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Productivity and resource use in intensified cropping systems in the Rolling Pampa, Argentina

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ABSTRACT

Increasing cropland productivity is critical to meet future global demand of food, fibers and biofuels. Recent innovations in grain crop management are aimed at designing more ecologically complex cropping systems by growing doublecrop sequences comprising a great variety of crop species. The objectives of this study were to compare (i) the pattern of resource use and the productivity in cool-season crops and their influence on the following warm-season second crops, and (ii) the overall resource capture, resource use efficiency, and productivity of various single and double cropping systems. Hence, three field experiments under rainfed conditions and computer-simulated experiments were conducted in contrasting sites in the Rolling Pampa. Seven cropping systems were evaluated, which included five double crop sequences (rapeseed/soybean, wheat/soybean, barley/soybean, field pea/soybean, and field pea/maize) and maize and soybean as single crops. Cool-season crops differed in resource use, which therefore affected differently the following second crop. The highest and the lowest yields with double cropped soybean were produced after field pea and wheat, respectively. Soybean single crop was the least productive treatment because of low resource capture and moderate resource use efficiency. Double cropping systems including soybean as second crop outperformed soybean single crop productivity due to larger resource use. Comparatively, maize single crop used fewer resources but with higher efficiency than the cropping systems including soybean, which led to higher yields when water was not limiting. Field pea/maize double crop was the most productive system, since field pea allowed for long resource use periods, while maintaining similar resource use efficiency as maize single crops. Field experiment results were confirmed by crop yield simulations based on 39 years of environmental data from the same sites. Wheat/soybean double crops expanded and contributed to raise productivity in the Pampas with available farming technologies. However, novel crop type combinations appeared as feasible ways for improving resource use balance in the growing season among the component crops. This may raise the total annual productivity or, at least, increase the grain yield of soybean, the more profitable component at present. These findings have important implications regarding the ecological intensification of commodity grain cropping systems, which can be implemented by proactive farmers in the short-term in various regions of the world.

1. Introduction

Increasing demand of agricultural products by the growing global population has raised concern because of the challenge imposed by achieving food security in the near future. Improving cropland productivity has become of paramount importance to raise global food supply, especially when considering that expanding the current world cultivated area is limited and will imply the loss of natural habitats and risks from environmental pollution (Bruinsma, 2009; Cassman et al., 2003; Harvey and Pilgrim, 2011; Miyake et al., 2012). In the last decades, many regions over the globe, including the Argentine Pampas, have increased yields of annual field crops thanks to growing highly productive genotypes, increasing resource use through fertilization and irrigation, and protecting crops from weeds, pests, and diseases (Cassman, 1999; Foley et al., 2005; Satorre, 2005). Moreover, cultivating two

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or more crops on the same land area, each year has also become a feasible alternative in temperate regions with extended growing seasons (Andrade and Satorre, 2015; Calviño and Monzon, 2009; Monzon et al., 2014).

Double cropping is the sequential cultivation of two crops in the same field and growing season, where the succeeding crop is sown after the preceding crop has been harvested. In this sense, farming is only intensified in time, and thus, there is no competition between the component crops (Francis and Smith, 1985). The growing season in the Rolling Pampa allows sequencing a cool-season crop followed by a warm-season crop, but double cropping two summer crops is rarely feasible (Monzon et al., 2014). Double cropping has been spread in the Rolling Pampa of Argentina during the last 20 years, being wheat/soybean, the prevalent double crop (Calviño and Monzon, 2009). This cropping system has been largely adopted by farmers because yields are usually higher and more stable than single crops, farmers' tradition for growing wheat, and soybean great incomes. Moreover, sowing soybean immediately after harvesting wheat was promoted by both the widespread adoption of no-tillage and the rapid spread of genetically modified soybean varieties that tolerate glyphosate since 1996 (INTA, 2011; Satorre, 2005). Sowing wheat/soybean double crops increases overall resource use and grain yield in comparison to both single crops, even though the lower yields of double cropped soybean due to the delayed sowing date and the resource depletion caused by precedent wheat crops (Caviglia et al., 2004; Daniels and Scott, 1991)

Besides wheat/soybean double crops, soybean and maize single crops are the most widespread cropping systems in the Rolling Pampa. Farmer's decision making on land use is subject to several off-farm factors including the inter-annual environmental variability, the availability of new technologies, international commodity prices and domestic market policies. Currently, national market policies have deterred wheat sown area, increasing the area sown with single soybean crops (http://www.siia.gov.ar). Although of minor importance, wheat sown area was replaced by other cool-season crops like barley, rapeseed or field pea which are also grown in double cropping schemes (Calviño and Monzon, 2009). These cool-season crops have different resource use patterns, and therefore, they differ in resources left available for the following crop (Van Opstal et al., 2011), which may thus produce some changes in yield and productivity. Furthermore, rapeseed, field pea and barley crops are usually harvested earlier than wheat crops, which may consequently increase yields and productivity of double cropped soybeans (Calviño et al., 2003; Monzon et al., 2007). This may also affect the overall annual productivity. In rainfed cropping systems, the early harvest of cool-season crops not only widens the options for sowing double cropped soybean, but it also could left more resources available to the following second crops. Moreover, both the quantity and quality of crop residues could also affect the availability and dynamics of several nutrients for following crops (Domínguez et al., 2005).

Although to a much lesser extent than soybean, maize is also being considered as a second crop to compose double cropping sequences. Some researchers analyzed the nutritional benefits on maize crops as a consequence of cultivating annual legumes as cover crops during the precedent winter (Clark et al., 1994; Clark et al., 1995). Conversely, sowing cool-season crops with long growing cycles before maize is not advisable for the Rolling Pampa, due to the high susceptibility of maize to water stress (Otegui et al., 1995). Nonetheless, effects on resource availability of sowing short-cycle, cool-season pulse crops before maize, and, therefore, on grain yield and annual productivity, need to be studied.

Several strategies have been proposed to increase grain production in the same land area. One feasible option is choosing cultivars with longer crop cycles for locations with long growing seasons (Capristo et al., 2007). However, this alternative does not necessarily mean that grain yield will increase, because not all resources used to produce biomass are actually converted into grain (Egli, 2011). Alternatively, since agriculture in the Argentine Pampas largely relies on summer crops, intensified cropping sequences are being oriented to use the resources available during the winter (Caviglia and Andrade, 2010). Recent innovations in crop management are aimed at designing more ecologically complex cropping systems by growing sequences of a greater variety of crop species to produce grains. However, to succeed in the short-term, designing such cropping systems should be based on both current technologies and simplicity of management, being double cropping a feasible option. We therefore, hypothesize that sowing a cool-season crop before a warm-season crop, such as soybean or maize, contributes to occupy a greater share of the growing season, which will consequently increase the overall use of resources available during the season. However, we also expect that this increase will vary according to the cool-season species sown as the first crop in the sequence and, that resource use efficiency may be also modified by it. Therefore, the objectives of this study were to (i) carry out a comparative analysis of cool-season crops in terms of resource use patterns and crop productivity, and their influence on the performance of second crops, and (ii) compare the overall resource capture, resource use efficiency, and productivity for a wide variety of single and double cropping systems, which comprise different sequences of cool- and warm-season crop species. For responding these questions about productivity and resource use patterns of cropping systems, large-scale field experiments and crop simulation modeling were thus carried out in three contrasting localities in the Rolling Pampa of Argentina.

2. Materials and methods

2.1. Sites and environmental conditions during the experimental growing season

Field experiments conducted under rainfed conditions were established in three contrasting sites of the Rolling Pampa, Argentina, in the 2010/2011 growing season. Experiments were located close to Junín (34°23′S; 60°48′W), Pergamino (33°55′S; 60°23′W) and San Pedro (33°47′S; 60°00′W) in the Buenos Aires province (Fig. 1). Soils in all locations were Mollisols, deep Typic Argiudolls, with ca. 3% of topsoil organic matter, but they differed in characteristics of their argillic horizons (from 0.4 to 0.8 m depth). Clay content in the argillic horizon is higher in San Pedro (50% clay; Ramallo soil series) than in Pergamino (38% clay; Urquiza soil series) and, is the least in Junín (28% clay; Rojas soil series; INTA, 1989).

Incident photosynthetically active solar radiation (PAR) was similar among sites, whereas temperature was slightly higher in San Pedro than in Pergamino and Junín along the season, with larger differences during winter and summer (Fig. 2a). Autumn and winter rainfalls were similar to the historical median for these locations (1970–2010), whereas a slight drought period occurred between November 2010 and early January 2011 (Fig. 2b). While the argillic horizon magnified drought impact in San Pedro, a water-table beyond 1.4 m depth attenuated its effects in Junín. In Pergamino, the loamy soil generated an intermediated water condition.

