Sunflower–Soybean Intercrop Productivity under Different Water Conditions and Sowing Managements

José F. Andrade,* Anibal Cerrudo, Roberto H. Rizzalli, and Juan P. Monzon

ABSTRACT

The sunflower (*Helianthus annus* L.)–soybean [*Glycine max* (L.) Merr.] intercrop has emerged as an option that increases land productivity in the southern Pampas of Argentina, compared with sole crops, because of complementary use of resources between species. A common management practice for this intercrop consists of delay soybean sowing, although delayed planting reduces the capacity of soybean to capture resources. Simultaneous sowing could improve total intercrop productivity because of an increase in soybean grain yield with no or little detrimental effects on sunflower grain yield. The objectives of this study were to analyze the response of the sunflower–soybean intercrop and of their component species under different sowing management (i.e., relay or simultaneous sowing) and water availability conditions. Three experiments were conducted at Balcarce, Argentina. Four cropping systems were evaluated: (i) sunflower–soybean intercrop with simultaneous sowing management (I00), (ii) sunflower–soybean intercrop with 30 d of delay between sunflower and soybean sowing (I30), (iii) sunflower sole crop (SUN), and (iv) soybean sole crop (SOY). Sunflower–soybean intercrop grain yield tend to be higher than that for sole crops of the component species. This yield advantage for intercrop increased with water availability and was associated with an increase in intercropped soybean productivity. Intercrop sowing management had no effect on total intercrop grain yield. However, simultaneous sowing increased soybean contribution to intercrop yield. Finally, our results indicate that agronomic practices that promote intercropped soybean performance increase intercrop productivity relative to the sole crops of their component species.

INTERCROPPING IS AN agricultural production system in which two or more species develop simultaneously during part or all of the growing season and compete with each other for available resources (Fukai and Trenbath, 1993). These production systems frequently increase resource capture and resource use efficiency in comparison with their sole crops counterparts (Andrews and Kassam, 1976; Ofori and Stern, 1987; Caviglia et al., 2004; Coll et al., 2012; Echarte et al., 2011). However, interspecific competition for resources often results in a lower productivity of the intercropped species in relation to its sole crop. If yield of an intercrop component is similar to its sole crop, this species is considered to be dominant, but if its yield is greatly reduced by the presence of another species, then it is considered a suppressed component (Fukai and Midmore, 1993).

Sunflower and soybean are two species that can be intercropped (Calviño and Monzon, 2009). In the southern Pampas of Argentina; Coll et al. (2012) and Echarte et al. (2011) reported higher yields for sunflower–soybean intercrops in comparison to sole crops. The greater intercrop yield was associated with an increase in capture and resource use efficiency. Intercropped sunflower and soybean complement each other in the use of resources because critical periods for yield determination occur at different times during a period of low resource demand by the other component (Coll et al., 2012). The critical period for yield determination for a crop is defined as the stage where a reduction in resources availability (water, nutrients, radiation) determines the greatest grain yield lost (Andrade, 1995; Cantagallo et al., 2004; Egli and Bruening, 2005). In the southern Pampas, sunflower sown in mid-October has its critical period for yield determination when soybean (sown in mid-November) is still in vegetative stages, and soybean critical period takes place near to sunflower maturity.

In Coll et al. (2012) and Echarte et al. (2011) studies, intercropped sunflower was sown on its recommended date and intercropped soybean was sown 30 d later (relay intercrop). The delay in soybean sowing increased the competition ability of sunflower (dominant component) in detriment of soybean (suppressed component, Midmore, 1993). Kandel et al. (1997) showed that the reduction of sowing delay between component species in a sunflower–legume intercrop increased legumes biomass with no or little effects on sunflower yield, although legumes analyzed in that work did not include soybean. Therefore, elimination of soybean sowing delay, while maintaining

J. F. Andrade, A. Cerrudo, R. Rizzalli and J.P. Monzon, UIB Facultad de Ciencias Agrarias UNMdP-INTA Balcarce. Ruta 226, km 73.5. CP 7620, Balcarce, Argentina. Current address: J.F. Andrade, Departamento de Producción Vegetal, Universidad de Buenos Aires, Buenos Aires, Argentina.
Received 9 Feb. 2012. *Corresponding author (jandrade@agro.uba.ar).

Published in Agron. J. 104:1049–1055 (2012)
Posted online 23 May 2012
doi:10.2134/agronj2012.0051
Copyright © 2012 by the American Society of Agronomy, 5585 Guilford Road, Madison, WI 53711. All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher.

Abbreviations: I00, simultaneous intercrop; I30, relay intercrop; INTsun, intercropped sunflower grain yield; INTsoy, intercropped soybean grain yield; PAR, photosynthecially active radiation; rysun, sunflower relative grain yield; rysoy, soybean relative grain yield; ryt, total relative grain yield; SOY, soybean sole crop; SUN, sunflower sole crop.

the gap between critical periods, may increase soybean competition ability and could improve total intercrop productivity.

Local experiments always included irrigation (Coll et al., 2012; Echarte et al., 2011); this practice reduces the severity of competition for water and promotes the suppressed component (Molla and Sharaiha, 2010). Despite that, intercropped soybean production was severely limited, and constituted the bottleneck of the system (Coll et al., 2012; Echarte et al., 2011). Furthermore, intercropped soybean condition could be worse under rainfed management and the advantage of intercrops over sole crops may depend on rainfall amount and distribution. Finally, since water availability would affect largely the suppressed component, it would also modify the response of intercropped soybean to simultaneous sowing.

