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Maize–soybean intensification alternatives for the Pampas

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ABSTRACT

Cultivating multiple crops as a land use alternative could increase system productivity and sustainability, providing options to soybean monoculture for the Argentinean Pampas. This study evaluates the performance of maize–soybean in double crop, relay crop and intercrop across a wide range of water supply and length of growing season in the Pampas. It also assesses the effect of maize cycle length and maize and soybean prices on these intensification alternatives. A total of 16 experiments, 6 rainfed and 10 irrigated, were conducted at four INTA Research Stations during five growing seasons. Yield ranged from 4390 to 16,862 kg ha^{-1}, for sole maize crops, and from 1884 to 5130 kg ha^{-1}, for sole soybean crops. The intensification alternatives productivity, measured as the land equivalent ratio (LER), was associated to the length of the growing season and was higher than 1.00 in 100%, 86% and 61% of the cases for maize–soybean double crop, relay crop and intercrop, respectively. Maize grain yield in double crop was similar to that of sole maize crop, whereas soybean yield in double crop was reduced compared to that of sole soybean crop due to sowing date delay. Maize and soybean grain yields under relay crop and intercrop were lower than their respective sole crops. The intercrop increased soybean yield and decreased maize yield compared with relay crop. Yield of soybean in intercrop and relay crop increased when sown with short cycle length maize hybrids. Maize and soybean sole crop yields were positively correlated ($P < 0.01$, $r = 0.82$). However, a negative correlation was found between maize and soybean yields for intensification alternatives under irrigated conditions ($P < 0.01$, $r = -0.68$), but not under rainfed conditions. The intercropping alternatives under rainfed conditions could reduce farm risk, due to the similar economic results with soybean sole crop, and the lack of correlation between soybean and maize yields.

1. Introduction

Soybean (*Glycine max* L. Merill) is the main rainfed crop of Argentina (Calviño and Monzon, 2009). The area cropped with soybean increased from 1.9 to 19.7 million hectares in the period 1980/1981–2012/2013 (Integrated Agricultural Information System, http://www.siia.gov.ar) representing around 70% of the cultivated area in the last three seasons. The trend to soybean monoculture is becoming a risk to system sustainability, with an increasing concern for soil deterioration and economic dependence (Viglizzo et al., 2011; Volante et al., 2012). Conversely, global agricultural production must increase up to 70% to keep pace with global food demand driven by population and income growth (Bruinsma, 2009; Van Ittersum et al., 2013). This agricultural challenge needs to take into account environmental concerns, i.e. increase grain production while maintaining farm sustainability (Bruinsma, 2009).

There are different strategies to increase grain production in the current cropping area. In locations with long growing seasons a clear and feasible way is to use cultivars with a longer than actually used crop cycle length (Capristo et al., 2007). But this does not necessarily means an increased grain yield, because the extra resources available in long growing seasons are not always converted into grain yield (Egli, 2011). Another option to intensify the use of agricultural land consists of sowing two or more crops per

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season as double crops, relay crops or intercrops (Caviglia et al., 2004; Neto et al., 2010; Coll et al., 2012). In Argentina, the double crop of soybean after the harvest of a winter cereal is a common practice (Caviglia et al., 2004). For summer species, one option is the double crop, that consists of maize (*Zea mays*) or sunflower (*Helianthus annuus*) followed after harvest by soybean as a second crop. However, the limited length of the growing season restricts this option for most cropping regions of Argentina (Hall et al., 1992).

An alternative to double crop of summer species consists in maize or sunflower intercropped 40–60 days after sowing, with soybean reducing the growing season length requirement (relay crop, Echarte et al., 2011; Andrade et al., 2012; Coll et al., 2012). The use of maize in these systems ensures a high biomass production, which contributes to maintaining the soil carbon balance (Oelbermann and Echarte, 2011).

In any intensification alternative that involves two or more crops, the reduced yield of individual crop components can be counterbalanced by an increase in total grain yield on an annual basis (Evans, 1993). Intercropping usually reduces the yield of soybean (suppressed crop) more than the yield of maize (dominant crop). Coll et al. (2012) suggested that management practices oriented to increase soybean competitive ability would result in a proportionally greater yield increase for soybean than a yield reduction for maize with an overall improvement in relay crop performance. There are several options to reduce severity of maize competition in order to improve productivity. For instance, reducing plant density in maize has resulted in a 5% increase of productivity in a maize–soybean relay crop (Echarte et al., 2011). Other promising options to increase productivity in maize–soybean intensification alternatives are (i) soybean sowing date adjustment and (ii) the use of short cycle length maize hybrids. In both options, the goal is to separate the critical periods for grain yield determination of both components in order to reduce interspecific competition and maximize productivity.

Climatic conditions, which vary widely across the Pampas of Argentina, are a key factor for the success of maize–soybean intensification alternatives. The frost free period increases mainly from south to north, and also from west to east, with temperature following a similar pattern. Rainfall increases in a northeast direction, and rainfall pattern is monsoonal in the west and becomes more isohydrous toward the east of the region (Hall et al., 1992; Calviño and Monzon, 2009). Accordingly, the feasibility of summer intensification alternatives could be regionally conditioned by climatic conditions.

The objectives of this work were to study the effect of soybean sowing date and maize hybrids of different cycle length on grain yield productivity of maize–soybean intensification alternatives for different environments across a wide range of water supply and length of growing season in the Pampas of Argentina.

2. Materials and methods

2.1. Experimental locations

A total of 16 experiments were conducted in Argentina at the INTA (National Institute of Agricultural Technology) research stations of Balcarce (−37.7°, −58.2°, 130 m above mean sea level, m), Pergamino (−33.9°, −60.6°, 56 m), Manfredi (−31.8°, −63.8°, 360 m) and Paraná (−31.5°, −60.3°, 77 m) during five growing seasons, from 2004/2005 to 2008/2009 (Fig. 1, Table 1). Soils were a loam Petrocalcic Argiudol (USDA Soil Taxonomy) constrained by a hardened layer of calcium carbonate at 0.7–1.6 m depth at Balcarce; a silty loam Typic Argiudol at Pergamino; a silty loam Entic Haplustol at Manfredi; and a silty loam Acuic Argiudol at Paraná.

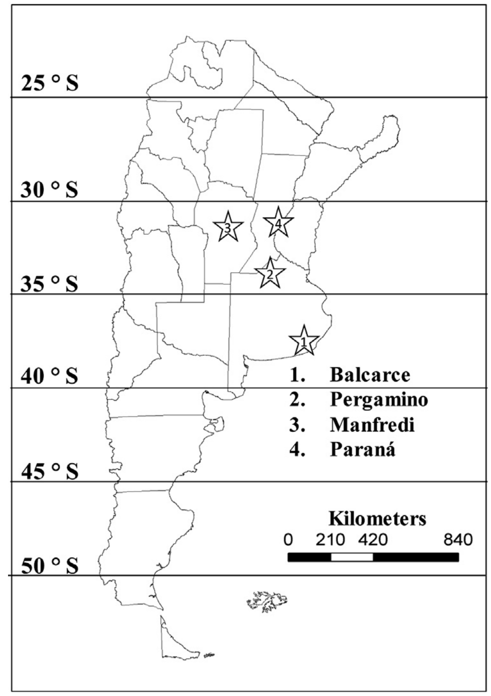

Fig. 1. Map of Argentina showing the locations where experiments were conducted.

