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Land use intensification in the Rolling Pampa, Argentina: Diversifying crop sequences to increase yields and resource use

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ABSTRACT

Increasing and maintaining high productivity levels presents a major challenge facing farmers today and will continue into the near future. More integrative and complex approaches to decision-making, besides adopting new technologies, are necessary for redesigning more productive, stable, and sustainable farming systems. Thus, novel crop sequences should be implemented to improve these properties of farming systems. The aim of our research was to characterize how different preceding crops that open recurrent sequences will impact on the productivity and resource use of the following crops, in order to determine the possibilities of increasing the frequency of double crops in rotations. Three field experiments were conducted under rainfed conditions at three sites in the Rolling Pampas of Argentina. The effects of seven cropping systems on the productivity of succeeding crops were evaluated at each location. The seven cropping systems included five double crops (rapeseed/soybean, wheat/soybean, barley/soybean, field pea/soybean, and field pea/maize) and two single crops (maize and soybean). The seven cropping systems were followed by the same crop sequence: wheat/soybean double crop and maize single crop in the first and second growing seasons, respectively. Radiation use and grain yield, water use and nitrogen uptake were evaluated for each crop in the sequence. Results indicate that repeating cereal crops in the cropping sequence reduces their productivities, while well balanced sequences that include legumes resulted in the highest productivities of cereal crops. Our findings highlight that diversifying cropping systems by adopting different double crops are practical options that can contribute to a more sustainable intensification of cropping systems specialized for grain crops. Increasing crop diversity in sequence influenced nitrogen uptake, among other factors, and may explain the enhanced crop yield in such systems. Our research highlights that crop diversification is critical in designing efficient and sustainable intensified crop sequences.

1. Introduction

The global capability for producing grain commodities will have to be increased to cope with future demands in the next decades (Bruinsma, 2009; Cassman, 2012; Godfray et al., 2010; Tilman et al., 2002; van Ittersum et al., 2013). Most of the productivity increase needed will come from measures applied in arable lands that are currently under continuous farming (Hall and Richards, 2013). However, being able to achieve and maintain higher productivity levels represents the major challenge that agriculturalists are going to face in the near future (Foley et al., 2005; Bommarco et al., 2013). Besides adopting novel technologies, more integrative decision-making approaches are necessary for redesigning more productive farming systems, which should be stable and sustainable as well (Tilman et al., 2002; Foley et al., 2005; Bommarco et al., 2013). Thus, novel crop sequences are needed to improve such properties of farming systems.

Double cropping has been largely implemented by farmers in many regions around the globe (Fischer et al., 2014), not only because annual land productivity and stubble inputs are increased (Amthor, 2000; Andrade et al., 2015; Caviglia et al., 2004; Calviño and Monzon, 2009; Francis and Smith, 1985; Graß et al., 2013), but also because double crops yields are usually more stable than those of single crops (Andrade and Satorre, 2015; Graß et al., 2013). Increasing the frequency of double cropping in rotations may lead to improve overall land productivity. However, most studies on double cropping are restricted to a single season (Caviglia

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et al., 2004; Graß et al., 2013), and therefore, the consequences of increasing the frequency of double crops in rotations are still uninvestigated.

One of the most widespread double crops in temperate regions around the world is that composed of wheat (*Triticum aestivum* L.) and double cropped soybean (*Glycine max* L. Merr.; Calviño and Monzon, 2009; Cordell et al., 2007; Kyei-Boahen and Zhang, 2006; Mercau and Otegui, 2014; Monzon et al., 2007). In the Argentine Pampas, almost one out of three years is grown with that double crop, usually composing the sequence soybean-wheat/soybean-maize. Since growing wheat or maize in consecutive seasons leads to declines in grain yields (Berzsenyi et al., 2000; Seymour et al., 2012), we hypothesize that including alternative crops, such as rapeseed (*Brassica napus* L.), barley (*Hordeum vulgare* L. var. *Distichum*) or field pea (*Pisum sativum* L.), grown as double crops with soybean or maize (*Zea mays* L.) may allow designing more intensified crop sequences without yield reductions. This is based on recognizing several benefits of crop rotation, such as improving water and nutrient use efficiencies (Reeves, 1994). Moreover, the volume and composition of crop harvest residues may also differentially affect the following crops in the sequence by modifying soil nutrient dynamics (Danga et al., 2009; Domínguez et al., 2005; Kumar and Goh, 1999; Seymour et al., 2012). Also, double cropping increases resource capture and delays the maturity and harvest dates of summer crops (Andrade et al., 2015). For these reasons, it is of interest to compare the effect of single and double crops on the initial conditions and productivity of following crops.

The aim of our research was to characterize how different preceding crops that open recurrent sequences will impact on the annual productivity and resource use of the following crops, in order to determine the possibilities of increasing the frequency of double crops in rotations. In a previous study, the resource use patterns and productivity of various single and double cropping systems were experimentally described in three contrasting sites in the Rolling Pampa, Argentina (Andrade et al., 2015). These opening cropping systems were followed by the wheat/soybean double crop in the first growing season and then by a maize single crop in the second season.

2. Materials and methods

2.1. Sites and environmental conditions

In the Rolling Pampa of Argentina, three field experiments were conducted under rainfed conditions from April 2011 to March 2013. One experiment was close to Junín (34° 23′ S; 60° 48′ W), another in Pergamino (33° 55′ S; 60° 23′ W), while the third was placed next to San Pedro (33° 47′ S; 60° 00′ W) in the Buenos Aires province (see Supplementary Fig. S1 in the online version at DOI: http://dx.doi.org/10.1016/j.eja.2016.09.013). Soils in all locations were Mollisols, deep Typic Argiudolls, with about 3% of topsoil organic matter. However, soil argillic horizons (from 0.4 to 0.8 m depth) largely differed among locations. Clay content in the argillic horizon is high in San Pedro (50% clay; Ramallo series), intermediate in Pergamino (38% clay; Urquiza series), and low in Junín (28% clay; Rojas series; INTA, 1989). These differences define contrasting water storage capacities (Andrade et al., 2015).

