use efficiency tended to be lower in Year 2 than in Year 1 (Table 6). Resource use efficiencies in biomass and grain production of sole crops were notably higher for maize than for sunflower and soybean.

3.5. Water and radiation productivity

Water and radiation productivities in biomass and grain yield of maize–soybean intercrop were between those of its respective sole crops (Table 8). Unlike this, water and radiation productivities of sunflower–soybean intercrop were higher than (Year 1) or similar to (Year 2) than those of its respective sole crops.

4. Discussion

Intercrops showed an increase in crop duration when compared to their sole counterparts; this increase was higher for sunflower–soybean intercrop and was related to a short overlapping period between the growing cycles of the component crops (Fig. 2).

The land equivalent ratio ranged from 0.97 to 1.24, A LER of 1.24 for example, indicates that the area planted to monocultures would need to be 24% greater than the area planted to intercrop for the two sole crops to produce the same combined yield. Where the LER is used as a measure of productivity great care needs to be taken in making inferences (Connolly et al., 2001). LER > 1 not

Table 6
Water use efficiency on dry matter or energy equivalent basis for maize–soybean and sunflower–soybean intercrops and sole crops in Year 1 and Year 2. Water use efficiency was calculated considering aboveground biomass at maturity or grain yield. Means followed by the same letter within a column are not statistically different ($P < 0.05$).

	Aboveground biomass				Grain yield			
	Dry matter (g m^{-2} mm^{-1})		Energy (MJ m^{-2} mm^{-1})		Dry matter (g m^{-2} mm^{-1})		Energy (MJ m^{-2} mm^{-1})	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Maize	4.94 a	4.54 a	0.110 a	0.098 a	2.67 a	2.06 a	0.059 a	0.052 a
Sunflower	2.19 c	2.40 bc	0.058 c	0.063 b	0.67 c	0.78 c	0.024 c	0.029 bc
Soybean	2.27 c	1.78 cd	0.055 c	0.046 bc	0.71 c	0.75 c	0.023 c	0.024 c
Maize–soybean	3.88 b	2.82 b	0.087 b	0.063 b	2.08 b	1.40 b	0.048 b	0.035 b
Sunflower–soybean	2.25 c	1.57 d	0.059 c	0.042 c	0.69 c	0.53 d	0.025 c	0.022 c

Table 7
Radiation use efficiency on dry matter or energy equivalent basis for sole crops and maize–soybean and sunflower–soybean intercrops in Year 1 and Year 2. Radiation use efficiency was calculated considering aboveground biomass at maturity or grain yield. Means followed by the same letter within a column are not statistically different ($P < 0.05$).

	Aboveground biomass				Grain yield			
	Dry matter (g m^{-2} mm^{-1})		Energy (MJ m^{-2} mm^{-1})		Dry matter (g m^{-2} mm^{-1})		Energy (MJ m^{-2} mm^{-1})	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Maize	2.79 a	2.59 a	0.062 a	0.056 a	1.51 a	1.17 a	0.033 a	0.030 a
Sunflower	1.27 d	1.32 c	0.034 d	0.035 b	0.39 c	0.43 d	0.014 c	0.016 b
Soybean	1.25 d	1.28 c	0.030 e	0.033 b	0.39 c	0.54 c	0.013 c	0.018 b
Maize–soybean	2.39 b	2.16 b	0.054 b	0.048 a	1.28 b	1.07 b	0.029 b	0.026 a
Sunflower–soybean	1.39 c	1.41 c	0.036 c	0.038 b	0.43 c	0.47 cd	0.015 c	0.020 b

necessarily indicates that production of intercropping is greater than the average production of sole crops. LER is not indicative of resource productivity of the system, especially when the difference between achievable yields of sole crops is high, as in the case of maize–soybean intercrop.

