



Yield and Quality of Wheat and Soybean in Sole- and Double-Cropping

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ABSTRACT

In temperate environments, the wheat–soybean [*Triticum aestivum* L.–*Glycine max* (L.) Merr.] double-crop system often improves the capture and use efficiency of radiation and water in relation to single crops. Here we assessed the yield and quality of wheat and soybean in relay and sequential double-crops as compared with control sole-crops in the southeastern Pampas of Argentina during two seasons (2000/2001–2001/2002). Soybean controls included crops sown on optimum dates or on dates coincident with those of double-crops. Wheat grain yield and protein concentration were similar in both sowing arrangements of relay (skip row, where one wheat row out of four was unsown) and sequential (solid-seeded) double-crops (yield: 4070 vs. 4100 kg grain ha⁻¹; protein: 164 vs. g kg⁻¹). Yields of relay cropped soybean were 74 to 77% of their respective controls sown on the same date. In contrast, yields of sequentially cropped soybean were 85 to 110% of controls sown on the same date. The land equivalent ratio did not differ between cropping strategies and ranged from 1.58 to 1.82. In comparison to sole-crops, double-cropping increased grain yield and glucose equivalent yield by 58 to 82% and harvest residues by 91 to 143%. Late sowing reduced oil concentration of soybean seed in Year 2, when temperature during seed filling accounted for 58% of the variation in oil concentration. Early growing conditions were critical to the yield of double-cropped soybean. Management of the cropping system to increase soybean shoot biomass at first flower (R1) could further enhance the production and environmental benefits of double crops in temperate environments.

THE WHEAT–SOYBEAN DOUBLE-CROP system is widespread in many temperate and subtropical areas. The current harvested area is strongly unbalanced in many areas of South America in terms of the soybean/maize (*Zea mays* L.) ratio, which is as high as 5 to 6 in Uruguay and Argentina and 2 in Brazil (FAO, 2010). In South America, there has been a progressive simplification of the cropping systems, which has led to the dramatic increase in the proportion of soybean in the cropped area. Factors involved in this process include the availability of glyphosate-resistant transgenic soybean, the overwhelming adoption of no-till (Satorre, 2005), and the lower production cost of soybean as compared to cereals.

Cropping intensification, including wheat–soybean double-cropped, is becoming critical to improve economic and environmental outcomes of farming systems in the Pampas of Argentina (Calviño et al., 2003a; Caviglia et al., 2004). In the southern Pampas, the yield of late-sown soybean in double-cropping systems is severely restricted by the short frost-free period and the important decrease in the photoperiod and temperature that leads to a drastic reduction in seed number and weight per seed (Calviño et al., 2003a). Agronomic background and management alternatives

to mitigate yield reductions in late-sown, double-cropped soybean have been widely studied in our environment (Calviño and Sadras, 2002; Calviño et al., 2003a; Calviño et al., 2003b).

Double-cropped soybean can be sown using two cropping strategies: after wheat harvest (sequential) or into standing wheat during grain filling (relay intercropping). Previous research has shown that double-cropping improves the capture and efficient use of annual precipitation and photosynthetically active radiation (PAR) in comparison to single wheat and soybean crops (Caviglia et al., 2004). Although advantages of a wheat–soybean double-crop system in terms of the use of environmental resources are evident, the yield of its components could be dramatically reduced in relation to that of sole-crops. The reported drop in yield of wheat as a component of relay intercrops ranges from 4 to 35% (Chan et al., 1980; Duncan and Schapaugh, 1997; Porter and Khalilian, 1995). Yield losses of relay intercropped soybean in comparison to single crops range from insignificant to 73% (Duncan and Schapaugh, 1997; Jacques et al., 1997; McBroom et al., 1981b; Reinbott et al., 1987; Wallace et al., 1996). These reductions are related mainly to the length of the competition period and environmental conditions for soybean growth after wheat harvest. Soybean yield in late sowings is affected mainly by reductions in: (i) crop growth rate during the period when seed number (Egli and Bruening, 2000) and weight per seed (R5–R7, i.e., from beginning seed filling to beginning maturity) (Calviño et al., 2003a) are defined, and (ii) the duration of reproductive phases. Yield of late-sown soybean could be

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Abbreviations: CGR, crop growth rate; DC_{rel}, relay intercropped double-crop; DC_{seq}, sequential double-crop; IPAR, intercepted photosynthetically active radiation; LAI, leaf area index; LER, land equivalent ratio; PAR, photosynthetically active radiation; R1, first flower; R5, beginning seed filling; R7, beginning maturity; R8, full maturity; RUE, radiation use efficiency; RY, relative yield; SC_{opt}, soybean sole-crop sown on optimum date; SC_{rel}, soybean sole-crop sown on the same date as intercropped double-crop; SC_{seq}, soybean sole-crop sown on the same date as sequential double-crop.

further affected in a double-crop system by other factors, such as water and nutrient availability and the amount of wheat stubble. The combined effect of sowing date and double-cropping systems in a single experiment has not been yet explored.

Agronomic practices for wheat and soybean as components of a double-crop system have received substantial attention. For wheat, there are reports of the effects of N fertilization (Reinbott et al., 1987), spatial arrangement to allow sowing and cultivation of soybean (Crabtree and Rupp, 1980; Chan et al., 1980; Duncan and Schapaugh, 1997; Porter and Khalilian, 1995), and plant population and genotypes (Duncan and Schapaugh, 1997; Wallace et al., 1996). For soybean, there are studies on the effects of tillage systems (Crabtree et al., 1987; Crabtree and Rupp, 1980), genotype and cultivar blends (Jacques et al., 1997; McBroom et al., 1981a, 1981b; Board et al., 2003), sowing date and row spacing (Reinbott et al., 1987) and N fertilization (Taylor et al., 2005).

The mechanisms involved in the trade-offs between the yield of wheat and soybean as components of a double-crop system and the impact of double-cropping on grain quality have received less attention. Here, trade-offs will be investigated using the land equivalent ratio (LER), that is, the land area required for individual crops to produce the same yield as double-crops in a unit area. This is a useful and conceptually adequate indicator of performance of multiple crops in relation to sole-crops (Caviglia and Andrade, 2010).

