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Improving resource productivity at a crop sequence level

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ABSTRACT

The challenge to increase agricultural production with a minimum environmental impact requires to reach the maximum efficiency in the capture and use of resources such as photosynthetically active radiation (PAR), water, and nitrogen (N). Such requisites are encompassed in the ecological intensification (EI) concept. The aims of this work were to evaluate at a crop sequence level: i) crops yields, ii) water and radiation productivity and its components, i.e. resource capture and resource use efficiency, and iii) partial factor productivity of applied N (PFPN), partial nutrient balance for N (PNB), N uptake and N utilization efficiency of a two-year, three-crop sequence (wheat [*Triticum aestivum* L.]/soybean [*Glycine max* (L.) Merr.] double crop – maize [*Zea mays* L.]) carried-out under EI principles in comparison with the same crop sequence under current farmer practices (FP) in two contrasting locations of the Argentinean Pampas, i.e. Paraná (-31°50′; -60°31′) at the northern Pampas and Balcarce (-37°45′, -58°18′) at the southern Pampas. Experiments were carried-out during four consecutive years, covering two complete cycles of the crop sequence. For the accumulated grain production of the crop sequence, EI management outyielded FP from 13 to 42%, depending on environmental conditions. Maize yield accounted for most of the variation (41–64%) of the accumulated grain yield of crop sequence, whether in EI as in FP. Average grain yield differences between EI and FP treatments were 274 $g\ m^{-2}$ for maize, 69 $g\ m^{-2}$ for wheat and -2 $g\ m^{-2}$ for soybean. Water and radiation productivities of the sequence were higher in EI than in FP (26% for water and 17% for radiation; $P < 0.0001$), mainly because of increases in resource use efficiencies. EI reduced partial factor productivity of applied N, but improved partial nutrient balance for N as compared with FP. These reductions in partial factor productivity of applied N were less than proportional than the increases in N rate. Moreover, in spite of the higher N rate in EI respect to FP, N utilization efficiency ($N_{ut}E$), i.e. grain per unit N uptake, was higher across all situations in EI. Our results showed that the challenge to obtain high grain yields by increasing N rate in a medium-input system could be achieved even with an increase in $N_{ut}E$. Grain yields improvements, and increases in radiation and water productivity were reached by applying a set of agronomic practices that included improved genetics, crop and fertilizer N management englobed under EI concept.

1. Introduction

The predicted increase in global population and changes in dietary habits will rise the demand for agricultural products in the next years. South American agroecosystems can satisfy an important proportion of the future global demands (OECD-FAO, 2018). The goal should be reached while maintaining or improving the quality of the natural resources involved in agricultural production and the life quality of rural and urban populations (Lobell et al., 2009; Tillman et al., 2011; Andrade, 2016; Cassman, 2017). Such requisites are encompassed in the ecological intensification (EI) concept defined by Cassman (1999, 2017).

Decisions on agronomical practices based on EI concepts are oriented to closing the gap between water limited yield potential (Y_w) and actual yield and improving natural resource and input productivities using a field-specific management according to Cassman (2017). Improving resource and input productivity is a key step towards sustainable intensification.

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The implementation of EI concepts in cropping systems often involves the application of a set of agronomical practices targeted to a specific site, rather than a single management factor. However, most literature on agronomy, in general, and on crop resource use efficiency, in particular, is based on reductionist experiments, i.e. under *ceteris paribus* clauses (van Bruchem et al., 1999), that implies the change in one single variation source while keeping all others constant. In fact, studies comparing EI with common farmer practices (FP) at a crop level in a given region are less abundant (Rodríguez and Sadras, 2011; Zhao et al., 2016). Moreover, the benefits of the implementation of EI concepts at the crop sequence level has been scarcely reported (e.g. Chen et al., 2011; Zhao et al., 2016; Monzon et al., 2018).