Maize–soybean intercrop improved radiation and water productivities compared to soybean and to the average of its respective sole crops; however, maize cultivated as sole crop attained the highest resource productivity because it is a C4 specie (Andrade, 1995) that almost fully explored the growing season, i.e. the period of the year during which growing conditions for crops are most favorable (Fig. 1). On the other hand, resource productivity of sunflower–soybean intercrop was higher than or similar to its corresponding sole crops (Table 8). The fact that both intercropping systems resulted in higher or similar resource productivity compared with soybean sole crop is relevant considering the need of crop diversification in the south-east Pampas where soybean is the predominant crop (Navarrete et al., 2009; Satorre, 2005).

The improvement in water productivity for maize–soybean intercrop compared with soybean sole crop (for aboveground biomass expressed in an energy basis) was explained by an increase in annual water capture efficiency (22% average) and an increase in water use efficiency (48% average). This last increment was probably associated with the higher water use efficiency of maize compared to soybean (Tables 4, 6 and 8). When occurred (Year 1), the increase in water productivity of sunflower–soybean intercrop compared to soybean and sunflower sole crops (approx. 21%) was only explained by an increase in annual capture efficiency. This result agrees with previous reports in which annual water capture efficiency was improved by intercropping (Caviglia et al., 2004; Reddy and Willey, 1981; Willey, 1990). Water capture efficiency on an annual basis was closely correlated with the proportion of the explored season, in accordance, the dynamic of water consumption follow the same pattern for single crops and intercrops alternatives when they coexisted in the field (Fig. 3). An increase in water capture could contribute to a sustainable intensification by reducing environmental risks associated with erosion processes or aquifer contamination produced by water excess (Cassman, 1999; Caviglia and Andrade, 2010).

The higher evapotranspiration for intercrops in Year 2 than in Year 1 (Table 4, Fig. 3) was not translated to biomass or grain yield, suggesting a greater proportion of evaporation during Year 2. Accordingly, radiation capture during Year 2 was reduced compared to Year 1 (Table 5). The scarce water availability early in the growing season (Table 1) affected ground cover (Fig. 4), particularly for the intercrops in which former crops were sown in wide rows. This period of scarce water input was followed by a period of high irrigation plus rainfall that combined with poor ground cover could have enhanced soil evaporation process. Therefore, further experiments should be oriented to assess the proportion of transpiration and evaporation in these intercropping systems and their interaction with the pattern of water availability during the growing season.

The increase in radiation productivity for maize–soybean intercrop compared with soybean sole crop (for total biomass expressed in an energy basis) was the result of an increase in radiation use efficiency (63% average) and of a minor but significant increase in radiation capture efficiency (13% average, Tables 5, 7 and 8). The improvement in resource use efficiency is consistent with the higher radiation use efficiency of maize compared to soybean. Contrarily, the improvement in radiation productivity for sunflower–soybean intercrop compared to soybean and sunflower sole crops was small or null (Table 8) since these crops present similar radiation use efficiency and the capture efficiency was barely improved by this intercrop; even though it extended the crop duration (Fig. 2). In previous works, radiation productivity increments in response to intercropping were mainly associated with resource capture (Awal et al., 2006; Caviglia et al., 2004; Jahansooz et al., 2007; Tsubo et al., 2001). The considerations for productivity of water and radiation expressed as energy in total biomass also applied for resource productivity expressed as energy in grains.

As previously discussed, maize sole crop attained the highest productivity for water and radiation. However, at lower latitudes, where growing season is longer, maize–soybean intercrop may improve annual resource productivity of maize sole crop by an increase in capture efficiency (Caviglia and Andrade, 2010).

While resource capture efficiency on an annual basis is a component of resource productivity (Eqs. (2) and (3)), the analysis of

Table 8
Productivity of water (WP) and radiation (RP) expressed as energy produced in aboveground biomass at maturity and grain yield per unit of annual available water or radiation, for sole crops and maize–soybean and sunflower–soybean intercrops in Year 1 and Year 2. Means followed by the same letter within a column are not statistically different ($P < 0.05$).