The objectives of this work was (i) to evaluate the effect of different sowing management in sunflower–soybean intercrops on aboveground biomass and grain yield of its component species and (ii) compare intercrop productivity with their respective sole crops, both under different levels of water availability.

MATERIAL AND METHODS

Site and Experimental Design

The study was performed at the Estación Experimental Agropecuaria INTA-Balcarce, Buenos Aires, Argentina (37.5° S; 58.2° W) under conventional tillage (moldboard plowing, disking, and harrowing). Experiments were established on a fine, mixed, thermic Typic Argiudoll, with a slope <2% (no erosion). The top horizon has loamy texture, 5.6% of organic matter, 34 mg kg^{-1} of Bray and Kurtz P, and pH 6.1 (1:2.5 in water).

Three experiments were performed, two under irrigation, one in 2007/2008 (Exp. 1) and the other in 2008/2009 (Exp. 2); and one under rainfed conditions in 2008/2009 (Exp. 3). All experiments were randomized block designs with 3 replications. Four cropping systems were evaluated: (i) sunflower–soybean intercrop with simultaneous sowing management (I00), (ii) sunflower–soybean intercrop with a delay of 30 d in soybean sowing after sunflower sowing (I30), (iii) sunflower sole crop (SUN), and (iv) soybean sole crop (SOY).

The experimental unit was 12 m long and 10 rows wide for intercrops and 12 m long and 8 rows wide for sole crops. All treatments were sown with a north–south orientation with rows 0.52 m spaced (Fig. 1). The intercrops spatial arrangement consisted of two soybean rows per sunflower row. Therefore, intercropped sunflower rows were established 1.56 m apart, whereas intercropped soybean was sown in pairs of rows 0.52 m spaced between them and 0.52 m apart from the intercropped sunflower row.

Hand sowing at high density was performed, and subsequently seedlings were thinned to achieve target density and uniformity of plants spacing. Sunflower plant density was 3.5 plants m^{-2} for sole crop and intercrop. Soybean plant density was 30 plants m^{-2} for sole crop and intercrop. An intermediate cycle length sunflower hybrid (Paraíso 68, Nidera) was used for sole crop and intercrops. To maintain the gap between critical periods for grain yield determination, a soybean maturity group IV (SPS 4500, SPS) was used for I30 and a soybean Maturity Group V (A5009, Nidera) was used for I00.

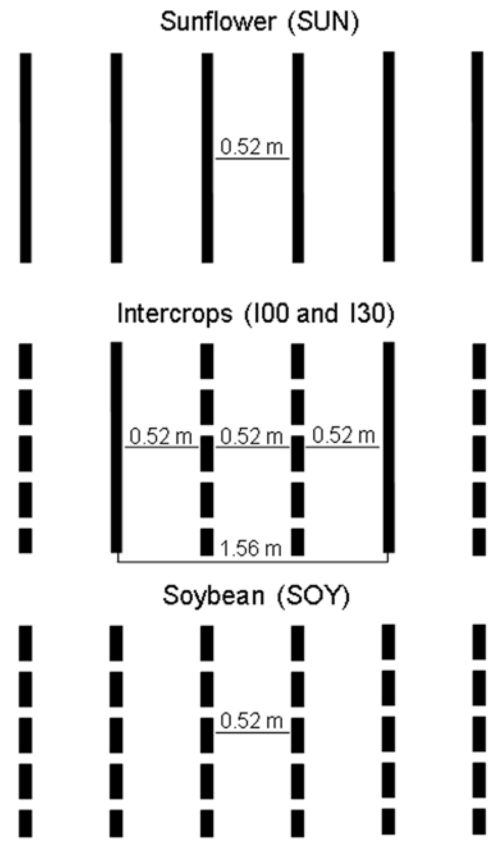

Fig. 1. Intercrops and sole crops row arrangement. Continuous lines represent sunflower rows and discontinuous lines correspond to soybean rows.

In Exp. 2 and 3, both soybean varieties were sown as sole crops. Unlike this, in Exp. 1, only SPS 4500 was evaluated as a sole crop. Results presented for SOY correspond to SPS 4500 variety since it corresponds to a maturity group widely used in the region and was evaluated in all experiments.

Intercropped and sole cropped sunflower and simultaneous intercropped soybean (A5009) were sown on 21 Oct. 2007 (Exp. 1) and 15 Oct. 2008 (Exp. 2 and 3). Soybean in relay intercrop and sole crop (SPS 4500) was sown on 18 Nov. 2007 (Exp. 1) and 15 Nov. 2008 (Exp. 2 and 3).

The amount of irrigation, applied with a sprinkler system, was 136, 333, and 0 mm for Exp. 1, 2, and 3, respectively. In all experiments, 30 kg P ha^{-1} were incorporated into the soil as superphosphate before sowing. Intercropped and sole cropped sunflower were fertilized by hand with 100 kg N ha^{-1} applied as urea along and close to sunflower rows at the V6 stage. Soybean seed was inoculated with *Bradyrhizobium japonicum* previous to sowing. Weeds were controlled with a manual hoe. Chemical control was necessary to regulate insect populations.