Average annual rainfall is similar among the experimental sites (ca. 1050 mm; 1971–2010). Annual rainfall was slightly lower than the historical average during the first experimental season (April 2011 to March 2012), being 879, 920, and 953 mm for Junín, Pergamino and San Pedro, respectively. In the second experimental season (from April 2012 to March 2013), annual rainfall exceeded the historical average, reaching amounts of 1176, 1244, and 1482 mm for Junín, Pergamino and San Pedro, respectively (see Supplementary Fig. S2b in the online version at DOI: http://dx.doi.org/10.1016/j.eja.2016.09.013). Rainfall in both experimental seasons was relatively high during spring and summer (October to March), while it was low during winter (from June to July). However, rainfall in the first experimental season was very low during December, especially in Junín. Rainfall was low during January in the second experimental season, but abundant precipitation during the preceding months prevented crop water stress during summer (see Supplementary Fig. S2b in the online version at DOI: http://dx.doi.org/10.1016/j.eja.2016.09.013). Incident solar radiation was similar for all locations in the first experimental season. Nevertheless, incident radiation differed between sites during the warm season of the second experimental season, when incident radiation was the highest in Junín and the lowest in Pergamino. In addition, Pergamino tended to be the coolest site in both seasons (see Supplementary Fig. S2a in the online version at DOI: http://dx.doi.org/10.1016/j.eja.2016.09.013).

2.2. Experimental design and management

The effects of seven cropping systems established in April 2010 to March 2011 on productivity of crops that follow in rotation were evaluated. The cropping systems consisted of five double crops [rapeseed/soybean (R/SB), wheat/soybean (W/SB), barley/soybean (B/SB), field pea/soybean (P/SB), and field pea/maize (P/MZ)] and two single crops [maize (MZ) and soybean (SB)]. The cropping systems were followed by a sequence composed of wheat/soybean double crop in the first season and followed by maize in the second season (Fig. 1). Details on the productivity and resource use of the seven cropping systems in the preceding season are published elsewhere (Andrade et al., 2015).

A completely randomized block design with two replicates was used in all experiments. Each experiment comprised 14 plots, each measuring 22 m wide and 200 m long (4400 m^2). Thus, each experiment covered 6 ha. Field activities were conducted following regular commercial field operations with typical machinery used by farmers in the region. Hence, no-till sowing system was implemented and crop varieties with high potential yield in the region were cultivated (Table 1). Sowing date, plant density, and row spacing used in the experiments were based on regional recommendations to achieve high yields (Table 1). Crop row spacing varied slightly depending on the planter available at each experimental site.

Soil nutrient status was analyzed (N: $CuSO_4$/Snedd; P: Bray & Kurtz; S: $AcONH_4$ pH 5) 20 days before sowing wheat and maize crops. Fertilizers were applied at sowing in the 2011/2012 cropping season to complement soil nutrient status and fulfill the combine demand of wheat/soybean double crop according to recommendations for the Rolling Pampa (i.e. soil nutrients plus fertilization at wheat sowing: $N = 160\ kg\ ha^{-1}$; P-Bray > 15 ppm). Double cropped soybean was sown after harvesting wheat crops, later than its optimum date. Soybean seeds were inoculated with *Bradiryzhobium japonicum* before sowing. Following maize crops were sub-fertilized with nitrogen to supply an initial status of 100 $kg\ N\ ha^{-1}$ at sowing, considering soil and nitrogen fertilizer. Sub-fertilization was performed in order to amplify preceding crops effects on maize. Weeds, insects, and diseases were maintained below damage thresholds by applying chemical controls using a self-propelled sprayer when necessary. Thus, to prevent *Drechslera tritici* attack, wheat crops cultivated after W/SB received an additional fungicide application (Strobilurin combined with Triazole).

2.3. Sampling and analysis

At least three aboveground biomass samples (1 m^2) were harvest from each plot at maturity by cutting plants at ground level,

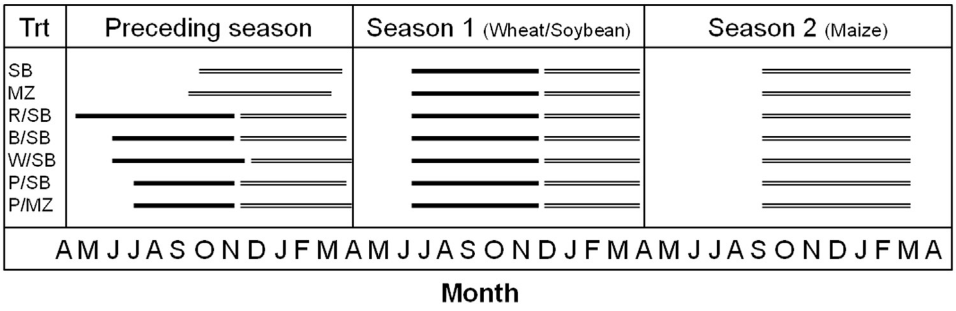

Fig. 1. Schematic representation of crop growing seasons composing each treatment (Trt) during the preceding season and the two seasons analyzed in this study. Treatment names refer to the crops grown during the preceding season: soybean (SB) and maize (MZ) single crops, rapeseed/soybean (R/SB), barley/soybean (B/SB), wheat/soybean (W/SB), field pea/soybean (P/SB), and field pea/maize (P/MZ) double crops. All plots were cultivated with wheat/soybean double crop during season 1, and with maize single crop during season 2. The growing periods of cool season crops (wheat, barley, rapeseed, and field pea) are indicated with a solid black line. Warm season crops growing periods (soybean and maize) are indicated with a double line.

Table 1
Genotype, sowing date, plant density, and row spacing for wheat, double cropped (DC) soybean, and maize at all sites. All treatments were managed similarly across sites.