Experiments were irrigated to avoid all water stresses at Pergamino and Balcarce.

2.2. Crop management

The experiments evaluated crops of maize and soybean, as sole crop treatments, with one to three intensification alternatives: (i) soybean sown after maize, “double crop”; (ii) soybean sown 40–60 days after maize sowing (maize at V6–V8, Ritchie and Hanway, 1982), “relay crop”; and (iii) maize and soybean sowing simultaneously (or with a maximum sown delay of eight days), “intercrop”. Table 2 indicates for all the locations the sowing date of maize and soybean for intensification alternatives. Row spacing was 0.52 m for sole crop, double crop, relay crop and intercrop; and the arrangement in relay crop and intercrop was two rows of soybean per row of maize (1.56 m between maize rows). See Coll et al. (2012) and Echarte et al. (2011) for schematic representations. These intensification alternatives were combined with three maize hybrids that differed in their cycle lengths (relative maturity (RM) of 120, 100 and 90). Different maize hybrids were sown depending on location and year, most of them were glyphosate resistant. The RM120 hybrid was planted as the maize sole crop treatment, which is in accordance with the common farmer practice; the exception was Balcarce during 2008/2009 season where the RM100 hybrid was used as sole crop (see bold letters in Table 3). Soybean cultivars adapted to each location were selected, varying from maturity group (MG) IV at Balcarce to MG VII at Manfredi and all of them were glyphosate resistant. The soybean MG used in the intercrop treatment was longer compared to relay crop in order to maintain the gap between maize and soybean critical periods for grain yield determination. The double crop was only tested at Pergamino 2007/2008 and 2008/2009 (under irrigation) and at Manfredi 2007/2008 (rainfed). This treatment was not evaluated at Balcarce because of the short growing season of this location, and in Paraná and Manfredi in 2008/2009 season because summer rainfall pattern prevented soybean sowing.

Crops were manually sown and we used a conventional tillage system. Plant densities for sole maize crops were 8.0, 8.8 and

Table 1
Meteorological description for different locations and seasons in the Pampas of Argentina. LF, last frost and FF, first frost.

Location	Season	Last frost (LF)[a]	First frost (FF)[a]	Growing degree days from LF to FF[b]	Solar radiation from LF to FF ($MJ\,m^{-2}$)	Rainfall from LF to FF (mm)	Water management
Balcarce	2004/2005	01/10/2004	04/04/2005	1926	3690	384	Irrigated
	2005/2006	08/11/2005	18/05/2006	1775	3495	491	Irrigated
	2006/2007	18/11/2006	10/05/2007	1866	3118	749	Irrigated
	2007/2008	16/11/2007	03/05/2008	1836	3248	600	Irrigated
	2008/2009	08/10/2008	30/05/2009	2513	4260	392	Irrigated, rainfed
Pergamino	2004/2005	28/10/2004	26/04/2005	2229	3612	617	Irrigated
	2005/2006	18/09/2005	05/05/2006	2665	4311	673	Irrigated
	2006/2007	24/09/2006	07/05/2007	2750	4160	1124	Irrigated
	2007/2008	25/09/2007	14/04/2008	2555	4108	487	Irrigated
	2008/2009	15/09/2008	15/05/2009	3206	4882	655	Irrigated
Manfredi	2007/2008	14/11/2007	13/04/2008	2066	3344	474	Rainfed
	2008/2009	05/10/2008	04/05/2009	2765	4146	472	Rainfed
Parana	2004/2005	22/09/2004	25/05/2005	3177	4815	1056	Rainfed
	2007/2008	27/08/2007	14/04/2008	3129	4646	591	Rainfed

[a] Minimum day temperature at 1.5 m below 2 °C.
[b] Calculated on a 8 °C base temperature.

9.9 pl m^{-2} for RM 120, 100 and 90 respectively. In relay crop and intercrop, maize plant density was 5.3 pl m^{-2} for all RM. In soybean, plant density was 38 pl m^{-2} for sole and double crop, and 20 pl m^{-2} in relay crop and intercrop.

All crops were adequately fertilized based on soil analysis. Phosphorus was applied prior to crop sowing and nitrogen was applied in bands closed to the maize row. Soybean was inoculated with *Bradyrhizobium japonicum*. Insects in soybean were controlled when needed with insecticides (mainly chlorpyrifos and cypermethrin). No insecticides applications were necessary for the maize crop. Glyphosate was used to control weeds when maize and soybean were glyphosate resistant, otherwise, herbicides that were tolerated by both crops, like atrazine (up to 30 days before soybean sowing) and metolachlor were used.

Each experimental unit had six to ten rows with a length of 10 to 12 m, covering an area of 42–78 m^2. Grain yield of maize and soybean was determined by manually harvesting in the central rows an area of 10.1 and 4.4 m^2 respectively. Two (sole crop) or three to four rows (intensification alternatives) were left as border rows. The maize was harvested with a grain moisture content of 18–20% in order to allow a rapid recovery of the soybean. Maize stalks were cut at 0.4 m height above ground to simulate harvest operations. Samples were oven dried and threshed and grain yields (kg ha^{-1}) were expressed at 14.0% and 13.5% grain moisture for maize and soybean, respectively. Crop phenology for maize (Ritchie and Hanway, 1982) and soybean (Fehr and Caviness, 1977) was record for most of the experiments.

2.3. Data analysis

Land equivalent ratio (LER) was used as an indicator of the land productivity for the intensification alternatives evaluated. The LER was obtained as the sum of relative grain yields of maize (rymz) and soybean (rysoy) according to:

$$LER = rymz + rysoy$$

$$rymz = \frac{mzINT}{mzSC}$$

$$rysoy = \frac{soyINT}{soySC}$$

where mzINT is maize grain yield in double crop, relay crop or intercrop, mzSC is sole maize crop grain yield, soyINT is soybean grain yield in double crop, relay crop or intercrop and soySC is sole soybean crop grain yield. A LER higher than 1 means that the intensification alternative is more productive, in relative terms, than the sum of sole crops of its component species.

Each experiment was analyzed as completely randomized block design with three replications. ANOVA was performed using the R commander package (v 2.12.1, R Development Core Team, 2008). In addition data were processed by linear regression analysis.