2.2. Experimental design and management

Seven treatments were evaluated on each location, which included five double crops, combining cool- and warm-season species, and two warm-season single crops. Cropping systems were rapeseed/soybean, wheat/soybean, barley/soybean, field pea/soybean, and field pea/maize as double crops, and maize and

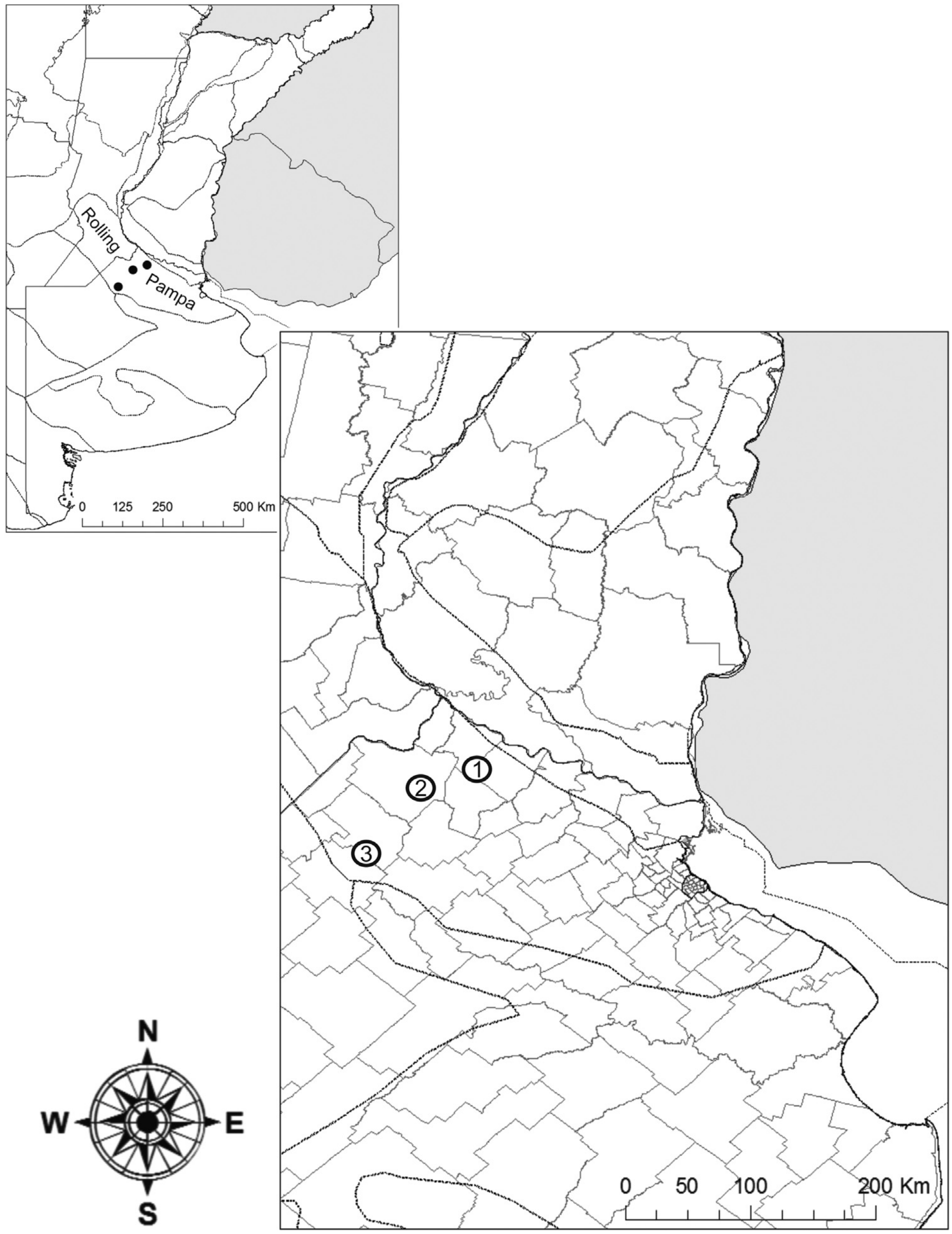

Fig. 1. Region map. Numbers indicate experimental locations: San Pedro (1), Pergamino (2) and Junín (3).

soybean as single crops. At each location, experiments consisted on a completely randomized block design with two replications. Each experiment covered 6 ha, conformed by 14 plots of 4400 m^2 each (22 m wide and 200 m long). Crops were managed with the typical machinery used by farmers in order to generate similar conditions to regular commercial fields in the region. In this sense, no-till sowing system was implemented because over 90% of croplands in the region are under no-tillage management. Crop varieties with high

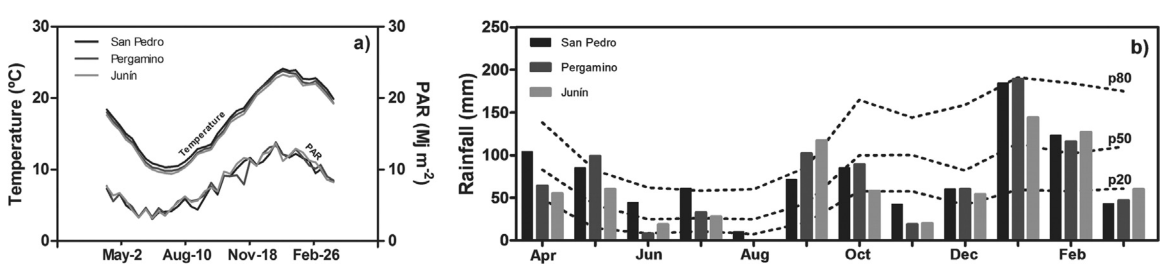

Fig. 2. Environmental conditions from April 2010 to March 2011 for the three sites. (a) Temperature (°C) and photosynthetically active radiation (PAR; Mj m^{-2}) at all sites. (b) Seasonal rainfall (bars) and historical rainfall average (1970–2010; line), expressed in millimeters (mm). Black symbols correspond to San Pedro, grey to Pergamino, and light grey to Junín.

Table 1
Genotypes, sowing date, target density (pl m^{-2}), row spacing (cm), and average nitrogen (N) fertilization rate (kg ha^{-1}) implemented for every crop at all sites.

Crop	Genotype			Sowing date			Target density (pl m^{-2})	Row spacing (cm)			N fertilization rate (kg ha^{-1})
	San Pedro	Pergamino	Junín	San Pedro	Pergamino	Junín		San Pedro	Pergamino	Junín	
Rapeseed	SRM 2836	SRM 2836	SRM 2836	11-May	22-April	26-April	60	20	21	21	110
Barley	Scarlett	Scarlett	Scarlett	10-June	09-June	17-June	280	17.5	21	17.5	110
Wheat	SRM nogal	Baguette 11	Baguette 11	10-June	09-June	17-June	250	17.5	21	17.5	110
Field pea	Viper	Viper	Viper	26-July	17-July	14-July	90	17.5	21	17.5	0
Maize	DK 747	DK 747	DK 747	25-September	18-September	23-Sepember	8	50	52.5	52.5	115
DC maize	DK 747	DK 747	DK 747	06-December	14-December	04-December	7	50	52.5	52.5	60
Soybean	DM 4670	DM 4670	DM 3810	20-October	19-October	25-October	30	35	21	35	0
DC soybean	A 4990	DM 4670	DM 3700	See Table 2	See Table 2	See Table 2	37	35	21	35	0

DC: double cropped.

potential yield in the region were cultivated (Table 1). Sowing date, plant density and row spacing were settled according to regional recommendations to achieve high yields (Table 1). Crop row spacing slightly varied depending on sowing machine available on each site. Soybean second crops were sown immediately after the harvest of cool-season crops, whereas maize second crops were sown when soil moisture ensured seeds germination.

Soil nutrient status was analyzed 20 days before sowing. Fertilizers were applied at sowing in order to complement soil nutrition and supply the crops demands during their growing cycles, according to technical recommendations for the Rolling Pampa (Table 1; Echeverría and Garcia, 2005). Soybean and field pea seeds were inoculated before sowing with *Bradiryzhobium japonicum* and *Rhizobium leguminosarum* var. pisi, respectively. Weeds, insects, and diseases were maintained below significant damage thresholds by applying chemical controls using a self-propelled sprayer when it was necessary.

2.3. Sampling and analysis

Above-ground biomass and grain yield of each crop were measured. At least 3 samples of 1 m^2 were taken in each plot by cutting plants at ground level, then dried in a stove at temperatures not exceeding 60 °C, and weighted to obtain the dry weight of above-ground biomass at maturity. For yield determination, grains on every plot were harvested with a combine harvest machine and then transferred to a hopper with scale to weight them. Figures of both above-ground biomass and grain yield of all crops were expressed per hectare for every crop. Crop grain yield was expressed as kilograms of dry grain per hectare (kg ha^{-1}) and in glucose-equivalent terms, i.e, expressed as kilograms of glucose equivalents (g.e.) per hectare (kg g.e. ha^{-1}). The aim of expressing grain yields in glucose units was to compare crop types and cropping systems with different grain composition. Glucose equivalent is the amount of glucose necessary to produce 1 kg of grain, which depends on grain chemical composition. Penning de Vries et al. (1983) established that 1 kg of glucose is equivalent to 0.83 kg of carbohydrates, 0.33 kg of lipids, or 0.41 kg of proteins. Grain composition of several field crops has been described in many reports (Sinclair and de Wit, 1975; Watson and Ramstad, 1987; Gooding and Davies, 1997; Stone and Savin, 1999), allowing to determine the value of glucose equivalent per kg of grain of a given crop type. Here, glucose equivalents for grains of rapeseed, barley, wheat, field pea, maize, and soybean grain were settled on 2.18, 1.20, 1.28, 1.26, 1.32, and 1.86 kg g.e./kg of grain, respectively.

Resource use of crops was measured in all treatments. Solar radiation, water, and nutrients were considered for the analysis. Incident photosynthetically active radiation (PAR) during crop growing stage (from crop emergence to maturity), interception efficiency (e_i), radiation use efficiency to produce above-ground biomass (RUEb) and harvest index (HI) were considered to be grain yield determinants (Eq. (1)).

$$GY = PAR \times e_i \times RUEb \times HI \tag{1}$$

Daily incident radiation was obtained from meteorological stations nearby the experimental sites, whereas the non-intercepted PAR ($PAR_{non-intercepted}$) was measured with a photosynthetic photon flux (PPF) portable sensible bar (Cavadevices Argentina; http://www.cavadevices.com). At least 5 measurements were taken by plot every 15 days until crop physiological maturity. Intervals between dates were linearly interpolated. Interception efficiency (e_i) was then calculated (Eq. (2)):

$$e_i = 1 - \left(\frac{P\,AR_{non-intercepted}}{PAR}\right) \tag{2}$$

Crop evapotranspiration (ET; mm) was estimated through water balance during the crop cycle. The difference between the soil water content at sowing (SWC_s) and maturity (SWC_m) was obtained up to 1.8 m depth. Then, rainfall (RF) was added (Eq. (3)).

$$ET = (SWC_s - S\,WC_m) + RF \tag{3}$$

Soil water content was measured gravimetrically as the weight differences between soil samples before and after being dried in stove at 110 °C for 72 h. After that, moisture content was affected by soil apparent density (INTA, 1989) to obtain the volumetric water content (%) and water lamina (mm) at the sampling dates.