Crop	Management	San Pedro	Pergamino	Junín
Wheat	Genotype	Baguette 11	Baguette 11	Baguette 11
	Sowing date	11-jun	10-jun	12-jun
	Density (pl m^{-2})	290	320	275
	Interrow (cm)	17.5	21	17.5
DC Soybean	Genotype	DM 4250	DM 3810	DM 4210
	Sowing date	7-dec	2-dec	9-jan
	Density (pl m^{-2})	39	35	32
	Interrow (cm)	35	21	42
Maize	Genotype	DK 692	DK 747	DK 747
	Sowing date	28-sep	15-sep	23-sep
	Density (pl m^{-2})	7.2	7.1	7.4
	Interrow (cm)	50.0	52.5	52.5

dried in an oven at temperatures not exceeding 60 °C, and weighed to obtain the dry weight. For yield determination, grains were harvested from every plot with a combine harvester. Grains were then transferred to a hopper with scale to weighing. Both aboveground biomass and grain yield of all crops were expressed as kilograms of dry matter per hectare (kg ha^{-1}).

Resource use in all crop treatments was assessed by measuring solar radiation interception and water and nutrients use. Incident photosynthetically active radiation (*PAR*) during the crop cycles (from crop emergence to maturity), interception efficiency (e_i), radiation use efficiency to produce aboveground biomass (RUEb), and harvest index (HI) were considered as the eco-physiological determinants of grain yield (GY; Equation (1)).

$$GY = PAR * e_i * RUEb * HI \qquad (1)$$

Daily incident PAR was obtained from meteorological stations near each experimental site. Fraction of incoming radiation reaching the ground (PARnon-intercepted/PAR) was measured with a photosynthetic photon flux sensor bar (Cavadevices Argentina; http://www.cavadevices.com) every 10–15 days, from emergence to maturity. Interception efficiency (e_i) was then calculated with the following equation (Equation (2)):

$$e_i = 1 - \left(\frac{PAR_{\text{non-intercepted}}}{PAR}\right) \qquad (2)$$

Crop evapotranspiration (ET; mm) was estimated through calculating the water balance during the crop cycle (from sowing to maturity). The difference between soil water contents at sowing (SWCs) and maturity (SWCm) was obtained up to 1.8 m depth. Then, rainfall (RF) was added (Equation (3)). Given the amount and distribution of rainfall in the second season, the effective infiltration was considered instead of rainfall for maize crops, using the curve number method to estimate runoff (USDA, 1986).

$$ET = (SWC_s - SWC_m) + RF \qquad (3)$$

Soil water content was calculated gravimetrically as the weight differences between soil samples before and after drying in an oven at 110 °C for 72 h. After that, moisture content was calculated as water lamina (mm) considering soil apparent density at each location (INTA, 1989).

Resource use efficiencies were calculated as the quotient between productivity and resource capture. Aboveground biomass produced per unit of PAR intercepted (RUEb) and ET (WUEb) were calculated for each crop in the sequence. SPAD values were measured around anthesis of wheat and maize crops. Measurements were performed on flag leaf of wheat, and on the ear leaf, the leaf above the ear leaf (+1), and below the ear leaf (-1) of maize. Finally, nitrogen (N) concentration in grain and aboveground biomass was determined by Kjeldahl method to calculate total N uptake and associate N uptake values with crop productivity.

Statistical analyses were performed with 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.

3. Results

3.1. Initial growing conditions

Water availability at the time of sowing wheat differed among preceding cropping systems in San Pedro and Pergamino, where more water was available after single summer crops than after

Table 2
Initial soil conditions for wheat crops across experiments. Variables presented are: water lamina above the lower limit (mm); available soil nitrogen (N) at 0–60 cm layer; extractable sulfur (S) for 0–20 cm soil layer; and quantity of stubble left over the field as kilogram of aerial dry matter per hectare. Treatment refers to cropping systems established in the previous season: soybean (SB), maize (MZ), rapeseed/soybean (R/SB), barley/soybean (B/SB), wheat/soybean (W/SB), field pea/soybean (P/SB), and field pea/maize (P/MZ).

Treatment	Water lamina (mm)	N in soil (kg ha^{-1})	Extractable S in soil (ppm)	Stubble of preceding cool season crop (kg ha^{-1})	Stubble of preceding warm season crop (kg ha^{-1})
San Pedro					
SB	232 ab	49	3.2 bc	0 d	4891 b
MZ	235 a	53	3.3 b	0 d	8000 a
R/SB	196 bc	43	5.2 a	5824 b	3335 c
B/SB	227 ab	50	5.1 a	8151 a	3549 c
W/SB	203 abc	31	2.5 c	8327 a	2001 d
P/SB	185 c	45	3.1 bc	3804 c	3637 c
P/MZ	198 bc	44	3.0 c	3803 c	7565 a
	*	ns	***	***	***
Pergamino					
SB	252 a	53 b	3.2	0 e	4690 b
MZ	254 a	71 a	3.5	0 e	8083 a
R/SB	247 ab	47 bc	2.6	4972 c	3521 c
B/SB	253 a	37 cde	2.8	6842 a	2872 cd
W/SB	223 b	33 de	1.9	6089 b	2218 d
P/SB	233 ab	43 bcd	2.0	4104 d	3493 c
P/MZ	226 b	26 e	2.7	3967 d	7990 a
	*	***	ns	***	***
Junín					
SB	408 ab	46 a	2.6	0 e	5026 c
MZ	425 ab	27 cd	3.5	0 e	8789 a
R/SB	433 a	31 bc	3.1	5781 c	3671 d
B/SB	406 ab	27 cd	3.3	7938 b	3131 de
W/SB	434 a	29 cd	3.5	8531 a	2920 e
P/SB	396 b	35 b	4.1	4382 d	3067 de
P/MZ	391 b	26 d	4.1	4735 d	7225 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).

double cropping systems. However, no consistent differences were found among double crops for any experiment (Table 2).

Nitrogen (N) and sulfur (S) available in the soil at the time of sowing wheat also differed among treatments. N in soil tended to be the highest after either MZ or SB (Table 2). In addition, extractable S tended to be the lowest after W/SB in Pergamino and San Pedro. Phosphorus (P) in soils did not vary among preceding crops.