The challenge to increase agricultural production requires to maximize the capture and use of resources such as water, photosynthetically active radiation (PAR) and nitrogen (N) (Lobell et al., 2009). The implementation of EI concepts in certain cropping systems has been effective to increase grain productivity and reduce some negative environmental outcomes (Chen et al., 2011; Zhao et al., 2016; Monzon et al., 2018), as compared with farmer practices (FP). However, a collective analysis of their impact in resource capture and resource use efficiency has not yet been reported. Moreover, reports of studies applying EI concepts were carried-out most at the crop level rather than at the crop sequence level (e.g. Rodriguez and Sadras, 2011 for wheat; Zhao et al., 2016 for maize).

In rainfed farming systems, water, PAR and N are different in the way they are captured and stored by crops. Water, received as rainfall, can be stored in the soil; PAR is received as an instant, non-storable flux, whereas N is mainly supplied from mineralization of soil organic N-compounds, and differs from water and PAR because it is possible to supply additional amounts of N through fertilization and biological fixation. At the crop sequence level, the productivity of these resources depends on: i) resource capture efficiency, i.e. the ability to capture the total offer of resources, and ii) resource use efficiency, i.e. the ability to transform the captured resource into grains, aerial and root biomass (Caviglia et al., 2004).

For a given crop sequence, the use of EI concepts may lead to similar radiation capture by the crops as compared to FP, because the period with full canopy cover is quite similar (e.g. Andrade et al., 2002; Barbieri et al., 2012; Nagore et al., 2014; Hernández et al., 2015). In contrast, the total amount of N captured would probably be increased with the use of EI as suggested by several studies reporting a higher N uptake when proper management practices are adopted, i.e. available diagnosis methods, crop management techniques, and others (Cassman et al., 2002; Barbieri et al., 2008). Moreover, crop yield is increased in less proportion than the increase in the N rate prescribed by the local diagnosis method. As a consequence, a reduction of N utilization efficiency ($N_{ut}E$, quantified as the quotient of grain yield and N uptake, also called internal N use efficiency) and partial factor productivity of applied N (PFPN, quantified as the quotient of grain yield and applied N rate) may be anticipated for EI as compared with FP.

The study of the water, radiation and N productivity appears as crucial to understand the actual impacts of EI as compared with FP at a crop sequence level in the Argentinean Pampas. Since the use of EI concepts in our cropping systems involves the use of higher N rates compared with FP, the most relevant challenge would be to increase the productivity of water and radiation with a minimal reduction in PFPN and $N_{ut}E$. We hypothesized that the combination of several agronomical practices in EI, such as plant density and row spacing, genotype, and N rates to reach the estimated Y_w (Aramburu Merlos et al., 2015), can increase the productivity of water and radiation with a minimal reduction in PFPN and $N_{ut}E$ when compared with FP treatment.

The aims of this work were to evaluate: i) water and radiation productivity and its components, i.e. resource capture and resource use efficiency, and ii) partial factor productivity of applied N, N uptake and N utilization efficiency for a two-year sequence (wheat/soybean double crop – maize) carried-out under EI concepts in comparison with the same sequence under FP in two contrasting locations of the Argentinean Pampas.

2. Materials and methods

2.1. Locations, experiment and crop management

Two long-term experiments started in 2009 at Paraná (province of Entre Rios) (−31°50′; −60°31′; 110 m a.s.l.) and Balcarce (province of Buenos Aires) (−37°45′, −58°18′; 130 m a.s.l.) located at the northern and southern borders of the Argentinean Pampas, respectively (Hall et al., 1992), were evaluated during the 2009–2012 period. These experiments are part of the "Global Maize Project", an international research effort of the International Plant Nutrition Institute (IPNI, 2016), with the overall goal of testing the impact of EI and FP on maize production and resource productivity.