Resource use efficiency was calculated as the quotient between productivity and resource capture. Above-ground biomass produced per unit of PAR intercepted, and ET was calculated for each crop in single and double crops, and annual grain yield produced (in g.e. units) per unit of resource utilized was estimated for all treatments.

Finally, nitrogen (N), phosphorus (P), and sulfur (S) contents in grains were determined to retrospectively reflect any nutritional shortage during the growing cycle of soybean crops. Techniques implemented to estimate nutrient concentration were Kjeldahl, colorimetry, and turbidimetry for N, P and S, respectively.

Statistical analysis was performed using Infostat software (Di Rienzo et al., 2011). Treatments effects were evaluated using analysis of variance (ANOVA) and associations between variables were evaluated with regression analysis.

2.4. Simulation experiments

Single and double crop yields were simulated using CERES (Ritchie and Otter, 1985) and CROPGRO (Boote et al., 1998) models of DSSAT v.4.5 (Hoogenboom et al., 2012). CROPGRO-soybean, CERES-maize, CERES-wheat (Monzon et al., 2013), and CERES-barley were adapted, locally calibrated and tested to evaluate their performance under a long-term weather data series (39 years).

Table 2
Winter crops comparative analysis [rapeseed, barley, wheat, and field pea before maize (m) and soybean (s)]. The analysis includes grain yield, above ground biomass and stubble quantity, all of them expressed in kilograms of dry matter per hectare (kg ha^{-1}), harvest index (HI), photosynthetically active radiation interception (IPAR; Mj m^{-2}), evapotranspiration (ET; mm), water availability at maturity (M; mm), maturity date and sowing date allowed for double cropped (DC) soybean after every winter crop evaluated.

Winter crop	Grain yield (kg ha^{-1})	Aboveground biomass (kg ha^{-1})	Stubble biomass (kg ha^{-1})	HI	IPAR (Mj m^{-2})	ET (mm)	Water availability at M (mm)	Maturity date	Sowing date of DC soybean
San Pedro									
Rapeseed	2083	7906	5824	0.26	625 a	383 a	218 b	13-November	23-November
Barley	5311	13461	8151	0.40	535 b	345 b	217 b	03-November	18-November
Wheat	5629	13956	8327	0.41	641 a	401 a	178 c	20-November	06-December
Field pea (s)	2592	6396	3804	0.41	406 c	242 c	250 a	17-November	23-November
Field pea (m)	2628	6430	3803	0.41	409 c	227 c	261 a	17-November	–
					***	***	***		
Pergamino									
Rapeseed	1906	6877	4972	0.28	687 a	439 a	312 a	08-November	18-November
Barley	5055	11897	6842	0.43	516 c	392 bc	240 b	12-November	25-November
Wheat	4618	10707	6089	0.43	595 b	406 ab	236 b	02-December	16-December
Field pea (s)	2977	7080	4104	0.42	405 d	362 c	249 b	17-November	25-November
Field pea (m)	2909	6876	3967	0.42	404 d	366 bc	257 b	17-November	–
					***	***	**		
Junín									
Rapeseed	2352	8133	5781	0.29	559 ab	318 b	403 a	11-November	04-December
Barley	4298	12236	7938	0.35	536 b	321 b	371 b	11-November	04-December
Wheat	4756	13286	8531	0.36	613 a	423 a	306 d	01-December	23-December
Field pea (s)	2810	7192	4382	0.39	406 c	334 b	318 cd	20-November	04-December
Field pea (m)	2734	7469	4734	0.37	413 c	312 b	336 c	20-November	–
					***	***	***		

Different letters indicate significant differences (LSD, $p < 0.05$); $^{*}P < 0.1$; $^{**}P < 0.05$; $^{***}P < 0.01$ (ANOVA).

CROPGRO-cowpea was modified, adapted, calibrated, and tested in order to simulate field pea crops. Model performance for barley and field pea was assessed by using regression analysis and the root mean square error (RMSE; Table 7; Fila et al., 2003). Rapeseed was not considered in this analysis because the lack of experimental information to properly test this model in the region.

Three initial levels of soil water availability (low: 45%, intermediate: 67% and high: 100% of maximum available soil water) were set on June 1 for the same three locations where the field experiments were conducted. Wheat and barley sowing dates were set on June 10, whereas sowing date for field pea was July 15. Single crops of maize and soybean were sown on September 25 and November 1, respectively. Second crops in double cropping were sown immediately after the average harvest date of cool-season crops. Since crop simulation models estimate physiological rather than harvest maturity, harvest date was estimated to be 15 days after wheat and barley maturity (Monzon et al., 2007) and 7 days after field pea maturity. Soil water output information at maturity of cool-season crops or after the fallow period was considered as the initial condition for warm-season crops. The probabilistic distribution of water in the soil profile was included for warm-season crop analysis. Three percentiles (20th, 50th, and 80th) were set as the initial conditions for warm-season crops to perform more sensitive analysis. Crop grain yields were expressed as dry grain after considering 7% harvest lost for soybean and 3.5% for the other crops (Ermácora, personal communication). No detrimental effects of nutrients and pests were considered.

3. Results

3.1. Resource use patterns and productivity in cool-season crops

3.1.1. Interception of solar radiation

Total photosynthetically active radiation intercepted by crops (IPAR, MJ m^{-2}) and the interception efficiency (e_i, %) patterns during winter and spring seasons differed among treatments. Wheat and rapeseed reached the highest IPAR at all locations. However, maximum interception levels occurred earlier in rapeseed than in wheat as consequence of differences in the growing cycles of both crops (Fig. 4). Moreover, wheat crops intercepted more PAR than barley ones, whereas field pea had the lowest PAR interception in all sites (Table 2).

3.1.2. Water use

Wheat and rapeseed evapotranspiration (ET, mm) were the largest in San Pedro. As observed for PAR interception, crop ET of either wheat or rapeseed crops was greater than that of barley and field pea crops in San Pedro, Pergamino and Junín (Table 2). Likewise IPAR results, field pea was among crops of lowest water use at all locations (Table 2).

Including cool-season crops in the sequence reduced water availability for the following warm-season second crops, especially up to 0.8 m depth, when compared to the fallow period that preceded soybean and maize single crops (Fig. 3a and b). Water use patterns in cool-season crops resulted in different water availability at maturity. Soil water content at crop maturity was higher in rapeseed than in the other crops in Junín and Pergamino (Table 2). On the contrary, soil water content after wheat crops was the lowest in San Pedro and Junín and tended to be the lowest in Pergamino.

Water distribution throughout the soil profile also differed among treatments. At rapeseed maturity, large amounts of water were available up to 0.8 m depth. In contrast, albeit field pea left relatively large amounts of available water in soil after maturity, water availability was low from 0 to 0.8 m depth. Finally, wheat crops left the lowest amount of available water along the whole soil profile (up to 1.8 m depth; Fig. 3a).

3.1.3. Crop maturity date

Harvest dates of cool-season crops were associated with crop maturity, which also defined the sowing dates of second crops. Maturity date of field pea crops occurred later than rapeseed and barley. However, the period between maturity and harvest was the shortest in field pea crops, which allowed sowing second soybean crops in similar dates to those sown after rapeseed and barley. In

Table 3
Single and double cropped soybean performances after different cool-season crops. Grain yield was analyzed as the resultant of resource capture, resource use efficiency and harvest index. Therefore, values of incident photosynthetically active radiation (PAR; Mj m^{-2}), interception efficiency, radiation use efficiency to produce biomass (RUEb; g Mj^{-1}), evapotranspiration (ET; mm), water use efficiency to produce biomass (WUEb; kg ha^{-1} mm^{-1}), harvest index (HI) aboveground biomass and grain yield (kg ha^{-1}) are presented.