Measurements

Incident radiation, temperature, and rainfall during the growing season were measured at the meteorological station of INTA Balcarce, situated 400 m from the experimental site. Incident radiation was transformed to photosynthetically active radiation (PAR, Monteith, 1965).

Every week, crop phenological stages were recorded according to Fehr et al. (1971) scale for soybean and Schneiter and Miller (1981) scale for sunflower. Based on local information

(Andrade, 1995; Andrade and Ferreiro, 1996; Otegui and Andrade, 1998; Cantagallo et al., 2004) critical periods for grain set were assumed to be from: (i) R1 to R7 for sunflower and (ii) R4 to R6 for soybean.

Aboveground biomass production was estimated at physiological maturity. Plants of a known area (approximately 2 m^2) were cut at the soil surface level and oven-dried (60°C) until a constant weight was reached. To determine grain yield, entire plants of soybean and capitulums of sunflower were harvested, dried, and threshed in a static machine. Grain moisture percent was estimated with a hygrometer (Delver, Argentina). In all cases, harvested area varied between 5 and 10 m^2. Grain number and weight per grain were also measured. Grain yield was always expressed at 0% moisture content.

An estimation of productivity on an energy basis was made to compare grain yields among different treatments. The ratio used to convert grain yield to energy was 1.93 and 2.22 kg of glucose equivalent per kg of grain of soybean and sunflower, respectively (Penning de Vries et al., 1983; Andrade, 1995).

Intercrop productivity was also expressed as total relative grain yield (ryt), obtained from the sum of relative grain yields of sunflower (rysun) and soybean (rysoy) according to the following formulas.

$$\text{rysun} = \frac{\text{INTsun}}{\text{SUNy}}$$

$$\text{rysoy} = \frac{\text{INTsoy}}{\text{SOYy}}$$

$$\text{ryt} = \text{rysun} + \text{rysoy}$$

where INTsun and SUNy are intercropped and sole cropped sunflower grain yield, respectively; while INTsoy and SOYy are intercropped and sole cropped soybean grain yield, respectively. A ryt higher than 1 means that intercrop is more productive, in relative terms, than sole crops of its component species.

The interaction between the cropping system and the experiment was evaluated using a linear mixed-effect ANOVA. Relationships between variables were evaluated with regression analysis. All analyses were performed using R software (v 2.12.1, R Development Core Team, 2008).

RESULTS

Climatic Conditions

The cropping season in 2007/2008 presented similar mean temperatures but lower incident photosynthetically active radiation (PAR); whereas for 2008/2009, both incident PAR and temperature were slightly above the historical average during the entire season (Fig. 2a).

Historical rainfall (1930–2009) from September to April is 656 mm. During 2007/2008 rainfall was 903 mm (38% above historical average) and in 2008/2009 rainfall was 330 mm (50% below historical average, Fig. 2b). Large differences in rainfall between cropping seasons generated differences in irrigated water contribution to total water supply. In 2007/2008, irrigation was a complement of rainfall, while in 2008/2009 half of the water provided to crops came from irrigation, and was not

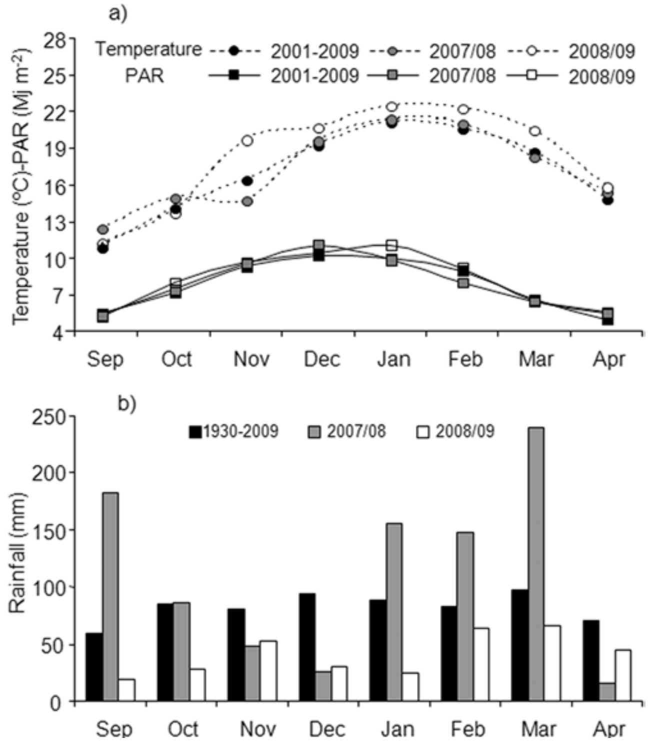

Fig. 2. (a) Average monthly temperature (circles, discontinuous lines, °C) and monthly incident photosynthetically active radiation (PAR, squares, continuous lines, Mj m^{-2}) at Balcarce from September to April of 2007/2008 (gray), 2008/2009 (white) and the average for the period 2001–2009 (black). (b) Monthly rainfall (mm), at Balcarce from September to April for 2007/2008 (gray) and 2008/2009 (white) and the average for the period 1930–2009 (black).

high enough to supply crops demand for the entire cropping season. In summary, from September to April, Exp. 1 received 1039 mm of water (136 from irrigation), Exp. 2 663 mm (333 from irrigation) and Exp. 3 only 330 mm (all from rainfall).