In Paraná, the soil is a fine, mixed, thermic Aquic Argiudoll under no-till since 1998, with 2.90–3.05 g kg^{-1} topsoil (0–0.20 m) organic matter. In Balcarce, the soil is a Typic Argiudoll, under no-till since the beginning of the experiment, with 4.00 g kg^{-1} topsoil (0–0.20 m) organic matter. Mean annual rainfall, based on historical records (> 40 yr), is 1104 mm in Paraná and 916 mm in Balcarce, whereas mean annual temperature is 18.7 °C in Paraná and 14.3 °C in Balcarce. The frost-free period is 240 d in Paraná and 217 d in Balcarce. Compared with historical data (1983–2017) the 2009–2012 period had a higher average temperature (14.9 vs 14.3 °C in Balcarce and 18.7 vs 18.3 °C in Paraná) and a slightly higher incident radiation (16.7 vs 16.4 MJ m^{-2} d^{-1} in Balcarce and 16.8 vs 16.3 MJ m^{-2} d^{-1} in Paraná). Annual rainfall in the 2009–2012 period was lower than the historical data in Balcarce (867 vs 916 mm y^{-1}) but higher in Paraná (1122 vs 1027 mm y^{-1}).

Two treatments, EI and FP, were randomized in a complete block design with four replicates in a two-year crop sequence of wheat/soybean-maize, i.e. wheat/soybean as a double crop in a year and maize in the following year (Fig. 1). We incorporated the two phases of the sequence in order to include wheat/soybean and maize in each year, i.e. at the onset of the experiment, Phase I started with wheat/soybean whereas Phase II started with maize. Each phase of the sequence was replicated during two complete cycles from the 2009/10 to the 2012/13 cropping seasons. The duration of each cycle was two year, from 1 May of the first year to 30 April of the third year. The selected rotation is the most used by leading farmers of the Pampas region, whose objective is to intensify the crop sequence.

Each experiment involves two consecutive cycles of a wheat/soybean-maize sequence, carried-out in its two phases (see Fig. 1). It should be emphasized, however, that the focus of this paper is to compare the two treatments, i.e. FP and EI. The experimental design is oriented to include the two components of the same crop sequence, i.e. wheat/soybean double crop or maize, under similar climatic conditions in each year (two phases). A sequence is a number of crops, here wheat/soybean double crop or maize, growing consecutively in the same plot in a preassigned order, and the cycle is the consecutive repetition of the preassigned order of the sequence.

The main management differences between EI and FP are summarized in Table 1. In EI treatment, agronomical practices were decided based on previous knowledge and recent research in order to increase grain production together with an increase in resource productivity (Cassman, 1999, 2017) with respect to FP.

The particular combination of input level and other management decisions in EI was based on the attainable yield, estimated to be 80% of Y_w, because farmers' yields tend to plateau at 75–85% of Y_w (Van Ittersum et al., 2015; Sadras et al., 2015). Y_w was 1250 g m^{-2} at Balcarce and 1220 g m^{-2} at Paraná for maize, 740 g m^{-2} at Balcarce and 500 g m^{-2} at Paraná for wheat, and 230 g m^{-2} at Balcarce and 360 g m^{-2} at Paraná for soybean as a second crop (Aramburu Merlos et al., 2015).