	WP (MJ m^{-2} mm^{-1})				RP (MJ MJ^{-1})			
	Aboveground biomass		Grain yield		Aboveground biomass		Grain yield	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Maize	0.066 a	0.043 a	0.036 a	0.023 a	0.024 a	0.021 a	0.013 a	0.011 a
Sunflower	0.030 d	0.023 c	0.013 d	0.010 b	0.012 d	0.011 c	0.005 d	0.005 b
Soybean	0.031 d	0.021 c	0.013 d	0.011 b	0.011 d	0.010 c	0.004 e	0.005 b
Maize–soybean	0.058 b	0.036 b	0.032 b	0.020 a	0.022 b	0.017 b	0.012 b	0.009 a
Sunflower–soybean	0.037 c	0.022 c	0.016 c	0.012 b	0.015c	0.011 c	0.006 c	0.006 b

capture efficiency on a seasonal basis contributed to explain the eco-physiological principles supporting the differences found in resource capture through the cropping systems. The low seasonal radiation capture efficiency for intercrops partially or fully reversed the effect of the increase in cycle length on radiation capture on an annual basis. This decrease in seasonal radiation capture efficiency of intercrops was associated with a low fraction of radiation interception during the beginning and during the end of the growing season, when only one species was present in the field (Fig. 4). In accordance, the correlation observed between cycle length and captured radiation ($r = 0.57$, $P < 0.05$) was lower than that found for consumed water ($r = 0.83$, $P < 0.05$). Intercropping systems with long growing season duration and, at the same time, with high efficiency in the seasonal capture of resources would result in high resource productivity.

Intercrops captured 54–65% of the annual available water (Table 4) but only 29–40% of the annual incident PAR (Table 5). This differential behavior between resources is partially explained because water can be stored in the soil up to a certain limit and, contrarily, non-intercepted radiation is lost.

In spite of the great interrow distance (1.56 m), grain yield for intercropped sunflower and maize were only 20% lower than yield for sole crops. Therefore, yield attained by intercropping was mainly limited by a poor production of the soybean component (Table 2). These results evidenced an interspecific competition that favored the former (taller) crop in detriment of soybean. At maize or sunflower harvest, the ability of soybean to recover from the competition of the former crop would be determinant in the result of the intercropping system.

Sunflower reached physiological maturity before the onset of soybean critical period for grain set, even so intercropped soybean yield was severely affected. From these data, it appears that critical period for grain set for intercropped soybean is extended to vegetative stages when crop defines the leaf area. Management practices oriented to increase soybean competitive ability would result in proportionally greater yield increase for soybean than yield reduction for former crops that should lead to an improvement in intercropping performance. Simultaneous sowing of the two components with the adequacy of soybean maturity group would help soybean initial canopy growth and would enhance resource capture efficiency of the intercrop. In accordance, Kandel et al. (1997) found that a reduction in sowing delay in various sunflower-legume intercropping doubled the legume biomass without affecting sunflower yield. Also a reduction in plant density of formers crops may help to increase soybean yield and thus total intercrop productivity (Echarte et al., 2011).

The use of maize or sunflower of shorter maturity groups would release competition on soybean earlier in the growing season allowing for an increase in soybean canopy growth and soil cover that should translate in a higher resources capture after the harvest of the former crop and in an improvement of the physiological condition of soybean during its reproductive stages.

Intercropping, originally a "subsistence farming" concept, was evaluated here as a high-tech alternative. These intercropping systems emerged from the interaction between leading farmers and researchers and can be carried out in fully mechanized large scale farms (Calviño and Monzon, 2009). This work provides eco-physiological basis to improve management practices of summer intercrops in the south-east Pampas.

5. Conclusion

This study has evaluated the performance of maize–soybean and sunflower–soybean intercrops in the south-east Pampas of Argentina in comparison to their sole crop counterparts. Intercrops alternatives increased crop duration, Maize, as a sole crop, showed the highest resource productivity (water and radiation). On the other hand, intercrops resource productivity was increased when compared to soybean as a sole crop. This is relevant considering the need for crop diversification in the Pampas where soybean is the predominant crop. Intercropping yield was limited by the soybean component. Futures investigations should focus on practices that increased the ability of soybean to recover from the competition of the former crop.

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