Whereas double-cropping is expected to have little effect on wheat grain protein concentration, important changes are expected for soybean seed quality. The fall in seed oil concentration of late sown soybean (Kane et al., 1997b; Ray et al., 2008) may be related to reduced incident radiation during seed growth (Dosio et al., 2000). Moreover, soil water depletion by wheat could reduce canopy growth in double-cropped soybean, leading to further reduction in both radiation interception and seed oil content. The decline in seed oil concentration is likely to be associated with increased protein concentration (Wilcox, 1998).

The objective of this paper was to evaluate the growth, yield, and grain quality of the components of sequential and intercropped wheat–soybean double-crops in comparison with individual control crops. Our working hypotheses were that (i) a decrease in the initial growth of double-cropped soybean reduces its yield in relation to sole-soybean crops sown on the same date (controls), (ii) a decrease in the initial growth reduces soybean weight per seed and oil concentration and increases seed protein concentration of double-cropped soybean compared with sole-soybean crops at the optimum sowing date, and (iii) LER in relay intercropping is higher than in sequential cropping because of the greater soybean yield in the former cropping strategy.

MATERIALS AND METHODS

Site, Experiment, and Crops

Rainfed crops were grown at INTA Balcarce, Argentina (37°30' S, 58°12' W; 130 m above sea level) during two consecutive growing seasons from 1 May to 30 April in 2000–2001 (Year 1) and 2001–2002 (Year 2). Soils were fine, mixed, thermic Typic Argiudolls, with a depth \times 1.6 m. Cultivars were soybean, 'A3901RR' (Maturity Group III, glyphosate resistant), and spring wheat, 'PROINTA Imperial'. Fertilization was managed for maximum yield according to local guidelines. Wheat plots received 25 kg P ha⁻¹ before sowing and

120 kg N ha⁻¹ at early tillering. Soybean crops were inoculated with locally adapted *Bradyrhizobium japonicum* strains. Weeds and insects were adequately controlled when necessary.

Treatments were wheat–soybean double-cropped in sequential (DC_{seq}, soybean sown after wheat harvest) and relay intercropping (DC_{rel}, soybean sown into standing green wheat at mid-grain filling); sole soybean (SC) without a previous wheat crop sown on the optimum date (SC_{opt}), on the same date of the relay intercropping (SC_{rel}) and on the same date of the sequential crop (SC_{seq}). Wheat and sole soybean (SC_{opt}) were sown on dates close to optimum: 13 July 2000 and 24 July 2001 (wheat) and 18 Nov. 2000 and 19 Nov. 2001 (soybean). Relay intercropped soybean (DC_{rel}) was sown on 30 Nov. 2000 and 25 Nov. 2001, whereas sequential soybean was sown immediately after wheat harvest on 28 Dec. 2000 and 26 Dec. 2001. Seeding rates were 300 seeds m⁻² for wheat, 30 seeds m⁻² for soybean sole-crops (SC_{opt}, SC_{seq}; SC_{rel}), 45 seeds m⁻² for relay and 50 seeds m⁻² for sequential double-cropped soybean. Treatments were laid out in a randomized complete block design with three replicates. Two sowing arrangements were used for wheat: solid-seeded with 0.18 m spacing between rows in sequential double-crop, and skip rows, where one wheat row out of four was unsown to allow for later soybean sowing in relay intercrop. Distance between soybean rows was 0.66 to 0.70 m. Row orientation was east to west. Plots were 12 m long and 7 soybean rows width.

Measurements

Crop phenological stages of 10 wheat and five soybean tagged plants per plot were recorded weekly using the Zadoks et al. (1974) decimal code for wheat and Fehr and Caviness (1977) scale for soybean.

Soil water content was measured in both crops, weekly, gravimetrically in the upper soil layer (0–0.1 m) and with a neutron probe (Troxler 4300, Troxler Electronic Lab., Durham, NC) at 0.1 m intervals down to 1.0 and at 0.2 m intervals from 1.0 m down to 1.6 m.

Photosynthetically active radiation (PAR) interception was calculated as $[1 - (I_t/I_0)] \times 100$, where I_t is the PAR at ground level beneath the crop canopy and I_0 is the incident PAR at the top of the canopy. At least five measurements per plot were taken every 2 wk, in both crops, using a line quantum sensor (Model 191 SB, Li-Cor, Lincoln, NE) around noon (i.e., 1200–1400 h) on sunny days.

During the growing season, shoot biomass was measured in oven-dried (forced air at 60°C) samples taken, both at vegetative and reproductive (R1, R3, R5, R7) growth stages, from the central rows (0.7 m²) of each plot. Green leaf area was measured using a LICOR 3100 leaf-area meter (LICOR, Lincoln, NE). At physiological maturity, grain yield and shoot biomass were determined from samples of 3 m² from the central rows of each plot. We harvested the plots by hand and threshed the sample using a static machine. Individual grain weight was estimated by weighing two samples of 500 grains per replicate.

Soybean and wheat grains were milled and N concentration was determined using a Tecator Kjeltac Auto 1030 Analyzer (Tecator AB, Hoganas, Sweden) by a Kjeldhal microdistillation technique (Nelson and Sommers, 1973). Soybean seed oil concentration was determined by nuclear magnetic resonance using an NMR Analyzer Magnet Type 10 (Newport Oxford Instruments, Buckinghamshire, England).

Meteorological data were obtained from a weather station located 400 m from the experimental plots.

Calculations and Data Analysis

Crop evapotranspiration was calculated using a water balance based on measured soil water content and rainfall. Leaf area index (LAI) was calculated as the ratio between green leaf area and sample area. Crop growth rate (CGR) was estimated as the ratio of shoot biomass accumulated between two growth stages and the duration of the period. Soybean shoot biomass at R7 was estimated as dry matter of stems and pods at stage R8 (full maturity) plus leaves (lamina + petiole) at R5.5 (full leaf expansion) to account for foliar abscission. This procedure could underestimate total shoot biomass when water stress induces premature leaf senescence, as in Year 1.