Crop Phenology, Biomass, and Grain Yield

Intercrops showed a longer growing season than their respective sole crops (I00: 161 d; I30: 162 d; SOY: 130 d and SUN 118 d when averaged across the three experiments). As it was proposed, critical periods for yield determination of intercropped soybean and sunflower were not overlapped (Fig. 3).

Sunflower development was similar among treatments in all experiments (Fig. 3). Soybean in I30 and SOY did not show phenological variations in Exp. 1 and 2. However, in Exp. 3 soybean in I30 extended its reproductive stage in relation to SOY. Although varieties of soybean used for I30 and I00 were from different maturity groups, critical periods took place at similar moments and reached maturity at the same time in all experiments (Fig. 3). Moreover, in Exp. 2 and 3, both soybean varieties as sole crops presented similar grain number ($p > 0.27$), weight per grain ($p > 0.41$), aboveground biomass and grain yield ($p > 0.31$ in Exp. 2 and $p > 0.17$ in Exp. 3). This indicates that variety selection was appropriate for the comparison purposes of our study.

Aboveground biomass varied between treatments for both species in all experiments, except for sunflower in Exp. 3 (Table 1). In general, soybean and sunflower biomass was lower in intercrops in comparison to sole crops. Intercropped soybean

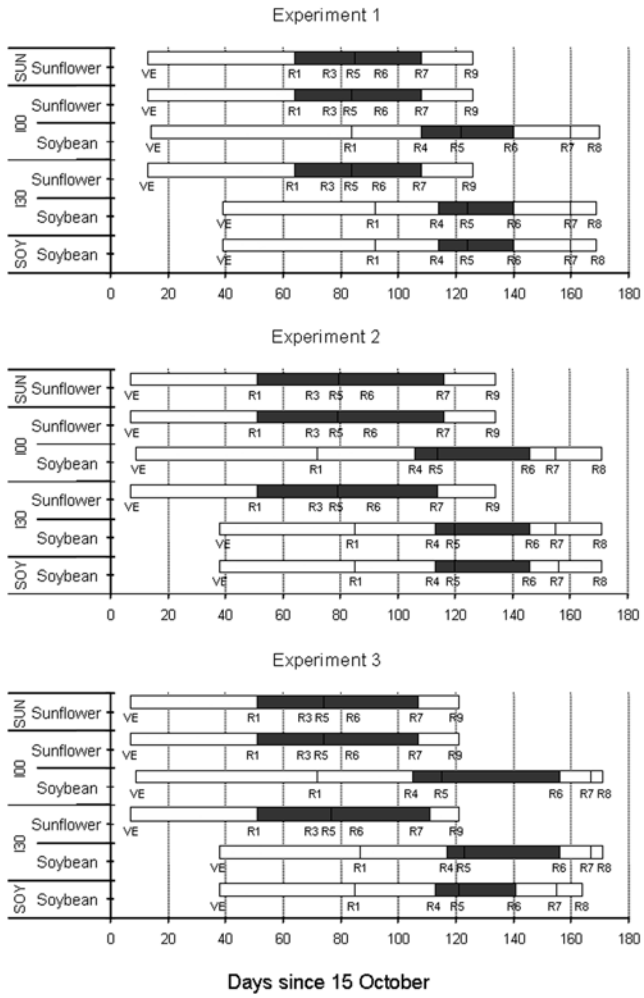

Fig. 3. Main phenological stages of sunflower and soybean in all experiments. Treatments are sunflower sole crop (SUN), soybean sole crop (SOY), simultaneous intercrop (I00), and relay intercrop (I30). The development scales employed were Schneiter and Miller (1981) for sunflower and Fehr et al. (1971) for soybean. Time is expressed in days since 15 October. Critical periods for grain set were assumed to be from: (i) R1 to R7 for sunflower and (ii) R4 to R6 for soybean; and are identified as dark bars (Andrade, 1995; Andrade and Ferreiro, 1996; Otegui and Andrade, 1998; Cantagallo et al., 2004).

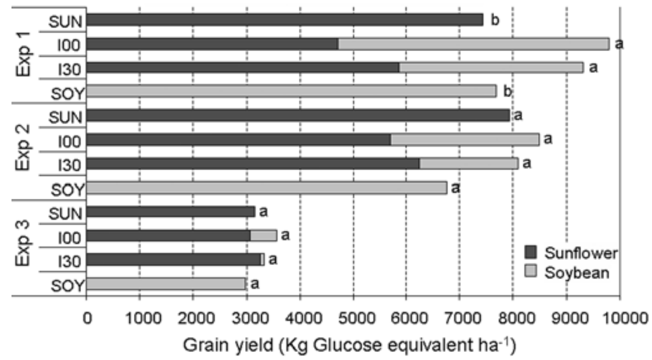

Fig. 4. Sunflower and soybean grain yield expressed as energy equivalents (kg glucose equivalent ha^{-1}) for all treatments and experiments. Treatments are sunflower sole crop (SUN), soybean sole crop (SOY), simultaneous intercrop (I00), and relay intercrop (I30). Different letters for one experiment represent significant differences (LSD, *p* < 0.05).

biomass increased in I00 compared to I30 (Table 1). Instead, sunflower biomass was reduced in I00 compared to I30 in Exp. 1 and 2, and presented no effect when water availability was severely restricted in Exp. 3 (Table 1). In I00 compared to I30, soybean biomass production increased 2361, 1678, and 792 kg ha^{-1} (75, 78, and 159%) in Exp. 1, 2, and 3, respectively; whereas sunflower biomass was reduced 1256, 1765, and 128 kg ha^{-1} (19, 17, and 2.5%) in Exp. 1, 2, and 3, respectively.