Stubble accumulated during the 2010/2011 season (cool + warm season crop) ranged from 4690 to 11960 kg ha^{-1} (Table 2). Percent N content in stubble, measured only in few plots, also varied among treatments. Nitrogen content in wheat and barley stubbles was low (~0.25–0.30%), whereas that of field pea and soybean was comparatively higher (~0.60%). Rapeseed and maize had intermediate N concentration in the stubble (~0.35 and 0.45%, respectively; data not shown).

3.2. *Effects of preceding cropping systems on the following crops*

3.2.1. *Wheat (2011)*

3.2.1.1. Radiation use and grain yield. Preceding crops affected the capacity of wheat crops to intercept PAR (Table 3 ; $P < 0.05$). Wheat crops after P/SB and SB were always among the treatments with the highest interception of PAR, whereas wheat after W/SB and B/SB were consistently among the treatments with the lowest PAR intercepted (Table 3). Preceding crops also influenced RUEb of wheat in San Pedro and Pergamino ($P < 0.001$). In these locations, wheat crops grown after double crops including field pea or single summer crops exhibited a higher RUEb than wheat crops grown after W/SB (Table 3).

Overall, wheat crops after SB and P/SB presented high efficiencies for intercepting the incident PAR (e_i) and converting it into aboveground biomass (RUEb) at all sites. Hence, aboveground biomass in those treatments was the highest in all experiments. In contrast, W/SB and B/SB as previous crops affected capacity of wheat to both intercept PAR and convert it into biomass, leading to low aboveground biomass production (Table 3). Finally, HI only differed significantly in San Pedro, where wheat after B/SB resulted in the highest value among all treatments (Table 3).

The product of PAR, RUE and HI determined high grain yield variability in wheat crops. There were consistent results among all experiments, which indicated good performances for wheat crops following SB, MZ, R/SB, P/SB, and P/MZ; whereas wheat grain yields after W/SB and B/SB were markedly reduced. Wheat grown after P/SB produced the highest grain yield in San Pedro and Junín and it was among the most productive crops in Pergamino. On the contrary, wheat after W/SB exhibited the lowest grain yield at all locations. The grain yield gaps between those wheat crops (P/SB and W/SB treatments) were 2034, 1803, and 1066 kg ha^{-1} for San Pedro, Pergamino, and Junín, respectively (Table 3).

3.2.1.2. Water use. Rainfall was abundant during the critical period for seed setting in wheat crops (October 2011), avoiding water stress during this stage for any treatment (Fig. S2b). Evapotranspiration ranged from 345 to 425 mm without differing among treatments ($P > 0.1$), albeit wheat productivity varied according to previous management. Consequently, water use efficiency (WUEb), calculated as the ratio of aboveground biomass production and evapotranspiration during the crop cycle, greatly varied, especially in San Pedro and Pergamino ($P < 0.05$; Table 3).

3.2.1.3. Nitrogen uptake. Nitrogen uptake differed among treatments in San Pedro and Pergamino ($P < 0.05$; Table 6). Overall, wheat after P/SB and SB had the highest N uptake. By contrast, wheat N uptake was affected by W/SB and B/SB as preceding crops, with reductions in the order of 43 and 33% compared to P/SB. Similar tendencies, although not significant, were found in Junín, with

Table 3

Comparative analysis of wheat crops after different opening crop systems. Grain yield (kg ha^{-1}) was analyzed as the resultant of resource capture, resource use efficiency and harvest index. Therefore, values of intercepted photosynthetically active radiation from emergence to maturity (IPAR; MJ m^{-2}), 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}), aboveground biomass (kg ha^{-1}), and harvest index (HI) are presented. Treatments refer to the opening crop system: soybean (SB), maize (MZ), rapeseed/soybean (R/SB), barley/soybean (B/SB), wheat/soybean (W/SB), field pea/soybean (P/SB), and field pea/maize (P/MZ).

Treatment	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							
SB	547 ab	2.24 b	406	30.2 b	12263 b	0.39 b	4742 b
MZ	473 d	2.36 a	420	26.6 b	11181 c	0.39 b	4319 c
R/SB	518 bc	2.22 bc	399	28.9 b	11476 c	0.38 b	4401 c
B/SB	436 e	2.03 d	420	21.2 c	8853 d	0.43 a	3822 d
W/SB	373 f	2.12 cd	352	22.6 c	7911 e	0.38 b	3002 e
P/SB	564 a	2.41 a	371	36.6 a	13575 a	0.37 b	5037 a
P/MZ	495 cd	2.32 ab	399	28.8 b	11487 c	0.39 b	4421 c
	***	***	ns	***	***	**	***
Pergamino							
SB	526 ab	1.98 ab	425	24.6 ab	10426 a	0.38 c	3918 ab
MZ	508 ab	2.09 a	419	25.3 ab	10612 a	0.38 c	4006 a
R/SB	500 ab	1.63 cd	403	20.2 c	8133 b	0.43 a	3513 bc
B/SB	459 bc	1.82 bc	370	22.5 bc	8305 b	0.40 abc	3290 c
W/SB	413 c	1.40 d	364	15.9 d	5765 c	0.42 ab	2443 d
P/SB	553 a	1.96 ab	400	27.3 a	10853 a	0.39 abc	4246 a
P/MZ	483 abc	2.12 a	391	26.3 a	10262 a	0.39 bc	3947 ab
	**	***	ns	**	***	*	***
Junín							
SB	594 ab	2.10 b	345	36.1 a	12479 ab	0.39	4881 b
MZ	516 c	2.22 ab	370	30.9 bc	11455 bcd	0.41	4674 bc
R/SB	577 b	2.16 ab	371	33.7 ab	12519 ab	0.39	4796 b
B/SB	514 c	2.14 b	367	30.0 cd	10997 cd	0.41	4467 c
W/SB	469 d	2.20 ab	381	27.1 d	10298 d	0.40	4099 d
P/SB	625 a	2.08 b	387	33.6 ab	12989 a	0.40	5166 a
P/MZ	525 c	2.33 a	364	33.5 abc	12208 abc	0.40	4827 b
	***	*	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 4

Comparative analysis of double cropped soybean after wheat, in plots previously cultivated with different opening crop systems. Grain yield (kg ha^{-1}) was analyzed as the resultant of resource capture, resource use efficiency and harvest index. Therefore, values of intercepted photosynthetically active radiation (IPAR; Mj m^{-2}), 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}), aboveground biomass (kg ha^{-1}), and harvest index (HI), are presented. Treatments refer to the opening crop system: soybean (SB), maize (MZ), rapeseed/soybean (R/SB), barley/soybean (B/SB), wheat/soybean (W/SB), field pea/soybean (P/SB), and field pea/maize (P/MZ).