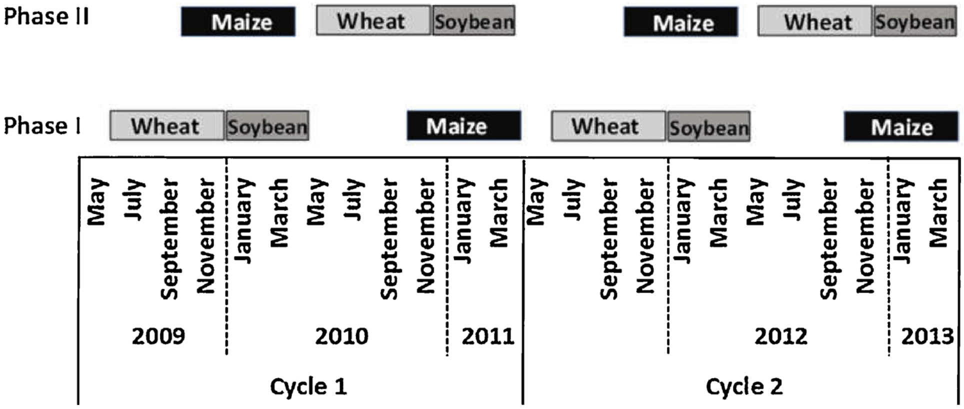

Fig. 1. Schematic representation of the two phases of the sequence carried-out both under ecological intensification practices (EI) and current farmer practices (FP) in two locations at the northern (Paraná) and southern (Balcarce) Pampas of Argentina during two consecutive cycles. The length of crop cycles as well as sowing and harvest dates may vary depending on location. Solid vertical lines indicate the boundaries of the cycles whereas dotted vertical lines indicate the boundaries of calendar year.

In FP treatment, crop management included the average input level as well as most commonly used practices, based on the opinion of expert agronomists who are devoted to advice farmers. Genotypes as well as plant density in FP treatment were the most widely used in the area of Balcarce and Paraná (Table 1). Applied N rate in FP was a fixed amount based on the average in the region of Paraná, whereas in Balcarce applied N rate was derived from a N budget based on soil analysis and a target yield for each crop.

Although the management was not the same in Paraná and Balcarce, the criteria used were mainly based on the selection of: i) superior genotypes of each crop using the available local information from official trials, i.e. those that have demonstrated high yield potential together with high yield stability were included in EI (Di Matteo et al., 2016), ii) the most proper plant density and row spacing for each genotype under rainfed conditions, and iii) crop N nutrition based on Y_w and on soil analysis following the 4R Nutrient Stewardship (fertilizer right source, rate, time and placement; IPNI, 2012; Fixen et al., 2015). In both treatments, we used single-cross and tolerant glyphosate [N-(phosphonomethyl) glycine] maize hybrids, with a relative maturity ranging from 116 to 122 days. In EI treatment, maize genotypes were those hybrids with superior performance in local trials and that included staked events carrying Bt and RR genes. Wheat genotypes were hard spring type in both locations. Plant density for maize was 23–29% (Balcarce and Paraná, respectively) higher in EI than in FP whereas for wheat, plant density was 33% higher in EI than in FP in both locations. Only in Balcarce, EI included a reduction in row spacing for maize respect to FP (from 0.70 m to 0.52 m). Increases in plant population density in maize and wheat and the reduction in row spacing in EI respect to FP were included with the aim to increase resource capture (especially N) (Barbieri et al., 2008; Pietrobón, 2012). In Balcarce, timing of N fertilizer application in EI was delayed respect to FP in order to better match the N supply with crop demand (Sainz Rozas et al., 1999). In Paraná, the timing of N fertilizer application did not differ between treatments.

For maize, average N rate was 29% (Balcarce) and 56% (Paraná) higher in EI than in FP, whereas for wheat average N rate was 29% (Balcarce) and 69% (Paraná) higher in EI than in FP (Table 1).

In Balcarce, we used the same soybean management in both treatments (maturity group III or IV), whereas in Paraná only genotype choice was different between treatments. The choice of soybean genotypes in EI at Paraná was based on their maturity group and cycle length appropriate for late planting as a second crop as well as their performance in official trials. Thus, in this location, we used a maturity group V cultivar in EI treatment and a maturity group VI cultivar in FP treatment. Our aim was to evaluate the impact of FP and EI at a cropping sequence level. Moreover, we do not consider the soybean as a single crop, indeed it is part of a double crop, i.e. wheat/soybean double crop. The main practices reported to closing the yield gap in double cropped soybean in Argentina are: i) to advance sowing date through an earlier harvest date of winter crop and, ii) to increase P fertilization (Calviño et al., 2003; Di Mauro et al., 2018). Since sowing and harvest date in our winter crop were similar, there were no possibilities to establish differences between treatments in soybean sowing date. Also, P fertilization was not required in our EI treatments because the soil P levels were up to critical thresholds for each location.