Daily PAR interception was obtained from fitted polynomials ($0.93 < R^2 < 0.99$) that describe the dynamics of the measured PAR interception. Daily values of intercepted photosynthetically active radiation (IPAR) were obtained as a product of daily incident PAR (solar radiation \times 0.48) and daily PAR interception.

Lost time to growth (adapted from Goudriaan and Monteith, 1990) was estimated as days from crop emergence to 0.80 fractional PAR interception, rather than full interception, as some treatments did not reach full cover. The estimation of Lost time to growth from the exponential function proposed by Goudriaan and Monteith (1990) was unreliable, since it assumes that crops reach full interception and hence maximum CGR.

The radiation use efficiency was calculated as: (i) the slope of the linear regression between cumulative dry weight and intercepted radiation (IPAR) for a seasonal value and (ii) the ratio of cumulative shoot biomass and intercepted PAR between two growing stages, that is, R3–R5 or R5–R7.

The harvest index was calculated as the ratio between grain yield and shoot biomass at physiological maturity; in soybean, it indicates apparent harvest index (i.e., ratio of seed yield and stems plus pods at R8).

Total yield of the double-crop system was calculated as the sum of wheat and soybean yield in mass or glucose equivalents. Glucose equivalents were calculated using the measured protein content of wheat and the protein and oil content of soybean, and literature data for carbohydrates, ash content (Sinclair and de Wit, 1975), and production values (Penning de Vries, 1972).

The land equivalent ratio (LER) was estimated for each plot as the sum of relative yields (RY) of crop components (Eq. [1]), which in turn were calculated as ratios between yield in double-crops and yield in sole-crops sown on optimum dates (Eq. [2] and [3]) (Trenbath, 1976).

$$\text{LER} = \text{RY}_{\text{SOY}} + \text{RY}_{\text{WH}} \quad [1]$$

where RY_{SOY} and RY_{WH} are relative yield for soybean and wheat in double-crops, respectively. In turn, RY was calculated as:

$$\text{RY}_{\text{SOY}} = \frac{Y_{\text{SOYdc}}}{Y_{\text{SOYsc}}} \quad [2]$$

$$\text{RY}_{\text{WH}} = \frac{Y_{\text{WHdc}}}{Y_{\text{WHsc}}} \quad [3]$$

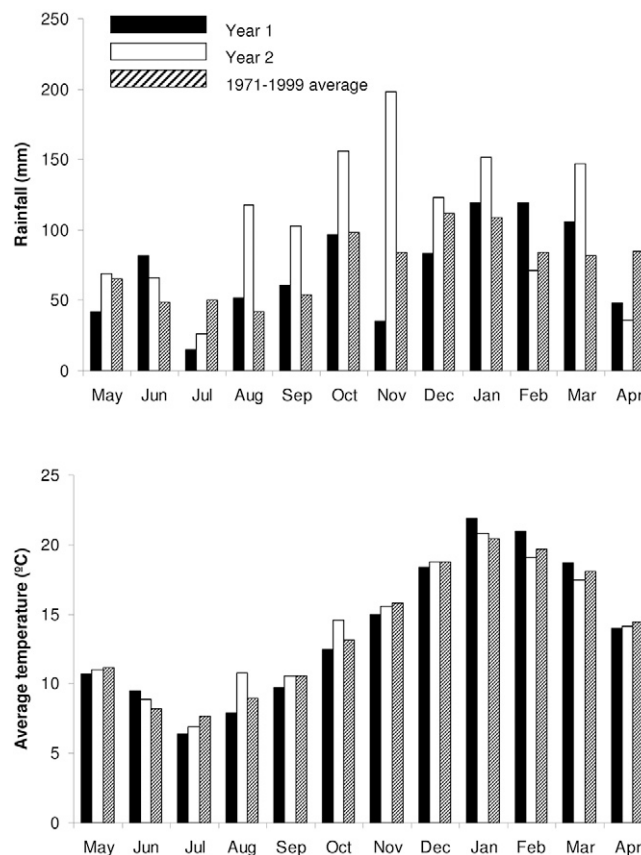


Fig. 1. Monthly rainfall and average temperature during Years 1 and 2 in Balcarce, Argentina (37°30' S latitude). Long-term averages are also shown for comparison.

where Y_{SOY} is soybean yield, Y_{WH} is wheat yield, and subscripts indicate sole (sc) or double crop (dc).

Treatment effects were assessed using PROC GLM included in the SAS package (SAS Institute, 2003) for each year. Replicates were considered as a random effect in the model. Tukey tests for means comparisons were performed when treatments effects were significant ($P < 0.05$).

Regression and correlation analysis were performed to study the relationships between variables, within years or across years, using PROC CORR and PROC REG (SAS Institute, 2003).

RESULTS

Environmental Conditions

Figure 1 summarizes rainfall and average temperature during the experiment. Analysis of daily rainfall patterns (not shown) indicated a severe drought in January-February of Year 1 resulting from low rainfall (61 mm) in relation to potential evapotranspiration (215 mm). The dry period ended on 29 February with a heavy rainfall of 97 mm.

Wheat: Growth, Yield, and Grain Protein

No obvious differences in phenological development were recorded between treatments. Although crops with the solid-seeded arrangement had greater LAI early (not shown), they did not differ from their counterparts with the skip-row arrangement in the amount of intercepted PAR (Fig. 2, Table 1). As a result of the lack of differences in intercepted PAR and RUE between spatial arrangements, there was no difference in shoot biomass production (Table 1).

Table 1. Intercepted photosynthetically active radiation (IPAR), radiation use efficiency (RUE), total shoot biomass production, grain yield, kernel number per unit area (KN), weight per kernel (WK), and protein of wheat crops in two spatial arrangements. Solid: traditional arrangement with 0.18 m between rows. Skip: one wheat row out of four was unsown to allow for soybean sowing in relay intercrop.