2.4. Economic analysis

An economic analysis was performed based on historical data for on-farm costs and commodity prices. Total sole crop costs (including harvest) and net farm prices (market price minus transport and trade costs) were obtained for the last nine cropping seasons (2004/2005–2012/2013) from the Research and Development unit of CREA (Regional Agricultural Experimentation Consortia, crea.org.ar). With detailed information about input and labor costs provided by CREA and local farmers for the 2012/2013 cropping season, the total costs for all the intensification alternatives and sole crops were calculated for that specific season. That information was used to establish the ratios between the costs for the intensification alternatives and their respective sole crops. Those ratios, together with the data corresponding to total costs of sole crops for all cropping seasons were used to estimate total costs of intensification alternatives for the rest of the cropping seasons. Costs and prices were assumed similar across locations. Gross margins were calculated as net farm incomes (price by quantity) minus total costs.

3. Results

3.1. Meteorological conditions

Experimental locations are shown in Fig. 1. Long term (1971–2008) average annual rainfall for Balcarce, Pergamino, Manfredi and Paraná was 929, 1022, 783 and 1104 mm, respectively (data not shown). From October 1st to May 1st (1971–2008) average rainfall was 661, 879, 699 and 879 mm respectively. Rainfall during the experimental period was below average for most of the locations and years ranging from 394 to 1056 mm in the experiment under rainfed conditions (Table 1). Growing degree days from last frost to first frost (GDD, base temperature of 8 °C) varied from 1775

Table 2
Sowing dates (dd/mm) for sole crops and the components of intensification alternatives for the different locations, seasons and water managements. RM, maize relative maturity. Harvest dates (dd/mm) between brackets, when available.

Location	Season and water condition	Crop	Maize sole crop or maize soybean double crop			Maize/soybean intercrop			Maize/soybean relay crop			Soybean sole crop
			RM90	RM100	RM120	RM90	RM100	RM120	RM90	RM100	RM120	
Balcarce	2004/2005, irrigated	Maize			20/10(28/03)						20/10(28/03)	
		Soybean									26/11(05/05)	26/11(05/05)
	2005/2006, irrigated	Maize		02/10(16/03)	02/10(30/03)					02/10(16/03)	02/10(30/03)	
		Soybean								22/11(15/04)	22/11(15/04)	22/11(15/04)
	2006/2007, irrigated	Maize	12/10(21/02)	12/10(28/03)	12/10(04/04)				12/10(21/02)	12/10(28/03)	12/10(04/04)	
		Soybean							29/11	29/11	29/11	29/11
	2007/2008, irrigated	Maize	19/10(14/03)	19/10(29/03)	19/10(12/04)	19/10(14/03)	19/10(29/03)		19/10(14/03)	19/10(29/03)	19/10(12/04)	
		Soybean				23/10(06/04)	23/10(06/04)		19/11(06/04)	19/11(06/04)	19/11(06/04)	19/11(05/04)
	2008/2009, irrigated	Maize		16/10(11/03)			16/10(11/03)					
		Soybean					17/10(20/04)					17/11(20/04)
	2008/2009, rainfed	Maize		16/10(11/03)			16/10(11/03)					
		Soybean					17/10(20/04)					17/11(20/04)
Pergamino	2004/2005, irrigated	Maize			26/10(16/03)						26/10(16/03)	
		Soybean									26/11(20/04)	26/11(20/04)
	2005/2006, irrigated	Maize		02/10(13/02)	02/10(24/02)					02/10(13/02)	02/10(24/02)	
		Soybean								21/11(19/04)	21/11(19/04)	21/11(19/04)
	2006/2007, irrigated	Maize	28/09		28/09				28/09			
		Soybean							15/11			15/11
	2007/2008, irrigated	Maize	20/09(17/01)	20/09(30/01)	20/09(13/02)	20/09(17/01)	20/09(30/01)		20/09(17/01)	20/09(30/01)	20/09(13/02)	
		Soybean	17/01(07/05)	31/01(07/05)		20/09(25/04)	20/09(25/04)		05/11(25/04)	05/11(25/04)	05/11(25/04)	05/11(25/04)
	2008/2009, irrigated	Maize	26/09(19/01)	26/09(26/01)	26/09(04/02)	26/09(19/01)	26/09(26/01)	26/09(04/02)	26/09(19/01)	26/09(26/01)	26/09(04/02)	
		Soybean	19/01	26/01	06/02	03/10	03/10	03/10	05/11	05/11	05/11	05/11
Manfredi	2007/2008, rainfed	Maize	10/10(31/01)	10/10(12/02)	10/10(12/03)	10/10(31/01)	10/10(12/02)		10/10(31/01)	10/10(12/02)	10/10(12/03)	
		Soybean	31/01	12/02		10/10	10/10		05/12	05/12	05/12	10/10(06/04)
	2008/2009, rainfed	Maize		08/10	08/10		08/10	08/10		08/10	08/10	
		Soybean					08/10	08/10		20/11	20/11	20/11
Parana	2004/2005, rainfed	Maize			29/10(07/03)						29/10(07/03)	
		Soybean									29/11(20/04)	29/11(20/04)
	2007/2008, rainfed	Maize	16/10(14/02)	16/10(14/02)	16/10(21/02)	16/10(14/02)	16/10(14/02)		16/10(14/02)	16/10(14/02)		
		Soybean				16/10(30/04)	16/10(30/04)		06/12(30/04)	06/12(30/04)		16/10(30/04)
	2008/2009, rainfed	Maize	06/10(25/02)	06/10(25/02)	06/10(25/02)	06/10(25/02)	06/10(25/02)	06/10(25/02)	06/10(25/02)	06/10(25/02)	06/10(25/02)	
		Soybean				06/10(20/04)	06/10(20/04)	06/10(20/04)	20/11(20/04)	20/11(20/04)	20/11(20/04)	06/10(20/04)

Table 3
Crop grain yield (kg ha^{-1}) for sole crops and intensification alternatives components for different locations, season and water conditions. Bold letters indicate sole treatments.

Location	Season and water condition	Crop	Maize sole crop or maize soybean double crop			Maize/soybean intercrop			Maize/soybean relay crop			Soybean sole crop
			RM90	RM100	RM120	RM90	RM100	RM120	RM90	RM100	RM120	
Balcarce	2004/2005, irrigated	Maize			**10,625**						9147	
		Soybean									309	**2699**
	2005/2006, irrigated	Maize		12,778	**16,862**					10,676	13,762	
		Soybean								1176	830	**4023**
	2006/2007, irrigated	Maize	9326	11,610	**11,953**				7198	9446	9186	
		Soybean							2000	1278	1295	**4532**
	2007/2008, irrigated	Maize	10,351	12,549	**16,140**	5791	7512		7590	8754	12,308	
		Soybean				2350	2309		2663	1891	1234	**4613**
	2008/2009, irrigated	Maize		**14,423**			9094					
		Soybean					1956					**4049**
	2008/2009, rainfed	Maize		**4390**			2467					
		Soybean					548					**1794**
Pergamino	2004/2005, irrigated	Maize			**12,360**						9036	
		Soybean									1295	**3891**
	2005/2006, irrigated	Maize		13,330	**14,323**					10,781	11,279	
		Soybean								2364	1391	**5130**
	2006/2007, irrigated	Maize	10,211		**14,560**				7344			
		Soybean							2913			**4999**
	2007/2008, irrigated	Maize	9391	11,252	**12,190**	5576	5668		5321	6446	7851	
		Soybean	1806	917		4541	3686		3660	2732	2036	**5003**
	2008/2009, irrigated	Maize	9160	10,997	**11,333**	6472	7663	8853	6760	8581	8596	
		Soybean	2621	2204	1669	2645	2515	2198	2471	2243	1683	**4230**
Manfredi	2007/2008, rainfed	Maize	7240	7843	**8171**	2769	3552		4230	6064	6457	
		Soybean	1293	286		2340	2663		3303	3072	2356	**3233**
	2008/2009, rainfed	Maize		5934	**6369**		3240	6780		4478	7398	
		Soybean					504	292		440	615	**1884**
Paraná	2004/2005, rainfed	Maize			**11,382**						9481	
		Soybean									1007	**3521**
	2007/2008, rainfed	Maize	4585	9494	**12,472**	4916	6030		5392	6700		
		Soybean				1991	1611		1637	1635		**3388**
	2008/2009, rainfed	Maize	7448	7819	**7566**	5261	5800	4202	6731	7035	7207	
		Soybean				1643	1472	553	707	651	553	**2268**