Plots were 10 m width and 30 m long in Paraná and 10 m width and 50 m long in Balcarce. Experiments were carried-out under rainfed and no-till conditions at both locations. Crop residues were left on soil surface after each harvest.

Pest and weed management was similar between treatments, although maize genotypes carrying Bt genes were used in EI. Weeds were controlled with different herbicides depending on crop according to local recommendations. In maize, seeds received a conventional insecticide and fungicide treatment. Specific insecticides were used only when economic injury level was reached in soybean, according to the concepts of integrated pest management developed in each location. For wheat, fungicides to prevent foliar diseases were applied at booting stage in EI only in Balcarce.

The soils had no physical restrictions, and P availability was adequate in both locations (> 20 mg P Bray I kg^{-1}). However, in Paraná the experiment was further fertilized with 2 g P m^{-2} at the fall of each year broadcasting triple superphosphate (0-46-0). At Balcarce, soil P level was maintained above 16–18 mg P Bray I kg^{-1} by annual fertilizations with diammonium phosphate (18-46-0).

2.2. Measurements

Soil samples were taken in each plot 7–10 d before sowing at 0.20 m intervals up to 0.60 m depth. Samples were air-dried, milled and sieved to 2 mm. The concentration of $N\text{-}NO_3^-$ was determined using a colorimetric method (Bremner, 1965). Bulk density was determined by the core method in each location (Blake and Hartge, 1986) up to 0.60 m depth. Soil moisture was measured every 10–15 days using a neutron probe (Troxler 4300, Troxler Electronic Laboratories Inc., Research Triangle Park, NC, USA) at 0.20 m intervals up to 1.60 m depth. At 0 - 0.20 m depth soil moisture was determined using a gravimetric method.

The fraction of photosynthetically active radiation (PAR, 400–700 nm) intercepted by crops was measured at noon (12:00-13:30 PM) every 7–15 days under full sun conditions using a linear ceptometer (Decagon Devices, Buenos Aires, Argentina).

At physiological maturity (R6 for maize, R7 for soybean and Z92 for wheat), above-ground biomass samples were taken from the central row of each plot and oven-dried at 65 °C. After drying, the samples were weighed. Grain yield was determined by harvesting the central rows of each plot on a variable area, depending on crop and location (Table 1). Grain yield was adjusted at 0 kg H_2O kg^{-1} grain in order to keep the consistency with the results of resource use efficiencies, which are usually based on dry grain yield.

Table 1

Main management features of the treatments of ecological intensification (EI) and the average farmer practice (FP) in the experiments carried-out in two consecutive cycles of the two phases of a wheat/soybean-maize cropping sequence in Balcarce and Paraná, Argentina.

	Balcarce		Paraná	
	EI	FP	EI	FP
Plant density (plant m^{-2})	8 for maize, 40 for soybean and 400 for wheat	6.5 for maize, 40 for soybean and 300 for wheat	9 for maize, 40 for soybean and 400 for wheat	7 for maize, 40 for soybean and 300 for wheat
Row spacing (m)	0.52 for maize, 0.175 for wheat and soybean	0.7 for maize, 0.175 for wheat and soybean	0.52 m for maize and soybean, 0.21 for wheat	
Rule for N rate decision	Target yield 950 g m^{-2} for maize and 600 g m^{-2} for wheat; considering soil N-NO_3^- at V4 (0-0.30 m depth) for maize and at sowing (0-0.60 m depth) for wheat. Average applied N rate was 6.2 g N m^{-2} for maize and 12.8 g N m^{-2} for wheat	Target yield 750 g m^{-2} for maize and 400 g m^{-2} for wheat considering soil N-NO_3- at sowing (0-0.60 m depth). Average applied N rate was 4.8 g N m^{-2} for maize and 10.0 g N m^{-2} for wheat	Target N amount of 13.5 g N m^{-2} for wheat and 15.0 g N m^{-2} for maize considering N-NO_3- at sowing (0-0.60 m depth) and N from fertilizer. Target N amount is derived from a wide regional net of trials and obtained as those N rate required to reach 95% of relative yield. Average applied N rate was 10.3 g N m^{-2} for maize and 8.2 g N m^{-2} for wheat	Fixed rate, average in the region. Average applied N rate was 6.6 g N m^{-2} for maize and 4.9 g N m^{-2} for wheat
N source	UAN for maize and urea for wheat	Urea for maize and wheat	Urea	
Time and method of fertilizer application	Dribbled at V6 in maize and broadcasted at early tillering for wheat	Broadcasted at sowing time in maize and at early tillering for wheat.	Broadcasted at early tillering for wheat and at emergence in maize.	
Harvest	105 m^2 with plot combine for wheat and soybean; 20 m^2 by hand for maize		With plot combine, 14 m^2 for wheat and soybean; 31 m^2 for maize	