Crop variables	Year	Spatial arrangement†		SE
		Solid	Skip	
IPAR	Year 1	581	502	19
MJ m ⁻²	Year 2	613	562	11
RUE‡	Year 1	2.38	2.69	0.12
g MJ ⁻¹	Year 2	2.33	2.70	0.16
Shoot biomass	Year 1	13,437	13,179	730
kg ha ⁻¹	Year 2	14,605	14,384	795
Yield	Year 1	4,207	4,143	238
kg ha ⁻¹	Year 2	3,931	4,057	283
KN	Year 1	14,023	13,407	346
# m ⁻²	Year 2	10,799	11,238	639
WK	Year 1	30.0	30.9	1.1
mg	Year 2	36.4	36.1	0.5
Protein	Year 1	156	150	0.8
g kg ⁻¹	Year 2	171	156	0.4

† Means of Solid and Skip arrangement are not significantly different at $P < 0.05$ in each year. SE: standard error of the mean.

‡ RUE was calculated as the slope of the linear regression between cumulative dry weight and intercepted radiation (IPAR).

Grain yield, kernel number, kernel weight, and protein concentration were similar in both sowing arrangements (Table 1). Grain protein concentration was greater in Year 2, when crops were sown after soybean, than in Year 1, when they were grown after maize.

Soybean: Photosynthetically Active Radiation Interception, Biomass and Radiation Use Efficiency

Figure 3 shows the dynamics of LAI and PAR interception in soybean crops. At early crop stages, LAI was lower in DC_{rel} than in SC_{rel} in both years. Differences between double-cropped and sole soybeans, however, were not evident in late-sown crops, that is, there was no difference in early LAI between sequential (DC_{seq}) and sole soybeans (SC_{seq}). In Year 1, differences between DC_{seq} and SC_{seq} were evident only near maturity; in contrast, SC_{seq} had a higher LAI than DC_{seq} during the middle stages of the crop cycle (Fig. 3). The LAI was generally higher in SC_{rel} than in DC_{rel}, except late in Year 1.

Table 2. Lost time to growth, intercepted photosynthetically active radiation (IPAR) and radiation use efficiency (RUE†) of soybean crops during two growing seasons. SC_{opt}: sole-crop sown on optimum date; SC_{rel}: sole-crop sown simultaneously with intercropped double-crop, SC_{seq}: sole-crop sown simultaneously with sequential double-crop, DC_{rel}: relay intercropped double-crop, DC_{seq}: sequential double-crop.

Treatment	Crop description	Lost time		IPAR		RUE†	
		Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
		d		MJ m ⁻²		g MJ ⁻¹	
SC _{opt}	Sole, sown 18 or 19 Nov	64.0b‡	39.3d	607b	810a	1.37a	2.24a
SC _{rel}	Sole, sown 30 or 25 Nov	60.0b	45.0c	718a	705b	1.01a	2.21a
SC _{seq}	Sole, sown 30 or 25 Dec	55.0b	41.3d	482bc	602c	1.02a	1.81a
DC _{rel}	Double relay, sown 30 or 25 Nov	87.0a	95.3a	402c	428d	1.32a	2.34a
DC _{seq}	Double sequential, sown 30 or 25 Dec	60.0b	67.7b	333c	408d	1.35a	2.19a
SE		3.6	0.5	23.0	8.1	0.7	1.4

† RUE was calculated as the slope of the linear regression between cumulative dry weight and intercepted radiation (IPAR).

‡ Means followed by the same letter within a column are not significantly different at $P < 0.05$ (Tukey test). SE: standard error of the mean.

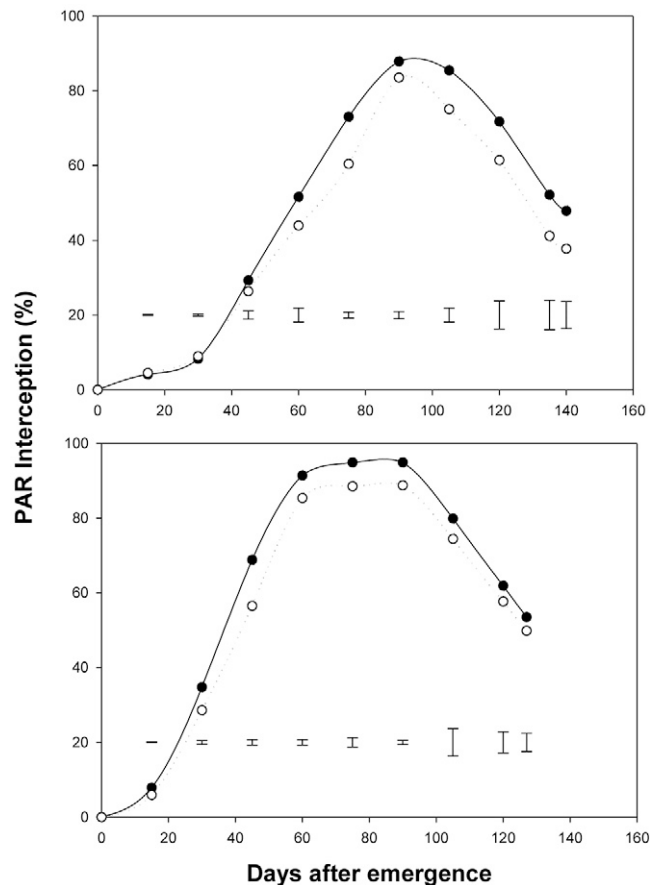


Fig. 2. Photosynthetically active radiation (PAR) interception of wheat crops in two spatial arrangements. Closed symbols, solid sowing at 0.18 m between rows; open symbols, skip treatment, where one wheat row out of four was unsown to allow for later soybean sowing in relay intercrop. Vertical bars indicate the standard error of the mean.

The total amount of intercepted PAR was higher in early-sown sole-crops (SC_{opt} and SC_{rel}) than in sequential and relay double-cropped soybean, irrespective of the cropping strategy (Table 2). In both years, double-cropped soybean (DC_{rel} and DC_{seq}) had lower PAR interception (Fig. 3) and IPAR than sole-crops. In Year 2, IPAR was reduced by delaying sowing date in sole-crops (Table 2, Fig. 3).