Treatment	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							
SB	533 ab	0.86 bcd	433	15.2	4588	0.49	2262 a
MZ	509 ab	0.89 b	409	16.4	4531	0.47	2144 ab
R/SB	508 ab	0.89 bc	433	15.0	4510	0.48	2151 ab
B/SB	468 bc	0.84 d	427	13.4	3950	0.45	1801 bc
W/SB	404 c	0.97 a	427	13.6	3920	0.43	1674 bc
P/SB	566 a	0.88 bcd	467	14.8	4957	0.49	2441 a
P/MZ	528 ab	0.85 cd	421	15.4	4470	0.51	2280 a
	*	***	ns	ns	ns	ns	**
Pergamino							
SB	469	0.99	358	18.4	4646	0.42	1927
MZ	506	0.89	383	16.4	4498	0.43	1939
R/SB	457	0.92	373	15.8	4179	0.45	1887
B/SB	474	0.93	414	14.3	4387	0.44	1912
W/SB	475	0.90	378	16.1	4283	0.44	1889
P/SB	504	0.89	388	16.0	4503	0.45	2011
P/MZ	539	0.94	364	19.7	5079	0.42	2134
	ns	ns	ns	ns	ns	ns	ns
Junín							
SB	365	1.13	427 ab	13.0 b	4111	0.42	1730
MZ	355	1.13	444 a	12.1 b	4017	0.44	1776
R/SB	360	1.08	436 a	12.0 b	3894	0.44	1726
B/SB	360	1.10	390 c	14.2 ab	3950	0.44	1755
W/SB	357	1.11	412 abc	13.2 b	3957	0.44	1743
P/SB	368	1.19	395 bc	15.5 a	4391	0.40	1769
P/MZ	364	1.19	418 abc	14.1 ab	4341	0.41	1769
	ns	ns	*	*	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

Comparative analysis of maize crops after wheat/soybean double crop, in plots previously cultivated with different opening crop systems. Grain yield (kg ha^{-1}) was analyzed as the resultant of resource capture, resource use efficiency and harvest index. Therefore, values of intercepted photosynthetically active radiation (IPAR; MJ m^{-2}), radiation use efficiency to produce biomass (RUEb; g MJ^{-1}), evapotranspiration (ET; mm), water use efficiency to produce biomass (WUEb; kg $ha^{-1}mm^{-1}$), aboveground biomass (kg ha^{-1}), and harvest index (HI), are presented. Treatments refer to the opening crop system: soybean (SB), maize (MZ), rapeseed/soybean (R/SB), barley/soybean (B/SB), wheat/soybean (W/SB), field pea/soybean (P/SB), and field pea/maize (P/MZ).

Treatment	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							
SB	655 ab	2.43	568 bc	28.0	15921 a	0.45	7212 a
MZ	587 c	2.45	609 a	23.8	14366 ab	0.43	6192 b
R/SB	596 bc	2.28	597 ab	22.8	13606 b	0.46	6310 b
B/SB	605 bc	2.21	525 d	22.5	13376 b	0.46	6160 b
W/SB	600 bc	2.26	540 cd	25.3	13606 b	0.46	6203 b
P/SB	667 a	2.48	571 b	28.9	16482 a	0.46	7644 a
P/MZ	577 c	2.29	534 d	24.7	13184 b	0.44	5776 b
	*	ns	***	ns	**	ns	***
Pergamino							
SB	679 a	2.52 a	480	35.7 a	17095 a	0.48	8270 a
MZ	611 bc	2.39 ab	500	29.1 c	14565 c	0.46	6681 bc
R/SB	648 ab	2.32 b	498	30.0 bc	14973 bc	0.46	6991 abc
B/SB	645 ab	2.30 bc	525	28.2 c	14792 c	0.46	6836 abc
W/SB	654 ab	2.39 ab	543	28.8 c	15597 abc	0.48	7466 ab
P/SB	695 a	2.37 ab	495	33.3 ab	16449 ab	0.49	8027 ab
P/MZ	589 c	2.12 c	464	26.9 c	12448 d	0.47	5822 c
	**	**	ns	**	***	ns	*
Junín							
SB	812 ab	1.87	608	24.9	15164 ab	0.52	7841 a
MZ	743 e	1.87	593	23.4	13870 d	0.50	6894 c
R/SB	760 de	1.92	563	25.8	14550 bc	0.49	7193 b
B/SB	790 bc	1.79	582	24.3	14130 cd	0.50	7069 bc
W/SB	775 cd	1.83	615	23.1	14151 cd	0.49	6982 c
P/SB	829 a	1.86	612	25.1	15359 a	0.52	7919 a
P/MZ	716 f	1.84	577	22.9	13135 e	0.51	6670 c
	***	ns	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).

reductions of 29 and 21% in wheat N uptake when W/SB and B/SB were the previous crops, respectively (Table 6).

As wheat crops were able to take up more N, they were also more efficient in intercept PAR and to converting it into aboveground biomass (Fig. 2). Higher grain yields resulted from the increase in both intercepted PAR and RUEb (Fig. 2). Considering all experiments together, intercepted PAR was affected when N uptake was less than 120 kg N ha^{-1} (Fig. 2a); whereas RUEb was not affected until N uptake was severely restricted below 90 kg N ha^{-1} (Fig. 2b).

As observed for both RUEb and PAR interception, SPAD records presented the lowest values for W/SB as preceding crops in San Pedro and Pergamino, and for MZ and W/SB in Junín (Table 6).