Samples of biomass and grain were milled to determine N concentration by a Kjeldhal micro-distillation technique (Nelson and Sommers, 1973).

2.3. Calculations and estimations

Since the focus of this work is at the crop sequence level, variables (resources and grain yield) were estimated within each cycle considering the three crops involved in the sequence. Within a cycle, accumulated grain yield (Y) of at the crop sequence level was estimated as the sum of wheat, soybean and maize yields. The relative contribution of each crop to Y at the crop sequence level was calculated as the quotient between the individual crop values and the accumulated grain yield of the crop sequence. In addition, we evaluated crop contribution using a linear regression between accumulated grain yield at the crop sequence level and grain yield of each crop. When this relationship was not significant, we considered that there was not a contribution of grain yield of a given crop to the variation in accumulated grain yield at the crop sequence level.

In order to account for the contribution in energy equivalent terms of the different crops to accumulated grain yield, this variable was expressed as glucose yield. The calculation was based on measured N concentration, whereas carbohydrates and lipids concentrations were obtained from literature values (Penning de Vries, 1972). We used production values of 0.45, 0.36 and 0.86 g product (g glucose)$^{-1}$ for protein, lipids and carbohydrates (Penning de Vries, 1972) yielding on average 0.80, 0.74 and 0.55 g grain (g glucose)$^{-1}$ for maize, wheat and soybean, respectively. Thus, accumulated grain yield of the crop sequence was expressed in two ways, as the sum of glucose equivalent and as the sum of grain mass of individual crops.

Crop evapotranspiration (ET) was estimated using a water balance based on the variation of water content in the soil profile (neutron probe data) and effective rainfall between two successive measurement dates. Effective rainfall was calculated from the total rainfall (USDA Method; Dastane, 1974) and adjustment coefficients for each daily data (Smith, 1992). The amount of PAR intercepted by the crop (IPAR) was estimated as the sum of daily values, which were obtained from the product of daily incident PAR and the fraction of intercepted PAR. The daily value of this fraction was estimated using polynomials functions fitted to measured values. Nitrogen captured was estimated from N concentration in above-ground biomass and accumulated above-ground biomass at crop maturity.

When data of soil moisture or fractional intercepted PAR were not available (mainly for wheat and soybean in Balcarce), we used crop models to estimate ET or IPAR. We used CERES-Maize, CERES-Wheat and CROPGRO-Soybean models embedded in DSSAT v 4.5 (Jones et al., 2003; Hoogenboom et al., 2010). The three models were recently evaluated in both Balcarce and Paraná areas on their performance to simulate water and radiation capture (Caviglia et al., 2013) and crop yields (see Fig. 1 in Aramburu Merlos et al., 2015) with satisfactory results.