Lost time to growth was longest in relay intercropped soybean (DC_{rel}) (Table 2). Pooling all treatments and seasons, IPAR from emergence to R1 (first flower) and from emergence

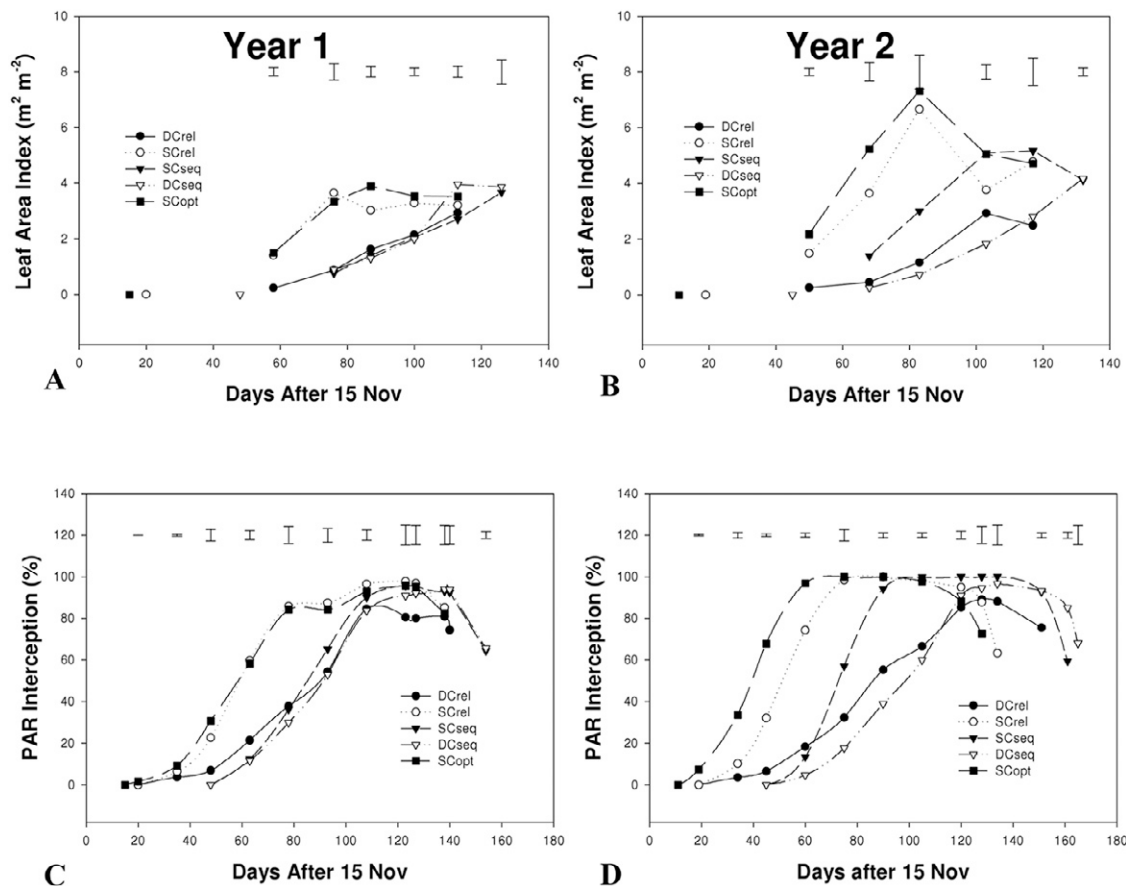


Fig. 3. (A, B) Leaf area index (LAI) and (C, D) photosynthetically active radiation (PAR) interception of soybean crops in 2 yr at Balcarce, Argentina. SC_{opt} : sole-crop sown on optimum date; SC_{seq} : sole-crop sown simultaneously with sequential double-crop, SC_{rel} : sole-crop sown simultaneously with intercropped double-crop, DC_{seq} : sequential double-crop; DC_{rel} : relay intercropped double-crop. Vertical error bars indicate standard error of the mean. Symbols on x axis (A, B) indicate time of crop emergence.

to R7 was negatively related to lost time to growth ($r^2 = 0.60$, $P < 0.009$ and $r^2 = 0.46$, $P < 0.04$, respectively).

Radiation use efficiency from emergence to R7 was not significantly different among treatments (Table 2). As a consequence, total shoot biomass production was strongly related to IPAR (Year 1: $r^2 = 0.69$, $P < 0.0002$; Year 2: $r^2 = 0.83$, $P < 0.0001$) and unrelated to RUE ($P > 0.40$, both years). Variation in RUE, however, contributed to the difference in shoot biomass production between years (Tables 2 and 3). Pooling all data, average temperature accounted for 38% ($P < 0.06$) of total RUE variation.

In Year 1, shoot biomass at R1 was highest in SC_{opt} and SC_{rel} and lowest in DC_{rel} and DC_{seq} (Table 3). In Year 2, shoot

biomass at R1 in double-crops was also markedly lower than in sole-crops. Owing to its effect on light interception, shoot biomass at R1 was more related to crop growth rate ($r^2 = 0.97$, $P < 0.0001$ in both years) than to the duration of the phase in days (Year 1: $r^2 = 0.25$, $P > 0.07$, Year 2: $r^2 = 0.05$, $P > 0.4$). For the pooled data, shoot biomass at R1 was closely related to evapotranspiration from emergence to R1 ($r^2 = 0.23$, $P < 0.007$), with weaker associations for individual years (Year 1: $r^2 = 0.30$, $P < 0.04$ and Year 2: $r^2 = 0.23$, $P < 0.07$). Shoot biomass at maturity was strongly related to shoot biomass at R1 ($P < 0.0001$ in both years) and to evapotranspiration from emergence to physiological maturity ($P < 0.0001$ in both years).

Table 3. Seed yield, shoot biomass at R1 (B_{R1}) and R8 (B_{R8}), seed number per unit area (SN) and individual weight per seed of soybean crops.