3.2.2. *Double cropped soybean (2011/2012)*

Grain yields of double cropped soybean ranged from 1726 to 1769 kg ha^{-1} in Junín, from 1887 to 2134 kg ha^{-1} in Pergamino, and from 1674 to 2441 kg ha^{-1} in San Pedro (Table 4). Resource use by double cropped soybean was slightly affected by preceding crops. Evapotranspiration averaged 409 mm combining all treatments and sites. Preceding crops significantly affected PAR interception of double cropped soybean only in San Pedro ($P < 0.05$), which ranged from 404 to 566 MJ m^{-2}, while averaged 361 MJ m^{-2} in Junín and 489 MJ m^{-2} in Pergamino (Table 4). In San Pedro, soybean crops intercepted more PAR, and therefore yielded more, in plots that had either winter legumes or single soybean crops than in plots with winter cereals as opening crops.

3.2.3. *Maize (2012/2013)*

3.2.3.1. *Radiation use and grain yield.* Maize crops also differed in their ability to intercept PAR depending on the species cultivated two seasons before. Maize crops had the highest levels of PAR interception in plots previously cultivated with SB or P/SB at all sites (Table 5). In contrast, the lowest PAR interception from emergence to maturity was observed in maize crops growing in MZ and, especially, in P/MZ plots (Table 5). RUE for aboveground biomass production was affected by the preceding crops only in Pergamino, where the SB plot tended to have the most efficient maize crop and P/MZ plot the lowest. Differences in radiation use led to the detection of differences in aboveground biomass production (Table 5). Consequently, maize crops grown during the 2012/2013 season presented significant differences in grain yield, since HI was not different among treatments. The highest maize yields were obtained in plots cultivated with SB or P/SB cropping systems in the 2010/2011 season at all locations. In contrast, maize cultivated after a sequence that included maize (either MZ or P/MZ) always had the lowest yields (Table 5).

3.2.3.2. *Water use.* Evapotranspired water ranged from 464 to 615 mm during the crop cycle, pooling all treatments and experiments together. Significant differences were found only in San Pedro, where ET was highest in plots with MZ as opening crop, whereas B/SB and P/MZ plots had the lowest values ($P < 0.01$; Table 5).

WUEb ranged from 22.5 to 35.7 kg ha^{-1} mm^{-1}, with significant differences occurring only in Pergamino due to similar ET but different aboveground biomass among treatments. The highest values for WUEb were those in treatments with the highest biomass production, obtained in SB and P/SB plots ($P < 0.05$).

3.2.3.3. *Nitrogen uptake.* When total N uptake is considered, differences among treatments were found in San Pedro and Pergamino. Maize in P/SB and SB plots had the highest overall N uptake,

Table 6
Total N uptake (kg ha^{-1}) at maturity and SPAD values measured around anthesis of wheat and maize crops. Measurements were performed on flag leaf of wheat, and on ear leaf, ear leaf +1, and ear leaf −1 of maize. Treatments refer to the opening crop system: soybean (SB), maize (MZ), rapeseed/soybean (R/SB), barley/soybean (B/SB), wheat/soybean (W/SB), field pea/soybean (P/SB), and field pea/maize (P/MZ).

	Wheat		Maize	
Treatment	N uptake (kg ha^{-1})	SPAD index	N uptake (kg ha^{-1})	SPAD index
San Pedro				
SB	126.5 ab	43.8 ab	77.6 b	53.3 ab
MZ	108.0 bc	42.9 b	74.8 b	48.3 cd
R/SB	111.5 bc	44.2 a	73.2 b	51.0 abc
B/SB	96.2 c	43.6 ab	69.7 bc	49.6 c
W/SB	84.4 c	41.6 c	72.1 b	50.6 bc
P/SB	148.5 ab	44.6 a	88.4 a	53.7 a
P/MZ	111.5 bc	44.0 ab	61.9 c	46.6 d
	**	**	***	***
Pergamino				
SB	112.4 a	43.9 bc	90.2	52.4 a
MZ	104.0 ab	44.8 ab	77.7	46.9 bc
R/SB	91.9 bc	42.9 de	82.3	48.9 ab
B/SB	81.1 cd	43.8 cd	80.5	48.3 abc
W/SB	66.9 d	42.7 e	82.6	49.1 ab
P/SB	117.6 a	45.6 a	97.0	51.8 a
P/MZ	88.6 bc	44.8 ab	62.2	44.6 c
	***	***	ns	**
Junín				
SB	113.7	44.3 bcd	90.7 a	53.6 ab
MZ	117.9	43.6 d	61.4 c	49.8 bc
R/SB	114.5	45.3 ab	69.7 bc	47.9 c
B/SB	106.0	44.7 abc	86.0 ab	49.8 bc
W/SB	89.4	44.1 cd	75.4 abc	49.2 bc
P/SB	126.3	45.3 a	78.8 abc	54.8 a
P/MZ	117.1	44.4 abcd	72.5 abc	49.1 bc
	ns	**	*	*