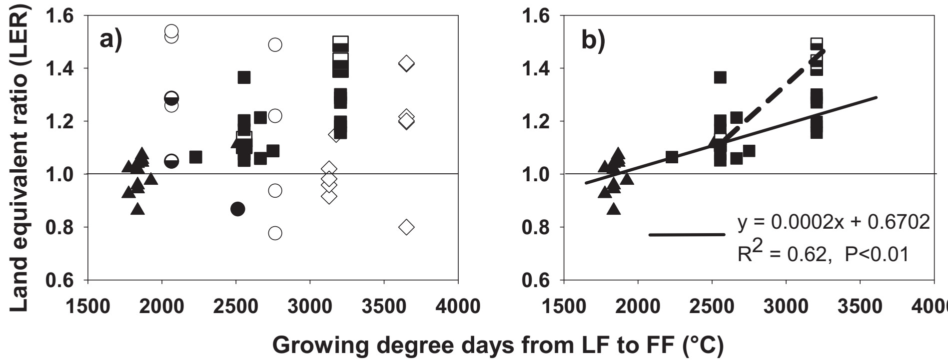

Fig. 2. Land equivalent ratio for intensification alternatives as a function of growing degree days (8 °C base temperature) from last (LF) to first (FF) frost date (temperature below 2 °C at 1.5 m). Filled symbols show irrigated experiments (a, b) and empty symbols show rainfed experiments (a). Relay crops or intercrops are shown as triangles for Balcarce, squares for Pergamino, circles for Manfredi and diamonds for Parana. Double crops are shown with semi filled squares for Pergamino under irrigated conditions and with semi filled circles for Manfredi under rainfed conditions. In (b), the solid and the dashed lines represents the linear functions fitted to irrigated intercrops, and to double crop at Pergamino, respectively.

to 3651 °C (Table 1). This variable was used as a measure of season length.

3.2. Grain yields and crop productivity

The grain yield of sole maize crops ranged from 4390 to 16,862 kg ha^{-1}. The highest grain yields were obtained at Balcarce under irrigated conditions, and the lowest under rainfed conditions at the same location (Table 3). For maize sole crops, RM100 yielded 11% and RM90 28% less than RM120. Grain yield of soybean in sole crop ranged from 1884 kg ha^{-1} at Manfredi under rainfed condition to 5130 kg ha^{-1} at Pergamino under irrigated conditions (Table 3).

Land equivalent ratio varied across locations (Fig. 2). In 75% of the experiments LER was higher than 1 (Fig. 2). LER was plotted as a function of GDD from last frost to first frost only for irrigated experiments (Fig. 2b). The productivity of the intensification alternatives was clearly related to the length of the growing season ($P < 0.01$, $R^2 = 0.62$, Fig. 2b, solid line). A minimum of 1850 GDD was required for the intercrops to achieve a LER higher than 1. Moreover, season length (in GDD) was positively correlated with the incident radiation received from last frost to first frost ($r = 0.98$, Table 1).

For maize–soybean double crop, a minimum of 2300 GDD was required to achieve a LER higher than 1, and a minimum of 2600 GDD was required to exceed the productivity of relay crop and intercrop (Fig. 2b, dashed line). This information should be considered cautiously because of the limited number of experiments (five irrigated experiments at Pergamino, Table 3).

3.3. Relative grain yield and LER

3.3.1. Irrigated experiments: maize hybrid cycle length and relay crop vs. intercrop

The relationship between rymz and rysoy is indicated in Fig. 3. The discontinuous line from (0;1) to (1;0) with a slope of −1 represents cases where LER is equal to 1. Treatments located above this line have a LER higher than 1. Lines I, II, and III are a reference of competition ability of both species for treatments and experiments. Line I describes cases where rymz is three times larger than rysoy; line II represents cases where maize and soybean are equally competitive; and line III is the opposite of line I.

LER was close to the line with slope −1 at Balcarce ($b = -1.03$, $P < 0.01$, C.I. −1.38 to −0.68, Fig. 3) and LER was always above 1 at Pergamino with a slope not different from −1 ($b = -0.69$, $P < 0.01$, C.I. −1.03 to −0.34, Fig. 3).

Table 4 presents data obtained at Balcarce and Pergamino under irrigated conditions to evaluate the effect of maize hybrid cycle length on the productivity of relay crop components.

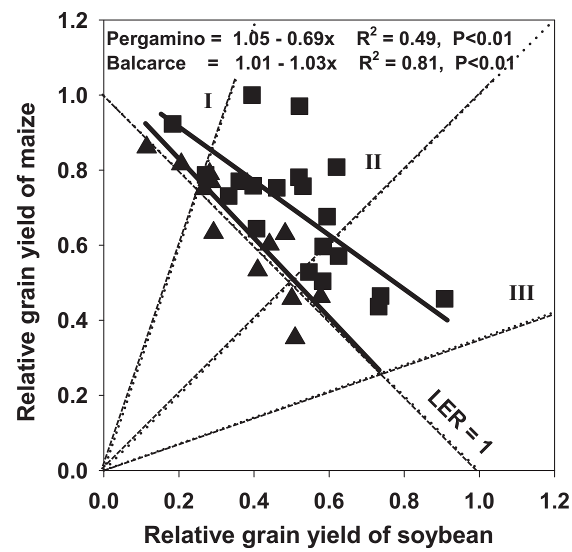

Fig. 3. Relative maize grain yield as a function of the relative soybean grain yield for all intensification alternatives conducted under irrigation for Balcarce (triangles) and Pergamino (squares). Land equivalent ratio (LER) = 1 is illustrated as a dashed line that goes from 0;1 to 1;0. Line I shows the relationship when maize relative grain yield is three times larger than soybean relative grain yield; line II shows the relationship when maize and soybean are equally competitive; and line III shows the relationship when yields of maize and soybean are the opposite to those of line I.