Treatments†	Yield		B_{R1}		$B_{R8}‡$		SN		Weight per seed	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
			kg ha ⁻¹				no. m ⁻²		mg seed ⁻¹	
SC_{opt}	3148a§	3489a	2160a	2719a	6046a	8225a	1691ab	1907a	186.1ab	183.0a
SC_{rel}	3564a	3304a	2570a	2435a	6940a	7597a	1866a	1851a	191.2a	178.5ab
SC_{seq}	2033c	2378b	1211b	2083a	4622b	5918a	1362c	1415b	149.4c	168.0bc
DC_{rel}	2636b	2536b	563b	361b	5155b	6956b	1661ab	1466b	158.9bc	173.0ab
DC_{seq}	2227bc	2025b	997b	920b	4962b	4792b	1573bc	1300b	141.4c	155.8c
SE	94	111	167	153	208	726	50	60	5.9	2.9

† SC_{opt} : sole-crop sown on optimum date; SC_{rel} : sole-crop sown simultaneously with intercropped double-crop, SC_{seq} : sole-crop sown simultaneously with sequential double-crop, DC_{rel} : relay intercropped double-crop, DC_{seq} : sequential double-crop.

‡ Shoot biomass at R8 does not include fallen leaves.

§ Means followed by the same letter within a column are not significantly different at $P < 0.05$ (Tukey test). SE: standard error of the mean.

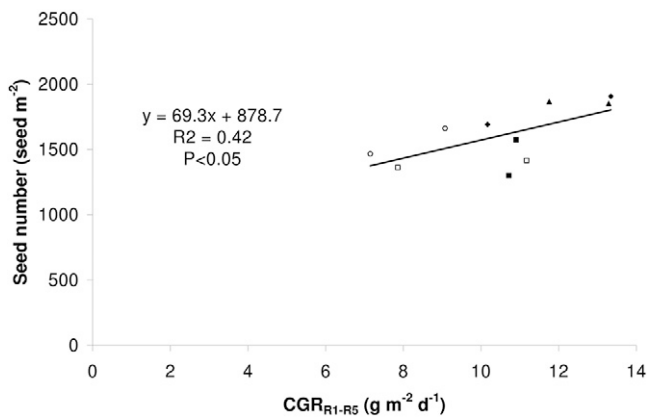


Fig. 4. Relationship between crop growth rate at the R1–R5 period (CGR_{R1-R5}) and seed number per unit area of soybean crops. SC_{opt} : sole-crop sown on optimum date, closed circles; SC_{seq} : sole-crop sown simultaneously with sequential double-crop, open squares; SC_{rel} : sole-crop sown simultaneously with intercropped double-crop, triangles; DC_{seq} : sequential double-crop, closed squares; DC_{rel} : relay intercropped double-crop, open circles.

Soybean: Seed Yield

In both years, seed yield was higher in SC_{opt} and SC_{rel} than in SC_{seq} (Table 3); these yield differences were directly related to both weight per seed ($P < 0.0001$; Year 1: $r^2 = 0.85$; Year 2: $r^2 = 0.74$) and seed number ($P < 0.0001$; Year 1: $r^2 = 0.77$; Year 2: $r^2 = 0.96$). The rate of decline in yield with delayed sowing was about 1.3% per day after 1 December for sole-crops and 0.5% per day for double-crops. Yield of relay double-crops was lower than that of their sole-crop counterparts, whereas the differences between sequential double-crops and their counterparts sown late in the season were negligible. In fact, compared with their respective sole-crops, the yield of relay intercropped soybeans ranged from 74 to 77%, whereas the yield of sequential cropped soybean ranged from 85 to 110%.

Crop growth rate during seed set period (CGR_{R1-R5}) and during seed-filling period (CGR_{R5-R7}) were related to IPAR in each period for the pooled data ($P < 0.0006$, $r^2 = 0.36$; $P < 0.0001$, $r^2 = 0.52$). Seed number was related to CGR for the pooled data (Fig. 4); although the correlations were slightly weaker for individual Years 1 ($P < 0.07$, $r^2 = 0.24$) and 2 ($P < 0.08$, $r^2 = 0.22$).

Seed yield was more closely related to shoot biomass at maturity ($P < 0.0001$; Year 1: $r^2 = 0.85$; Year 2: $r^2 = 0.71$) than to harvest index (Year 1: $r^2 = 0.48$, $P < 0.005$; Year 2: $r^2 = 0.40$, $P < 0.02$). In turn, seed number was more closely related to shoot biomass at R1 (Year 1: $r^2 = 0.30$, $P < 0.04$; Year 2: $r^2 = 0.49$, $P < 0.004$) than to CGR_{R1-R5} (Year 1: $r^2 = 0.25$, $P < 0.07$; Year 2: $r^2 = 0.22$, $P < 0.08$).

Pooling all data, seed yield was more closely related to IPAR during R1–R5 or R5–R7 than to CGR during those periods; IPAR during reproductive stages was, in turn, closely related to shoot biomass at R1, highlighting the important role of early growth on yield determination. There was a significant relationship between weight per seed and crop growth rate during the period of active seed growth (CGR_{R5-R7}) (Year 1: $r^2 = 0.37$, $P < 0.02$; Year 2: $r^2 = 0.53$, $P < 0.003$).

Soybean: Seed Composition

Treatments did not affect seed protein concentration. However, late sowing in Year 2 reduced seed oil concentration

(Table 4). In Year 2, oil content was directly related to seed yield ($r^2 = 0.67$, $P < 0.0003$) and negatively related to protein concentration ($r^2 = 0.49$, $P < 0.004$).

Relative Yield and Land Equivalent Ratio of Double-crops

Table 5 compares the performance of double-crops in relay and sequential systems. In both years, wheat relative grain yields were similar in relay and sequential strategies, whereas soybean yields relative to SC_{opt} were significantly higher in relay intercropping (0.73–0.84) than in their sequential counterparts (0.58–0.71). Despite the greater relative yield of soybean in relay intercropping, grain yield and glucose equivalent yield of double-crops did not significantly differ between both cropping strategies. Land equivalent ratios were large (>1.58) and not significantly affected by the double-cropping strategy (sequential- vs. relay-cropping) (Table 5).

Harvest Residue

Relay and sequential double-crops produced 91 to 143% more harvest residue than the average of sole-crops (Table 6). In double-crops, wheat contribution to total stubble was as much as 70 to 79%.