Previous crop	PAR (Mj m^{-2})	Interception efficiency	IPAR (Mj m^{-2})	RUEb (g Mj^{-1})	ET (mm)	WUEb (kg ha^{-1} mm^{-1})	Aboveground biomass (kg ha^{-1})	HI	Grain yield (kg ha^{-1})
San Pedro									
Fallow	1535	0.64 a	973 a	0.90 a	584 a	15.0 a	8774 a	0.44	3883 a
Rapeseed	1331	0.45 c	603 c	0.98 a	483 c	12.3 b	5908 b	0.44	2574 c
Barley	1394	0.46 c	646 c	0.94 a	458 cd	13.3 ab	6094 b	0.42	2544 c
Wheat	1067	0.57 b	603 c	0.70 b	441 d	9.6 c	4211 c	0.53	2210 d
Field pea	1359	0.54 b	736 b	0.90 a	520 b	12.7 ab	6615 b	0.45	2979 b
		***	***	*	***	**	***	ns	***
Pergamino									
Fallow	1497	0.68 a	1011 a	0.88	536 a	16.5 a	8867 a	0.47	4177 a
Rapeseed	1395	0.57 b	795 b	0.82	489 ab	13.4 bc	6551 b	0.46	3031 b
Barley	1378	0.45 c	615 c	0.87	484 ab	11.1 cd	5356 c	0.46	2484 c
Wheat	1165	0.46 c	542 d	0.86	445 b	10.5 d	4651 c	0.53	2433 c
Field pea	1406	0.56 b	787 b	0.86	469 b	14.5 ab	6799 b	0.49	3306 b
		***	***	ns	*	***	***	ns	***
Junín									
Fallow	1490	0.63 a	934 a	0.98 ab	430 c	21.2 a	9105 a	0.45	4079 a
Rapeseed	1371	0.41 c	558 b	1.19 a	491 a	13.4 b	6581 b	0.44	2910 bc
Barley	1371	0.41 c	563 b	1.05 ab	466 bc	12.7 b	5913 bc	0.47	2782 c
Wheat	1151	0.56 b	639 b	0.86 b	386 d	14.2 b	5483 c	0.47	2564 d
Field pea	1371	0.46 c	630 b	0.96 b	473 b	12.7 b	6020 bc	0.49	2953 b
		***	***	*	***	***	***	ns	***

Different letters indicate significant differences (LSD, $p < 0.05$); $^{*}P < 0.1$; $^{**}P < 0.05$; $^{***}P < 0.01$; ns: not significant effects (ANOVA).

contrast, wheat reached maturity later than the aforementioned cool-season crops and, therefore, soybean after wheat had the latest sowing date at all locations (Table 2). It is noteworthy that top-soil moisture allowed for sowing of these crops immediately after the harvest of cool-season crops at every location.

3.1.4. Stubble of cool-season crops

After the harvest of cool-season crops, the amount and quality of crop residues left on the ground varied depending on the cultivated species. The largest stubble quantity was left by wheat and barley (7649 and 7643 kg ha^{-1}, averaging all locations), less stubble was left by rapeseed (6242 kg ha^{-1}), and the smallest by field pea (4130 kg ha^{-1}). Stubble quality was not tested in all plots, but great differences were found after every cool-season crop. As average of several plots measured, the %N was 0.61, 0.35, 0.29 and 0.24 for field pea, rapeseed, barley and wheat, respectively (data not shown).

3.2. Soybean as single and second crop

Yield determination of single and second warm-season crops was analyzed with Eq. (1). Resource availability, resource capture efficiency, resource use efficiency to produce above-

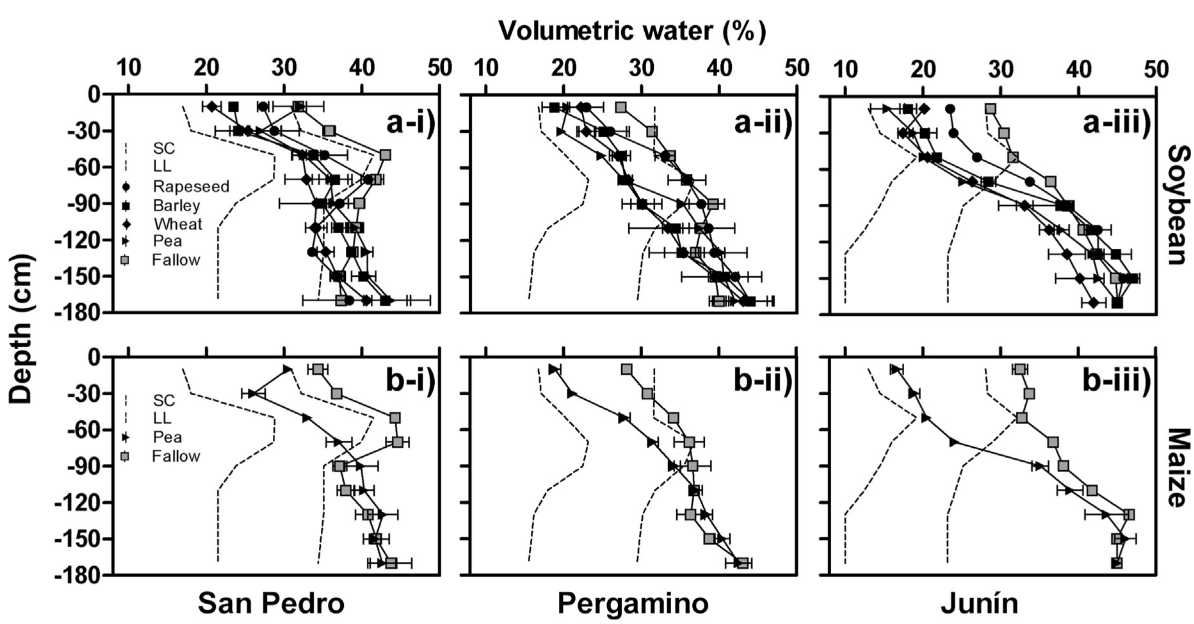

Fig. 3. Soil water profiles after cool-season crop alternatives and fallow periods, before the sow of soybean (a) or maize (b). Soil water content is expressed as volumetric water (%). Dashed lines indicate upper (SC; soil capacity) and lower limit (LL) of available water. Grey squares represent water content after a fallow period. Black symbols indicate water content at maturity of rapeseed (circles), barley (squares), wheat (diamonds), and field pea (triangles). Horizontal bars indicate standard deviation.

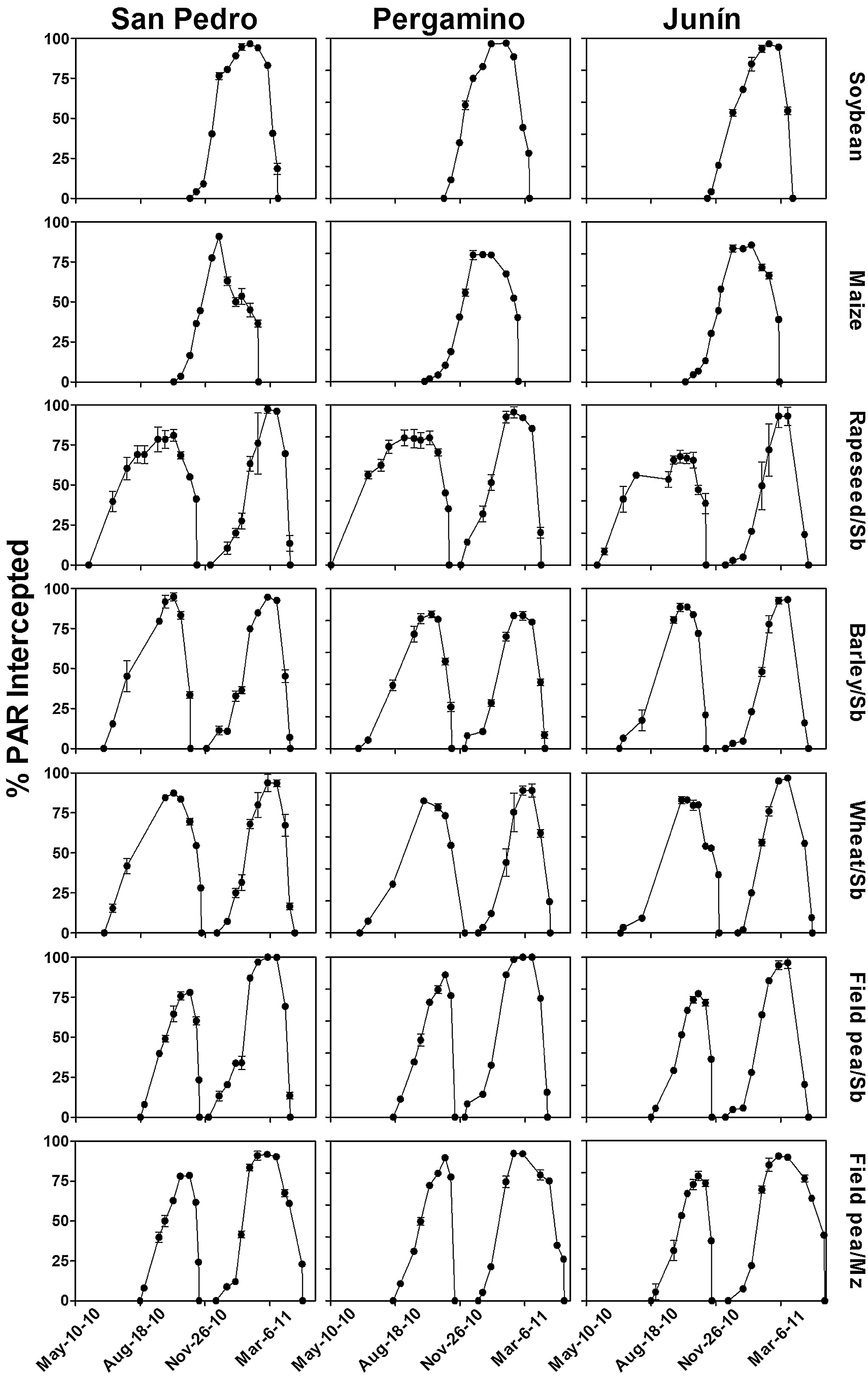

Fig. 4. Dynamics of photosynthetically active radiation (PAR) interception (% of incident PAR) of the seven cropping systems considered for the three sites, from May 2010 to May 2011. Mz: maize; Sb: soybean. Bars indicate standard deviation.

ground biomass and harvest index were considered as the eco-physiological factors determining grain yield.

Total incident PAR on soybean crops differed among treatments. Single soybean crops received greater amount of incident PAR during their growing cycle than any double cropped soybean. Incident PAR was similar in double cropped soybeans cultivated after barley (S_B), rapeseed (S_R) and field pea (S_P), but it was significantly reduced when the previous crop was wheat (S_W) at all experiments (Table 3).