Soybean grain yield was higher for sole crop than for intercrops in all experiments (Table 1). These differences were mainly due to a lower number of seeds per unit area in intercrops. A trend occurred for yield of intercropped soybean in I00 to be higher than in I30. This tendency was only significant in Exp. 1 (Table 1, Fig. 4). Grain yield differences between intercropped soybean were mainly accounted by an increase in the weight per grain (Table 1).

Grain yield and seed m^{-2} for sunflower decreased when it was intercropped in Exp. 1 and 2, but not in Exp. 3. Intercropped sunflower grain yield was similar in I30 and I00, but in Exp. 1 sunflower grain yield in I30 was significantly higher than in I00. This difference was accounted by variations in the weight per grain (Table 1).

Figure 4 illustrates grain yield, expressed as glucose equivalents per hectare, for both species in all treatments and experiments. The combined analysis evidenced interaction effect between cropping systems and water availability on total grain yield ($p < 0.01$). The ANOVA within each experiment determined that grain yield was significantly higher for intercrops than for sole crops only in Exp. 1. Low water availability resulted in a reduction of the grain yield advantage of intercropping. Finally, intercropping sowing management did not affect total grain yield.

Intercrops Productivity Relative to Sole Crops

The bivariate graph (Fig. 5) illustrates and compares average relative grain yield of both intercropped species (Snaydon and Satorre, 1989). Discontinuous line from (0;1) to (1;0) with slope of −1 represents situations where intercrop ryt is equal to 1. Any dot above this line has a ryt higher than 1 and below it lower than 1. Lines I, II, and III are a reference of competition ability of both species among treatments and experiments. Line I describes situations where sunflower relative grain yield is three times larger than soybean relative grain yield and therefore a better competitor; line II represents situations where sunflower and soybean are equally competitive; and line III is the opposite of line I.

Total relative grain yield average of both sowing management were above the line with slope of -1 for all experiments. From these data, simultaneous and relay intercrop ryt for Exp. 1 and simultaneous intercrop ryt for Exp. 2 were statistically higher than 1 (confidence interval: 95%, Fig. 5).

Increases in water supply enhanced soybean relative grain yield ($p < 0.0001$, Fig. 6). Simultaneous sowing also resulted in a higher total and relative grain yield for intercropped soybean in Exp. 1, and tended to a higher total and relative grain yield for intercropped soybean in Exp. 2 and 3 (Table 1, Fig. 4). Both effects increased soybean competitive ability against sunflower, reflected in points moving to the right across line I and forward to line II, where both species showed equal competitive ability (I00, Exp. 1, Fig. 5).

Table 1. Aboveground biomass (kg ha^{-1}), harvest index (HI), grain yield (kg ha^{-1}), relative grain yield (ry), grain number (grains m^{-2}) and weight per grain (mg) for all experiments (Exp). Treatments (Trt) are sunflower sole crop (SUN), simultaneous intercrop (I00), relay intercrop (I30), and soybean sole crop (SOY). Different letters for one experiment mean significant differences (LSD, p < 0.05).

		Soybean						Sunflower					
Trt†	Exp.	Aboveground biomass	HI	Grain yield	ry	Grain number	Weight per grain	Aboveground biomass	HI	Grain yield	ry	Grain number	Weight per grain
		kg ha^{-1}		kg ha^{-1}		seed m^{-2}	mg	kg ha^{-1}		kg ha^{-1}		seed m^{-2}	mg
SUN	1	–	–	–	–	–	–	8,460a	0.39a	3306a	1.00	5156a	64.3a
I00	1	5496b	0.48b	2633b	0.66	1283b	205a	5,272c	0.40a	2128c	0.64	4218b	50.7c
I30	1	3135c	0.57a	1789c	0.45	1038b	172b	6,525b	0.40a	2639b	0.80	4406b	59.7b
SOY	1	9745a	0.41c	3989a	1.00	2405a	166b	–	–	–	–	–	–
SUN	2	–	–	–	–	–	–	12,159a	0.30a	3576a	1.00	5672a	63.0a
I00	2	3832b	0.38a	1444b	0.41	870b	166a	8,895c	0.27a	2569b	0.72	4229b	61.0a
I30	2	2154c	0.43a	950b	0.27	644b	147a	10,660b	0.29a	2817b	0.79	4380b	64.3a
SOY	2	8945a	0.39a	3502a	1.00	2197a	151a	–	–	–	–	–	–
SUN	3	–	–	–	–	–	–	4,723a	0.30a	1426a	1.00	3997a	35.7b
I00	3	1289b	0.21b	264b	0.17	210b	126a	5,051a	0.27a	1378a	0.97	3411a	40.3a
I30	3	497c	0.09c	40b	0.03	60b	67b	5,179a	0.29a	1471a	1.03	3573a	41.0a
SOY	3	4637a	0.34a	1552a	1.00	1215a	128a	–	–	–	–	–	–

† Abbreviations: Trt, Treatment; Exp., Experiment; HI, Harvest index; ry, relative grain yield.