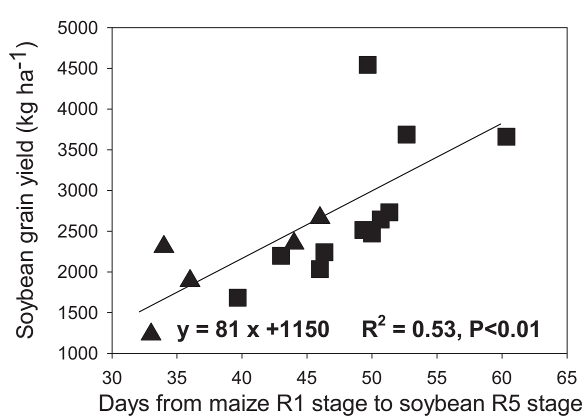

Fig. 4. Soybean grain yield (kg ha^{-1}) for relay crop and intercrop as a function of the days from maize silking (R1) to the beginning of the seed filling stage in soybean (R5) for Balcarce (triangles) and Pergamino (squares).

Table 4
Grain yield (kg ha^{-1}) for sole crops and for the relay crop components using maize hybrids that differed in relative maturity (RM) and land equivalent ratio (LER) for the intensification alternatives. Experiments were conducted under irrigated conditions. Standard deviation is shown between brackets. Values with the same letter do not differ at $P < 0.05$.

	Treatment	Maize grain yield	Soybean grain yield	LER
Balcarce 2006/2007	Sole crop	11,953(283)a	4532(278)a	1.00
	Relay RM120	9186(455)b	1295(74)c	1.05(0.047)
	Relay RM100	9446(310)b	1278(78)c	1.07(0.032)*
	Relay RM90	7198(540)c	2000(223)b	1.05(0.049)
LSD		773	351	
Balcarce 2007/2008	Sole crop	16,140(357)a	4613(81)a	1.00
	Relay RM120	12,308(534)b	1234(207)d	1.03(0.047)
	Relay RM100	8754(361)c	1891(128)c	0.95(0.038)
	Relay RM90	7590(788)d	2663(359)b	1.05(0.083)
LSD		1016	415	
Pergamino 2007/2008	Sole crop	12,190(535)a	5003(385)a	1.00
	Relay RM120	7851(339)b	2036(333)c	1.05(0.049)
	Relay RM100	6446(682)c	2732(514)bc	1.08(0.053)
	Relay RM90	5321(647)d	3660(867)b	1.17(0.120)*
LSD		1067	1063	
Pergamino 2008/2009	Sole crop	11,333(635)a	4230(118)a	1.00
	Relay RM120	8596(1106)b	1683(169)c	1.160(0.163)
	Relay RM100	8581(950)b	2243(248)b	1.292(0.120)*
	Relay RM90	6760(24)c	2471(171)b	1.282(0.032)
LSD		1497	344	

* Significantly different from 1 ($P < 0.05$).

Maize in relay crop (for all RM) yielded less than the sole maize crop (Table 4). The use of RM hybrids shorter than 120 reduced maize grain yield in the relay crop ($P < 0.05$, Table 4). Additionally, soybean in relay crop (for all maize RM) yielded less than soybean sole crop. Yields of soybean in relay crop increased when sown with maize hybrids of RM shorter than 120 ($P < 0.05$, Table 4). LER was higher than 1 at Balcarce 2006/2007 and Pergamino 2008/2009 for relay crop with RM 100 maize, and at Pergamino 2007/2008 with RM 90 maize.

Table 5 shows data from Balcarce and Pergamino under irrigated conditions to compare relay crop and intercrop alternatives using a RM 100 maize hybrid. Maize (RM 100) and soybean grain yields in relay crop and intercrop were lower than in sole crops, with no differences between relay crop and intercrop ($P < 0.05$, Table 5). For this set of data, LER was higher than 1 only at Pergamino 2008/2009, with no difference between relay crop and intercrop (Table 5).

The soybean grain yield in relay crop and intercrop (Tables 4 and 5) was positively associated with time elapsed between the critical period for grain yield determination of maize (silking, R1) and soybean (beginning of seed filling, R5, Fig. 4). Soybean yield increased by 81 kg ha^{-1} per day during that period.

3.3.2. *All experiments for intensification alternatives*

Maize grain yield in double crop was close to the sole crop with only slight decreases associated with maize hybrid cycle length (Fig. 5aI). Soybean yield in double crop was clearly affected by the delay in sowing date associated with maize harvest date (Fig. 5bI). LER was greater than 1 (from 1.05 to 1.49, $n = 7$) for all double crop treatments (in 71% of the cases LER was statistically higher than 1, $P < 0.05$, Fig. 5cI).

The grain yield gap between maize in relay crop and sole crop increased proportionally to increments in sole maize grain yield (Fig. 5aII). In contrast, soybean grain yield in relay crop increased as

Table 5
Grain yield (kg ha^{-1}) for sole crops and for relay crop and intercrop components and the land equivalent ratio (LER) for these intensification alternatives. Experiments were conducted under irrigated conditions. Standard deviation is shown between brackets. Values with the same letter do not differ at $P < 0.05$.

	Treatment	Maize grain yield	Soybean grain yield	LER
Balcarce 2007/2008	Sole crop	16,140(357)a	4613(81)a	1.00
	Relay crop RM100	8754(361)b	1891(128)b	0.95(0.040)
	Intercrop RM100	7512(1406)b	2309(412)b	0.97(0.062)
LSD		1724	506	
Pergamino 2007/2008	Sole crop	12,190(535)a	5003(385)a	1.00
	Relay crop RM100	6446(682)b	2732(514)b	1.08(0.051)
	Intercrop RM100	5668(528)b	3686(852)b	1.21(0.247)
LSD		1170	1231	
Pergamino 2008/2009	Sole crop	11,333(635)a	4230(118)a	1.00
	Relay crop RM100	8581(950)b	2243(248)b	1.29(0.121)*
	Intercrop RM100	7663(656)b	2515(322)b	1.27(0.031)*
LSD		1520	488	

* Significantly different from 1 ($P < 0.05$).