Water and radiation productivities of the crop sequence were estimated from the product between its two components (Caviglia et al., 2004), i.e. resource capture and resource use efficiency as:

$$WP = WC * WUE \quad (1)$$

$$RP = RC * RUE \quad (2)$$

where WP is water productivity (g m^{-2} mm^{-1}), RP is radiation productivity (g MJ^{-1}), WC is water capture (mm ET mm $rainfall^{-1}$), RC is radiation capture (MJ captured PAR MJ incident PAR^{-1}), WUE is water use efficiency (g m^{-2} mm^{-1}) and RUE is radiation use efficiency (g MJ^{-1}).

Water use efficiency was calculated as the quotient between accumulated grain yield and ET, whereas RUE was calculated as the quotient between accumulated grain yield and IPAR. Water capture was estimated as the quotient between ET and rainfall whereas radiation capture was estimated as the quotient between IPAR and incident PAR.

The variables associated with applied N productivity were estimated considering only maize and wheat crops. We considered that soybean N requirements were fulfilled by biological N fixation as it is indicated by median values of Salvagiotti et al. (2008) and Ciampitti and Salvagiotti (2018) when N contribution from roots was considered and as it has been suggested by Collino et al. (2015). Partial factor productivity of applied N (PFPN) at the crop sequence level was calculated as the quotient between total grain yield of wheat and maize and total N rate within a cycle (Dobermann, 2007). Similarly, N utilization efficiency ($N_{ut}E$) at the crop sequence level was calculated as the quotient between accumulated grain yield and total N uptake (N_{upt}) by maize and wheat within a cycle.

The partial nutrient balance for N (PNB) of the sequence was estimated as the quotient between N exported outside the systems in maize and wheat grains and total applied N rate as fertilizers in a cycle, i.e. PNB is the removal to application ratio for maize and wheat (Norton et al., 2015).

Resource (water, radiation and N) productivity, capture and use efficiency for the crop sequence were estimated for each cycle on a two-year basis, considering the period from 1 May of the first year to 30 April of the third year (see Fig. 1). As a consequence, each value of resource productivity or its components integrates the three crops of a cycle of the two-year sequence wheat/soybean-maize.

2.4. Data analysis

We used a linear mixed-model ANOVA to account for the effect of sources of variation. The model included the effects of four replicates, two treatments (EI and FP), two locations (Balcarce and Paraná), two cycles (1 and 2) and two phases (I and II). Treatment, phase and location were considered as fixed effects, whereas cycle and replicates were considered as random effects. Associations between variables were evaluated using least squares regression and correlation analysis. Statistical analyses were performed using software INFOSTAT (Di Rienzo et al., 2011).

3. Results

3.1. Grain yields for the crop sequence and individual crops

Accumulated grain yield of wheat/soybean-maize sequence was affected by all factors, i.e. treatments, location, phase and cycle (Table 2). The interaction phase x cycle was significant and affected all related interactions with the other factors (Table 2). However, these interactions were mainly driven by the impact of EI on accumulated grain yield in relation to FP, i.e. EI outyielded FP from 13% to 42%, according to the considered combination of location, phase and cycle.

Individual crops had a different relative contribution to accumulated grain yield of the crop sequence (Fig. 2). Maize contributed most to accumulated grain yield (41%–67%). Consequently, accumulated

Table 2

Grain and glucose yield in two consecutive cycles of the two phases of a wheat/soybean-maize crop sequence for two treatments: ecological intensification (EI) and average farmer practice (FP) in Balcarce and Paraná, Argentina. Means are the average of four replicates. To convert $g\ m^{-2}$ to kg ha^{-1} multiply by 10.