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

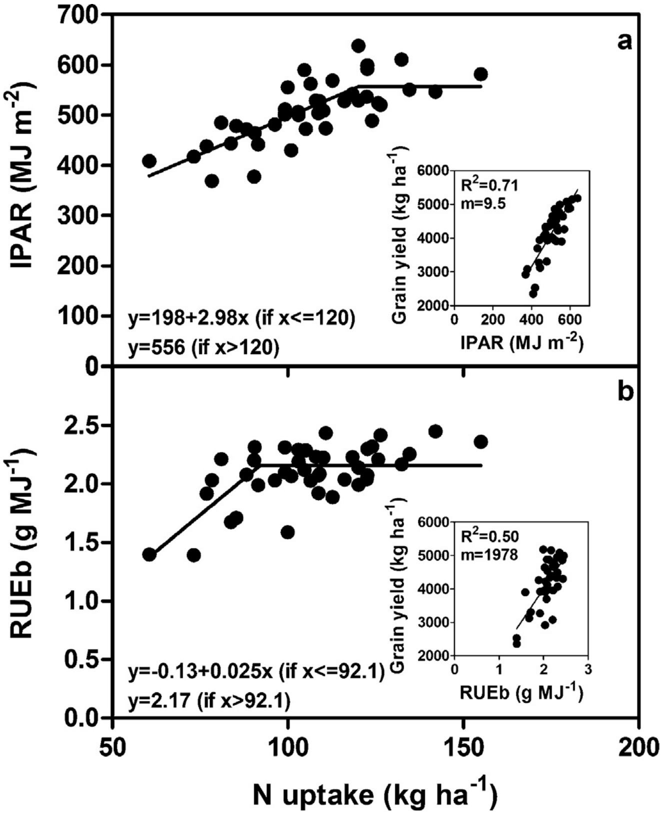

Fig. 2. (a) Intercepted photosynthetically active radiation (IPAR; MJ m^{-2}) for wheat from emergence to maturity as a function of nitrogen (N) uptake (kg ha^{-1}); [$R^2 = 0.59$]; and the association between grain yield (kg ha^{-1}) and IPAR (inset). (b) Radiation use efficiency to produce aboveground biomass (RUEb; g MJ^{-1}) as a function of N uptake; [$R^2 = 0.42$]; and the association between grain yield and RUEb (inset). All plots, treatments, and experiments were analyzed together.

while maize in P/MZ plots captured the least amount of N among all treatments (Table 6). Maize crops with large N uptake were more efficient in intercepting PAR at all sites, and also in converting the intercepted PAR into aboveground biomass in San Pedro and Pergamino. Increases in PAR interception and RUEb increased maize grain yield (Fig. 3a and b).

The ranking for SPAD measurements among treatments at anthesis were similar to those obtained for N uptake and PAR interception. In this sense, maize crops in SB and P/SB plots were always among those that recorded the highest SPAD measurements, whereas maize in P/MZ plots was among those that had the lowest SPAD measurements (Table 6).

4. Discussion

It is well known that double cropping increase annual productivity due to a more complete use of resources compared with single crops (Andrade et al., 2015; Caviglia et al., 2004; Caviglia and Andrade, 2010; Van Opstal et al., 2011). Our results provide further evidence indicating that double cropping may not affect the performance of following crops in diversified sequences. Furthermore, our results indicate that repeating cereal crops in the sequences reduces the productivity of cereals in the system compared with balanced sequences that include more legume crops. Nitrogen uptake, above other factors, may explain most of the grain yield variability obtained among different sequences (Fig. 2 and 3). Hence, our research highlights that crop diversification is crucial in the design of efficient intensified crop sequences.

Sequences with high frequency of double crops are implemented in large areas around the globe, especially in Asia using wheat/maize and wheat/rice systems (Fischer et al., 2014). There, most studies in double cropping are focused on novel cropping techniques to improve the resource use efficiencies to produce grain yield (Chauhan et al., 2012; Chen et al., 2010; Fan et al., 2012; Fang et al., 2010; Gupta and Seth, 2007; Ladha et al., 2003; Wang et al., 2009). Our work encourages further studies on crop diversification in other regions as an element to improve the resource use efficiency and, therefore, the productivity of crops in intensified sequences.

4.1. Preceding crop effects on wheat

Total N uptake by wheat plants largely differed among treatments (Table 6), though N in soil was supplemented by fertilization to a same level at sowing (ca. 160 kg ha^{-1}). Nitrogen uptake is commonly reduced when there is either a limited supply in the soil, a reduced demand by crops, or some combination of both (Lemaire and Gastal, 2009). Available N was probably reduced after fertilization in W/SB and B/SB plots. Low %N in preceding winter cereal crop harvest residues (Section 3.1) decreases mineralization rates and increases nutrient immobilization periods (Danga et al., 2009; Domínguez et al., 2005; Green and Biederbeck, 1995; Kumar and Goh, 2002), which therefore decreases N uptake by growing crops (Kumar and Goh, 1999; Seymour et al., 2012). Moreover, N deficiency was detected through SPAD measurements in some treatments (Table 6), indicating that wheat plants were not equally able to uptake available N. Reductions in N demand by crops could be expected when crop growth rate is affected by factors such as weeds, pests, diseases, water or even by co-limitation of other