PAR interception efficiency (e_i) was also affected by the previous crop with implicancies on total intercepted PAR (IPAR) by soybean crops. Single soybean crops intercepted a higher fraction of incident PAR during its growing cycle than the various double cropped soybeans. Comparing among double cropped soybeans, the e_i was higher for S_W and S_P than S_B and S_R in San Pedro, whereas the most efficient double cropped soybeans to intercept PAR were S_W in Junín and S_R and S_P in Pergamino. Overall, S_B was among the second soybean crops with the lowest capacity to intercept PAR at all locations (Table 3; Fig. 4). The product between incident PAR and e_i determined that S_P was among the second soybean crops with highest IPAR at all experiments (Table 3).

Variability in IPAR resulted in different amounts of above-ground biomass produced between treatments, because low differences in biomass radiation use efficiency (RUEb) were found, except in San Pedro, where S_W presented lower RUEb than the other treatments. For this reason, single cropped soybean accumulated more above-ground biomass than any double cropped soybean at all experiments, although field pea as previous crop allowed for high biomass productivity of double cropped soybean. Finally, harvest index (HI) did not significantly differ among treatments ($P > 0.1$; Table 3).

Soybean yield differences were mostly explained by changes in IPAR (Fig. 5b), produced by sowing date delays (Fig. 5a). In summary, soybean yields were always lower in double than in single crop, with yield reductions of 31–34% on the average of all treatments. Grain yield of double cropped soybean also differed depending on the previous cool-season crop ($P < 0.01$). As the average of all experiments, grain yield was 3079 kg ha^{-1} in S_P, 2838 kg ha^{-1} in S_R, 2603 kg ha^{-1} in S_B, and 2402 kg ha^{-1} in S_W. S_P grain yield was always higher than those of S_W and S_B, while exceeded S_R grain yield only in San Pedro. Moreover, S_R grain yield exceeded that obtained by S_W at all locations, whereas S_B surpassed that of S_W in San Pedro and Junín (Table 3).

Water use also greatly varied among double cropped soybeans according to the previous cropping systems in San Pedro and Junín ($P < 0.01$). In both sites, S_W used the lowest amount of water during the crop growing cycle, whereas the highest evapotranspiration was measured for S_R in Junín and S_P in San Pedro. In contrast, differences between treatments were low in Pergamino ($P < 0.1$; Table 3). Results on the total ET of soybean in single crops compared to second crops were erratic (Table 3). However, soybean single crop was among the most efficient soybean crops in using available water at all locations, whereas water use efficiency to produce biomass (WUEb) was low in S_W and significantly lower than other double cropped soybeans in San Pedro and Pergamino (Table 3).

Nutritional status was evaluated after crop harvest by analyzing the composition of soybean grains in all treatments. Phosphorus (P) and sulfur (S) contents in grain (% of dry matter) were affected by the previous crop ($P < 0.05$), while nitrogen contents (N) did not significantly differ among treatments ($P > 0.1$; Table 4). Sulfur percentage in grains of S_P was among the highest values at all locations and it was always higher than S_W and S_B. In contrast, phosphorus percentage in grains of double cropped soybean tended to be the lowest in S_P and the highest in S_R in Junín and Pergamino (Table 4). Sulfur concentration in grains of double cropped soybean denoted differences in nutritional status during crop development. Sulfur concentration was positively correlated with grain yield when rapeseed, barley and field pea as previous crops were compared (late sown treatments, i.e., after wheat crops, were excluded to isolate nutritional causes from sowing date effects). Therefore, a positive and significant correlation was found between grain yield and sulfur content in grains (Fig. 6). A better sulfur status increased grain yield by slight improvements in radiation interception efficiency (e_i) and HI of S_P when compared to S_R and S_B (Table 3).

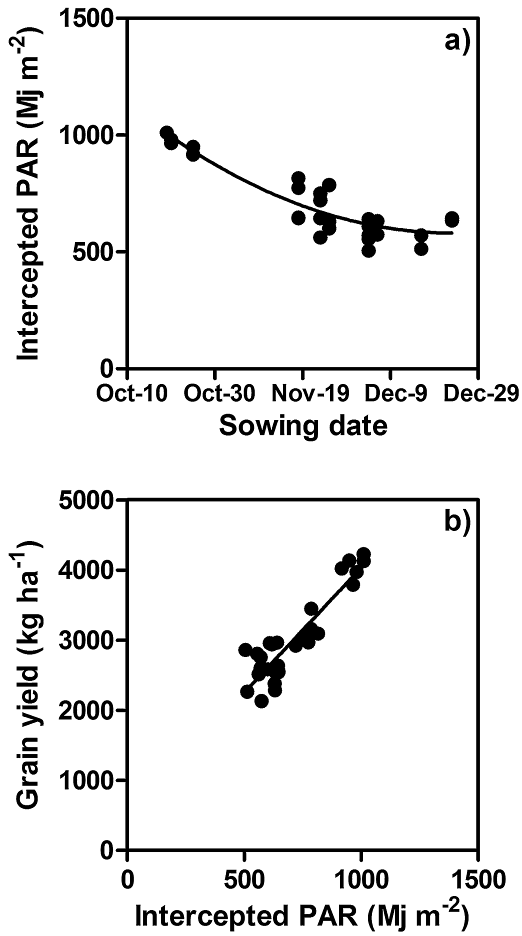

Fig. 5. (a) Soybean PAR intercepted (Mj m^{-2}) as a function of sowing date ($R^2 = 0.834$), and (b) soybean grain yield (kg ha^{-1}) as a function of intercepted PAR (Mj m^{-2}; $R^2 = 0.831$). Every soybean crops (single and second) at all sites were included in the analysis.

3.3. Maize as single and second crop

Sowing dates of maize crops grown after field pea (M_P) were later than those in maize single crops sown by late September (Table 1), which is the optimum sowing period for this crop in the region. Therefore, incident PAR during maize cycle was lower in the second crops after pea. However, M_P tended to compensate this reduction in PAR availability by intercepting higher fractions, which resulted in a similar IPAR to those of maize single crops in San Pedro and Pergamino. Moreover, RUEb was higher for M_P than for single cropped maize, particularly in San Pedro, which resulted in greater biomass production. Then, HI was also higher in M_P plots in San Pedro, thus increasing productivity differences in terms of grain yield. Patterns for Pergamino tended to be similar to those in San Pedro. In contrast, both maize crops performances were similar in Junín (Table 5).

Evapotranspiration was higher in single maize crops than in M_P in both Pergamino and Junín. Conversely, there were no apparent

Table 4
Nutrients composition of soybean grains in various crop sequences. Nitrogen (N), phosphorus (P) and sulfur (S) were analyzed for all soybean crops at all sites. Values are expressed as % of total dry matter.

Previous crop	San Pedro			Pergamino			Junín		
	N	P	S	N	P	S	N	P	S
Fallow	5.62	0.48 c	0.25 a	5.13	0.51 bc	0.17 b	5.06	0.46 b	0.21 b
Rapeseed	5.77	0.49 c	0.22 a	5.20	0.54 a	0.14 c	5.23	0.51 a	0.22 ab
Barley	5.62	0.53 a	0.18 b	5.12	0.52 ab	0.14 c	5.51	0.48 ab	0.20 b
Wheat	5.49	0.52 ab	0.19 b	5.18	0.51 bc	0.15 c	4.99	0.46 b	0.21 b
Field pea	5.94	0.50 bc	0.24 a	5.51	0.49 c	0.20 a	5.43	0.45 b	0.23 a
	ns	***	***	ns	***	***	ns	**	**

Different letters indicate significant differences (LSD; $p < 0.05$); *$P < 0.1$; **$P < 0.05$; ***$P < 0.01$; ns: not significant effects (ANOVA).

Table 5
Maize crops performances. Single maize crops after a fallow period and after a field pea crop. Grain yield was analyzed as the resultant of resource capture, resource use efficiency and harvest index. Therefore, values of incident photosynthetically active radiation (PARb; Mj m^{-2}), interception efficiency, radiation use efficiency to produce biomass (RUE; g Mj^{-1}), evapotranspiration (ET; mm), water use efficiency to produce biomass (WUEb; kg ha–^{1} mm^{-1}), harvest index (HI) aboveground biomass and grain yield (kg ha^{-1}) are presented.

Previous crop	PAR (Mj m^{-2})	Interception efficiency	IPAR (MJ m^{-2})	RUEb (g Mj^{-1})	ET (mm)	WUEb (kg ha^{-1} mm^{-1})	Aboveground biomass (kg ha^{-1})	HI	Grain yield (kg ha^{-1})
San Pedro									
Fallow	1496	0.48 b	720	1.96 b	557	25.3 b	14098 b	0.43	6099 b
Field pea	1142	0.61 a	695	2.33 a	596	27.3 a	16182 a	0.53	8617 a
		**	ns	**	*	***	**	*	**
Pergamino									
Fallow	1593	0.51	813	1.94	529 a	29.9	15787	0.49	7705 b
Field pea	1299	0.58	758	2.30	507 b	34.3	17386	0.54	9397 a
		ns	ns	*	**	ns	ns	ns	**
Junín									
Fallow	1679	0.54	909	2.05	580 a	32.1	18599	0.53 b	9810
Field pea	1471	0.53	772	2.14	514 b	32.1	16492	0.56 a	9267
		ns	*	ns	**	ns	**	**	*

Different letters indicate significant differences (LSD, $p < 0.05$); *$P < 0.1$; **$P < 0.05$; ***$P < 0.01$; ns: not significant effects (ANOVA).