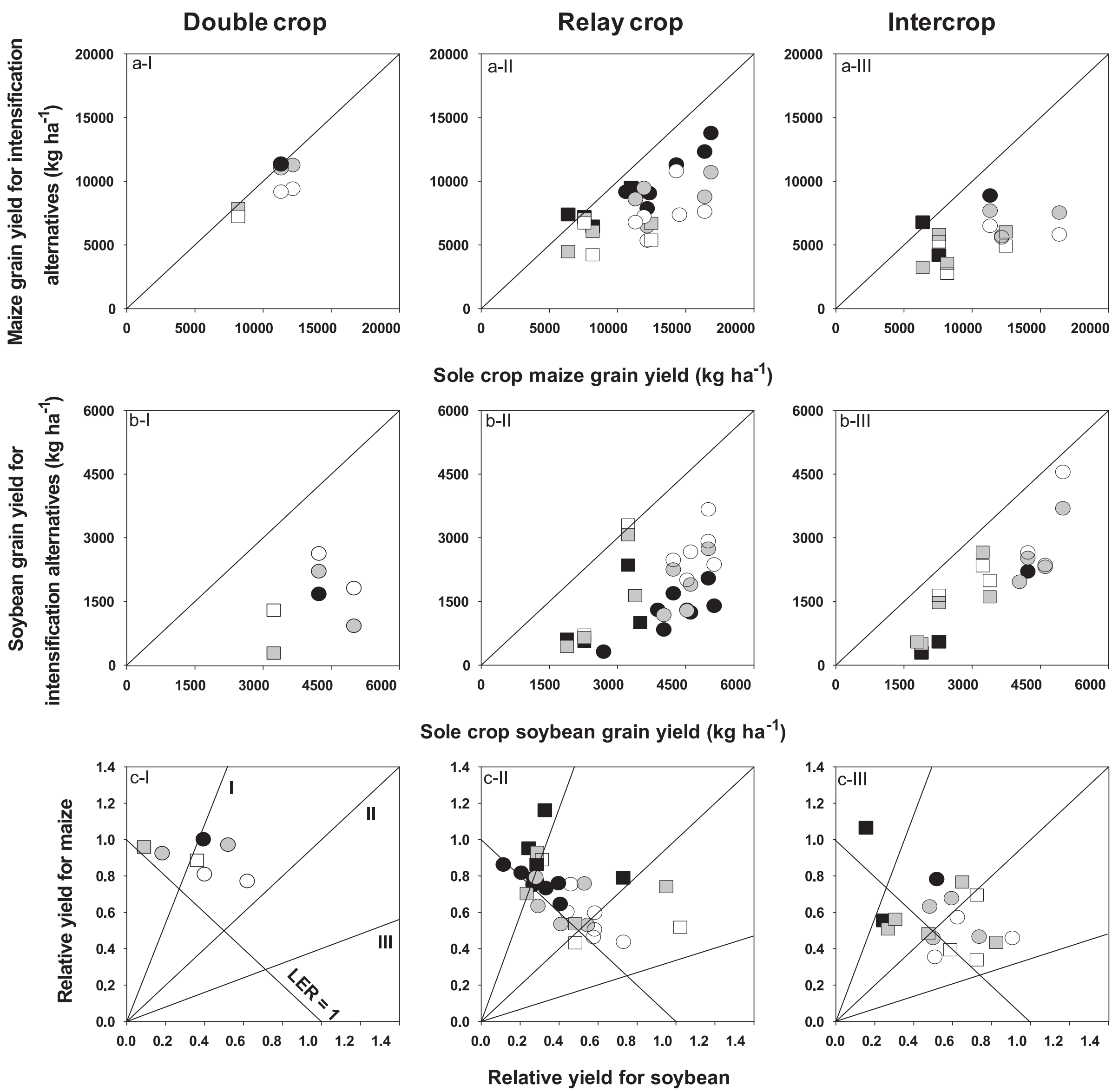

Fig. 5. (a) Maize grain yield for intensification alternatives as a function of sole crop maize grain yield (kg ha^{-1}). (b) Soybean grain yield for intensification alternatives as a function of sole crop soybean grain yield (kg ha^{-1}). (c) Relative grain yield of maize as a function of relative grain yield of soybean for intensification alternatives. Double crop (I), relay crop (II) and intercrop (III). Circles indicate irrigated conditions and squares indicate rainfed conditions. Maize relative maturity (RM), RM 120 (black), RM 100 (gray) and RM 90 (empty). LER = land equivalent ratio. Dots to the right from line of LER equal to 1 indicate that LER increases as soybean relative grain yield improves.

the RM of the maize counterpart decreased (Fig. 5bII). The average rymz was 0.82 for RM120 (from 0.64 to 1.26, n = 12), 0.68 for RM100 (from 0.53 to 0.93, n = 9) and 0.58 for RM90 (from 0.43 to 0.89, n = 9). In contrast, average rysoy was 0.32 when sown with RM120 maize (from 0.11 to 0.73, n = 12), 0.45 with RM 100 maize (from 0.23 to 0.95, n = 9) and 0.58 with RM90 maize (from 0.31 to 1.02, n = 9 Fig. 5bII). Considering all relay crop treatments (n = 30), LER varied from 0.92 to 1.69 and was greater than 1 in 86% of the cases (in 43% of the cases LER was statistically higher than 1, $P < 0.05$).

Maize in intercrop showed a higher yield reduction in comparison to double crop and relay crop. Likewise, this yield gap increased as grain yield of the sole crop improved (Fig. 5aIII). The reduction in the RM of the maize intercrop resulted in greater soybean grain yield (Fig. 5bIII). The average rymz in intercrop was 0.80 for RM120 (from 0.56 to 1.06, n = 3), 0.55 for RM100 (from 0.43 to 0.77, n = 9) and 0.47 for RM90 (from 0.34 to 0.70, n = 6). In contrast, average rysoy in intercrop was 0.31 when sown with RM120 (from 0.15 to 0.52, n = 3), 0.54 with RM100 (from 0.27 to 0.82, n = 9) and 0.68 with RM90 (from 0.51 to 0.91, n = 6, Fig. 5bIII). Considering all the intercrop treatments (n = 18) LER varied from 0.78 to 1.42 and was greater than 1 in 61% of the cases (in 50% of the cases LER was statistically higher than 1, $P < 0.05$, Fig. 5cIII).

3.4. Crop diversification and yield stability

For rainfed and irrigated conditions, sole crop yields of maize and soybean were positively correlated ($P < 0.01$, $r = 0.82$, Fig. 6). In contrast, for all intensification alternatives under irrigated conditions, soybean grain yield was negatively correlated with maize yield ($P < 0.01$, $r = -0.68$, Fig. 6). No correlation was found, however, between maize and soybean grain yields for all intensification alternatives under rainfed conditions ($P > 0.10$, Fig. 6).

3.5. Economic analysis

The average net prices across cropping seasons of soybean were more than double those of maize (222 vs. 100 U$S tn^{-1}, Table 6).

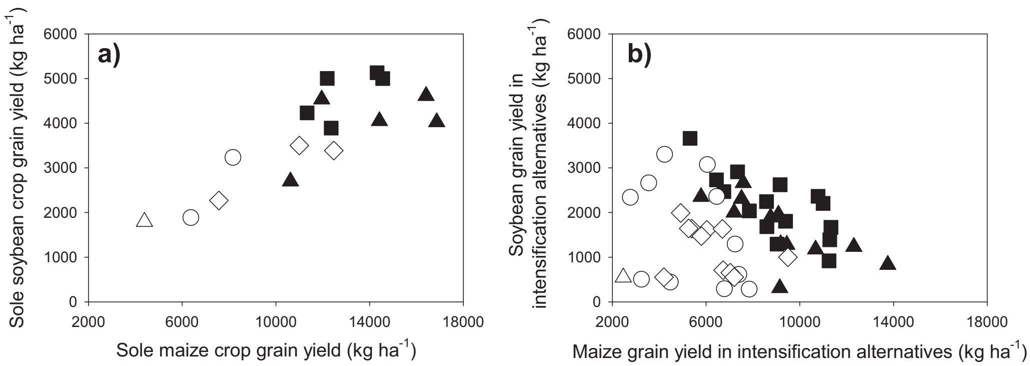

Fig. 6. (a) Grain yield (kg ha^{-1}) of sole soybean crop as a function of grain yield of sole maize crop for different locations, seasons and water managements. (b) Grain yield of sole soybean crop as a function of the yield of maize for the intensification alternatives for different locations, seasons and water managements. In (a) and (b), filled symbols indicate irrigated experiments and empty symbols indicate rainfed experiments. Balcarce: triangles; Pergamino; squares; Manfredi: circles and Parana: diamonds.