DISCUSSION

Yield of Wheat in Intercropping

The reported decrease in yield in wheat crops as affected by the sowing arrangement in relay intercrops ranges from 4 to 35% depending on the row spacing, the number of rows unsown, and the growing conditions (Chan et al., 1980; Duncan and Schapaugh, 1997; Porter and Khalilian, 1995; Wallace et al., 1996). In our experiments, wheat yield, its numerical components and protein content were unaffected by the sowing arrangement (Table 1). Lack of differences in biomass production and HI underlie this response. Compensation for reduced stand density in wheat is often associated with increased tillering and canopy growth (Satorre, 1999). In our study, there was an apparent trade-off whereby the slight reduction in PAR interception in skip rows was compensated by a small increase in RUE (Fig. 2, Table 1). Thus, in our experiment, the vegetative plasticity of wheat allowed skip crops to reach maximum PAR interception well before the critical preanthesis stage of spike growth (Fig. 2), explaining the lack of yield response to cropping arrangement.

Relationships between Yield and Growth Variables in Double- and Sole-Cropped Soybean

Yield in sole-crops decreased at a rate of 1.3% per day delay in sowing after 1 December; this rate is comparable to that reported by Calviño et al. (2003a). Yield reduction in comparison with their respective sole-crop controls was much higher in relay double-cropped soybean sown in late November (DC_{rel}) than in sequential double-cropped crops sown in late December (DC_{seq}). The consistently higher lost time to growth recorded in DC_{rel} could be related to initial shading by the wheat canopy with respect to DC_{seq} . Lost time to growth (Goudriaan and Monteith, 1990) is a useful concept for full-season crops only when they are able to reach full cover. Here we showed that this concept was useful for late-sown crops, which are unlikely to reach full canopy cover. Moreover, lost

time to growth was strongly associated with shoot biomass at R1, which was, in turn, associated with key yield components.

We used the same Maturity Group of soybean (GM III) irrespective of the cropping strategy and sowing date. A better adjustment of the maturity group to the sowing dates may have resulted in less yield reduction of relay intercrops in comparison to timely-sown sole-crops. The results are therefore conservative for relay intercropping, as they could underestimate soybean yield, because a longer-season genotype could contribute to enlarging the vegetative period and increasing shoot biomass at R1 and therefore PAR interception. Long-term simulations have shown that relay soybean out-yielded its sequential counterpart by approximately 20% and emphasized the role of practices to anticipate the sowing date of sequential soybean (Monzon et al., 2007).

The reported yield of relay intercropped soybean is often lower than that of sole-crop controls (McBroom et al., 1981a; Reinbott et al., 1987; Duncan and Schapaugh, 1997; Jacques et al., 1997). Wallace et al. (1992) found reduced initial LAI and shoot biomass in relay intercropping as compared to sole-crop, which is consistent with our results. In that study, however, these early differences decreased rapidly after a short competition period of 14 to 19 d. The effect of low latitude (34°N), high water availability (500–700 mm rainfall+irrigation) and genotype (MG VII) are factors that probably contributed to offset differences in initial growth.

A previous work with late-sown soybeans, using row spacing as a source of variation, highlighted the need to reach an early canopy closure to maximize yield (Board and Harville, 1998). Likewise, higher yields commonly obtained by cultivars of higher Maturity Group could be related to a long vegetative period, and therefore to an increased probability to reach full canopy cover. For example, in Louisiana (30° N latitude), in contrast to Oliveros (Argentina, 32°30' S latitude) higher yields of late-sown soybean were obtained with cultivars of longer Maturity Group (Board et al., 2003). This could be attributed to a shorter vegetative period at Louisiana driven by higher temperatures during the cropping season than in Oliveros. Similarly, results obtained by Holshouser and Whittaker (2002) in southeast United States suggest that the higher yield of long MG affected by early drought could be related to a longer vegetative period that increases the probability to reach a complete canopy cover.

Consistent with previous studies that also included late-sown soybeans (Egli and Bruening, 2000; Kane et al., 1997a), we found a weak association within years, and between the crop growth rate during seed set period (R1–R5) and the seed number (see section Soybean: Seed yield). In contrast with other reports (e.g., Egli and Bruening, 2000), we found that the crop growth rate during active reproductive growth (CGR_{R5-R7}) was strongly related to seed yield through its effect on weight per seed. The CGR_{R5-R7} was related to both intercepted PAR and RUE during the same period. In turn, IPAR_{R5-R7} was associated with both incident PAR during the R5–R7 period and shoot biomass at R1. Shoot biomass at R1 is used here as a useful and intuitive indicator of PAR interception at the onset of the critical period. In fact, seed yield was closely related to IPAR during R1–R5 or R5–R7, which in turn was related to shoot biomass at R1. Consequently, agronomical practices oriented to increase early crop growth, shortening the

Table 4. Oil and protein concentration of soybean seeds in two seasons at Balcarce. SC_{opt}: sole-crop sown on optimum date, SC_{rel}: sole-crop sown simultaneously with intercropped double-crop, SC_{seq}: sole-crop sown simultaneously with sequential double-crop; DC_{rel}: relay intercropped double-crop, DC_{seq}: sequential double-crop.

Treatments	Oil concentration		Protein concentration	
	Year 1	Year 2	Year 1	Year 2
	g kg ⁻¹			
SC _{opt}	202a†	199ab	385a	370a
SC _{rel}	200a	209a	387a	360a
SC _{seq}	198a	191bc	395a	379a
DC _{rel}	192a	187bc	387a	388a
DC _{seq}	186a	181c	406a	388a
SE	57	24	75	82

† Means followed by the same letter within a column are not significantly different at $P < 0.05$ as determined by Tukey's test.

SE: standard error of the mean.

Table 5. Relative yield (RY) of wheat and soybean as components of double-crops, land equivalent ratio (LER), total grain yield and glucose equivalent yield (Glueq) per unit area and time of relay intercropped (DC_{rel}) and sequential (DC_{seq}) double-crops in two seasons at Balcarce.