Table 6
Cropping systems resource capture and productivity. Photosynthetically active radiation intercepted (IPAR; (Mj m^{-2}), radiation use efficiency to produce grains (in glucose equivalent units; RUEg; Mj^{-1}), evapotranspiration (ET; mm), water use efficiency to produce grains (in glucose equivalent units; WUEg; kg ha^{-1} mm^{-1}), glucose yield and yield relative to the respective summer single crop.

Cropping system	IPAR (Mj m^{-2})	RUEg (g Mj^{-1})	ET (mm)	WUEg (kg ha^{-1} mm^{-1})	Glucose yield (kg g.e. ha^{-1})	Relative yield
San Pedro						
Soybean	973 c	0.74 d	584 e	12.4 cd	7223 e	1 d
Maize	720 d	1.12 b	557 e	14.5 b	8051 de	1 d
Rapeseed/soybean	1228 a	0.76 d	866 a	10.8 e	9327 c	1.29 c
Barley/soybean	1180 ab	0.94 c	803 c	13.8 b	11105 b	1.54 b
Wheat/soybean	1244 a	0.91 c	842 ab	13.4 bc	11315 b	1.57 b
Field pea/soybean	1141 ab	0.77 d	762 d	11.6 de	8806 cd	1.22 c
Field pea/maize	1104 b	1.33 a	820 bc	17.9 a	14685 a	1.83 a
	***	***	***	***	***	***
Pergamino						
Soybean	1011 c	0.77 d	538 c	14.5 b	7770 c	1 c
Maize	813 d	1.25 b	529 c	19.3 a	10170 b	1 c
Rapeseed/soybean	1481 a	0.66 e	927 a	10.6 d	9791 b	1.26 b
Barley/soybean	1131 b	0.95 c	876 ab	12.3 c	10686 b	1.38 b
Wheat/soybean	1136 b	0.92 c	851 b	12.3 c	10437 b	1.34 b
Field pea/soybean	1192 b	0.83 d	831 b	11.9 cd	9899 b	1.28 b
Field pea/maize	1162 b	1.38 a	873 ab	18.4 a	16069 a	1.58 a
	***	***	***	***	***	***
Junín						
Soybean	934 d	0.81 d	430 d	17.7 c	7586 f	1 d
Maize	909 d	1.42 a	580 c	22.4 a	12950 b	1 d
Rapeseed/soybean	1116 bc	0.95 c	809ab	13.0 d	10540 cd	1.39 ab
Barley/soybean	1099 bc	0.94 c	786 b	13.2 d	10332 d	1.36 b
Wheat/soybean	1252 a	0.87 cd	810 ab	13.4 d	10855 c	1.43 a
Field pea/soybean	1036 c	0.87 cd	806 ab	11.2 e	9032 e	1.19 c
Field pea/maize	1185 ab	1.32 b	827 a	19.0 b	15678 a	1.22 c
	***	***	***	***	***	***

Different letters indicate significant differences (LSD, $p < 0.05$); *$P < 0.1$; **$P < 0.05$; ***$P < 0.01$ (ANOVA).

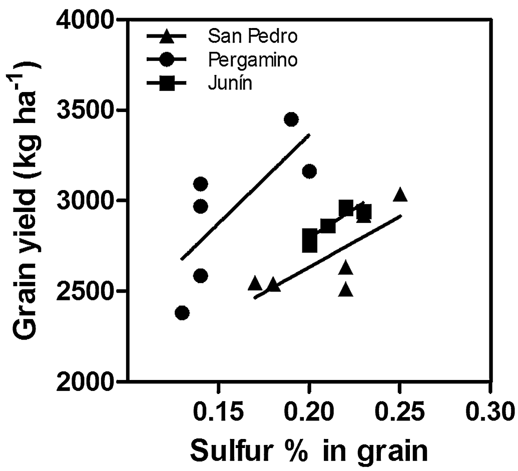

Fig. 6. Double cropped soybean grain yield (kg ha^{-1}) after barley, field pea and rapeseed crops as a function of sulfur concentration in grains for San Pedro (triangles; $R^2 = 0.59$), Pergamino (circles; $R^2 = 0.56$) and Junín (squares; $R^2 = 0.82$).

differences in San Pedro, where WUEb was reduced due to a moderate water deficit period during single maize critical period for seed setting, which was aggravated by the high soil water retention in the argillic horizon (Table 5; Figs. 2 and 3).

3.4. Overall performance of cropping systems

Cropping systems differed in both the amount of resources used and their resource use efficiencies ($P < 0.01$). Including cool-season crops before soybean or maize crops resulted in greater overall resource capture. Double cropping including maize as a second crop increased the IPAR by 30–53% and ET by 43–65% when compared to maize single crops. Moreover, double cropping including soybean as second crop improved IPAR by 11–46% and ET by 30–88% compared to single soybean crops. Among all double crops alternatives, the highest resource utilization was reached by wheat/soybean in Junín, rapeseed/soybean in Pergamino, and both cropping systems were above the others in San Pedro. In contrast, field pea/soybean was always among the double crops with lowest resource use (Table 6).

Cropping systems including maize were the most efficient in using resources. Moreover, growing field pea before maize improved the resource capture with no or little detrimental effects on the global resource use efficiency when compared with maize single crops. Including a cool-season crop before soybean increased the amount of resources used and also increased RUE to produce grains (RUEg) in many cases, especially in those sequences including wheat or barley. However, double crops including soybean had lower WUE to produce grains than single soybean crops in Pergamino and Junín (Table 6).

Regarding the consequences of the overall capture and use efficiency of resources, field pea/maize double crop and soybean single crop were the most and the least productive cropping systems, respectively (expressed in g.e. units; Table 6). Glucose equivalent yield of all treatments related to global IPAR and ET, respectively, is shown in Fig. 7a and b. Slopes of slashed lines denote resource use efficiencies of reference, with increasing values as the angle formed between lines and the *x* axis expands. These figures denote that field pea/maize double crops improved resource capture when compared to maize single crop, thus, maintaining resource use efficiency and increasing the overall grain yield in glucose equivalent terms.

Wheat/soybean and barley/soybean had similar grain glucose equivalent yields, while rapeseed/soybean was significantly less

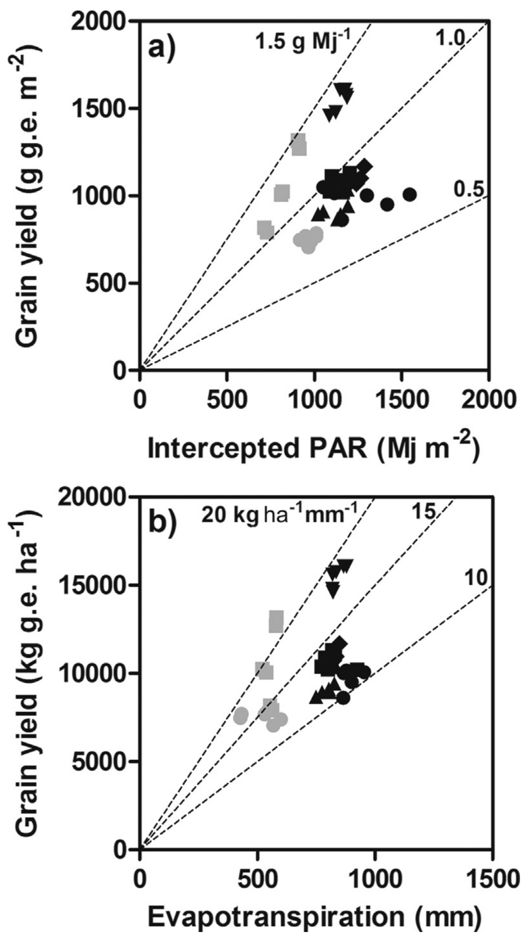

Fig. 7. Cropping systems grain yield (in glucose equivalents (g.e.) per unit area) related to (a) photosynthetically active radiation (PAR) intercepted (Mj m^{-2}) and (b) crop evapotranspiration (ET; mm). Dashed lines are a reference of resource use efficiency. Black symbols correspond to field pea/maize (inverted triangles), field pea/soybean (triangles), rapeseed/soybean (circles), barley/soybean (squares) and wheat/soybean (diamonds) doubles crops. Grey symbols correspond to maize (squares) and soybean (circles) single crops.

productive than former two double crops in San Pedro. Field pea/soybean reached the lowest annual yield among double crops in San Pedro and Junín (Table 6). However, resource utilization and use efficiency of double cropping systems including soybean as second crop presented low variability. These cropping systems are grouped and apart from soybean single crops in Fig. 7a and b.

Finally, comparison of relative yields showed that sowing the cool-season crops considered here before warm-season crops improved annual grain glucose equivalent yield in all experiments, with yield increments between 19 and 57% when double crops included soybean and between 22 and 83% in field pea/maize (Table 6).

3.5. Simulation experiments

Crop yield simulations showed that scenarios with restricted soil water availability on June 1 determined lower average yields and higher yield variability for wheat and barley, but not for field pea crops. Considering that cool-season crops in the field experiments were sown with initial available water contents close to soil capacity (data not shown), grain yields experimentally obtained were similar to the average simulated for Junín, ca. 10% above those for Pergamino, and 30% for San Pedro (Table 7).

As obtained in field experiments, simulated soil water contents at maturity of any cool-season crop were lower than those at the

Table 7
Simulated cool-season crop yields under three initial soil water scenarios (45, 67 and 100% of maximum available soil water). Wheat, genetic coefficients were already calibrated and tested by Monzon et al. (2013). Barley genetic coefficients evaluation on yield: RMSE (root mean square error) =353 kg ha^{-1}; slope = 0.99; intercept = 2.4; R^2 = 0.51. Barley genetic coefficients evaluation on phenology: RMSE = 3.2 days. Field pea genetic coefficients evaluation on yield: RMSE = 319 kg ha^{-1}; slope = 0.60; intercept = 1080; R^2 = 0.83. Field pea genetic coefficients evaluation on phenology: RMSE = 5.8 days.