Based on the data for the 2012/2013 cropping season, the total costs of soybean in double crop, relay crop and intercrop were 70%, 80% and 65% of the total costs of soybean sole crop, respectively; in the same way, the total cost of maize in double crop, relay crop and intercrop were 100%, 85% and 85% of the total costs of maize sole crop, respectively. Input and labor costs of intensification alternatives are lower than those corresponding to the sum of sole crops because of a reduction in the use of seeds, pesticides, fertilizers and labor.

The total cost of a soybean sole crop was 61% of that of maize sole crop (Table 6). Cropping season average gross margins of the soybean sole crop and of the intensification alternatives were similar (473 vs. 474 U$S ha^{-1}, Table 6). The gross margin of the intensification alternatives was larger than that of the soybean sole crop when the ratio between net farm price of soybean and maize was lower than 2.2 (Fig. 7). On average, maize sole crop gross margins were greater than sole soybean crop and intensification alternatives gross margins due to the high maize sole crops yields obtained under irrigation at Balcarce and Pergamino (data not shown).

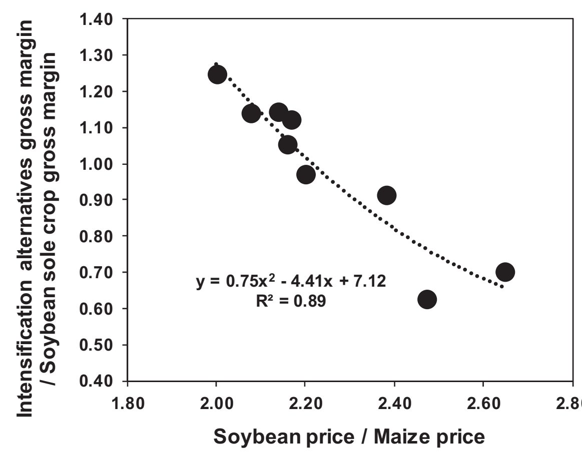

Fig. 7. Gross margins of intensification alternatives relative to that of soybean sole crop as a function of the soybean/maize price ratio for the 2004/2005 to 2012/2013 cropping seasons. Each point represents one growing season, data from Table 6.

4. Discussion

The maize–soybean intensification alternatives here evaluated showed a LER greater than 1 in 75% of the cases that included different water regimes and agronomical managements (Fig. 2a). Many authors have showed similar results for this combination of species and others in many regions around the globe (Fischer, 1977; Kandel et al., 1997; Caviglia et al., 2004; Tsubo et al., 2005; Ouda et al., 2007; Echarte et al., 2011; Andrade et al., 2012; Coll et al., 2012). Although in most cases the intensification alternatives outperformed the grain yield of sole crops in relative terms, there were many interactions in the response to environmental variables and crop management.

4.1. Environmental effects

Variability among locations, soils, water conditions and seasons during the experimental period permitted the full evaluation of the

Table 6
Net farm prices (U$S tn^{-1}), total costs for sole crops and intensification alternatives (U$S ha^{-1}) and gross margin for soybean sole crops and intensification alternatives (U$S ha^{-1}) for nine growing season (2004/2005–2012/2013) in Argentina.

Season	Net farm prices		Total cost			Gross margin	
	Soybean	Maize	Soybean sole crop	Maize sole crop	Intensification alternatives[a]	Soybean sole crop[b]	Intensification alternatives[a]
2004/2005	143	54	189	288	379	280	196
2005/2006	149	69	186	293	367	305	321
2006/2007	176	88	190	304	359	399	498
2007/2008	234	108	239	390	442	565	634
2008/2009	230	93	329	568	682	453	283
2009/2010	214	103	254	407	501	451	513
2010/2011	263	123	292	453	558	578	663
2011/2012	305	128	325	566	709	660	604
2012/2013	286	130	346	591	748	567	551
Average	222	100	261	429	527	473	474

[a] Average of all intensification alternatives from Table 3.
[b] Average of all soybean sole crops from Table 3.

performance of intensification alternatives under different environmental conditions. This is critical for the extrapolation of our results to similar environments worldwide.

Under irrigation, the feasibility and productivity of intensification alternatives was directly associated with the length of the growing season. Under rainfed conditions, crop management effects prevail over the relationship (Fig. 2). Mean temperature followed a latitudinal gradient that determined a long frost free period length and therefore a long growing season for summer species at northern locations of the study region. The suitability of Pampas of Argentina for intensification alternatives would improve if global warming results in higher temperatures with no or minor changes in rainfall or water balance. This has been shown for the south-eastern Pampas of Argentina, where the modeled productivity of wheat-soybean double crop improved because of high temperatures that increased soybean grain yield (Monzon et al., 2007). Moreover, a significant increase of cropping intensity was observed in response to climate warming in the Tibetan Plateau of China (Zhang et al., 2013).

4.2. Crop management

Maize grain yield relative to sole crop was little affected in double crops, and it was mainly related to hybrid cycle length (RM 90 vs. RM 120, Fig. 5aI). Capristo et al. (2007) found that short cycle maize hybrids intercept less solar radiation and, therefore, accumulate less biomass and set fewer grains than locally adapted hybrids. In contrast, maize relative grain yields in relay crop and intercrop were significantly lower than 1 (Fig. 5aII and aIII). This was related to soybean competition (Francis et al., 1982), and to crop spatial arrangement that consisted of wide rows that reduced maize radiation capture. Intercepted radiation became the most limiting factor for maize crop growth in relay crop and intercrop under high water availability scenarios. Andrade et al. (2002) demonstrated that the reduction in intercepted radiation with wider rows resulted in a detrimental effect on maize crop yield. On the other hand, when the scarcest resource was water, maize grain yield in relay crop and intercrop was similar and in some cases greater than the yield of sole crops. Wide rows increased water availability during the critical stages of grain yield determination (maize silking stage) counterbalancing the lower radiation interception (Coll et al., 2012). As a consequence, the yield gap between sole maize crop and maize in relay crop and intercrop increased as sole maize crop grain yield improved (Fig. 5aII and aIII).