On the other hand, as intercropped soybean enhanced its productivity, intercropped sunflower reduced its total and relative productivity at a lesser magnitude (Table 1, Fig. 4 and 6). The slope of ryt regression higher than –1 (m = –0.63, p = 0.0293, Fig. 5), indicates that the lower severity of competition over the suppressed component, the greater intercrop ryt. However, when intercropped soybean relative grain yield was largely affected, ryt was not lower than 1 (Exp. 3, confidence interval: 95%, Fig. 5 and 6).

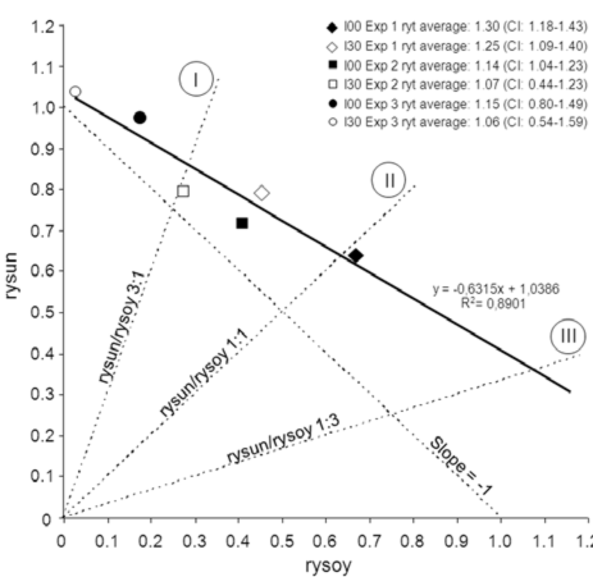

Fig. 5. Relative grain yield of intercropped sunflower in comparison to its sole crop (rysun) as a function of relative grain yield of intercropped soybean in comparison to its sole crop (rysoy) for all experiments. Iso-yield of intercrops against sole crops is illustrated as a discontinuous line with a -1 slope. Line I describes situations where sunflower relative grain yield is three times larger than soybean relative yield, and therefore a better competitor; line II represents situations were sunflower and soybean are equally competitives; and line III is the opposite of line I. Diamonds, squares, and circles symbolize treatments averages for Exp. 1, 2, and 3, respectively. Closed symbols represent simultaneous intercrop (I00) and empty symbols correspond to relay intercrop (I30). CI: confidence interval (95%).

DISCUSSION

Contrasting rainfall during both cropping seasons and the use of irrigation resulted in different scenarios of water availability. This allowed us to study the effect of two intercropping sowing managements across a gradient of water availability.

Intercrops extended the growing season compared with their respective sole crops. This has been previously associated with a larger capture of available resources (Caviglia et al., 2004; Coll et al., 2012). Critical periods for yield determination of intercropped sunflower and soybean occurred at different times during the cropping season, generally when the other component crop had a reduced demand for resources or had reached physiological maturity. Avoiding the overlapping of critical periods improves complementarities in the use of resources between intercrop components with positive implications on resources use efficiency (Fukai and Trenbath, 1993).

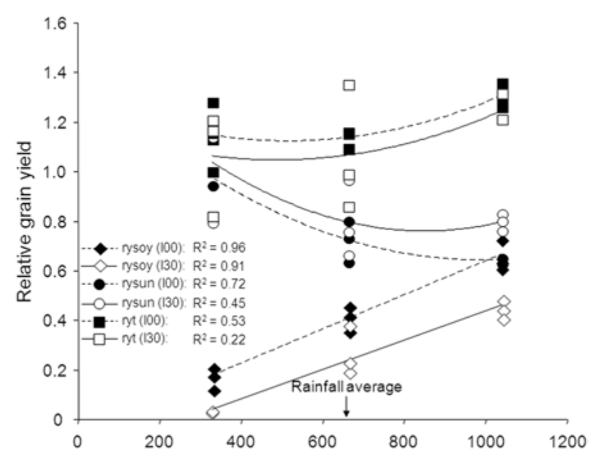

Fig. 6. Intercropped sunflower relative grain yield (rysun) and intercropped soybean relative grain yield (rysoy) in comparison to their sole crops and total relative grain yield (ryt) as a function of water supply (mm) for relay (I30, empty symbols, continuous line) and simultaneous sowing (I00, closed symbols, discontinuous line). Water supply includes rainfall and irrigation from September to April. Diamonds and circles correspond to intercropped soybean and intercropped sunflower respectively, squares represent ryt.

Competition for resources between intercrop components was evidenced by the reduction of productivity of each component compared with its corresponding sole crop. In addition, part of this reduction in productivity could be accounted by the limited ability of each intercrop component to capture resources that was imposed by the spatial arrangement (Andrade et al., 2002; Maddonni et al., 2006). For an extremely dry cropping season (Exp. 3), intercropped sunflower was as productive as sunflower sole crop because the low water consumption by a deteriorated intercropped soybean left water available to sunflower at reproductive stages (Hoag and Geisler, 1971; Robinson, 1978) and due to the photomorphogenetic sunflower responses that allowed for spreading of leaf area and relatively high capture of radiation (Lopez Pereira et al., 2008).