Grain yield (Kg ha^{-1}); (SD)						
	Soil water condition on June 1					
Crop	Dry (45%)		Intermediate (67%)		Wet (100%)	
San Pedro						
Barley	3892	(±909)	4126	(±693)	4164	(±660)
Wheat	3825	(±956)	3995	(±790)	4018	(±765)
Field pea	2033	(±412)	2057	(±395)	2059	(±396)
Pergamino						
Barley	3648	(±1055)	4234	(±763)	4474	(±581)
Wheat	3518	(±1040)	4051	(±815)	4166	(±753)
Field pea	2158	(±546)	2212	(±474)	2219	(±458)
Junín						
Barley	4253	(±751)	4651	(±535)	4748	(±502)
Wheat	4272	(±821)	4695	(±576)	4777	(±541)
Field pea	2526	(±494)	2567	(±497)	2568	(±498)

SD: standard deviation.

end of fallow periods preceding single warm-season crops (Fig. 8). Also, among cool-season crops, field pea usually left more available water in soil for second crops, as shown by the median values in the 50th percentile curve (Fig. 8). Moreover, the three cool-season crops evaluated had similar available water contents at maturity for the 20th and 80th percentiles.

Sowing dates of maize and soybean as second crops were delayed in comparison to the optimum sowing dates as single crops. Regarding double cropped soybeans, sowing date for S_B was slightly earlier than S_P and significantly earlier than S_W (Table 8), because physiological maturity usually occurred later in wheat than in barley and field pea.

Concerning yields of double cropped soybeans, field pea was the best preceding crop, which combined early harvest with the highest probability to find more water available in the soil at maturity. For these reasons, when the median initial condition (50th percentile) was set, the average records indicate that S_P outyielded S_B and S_W in Pergamino and Junín. Setting the initial soil water condition at the 80th percentile improved the yields estimated for S_B and S_W more than for S_P (Table 8).

Given the above mentioned initial conditions, all double cropped soybeans yielded less than single soybean crops. Differently, average yields of maize single crops were lower than those of M_P in San Pedro and Pergamino, but they did not differ in Junín (Table 8), thus, in agreement with the results obtained on field experiments.

4. Discussion

Double cropping systems, in which cool- and warm-season crops were grown in sequence, increased the overall resource use in the growing season. Moreover, annual land productivity was improved in all double cropping combinations, when compared with their respective single warm-season crops. However, this increase varied according to the cool-season crop grown before soybeans. Cool-season crops differed in both grain yield and the impact on the following soybean crop. This was mainly due to the delay in the sowing date and the differences in nutrient uptake in field experiments (Figs. 5 and 6; Table 4), whereas crop simulation results allowed for a more complete analysis about the relevance of available water. Our findings not only widen previous knowledge about the feasibility of double cropping to increase annual land productivity (Caviglia et al., 2004; Caviglia and Andrade, 2010; Van Opstal et al., 2011), but also provide insights on the resource use patterns and efficiency in diversified crop sequences grown in temperate regions with extended growing seasons.

4.1. Comparative performance of single and double crops

Double cropping systems improved land productivity in comparison to the respective single warm-season crops, which mostly resulted from a more complete interception of incoming solar radiation and uptake of available soil water during the growing season than that in single warm-season crops (Table 6). The greater resource capture in double crops resulted from the fact that cool-season crops had access to resources unused by either maize or soybean as single crops (Fig. 4). Moreover, the larger resource use by double crops occurred even though warm-season crops experienced low availability of soil resources and/or restricted ability for accessing radiation when sown late after harvesting cool-season crops. Regarding single warm-season crops, resources available during the growing season were underused, because incident radiation during winter cannot be stored and water storage is constrained by the retention capacity of soils. Moreover, in many situations, double crops increased resource capture with no or slight detrimental effects on resource use efficiency when single and double cropping with the same warm-season crop were compared (Table 6; Fig. 7).

4.2. Cool-season crops comparative analysis

Cool-season crop species diverged in some attributes associated with resource use. Overall, despite of temporal differences, the highest quantity of resources was captured by wheat and rapeseed, less by barley and the least amount by field pea (Table 2). It could be inferred that the larger resource use during winter and spring seasons, the lower resource availability is left to second warm-season crops. However, there was another aspect to be considered, the temporal dynamics of resource use. Wheat had an extended growing cycle and reached maturity later than the other cool-season crops, thus, making use of a great share of the resources available during the growing season. Rapeseed also presented a long growing season but that started before, which therefore allows using resources during autumn unlike the other cool-season crops.

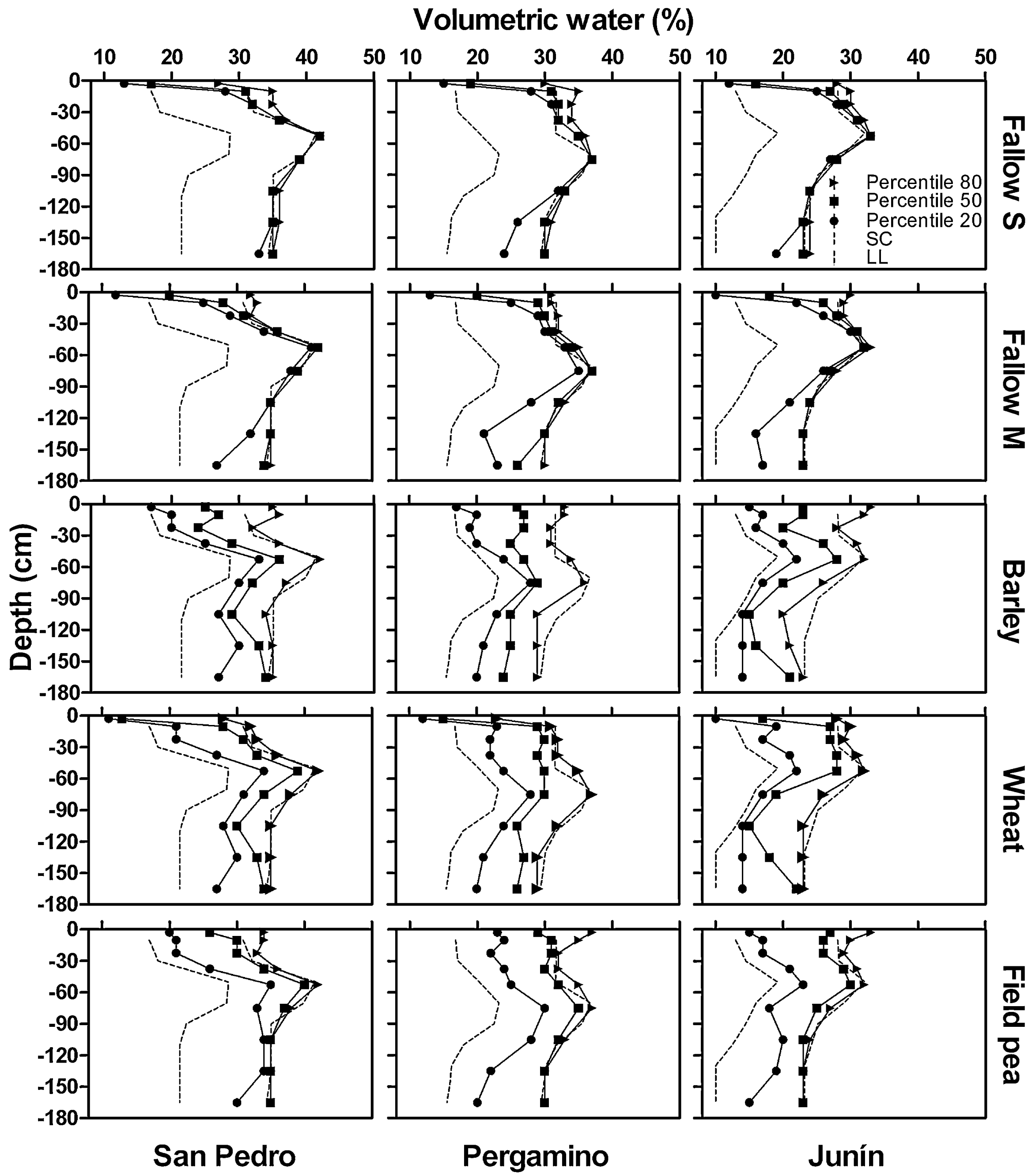

Fig. 8. Simulated soil water profiles at physiological maturity of cool-season crop alternatives and fallow periods before the single soybean (fallow S) or maize sown (fallow M). Soil water content is expressed as volumetric water (%). Dashed lines indicate upper (SC; soil capacity) and lower limit (LL) of available water. Triangles represent the probabilistic 80th percentile, squares the 50th percentile, and circles the 20th percentile.

Differences in soybean productivity on field experiments were not accounted for water availability due to rainfall in mid-summer (late January–February) satisfied the crop demand during the critical periods for seed-setting (Fig. 2). However, differences in soil water availability at sowing can determine greater variability in grain yield if rainfall is scarce during those stages as evidenced with crop yield simulations (Table 8). Field pea left large amounts of water available in the soil beyond 1 m depth, which may be attributed to the shorter growing season, the shallower soil profile exploration and lower density of roots in field pea than in wheat and barley crops (Hamblin and Tennant, 1987). Rapeseed allowed soil refilling before crop maturity because of low transpiration during grain filling given the early canopy senesce during this phase.