Soybean grain yield in intensification alternatives relative to sole crop was lower than 1 in all the cases except one, and differed among crop management treatments. Soybean in double crop had the lowest grain yield because of late sowing date that reduced resource capture and resource use efficiency (Calviño et al., 2003, Fig. 5bI). Relay crop and intercrop ameliorated this effect as they allowed for earlier soybean sowing dates (Fig. 5bII and bIII). Soybean, in association with maize, is the secondary or suppressed species as a consequence of its low canopy height and a shallow root system (Fukai and Trenbath, 1993; Allen et al., 1998; Ouda et al., 2007; Xia et al., 2013). However, interspecific competition in relay crop affected soybean more than in intercrop.

Intercropping reduced competition ability of maize and enhanced it for soybean in comparison with relay crop. Graphically, this is indicated by the positions of the data points and their distances from lines I, II and III in Fig. 5cII and cIII. Dot positions are between lines I and II for relay crop, whereas dots are around line II for intercrop indicating that competitive ability of maize and soybean is similar under intercrop. Similarly, as the maize cycle length was reduced, its grain yield decreased because of resource sub-exploitation (Capristo et al., 2007), whereas soybean grain yields increased due to an overall improvement in resource availability (Coll et al., 2012). Relay crop and intercrop, however, did not differ in crop system productivity expressed as LER ($P > 0.05$; Table 5).

The maize and soybean crops spatially and temporarily differ in the use of resources (Ouda et al., 2007). This complementary behavior is the reason why many relay crops and intercrops use radiation, water and nutrients more efficiently than sole crops (Willey, 1990, Coll et al., 2012). In fact, soybean grain yield in relay crop and intercrop improved as the interval between critical periods for grain yield determination of maize and soybean increased (Fig. 4). The separation of these periods generates conditions that increase crop capacity to capture resources and convert them into grain yield. This could be achieved by cropping techniques concerning sowing date management and variations of crop cycle length within the limits imposed by the growing season. Appropriate agronomic manipulations may transfer resources (water and nutrients) to the suppressed component and minimize consumption by the dominant crop component increasing the resource use efficiency of the system (Fukai and Trenbath, 1993). The promotion of the suppressed component (soybean) increased LER in Pergamino but not in Balcarce (Fig. 3) supporting the idea that temporal complementation occurs less often among components of intensification alternatives when the growing season is short. A high degree of overlap of growth stages critical for grain yield formation takes place in short growing seasons, resulting in severe competition more than in complementary use of resources.

4.3. Intensification alternatives stability and sustainability

Maize and soybean sole crops grain yields were highly correlated under rainfed and irrigated conditions (Fig. 6a), based on their similar environmental requirements and growing periods (Andrade, 1995). Similar results were found for the correlation between maize and soybean sole crop yields for simulated experiments ($r = 0.74$ for Balcarce and 0.75 for Pergamino, Calviño and Monzon, 2009) and on-farm yields ($r = 0.52$, Andrade and Satorre, personal communication). In contrast, maize and soybean grain yields in intensification alternatives under irrigated conditions were negatively correlated (Fig. 6b). As irrigated maize grain yield increased, soybean grain yield was reduced. Simultaneous sowings and the use of short cycle length maize hybrids increased relative soybean competition ability and negatively affected the dominant crop performance (Andrade et al., 2012). In Argentina, however, the success of cropping intensification alternatives depends on the adaptation of these alternatives to rainfed conditions. For the rainfed experiments, soybean and maize grain yields in intensification alternatives were not correlated. Soybean performance was mainly associated with rainfall amount during its critical period ($y = 22.7x - 775$, $R^2 = 0.74$, where y is soybean grain yield in kg ha^{-1} and x is the amount of rainfall from R4 to R6 in mm). Moreover, rainfall during the soybean and maize critical periods were not correlated. As the average economic results of soybean and intensification alternatives were similar, this lack of correlation between the components of the intensification systems could reduce farm risk under rainfed conditions, outperforming soybean monoculture economic results when the best design are chosen in each region.

All the information herein presented was used to determine the gross margins for intensification alternatives. The gross margins of the intensification alternatives varied from year to year, and its performance relative to the soybean sole crop was related to the ratio between soybean and maize prices. The relationship between the intensification alternatives and soybean sole crop margins decreased as the soybean/maize price ratio increased.

Soybean monoculture is becoming a risk to system sustainability in South America. The maize–soybean intensification alternatives are possible options to maintain or even increase soil organic carbon (SOC, Oelbermann and Echarte, 2011). In the Brazilian Cerrado the double cropping of maize after soybean harvest has increased steadily during the last ten years (http://www.sidra.ibge.gov.br). Neto et al. (2010) found that after twelve years of soybean-maize double crops under no tillage management, SOC stocks were no longer significantly different from the stocks under natural Cerrado vegetation. In Argentina, Miranda et al. (2012), based on the information presented here for Pergamino, and using a simple simulation model, compared mid term SOC levels of continuous double crop maize–soybean and soybean monoculture. The authors estimated a loss in SOC for the soybean monoculture and a gain in SOC for the double crop, contributing to crop system sustainability.

4.4. Perspectives for on farm adoption

The double crop is the intensification alternative most easily adopted by farmers. This is because one component is sown after the harvest of the other component with no overlapping periods, avoiding difficulties in sowing and harvest operations, and in disease, pest and weed control. The double crop of summer species, however, is environmentally limited. Long growing seasons are needed to fit two sequential summer crops in a season. Moreover, the lack of soil moisture at soybean sowing may be highly restrictive. The relay crop and intercrop of summer species seem to be a more appropriate alternative to intensify land use at high latitudes, where the growing season is short. Although relay crop and intercrop did not differ in total grain productivity, intercropping is a simple way to promote large-scale fully mechanized adoption (Calviño and Monzon, 2009). The maize–soybean intercrop only requires one sowing operation. A regular seeder can be used but it is necessary to adjust the sowing density per row (a density for maize and another for soybean). Only minimum adaptations to the combine for the maize harvest are required in order to avoid the damage to the soybean crop.

Innovations in crop management need to be performed under the leadership of farmers and research centers. Farmers organized in associations such as CREA (Regional Agricultural Experimentation Consortia; crea.org.ar) or AAPRESID (Argentine No-till Farmers Association; http://www.aapresid.org.ar), have conducted pioneering practices and performed local experiments to encourage adoption of intensification alternatives by farmers.

5. Conclusion

Intensification feasibility improves when growing seasons are longer, so that the northern areas of the Pampas are the most suitable for these alternatives. While double summer crops were limited to long growing season environments, under irrigation the productivities of all the intensification alternatives increased as the growing season became longer. Interestingly, across environments, the performance of relay crops and intercrops was very similar.

For all intensification alternatives, the use of maize hybrids shorter than 120 RM reduced maize grain yield and increased soybean grain yield. In relay crop and intercrop, the soybean grain yield was positively associated with time elapsed between the critical periods for grain yield determination of maize and soybean.

Under rainfed conditions, the intensification alternatives were an option to diversify crop risks due to the lack of correlation between maize and soybean yields. Moreover, the gross margins of intensification alternatives were similar to the soybean sole crops and were related to the ratio between soybean and maize prices.

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