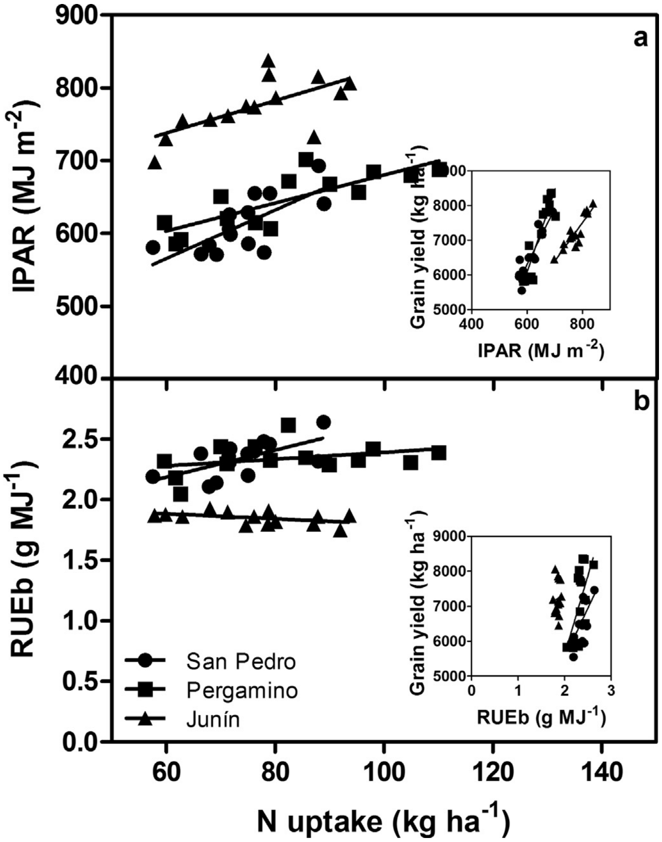

Fig. 3. (a) Intercepted photosynthetically active radiation (IPAR; MJ m^{-2}) for maize from emergence to maturity as a function of nitrogen (N) uptake (kg ha^{-1}); [San Pedro: m = 3.3, R^2 = 0.51; Pergamino: m = 1.93, R^2 = 0.65; Junín: m = 2.23, R^2 = 0.43]. (a; inset) Association between grain yield (kg ha^{-1}) and IPAR [San Pedro: m = 16.1, R^2 = 0.81; Pergamino: m = 23.6, R^2 = 0.83; Junín: m = 11.1, R^2 = 0.80]. (b) Radiation use efficiency to produce aboveground biomass (RUEb; g MJ^{-1}) as a function of N uptake [San Pedro: m = 0.011, R^2 = 0.40; Pergamino: m = 0.003, R^2 = 0.12 (ns); Junín: m = –0.002, R^2 = 0.22 (ns)]. (b; inset) Association between grain yield and RUEb [San Pedro: m = 2822, R^2 = 0.36; Pergamino: m = 4507, R^2 = 0.35; Junín: m = 805, R^2 = 0.01 (ns)]. Experiments were analyzed separately. m: slope; ns: not significant (p > 0.1).

nutrients. Wheat crops did not undergo water stress, while biotic stresses were effectively controlled in all treatments. However, low initial S, as found in W/SB plots in Pergamino and San Pedro (Table 2), affects N absorption by plants (Salvagiotti and Miralles, 2008; Salvagiotti et al., 2009).

The PAR interception and RUEb were higher in wheat crops with large N uptake (SB and P/SB) than in treatments with low N uptake (W/SB and B/SB), which in turn had low SPAD index. PAR interception was more responsive to N uptake than RUEb, which agrees with previous studies (Meinke et al., 1997; Gallagher and Biscol, 1978). Hence, PAR interception decreased when N uptake was below 120 kg ha^{-1} (Fig. 2a), while RUEb remained unaffected until values below 92 kg N ha^{-1} (Fig. 2b). Moreover, differences in grain yield were associated mainly with variations in PAR interception (Eq. (1); Fig. 2).

Preceding crops had no effect on evapotranspiration by wheat crops across sites. However, water use efficiency was affected by preceding crops due to the different aboveground biomass and grain yield produced with similar evapotranspiration rate (Table 3). Wheat crops with high N uptake had elevated WUEb, either by reducing evaporation from soil surface and/or by increasing the transpired water use efficiency (Caviglia and Sadras, 2001; Seymour et al., 2012). High PAR interception rates reduce incident radiation at ground level and therefore soil evaporation, whereas high soluble N in leaf could lead to improvements in photosynthetic rates with only slight increases in transpired water (Cabrera-Bosquet et al., 2009).

4.2. Preceding crop effects on double cropped soybean

Double cropped soybean was slightly responsive to the effects of the cropping systems of the preceding season (Table 4). Probably, the combination of several factors attenuated productivity variations. First, large water consumption by wheat (Table 3) homogenized soil water content at sowing (data not shown). Second, symbiotic fixation of N during soybean crop cycle reduces the relevance of soil N availability (Gutiérrez Boem and Salvagiotti, 2014). Finally, the typical delayed sowing date of second crops decreases potential yield of double cropped soybean (Andrade et al., 2015).

4.3. Preceding crop effects on maize

Similarly to what was found for wheat crops, N uptake of maize crops largely differed among preceding cropping systems, although available N at sowing was the same for all treatments. However, it is noteworthy that a low dose of N was applied at sowing in order to homogenize non-significant differences in soil N among plots to a level of 100 kg ha^{-1}, being 40% lower than that recommended for the region (Echeverría et al., 2014). This allowed detecting differences in soil fertility and its possible implications into a physiological response.

The highest maize grain yields were obtained in P/SB or SB plots, and corresponded with the largest N uptake values. In contrast, the lowest grain yield and N uptake was always obtained in P/MZ plots (Table 6). Nitrogen limitation reduces maize leaf area, leaf photosynthesis rate, and accelerates leaf senescence (Massignam et al., 2009, 2012). Consequently, when N limitation is severe, N content in leaves is associated with RUE and PAR interception (Massignam et al., 2012). This agrees with the results of the present study, which showed a positive association between N uptake, SPAD values at anthesis, and PAR interception (Fig. 5 ; Table 6). The low N uptake in systems that previously included maize as single crop (MZ) or in double crop (P/MZ) was probably due to a reduction in N availability in soil after fertilization. In those treatments, large amounts of maize residues (Table 2), with intermediate %N (Section 3.1), were still on the soil surface which may lead to nutrient immobilization during stubble decomposition (Dominguez et al., 2005).

Given the limited N supply at sowing, the attained yields in the experiments were lower than the water-limited potential yields (van Ittersum et al., 2013) for maize in 2012/2013. They were 8505, 12047, and 11404 kg ha^{-1} in San Pedro, Pergamino, and Junín, respectively. This information was obtained under non-limiting nutrient situations close to the experimental fields. The gap between those water-limited potential yields and the attained in P/SB plots was only 10% in San Pedro, and increased up to 30% in environments with higher potential yields. In this context, our findings suggest that rotating cereals with legumes could be also useful to reduce the dependence on mineral fertilizer at a farm-scale level, especially in restrictive environments (Horst and Härdter, 1994; Keating et al., 1988).

5. Conclusions

Crop diversification is important for the development of efficient and productive cropping sequences in the Rolling Pampa and other parts of the world. In the present study, wheat yield was lower when planted after wheat/soybean double cropping system than after other systems that had no wheat crop. Also, grain yield of maize in plots previously planted with maize or field pea/maize were the lowest among all cropping systems. There are many interacting causes that may explain the beneficial rotation effect. It could be partly due to the high amount of cereal residues with low %N which interacted with the soil organic fraction, immobilized soil N, and depleted N available for growing crops. When land use is intensified through double cropping, special care should be taken in the management of the large amounts of stubble produced. Appropriate crop sequences for intensive land use systems should alternate legumes, cereals, and other crops to meet high stubble inputs that are well balanced in nitrogen and carbon. While high stubble inputs is desirable for maintaining soil fertility in the long term, the nutritional balance of crop residues is necessary to avoid yield reductions in the short term.

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