A comparative analysis among sowing managements of intercrops showed that intercropped sunflower presented a slight reduction and intercropped soybean a considerably increment in aboveground biomass in response to simultaneous sowing. These results are in accordance with those obtained by Kandel et al. (1997), who worked with intercropping of sunflower and several legumes.

In general, sunflower is a better competitor than soybean because of its high ability to capture water (Aguirrezábal et al., 1996) and radiation (Lopez Pereira et al., 2008). Simultaneous sowing clearly increased intercropped soybean aboveground biomass. This effect was larger as water availability increased; however, the benefits relative to relay intercropped soybean were larger as water availability decreased. Under scarce water scenarios, simultaneous sowing constituted a management alternative to increase soybean water uptake, with slight effects on sunflower performance because of its tolerance to water stress (Cox and Jolliff, 1986; Bremner et al., 1986). When water was less limiting (Exp. 1 and 2) soybean vegetative growth was less restricted, plants were taller and turned a better competitor for light than under relay sowing (data not shown), causing a significant reduction on intercropped sunflower aboveground biomass.

In agreement with Fisher (1977), the relative grain yield advantage of intercropping was higher as water availability increased during the growing season (Fig. 6). This was associated with an increase in intercropped soybean relative grain yield that overcompensate the decrease in sunflower relative grain yield, especially beyond 650 mm of water supply from September to April. Since 656 mm is the historical rainfall average for this period in Balcarce, irrigation constitutes an important practice to increase intercrop total relative grain yield (ryt). Furthermore, intercrop ryt was not lower than 1 when a water stress occurred during the cropping season (Fig. 6). In addition, under scarce water scenarios intercropping has a much lower probability of failure than the sole crop of its component species (Rao and Willey, 1980; Lithourgidis et al., 2011).

Simultaneous and relay sowing did not differ in total grain productivity. However, a consistent tendency occurred for simultaneous sowing productivity to be higher than relay sowing. Moreover, simultaneous sowing is a simpler option to promote the large-scale, fully mechanized sunflower–soybean intercropping in the southern Pampas compared with relay sowing because only one sowing operation is required (Calviño and Monzon, 2009).

The regression line fitted to the relation between relative grain yield of intercropped sunflower and intercropped soybean (Fig. 5) presented a slope higher than -1. This demonstrates that as intercropped soybean performance increased, ryt enhanced because of a proportionally higher increase in relative grain yield of soybean than the reduction in relative grain yield of sunflower. Therefore, in the light of our results, simultaneous sowing and high water availability aimed to stimulate soybean performance in the intercrop would improve intercrop ryt. These practices increase intercrop ryt by varying the competitive balance between the dominant and the suppressed component. Appropriate cultural manipulations can transfer availability of resources to the suppressed component and minimize luxury consumption of resources by the dominant component increasing resource use efficiency (Fukai and Trenbath, 1993).

CONCLUSIONS

Sunflower–soybean intercrop tended to be more productive than sole crops of its component species across three experiments performed in the southern Pampas. This tendency became significant as water availability during the cropping season was increased and was associated with an increase in the competitive ability and productivity of intercropped soybean.

We also assessed intercrop sowing management and found no effect on total intercrop productivity. However, our results indicate that management or agronomic practices that promote intercropped soybean performance increase total intercrop relative grain yield.

ACKNOWLEDGMENTS

Thanks to Emiliano Veliz and Diego Gaitan for excellent field assistance and Pablo Calviño for technical assistance.

REFERENCES

Aguirrezábal, L.A.N., G.A. Orioli, L.F. Hernández, V.R. Pereyra, and J.P. Miravé. 1996. Girasol: Aspectos fisiológicos que determinan el rendimiento, 1a ed. INTA-Balcarce, editor, Mar del Plata, Argentina.

Andrade, F.H. 1995. Analysis of growth and yield of maize, sunflower and soybean grown at Balcarce, Argentina. Field Crops Res. 41:1–12. doi:10.1016/0378-4290(94)00107-N

Andrade, F.H., P. Calviño, A. Cirilo, and P. Barbieri. 2002. Yield responses to narrow rows depend on increased radiation interception. Agron. J. 94:975–980. doi:10.2134/agronj2002.0975

Andrade, F.H., and M.A. Ferreiro. 1996. Reproductive growth of maize, sunflower and soybean at different source levels during grain filling. Field Crops Res. 48:155–165. doi:10.1016/S0378-4290(96)01017-9

Andrews, D.J., and A.H. Kassam. 1976. The importance of multiple cropping in increasing world food supplies. In: R.I. Papendic, A. Sanchez, and G.B. Triplett, editors, Multiple cropping. ASA Spec. Publ. 27. ASA, Madison, WI. p.1–10.

Bremner, P.M., G.K. Preston, and C. Fazekas de St. Groth. 1986. A field comparison of sunflower and sorghum in a long drying cycle. I. Water extraction. Aust. J. Agric. Res. 37:483–493. doi:10.1071/AR9860483

Calviño, P., and J.P. Monzon. 2009. Farming systems of Argentina: Yield constrains and risk management. In: V. Sadras and D. Calderini, editors, Crop physiology. Applications for genetic improvement and agronomy. Academic Press, Amsterdam. p. 55–70.