4.3. Soybean performance greatly varied between single and double crops

Sowing date was the main determinant of differences in soybean grain yields, thus, affecting the IPAR during each crop growing cycle (Fig. 5). In this sense, single soybean crops intercepted more radiation and produced higher yields than any double cropped soybean. Moreover, S_W had the lowest yield due to soybean sowing date was the latest among this second crop. Reductions in both incident radiation and temperature from late summer to autumn are larger at high latitudes (Hall et al., 1992). Hence, it is reasonable to expect that sowing date delays in higher latitudes than the explored here will impose greater envi-

Table 8
Simulated warm-season crop yields in single and double cropping scenarios. Three initial soil water conditions were considered per crop according to the preceding cool-season cultivated species or fallow period [20th, 50th, and 80th percentiles (perc.) in Fig. 8]. Subscript letter indicates the preceding cool-season crop (W: wheat; B: barley; P: field pea). Maize and soybean genetic coefficients were already calibrated and tested by Monzon et al. (2013).

Crop	San Pedro			Pergamino			Junín		
	Grain yield (Kg ha^{-1}); (SD)			Grain yield (Kg ha^{-1}); (SD)			Grain yield (Kg ha^{-1}); (SD)		
	20th perc.	50th perc.	80th perc.	20th perc.	50th perc.	80th perc.	20th perc.	50th perc.	80th perc.
Soybean	2805 (±904)	2805 (±903)	2806 (±904)	3514 (±948)	3589 (±888)	3596 (±885)	3812 (±869)	3834 (±853)	3841 (±855)
Maize	8053 (±2827)	8707 (±1885)	8699 (±1872)	7922 (±3239)	8640 (±2386)	8672 (±2371)	9734 (±2951)	10020 (±2166)	10041 (±2146)
Soybean$_B$	2407 (±862)	2648 (±839)	2772 (±781)	2745 (±1036)	3222 (±909)	3570 (±709)	2902 (±1228)	3333 (±1021)	3658 (±774)
Soybean$_W$	2452 (±785)	2697 (±662)	2737 (±615)	2781 (±795)	3229 (±628)	3405 (±483)	2687 (±1012)	3070 (±777)	3247 (±621)
Soybean$_P$	2410 (±818)	2651 (±796)	2644 (±801)	2544 (±955)	3380 (±708)	3451 (±684)	2777 (±1100)	3452 (±813)	3517 (±785)
Maize$_P$	9045 (±1929)	9744 (±1567)	9889 (±1441)	8470 (±2215)	9545 (±1415)	9548 (±1411)	8814 (±2525)	10333 (±1349)	10349 (±1348)

SD: standard deviation.

ronmental constraints to growing second crops (Monzon et al., 2007).

Yields differed among S_P, S_B and S_R, even though these soybean second crops were sown in similar dates. Previous cool-season crops may affect both initial nutrients stocks and mineralization rates of soil organic matter during the growing cycle of following double cropped soybeans. Cool-season crops with large nutrients demands will deplete a greater soil nutrient share, thus, constraining the soil nutritional status when double cropped soybeans are sown. Additionally, stubble quality, characterized with the ratios between C, N, and S, determines the rates of soil organic matter mineralization and/or the immobilization periods of nutrients (Domínguez et al., 2005). Stubble left on the soil after barley harvest was characterized by large amounts of residues with low nitrogen content, similar to those in wheat. Rapeseed left less stubble quantity but with higher nitrogen content than in both winter cereals and field pea left an even lesser stubble amount but with the highest %N content.

Nutrient dynamics strongly defined grain yield differences among double cropped soybeans sown at similar dates. High %N in stubble leads to rapid mineralization of soil organic matter, which in turn increases the availability of associated nutrients and prevents nutrient depletion periods (Studdert and Echeverria, 2000). Hence, large variability in sulfur status occurred when grains were evaluated retrospectively to reflect any nutritional stress during crop cycle. Double cropped soybean after field pea presented the highest %S in grains, less after rapeseed and the least after barley. It is noteworthy that field pea crops received small sulfur fertilization (10 kg ha^{-1}), which is the typical management for this crop. The poorest sulfur status of double cropped soybean produced slightly decreases in e_i and HI (Table 4), because sulfur deficiencies affect soybean crops during the periods of pod setting and grain filling and consequently affect grain yield (Gutierrez Boem et al., 2007). Therefore, sulfur differences in grains were positively correlated with soybean yields at all sites (Fig. 6), which agrees with previous findings (Hitsuda et al., 2004)

Crop simulations estimated the effects of preceding cool-season crops on second crops based on harvest date and available soil water at maturity. Although simulations were not able to determine most nutritional constraints, results were consistent with on field findings. Field pea presented advantages as preceding crop when various double cropped soybean yields were compared. Average productivity of S_P outyielded that of S_B and S_W in Pergamino and Junín, while no apparent differences were obtained in San Pedro, when the most frequent soil water initial condition was simulated. In addition, under this assumption, S_P outyielded the S_W in 70 and 87% of the simulated seasons in Pergamino and Junín, respectively.

Yield increments in experimental double cropped soybean did not over-compensate the productivity reduction during the precedent winter and spring seasons as consequence of substituting wheat by rapeseed, field pea, or barley. However, farmers are frequently interested in soybean grain production because of the possibility of obtaining great income. Thus, these cool-season crops are interesting, feasible alternatives to maintain intensification and annual productivity while improving yields of double cropped soybean.

Although rapeseed and field pea are crops with lower cropping areas than wheat and barley, the effects on the following second crops observed here may guide agronomical practices aimed at increasing annual productivity or at least yields of double cropped soybeans. Wheat or barley varieties with similar characteristics to the above mentioned cool-season species could improve soybean productivity. Although the last frost date bounds flowering dates, wheat crops with shorter crop cycles may determine high water availability and earlier sowing for second crops. Moreover, sulfur limitations after winter cereals could be sorted out through fertilization in the precedent cool-season crop (Gutierrez Boem et al., 2007).

4.4. Maize and soybean performed differently as second crops

Single maize crops explored a considerably wide range of environmental conditions in field experiments. Although all experiments were carried out in the same growing season, variability in soil properties resulted in different water dynamics and availability across sites, especially during maize critical period for yield determination. Water deficit for this crop was the highest in San Pedro, intermediate in Pergamino, and the lowest or inexistent in Junín. San Pedro is characterized by argillic soils with reduced water conductivity, which therefore enhanced water deficit effects during December. In contrast, in Junín, a water-table lamina beyond 1.4 m depth mitigated water stress during the same period. Thus, single maize crops performance was more variable than single soybean crops. Moreover, as water stress increased, single maize grain yield was reduced and relative yields were raised in late sown crops. Yield of double cropped maize after field pea was higher than that of single maize at San Pedro and Pergamino. In this region, nearly one of four years has scarce rainfall from October to early January, which is usually associated with the climate phenomenon known as "La Niña" (http://www.noaa.gov). This period also corresponds to high vapor pressure deficits that promote crop water stress (Maddonni, 2012). In these experiments, yields of double cropped maize exceeded that of single maize crops when a water stress occurred, whereas yields were not significantly lower than single maize crops with low or without water stress. Average simulated yields were similar to those obtained in the field experiments. Despite of the hypothetically higher potential yields for single maize crops in the region, the low average yields obtained are due to extremely low yields in dry seasons that also generated a large yield variation (Table 8). For this reason, late maize sowing dates are expanding at present in the region, either after cool-season crops or as single crops following an extended fallow period (Sibaja et al., 2014).

At the temperate latitude explored in our study, maize seems to be better as a second crop than soybean, when both crops are compared to their respective single crops. When sown in late dates, maize and soybean may experience a reduction in both incident PAR and mean temperature during the grain yield determining period (Cirilo and Andrade, 1994; Kantolic and Slafer, 2001). Short day-length in late summer plays an important role in explaining differences among species. Day-length shortening in the late summer accelerates soybean development during pod setting and grain filling, thus, reducing resource capture during those critical phases (Kantolic and Slafer, 2001). However, duration of maize critical period for seed setting is not sensitive to day-length (Birch et al., 1998).

4.5. Implications of including double crops in intensively managed cropping systems

Soybean single crop was the less productive treatment because of low resource capture and moderate resource use efficiency. Double crops, including soybean as second crop, outperformed soybean single crop productivity due to larger resource use. Comparatively, maize single crop used fewer resources but with higher efficiency than the aforementioned cropping systems, which led to higher yields when water availability was not limiting. Among all, field pea/maize double crop was the most productive system because including this pulse crop allowed for resource exploitation during a longer period, while maintaining the resource use efficiency of maize as in single crops (Fig. 7).

Double cropping raises productivity while implementing current technologies, which in turn is a much simpler option than intercropping or strip cropping. Novel combinations of species are a feasible way to change the resource use balance among the component crops to raise the total annual productivity or, at least, increase the grain yield of the more profitable component. These new insights have important implications in intensively managed cropping systems, because they can be implemented in the short-term by proactive farmers. Double crops stabilize annual productivity in comparison with single warm-season crops because annual grain yield is defined in two different moments. Moreover, the larger amount of crop harvest residues left by double crops could increase soil organic carbon, which therefore contributes to the sustainability of current cropping systems in the Pampas (Miranda et al., 2012). However, the effect of intensification and double crops component species on following crops still remains unstudied.

5. Conclusions

Double cropping systems increased the overall resource use in the growing season compared with single warm-season crops, which resulted in an improvement of annual land productivity in all double cropping combinations. However, cool-season crops differed in both grain yield and the impact on the following second crop, in our case soybean. In this sense, double cropped soybean grain yield was mainly determined by the sowing date and nutritional conditions generated by the characteristics of previous cool-season crops. Interestingly the results showed that not only more land productivity but also less yield variability could be achieved by intensifying with double crop sequences in the Pampas. Crop simulation supported experimental results providing a more complete analysis of crop performances. However, more studies or analyses need to be done to extend these findings either to different weather conditions or locations.

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