Cropping system	RY† Wheat	RY Soybean	LER	Total yield‡		Glueq§
				kg ha ⁻¹ yr ⁻¹		
	Year 1					
DC _{rel}	0.98a¶	0.84a	1.82a	6779a	10005a	
DC _{seq}	1.01a	0.71b	1.72a	6434a	9371a	
SE	0.09	0.02	0.07	102	338	
	Year 2					
DC _{rel}	1.03a	0.73a	1.76a	6593a	9718a	
DC _{seq}	1.00a	0.58b	1.58a	5956a	8658a	
SE	0.04	0.002	0.07	117	374	

† Relative yields were calculated as the ratio between yield of double-cropped wheat or soybean and yield of sole-crop.

‡ Total yield represents the sum of grain yield of wheat and soybean in double-crops.

§ Glucose equivalent yield (Glueq) was calculated based on the grain composition of wheat and soybean.

¶ Means followed by the same letter within a column are not significantly different at $P < 0.05$ as determined by Tukey's test. SE: standard error of the mean.

Table 6. Total harvest residue and wheat contribution to stubble production in sole and double-crops. SC_{opt}: sole-crop sown on optimum date; SC_{rel}: sole-crop sown simultaneously with intercropped double-crop, SC_{seq}: sole-crop sown simultaneously with sequential double-crop; DC_{rel}: relay intercropped double-crop, DC_{seq}: sequential double-crop.

Crops	Harvest residue†	
	Year 1	Year 2
	kg ha ⁻¹ yr ⁻¹	
Wheat		
Solid	9,231a‡	10,674c
Skip	9,036a	10,328c
Soybean		
SC _{opt}	2,898b	4,736c
SC _{rel}	3,375b	4,293c
SC _{seq}	2,589b	3,540c
Double-crops		
DC _{rel}	11,555a	14,748b
DC _{seq}	11,966a	13,441a
SE	817	960

† Harvest residues were calculated as the difference between shoot biomass at maturity and yield, and do not include fallen leaves for soybean crops.

‡ Means followed by the same letter within a year are not significantly different at $P < 0.05$ (Tukey test) SE: standard error of the mean.

lost time to growth seems to be critical to manage late planted soybean under double-cropping systems in our region.

In Year 2, the duration of the seed set period (i.e., R1–R5) was at least as critical as the crop growth rate during that stage, in agreement with previous results (Egli and Bruening, 2000; Kantolic and Slafer, 2005; Calviño et al., 2003a).

The range of CGR_{R1-R5} in our crops (7.1 – 13.3 $g\ m^{-2}\ d^{-1}$) was somewhat lower than the ranges reported by Kane et al. (1997a) (8.1 – 17.4 $g\ m^{-2}\ d^{-1}$) and Egli and Bruening (2000) (11 – 19 $g\ m^{-2}\ d^{-1}$) in Kentucky (38° N latitude). The lower temperatures of our environment, located at a latitude similar to Kentucky, could contribute to these differences (Calviño et al., 2003a).

Relationships between Yield and its Components in Double- and Sole-Cropped Soybean

There was a strong, positive association between seed number and weight per seed (Year 1: $r^2 = 0.40$, $P < 0.02$; Year 2: $r^2 = 0.58$, $P < 0.002$). This is consistent with the model of simultaneous determination of seed number and potential weight per seed (Sadras, 2007; Sadras and Denison, 2009). Calviño et al. (2003a) also found a positive relationship between these variables for data pooled over seasons, but inconsistent associations for individual seasons. Reduced weight per seed reflected unfavorable environmental conditions as well as a limited ability of crops to sustain seed growth through reserve remobilization. The association between CGR_{R5-R7} and shoot biomass at R1 can be interpreted in terms of unfavorable conditions to accumulate shoot biomass at early developmental stages in double-crops. In addition, double-crops (DC_{seq} and DC_{rel}) had less biomass at R1 (Table 3), thus reflecting the reduction in vegetative growth associated with early reproductive development (Leonard, 1962), which eventually contributed to lower assimilate supply during seed filling. Conditions favoring shoot biomass accumulation at R1 could mitigate, in consequence, shortage of assimilate typical of late plantings

Soybean Seed Composition

Seed oil concentration of soybean in double-crops was lower than in early-sown sole-crops, particularly in Year 2. Oil concentration was not related to shoot biomass at R1 or CGR_{R5-R7} but to mean temperature during seed filling in Year 2.

Oil concentration of soybean seed decreases with temperatures below 20°C (Piper and Boote, 1999). Consistently, we found that temperature accounted for 58% of the variation in oil concentration in Year 2 ($P < 0.002$). The average temperature during seed filling was 19.0°C in early sole-crop (SC_{opt}) and 15.3°C in sequential double-crop (DC_{seq}), emphasizing the importance of the sowing date on this quality trait. This is also consistent with the results by Kane et al. (1997b), who reported increased protein concentration and reduced oil concentration in delayed sowings.

CONCLUSIONS

We demonstrated that, irrespective of whether soybean was sequentially or relay intercropped, double-crops outyielded sole-crops by 58 to 82% (LER, Table 5). Wheat relative yield was not different between the two cropping systems. Soybean relative yield was higher in relay than in sequential intercropping but differences were not enough to improve LER (Table 5). Jacques et al. (1997) reported LER between 1.75 to 2.18, depending

on the genotype and blend; these values are larger than those found in our study. Total double-crop yield expressed as glucose equivalent and gross income did not differ between modes of double-cropping; this was related to the important contribution of wheat to the total system production. Our environment has the most favorable photothermal quotient (Fischer, 1985) of the Pampas, which is conducive to the highest wheat yield potential (Magrin et al., 1993). Whereas this environment is well suited for wheat, there are important constraints for late-sown soybean, as discussed here and in previous studies (Calviño et al., 2003a, 2003b). With decreasing latitude, there is a reversal of conditions, that is, more favorable for late-sown soybean and less favorable for wheat. Thus, direct evaluation of the environmental and management factors influencing the performance of double-crops and its components is required in each condition.

Compared to sole-crops, double-crops are better able to capture rainfall and radiation and to exploit a greater fraction of the potential environmental productivity (Caviglia et al., 2004). Here we showed an enhanced return of crop residues to the soil, which may benefit soil condition and provides additional sink for atmospheric CO_2 (Caviglia and Andrade, 2010). Crop intensification can help improving spatial and temporal diversity compared with systems relying on fewer, dominant crops such as soybean in South America.

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