Cantagallo, J.E., D. Medan, and A.J. Hall. 2004. Grain number in sunflower as affected by shading during floret growth, anthesis and grain setting. Field Crops Res. 85:191–202. doi:10.1016/S0378-4290(03)00160-6

Caviglia, O.P., V.O. Sadras, and F.H. Andrade. 2004. Intensification of agriculture in the south-eastern Pampas I. Capture and efficiency in the use of water and radiation in double-cropped wheat-soybean. Field Crops Res. 87:117–129. doi:10.1016/j.fcr.2003.10.002

Coll, L., A. Cerrudo, R.H. Rizzalli, J.P. Monzon, and F.H. Andrade. 2012. Capture and use of water and radiation in summer intercrops in the southeast Pampas of Argentina. Field Crops Res. (in press).

Cox, W.J., and G.D. Jolliff. 1986. Growth and yield of sunflower and soybean under soil water deficits. Agron. J. 78:226–230. doi:10.2134/agronj1986.00021962007800020002x

Echarte, L., A. Della Maggiora, D. Cerrudo, V.H. Gonzales, P. Abbate, A. Cerrudo, V.O. Sadras, and P. Calviño. 2011. Yield response to plant density of maize and sunflower intercropped with soybean. Field Crops Res. 121:423–429. doi:10.1016/j.fcr.2011.01.011

Egli, D.B., and W.P. Bruening. 2005. Shade and temporal distribution of pod production and pod set in soybean. Crop Sci. 45:1764–1769. doi:10.2135/cropsci2004.0557

Fehr, W.R., C.E. Caviness, D.T. Burmood, and J.S. Pennington. 1971. Stage of development descriptions for soybeans, Glycine max (L.). Merrill. Crop Sci. 11:929–931.

Fisher, N.M. 1977. Studies in mixed cropping. I. Seasonal difference in relative productivity of crop mixtures and pure stands in the Kenya highlands. Exp. Agric. 13:177–184. doi:10.1017/S001447970000778X

Fukai, S., and D.J. Midmore. 1993. Adaptative research for intercropping. Field Crops Res. 34:459–467. doi:10.1016/0378-4290(93)90126-8

Fukai, S., and B.R. Trenbath. 1993. Processes determining intercrop productivity and yields of component crops. Field Crops Res. 34:247–271. doi:10.1016/0378-4290(93)90117-6

Hoag, J.A., and G.N. Geisler. 1971. Sunflower rows to protect fallow from wind erosion. N.D. Farm Res. 28:7–12.

Kandel, H.J., A.A. Schneiter, and B.L. Johnson. 1997. Intercropping legumes into sunflower at different growth stages. Crop Sci. 37:1532–1537. doi:10.2135/cropsci1997.0011183X003700050020x

Lithourgidis, A.S., C.A. Dordas, C.A. Damalas, and D.N. Vlachostergios. 2011. Annual intercrops: An alternative pathway for sustainable agriculture. Australian J. of Crop Sci. 5:396–410.

Lopez Pereira, M., N. Trapani, J.J. Casal, and A.J. Hall. 2008. Early response to high crop population density in sunflower: Controls and effects of the crop self-organization process. In: L. Velasco, editor, 17th International Sunflower Conference, Cordoba, Spain. 8–12 June 2008. Consejeria de Agric. y Pesca, Sevilla, Spain. p. 417 -422.

Maddonni, G.A., A.G. Cirilo, and M.E. Otegui. 2006. Row width and maize grain yield. Agron. J. 98:1532–1543. doi:10.2134/agronj2006.0038

Midmore, D.J. 1993. Agronomic modification of resource use and intercrop productivity. Field Crops Res. 34:357–380. doi:10.1016/0378-4290(93)90122-4

Molla, A., and R.K. Sharaiha. 2010. Competition and resource utilization in mixed cropping of barley and durum wheat under different moisture stress levels. World J. Agric. Sci. 6:713–719.

Monteith, J.L. 1965. Radiation and crops. Exp. Agric. 1:241–251. doi:10.1017/S0014479700021529

Ofori, F., and W.R. Stern. 1987. Relative sowing time and density of component crops in a maize/cowpea intercrop system. Exp. Agric. 23:41–52. doi:10.1017/S0014479700001113

Otegui, M.E., and F.H. Andrade. 1998. Physiology and modeling kernel set in maize. CSSA Spec. Publ. 29. CSSA, Madison, WI.

Penning de Vries, F.W.T., H.H. Van Laar, and M.C.M. Chardon. 1983. Bioenergetics of growth of seeds, fruits, and storage organs. In W.H. Smith and S.J. Banta, editors, Productivity of field crops under different environments. IRRI, Los Baños, The Philippines. p. 37–59.

Rao, M.R., and R.W. Willey. 1980. Evaluation of yield stability in intercropping: Studies on sorghum/pigeonpea. Exp. Agric. 16:105–116. doi:10.1017/S0014479700010796

R Development Core Team. 2008. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Robinson, R.G. 1978. Production and culture. In: J.F. Carter, editor, Sunflower science and technology. ASA, CSSA, and SSSA, Madison, WI. p. 89–143.

Schneiter, A.A., and J.F. Miller. 1981. Description of sunflower growth stages. Crop Sci. 21:901–903. doi:10.2135/cropsci1981.0011183X002100060024x

Snaydon, R., and E.H. Satorre. 1989. Bivariate diagrams for plant competition data: Modifications and interpretation. J. Appl. Ecol. 26:1043–1057. doi:10.2307/2403711