Location	Phase	Cycle	Treatment	Grain yield[§] $g\ m^{-2}$	Glucose yield $g\ m^{-2}$
Balcarce	I	1	EI	1703	2299
			FP	1463	2025
		2	EI	1598	2217
			FP	1413	1948
	II	1	EI	1772	2371
			FP	1462	1967
		2	EI	1303	1819
			FP	1049	1507
Paraná	I	1	EI	1402	1944
			FP	1196	1704
		2	EI	1637	2259
			FP	1158	1595
	II	1	EI	1688	2289
			FP	1190	1697
		2	EI	984	1405
			FP	849	1223

ANOVA

Source of variation	P- Value	
Treatment	< 0.0001	< 0.0001
Location	< 0.0001	< 0.0001
Phase	< 0.0001	< 0.0001
Cycle	< 0.0001	< 0.0001
Treatment*Location	0.0988	0.1272
Treatment*Phase	0.6604	0.8754
Treatment*Cycle	0,3088	0.7615
Location*Phase	0.6412	0.8200
Location*Cycle	0.3373	0.9470
Phase*Cycle	< 0.0001	< 0.0001
Treatment*Location*Phase	0.3410	0.2698
Treatment*Location*Cycle	0.9183	0.6854
Treatment*Phase*Cycle	0.0022	0.0014
Location*Phase*Cycle	0.0117	0.0116
Treatment*Location*Phase*Cycle	0.0023	0.0083

[§] Grain and glucose yield are the sum of maize, wheat and soybean grain (0% grain moisture) or glucose yield in a given phase per cycle combination of a wheat/soybean-maize crop sequence.

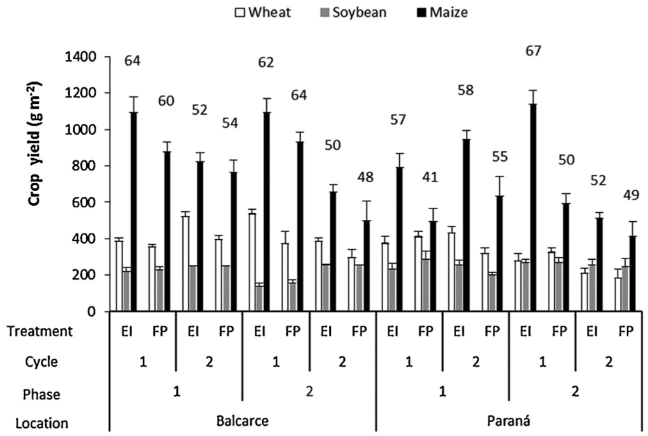

Fig. 2. Grain yield of wheat, soybean and maize (adjusted at 0 kg H_2O kg^{-1} grain) in two treatments: ecological intensification (EI) and average farmer practice (FP) during two consecutive cycles of the two phases of a wheat/soybean-maize crop sequence. Experiments were carried-out in two locations: Balcarce and Paraná, Argentina. The number over black bars indicate the contribution (%) of maize to the accumulated grain yield of a crop sequence in a cycle. Each bar is the average of four replicates whereas error bars indicate the standard deviation of each value. To convert g m^{-2} to kg ha^{-1} multiply by 10.

grain yield of sequences was strongly related to maize grain yields in both treatments ($P < 0.001$), and to a lesser extent with wheat grain yield ($P < 0.02$), but only in the FP treatment. Soybean grain yield variation did not contribute to the variation in the accumulated grain yield in the sequences.

EI consistently increased maize grain yield in comparison with FP in all situations, the increase ranged from 8% to 92% (35% on average, Fig. 3a). The lowest maize grain yield was recorded in phase II cycle 2 at both locations (Fig. 2). Differences in maize grain yield between FP and EI were not related to the grain yield level of FP. Remarkably, in Paraná differences between treatments were higher in years with high grain yields.

In Balcarce, EI significantly increased wheat grain yield in comparison with FP in all combinations of phases and cycles, with a grain yield difference that ranged from 9 to 44% (31% on average) (Fig. 2). In contrast, EI slightly depressed (not significant) soybean grain yield with respect to FP in both locations. In Paraná, EI increased wheat grain yields in comparison with FP only in some combinations of phases and cycles (Fig. 2 and 3a). Small differences in wheat grain yield were recorded between treatments in Paraná, because *Fusarium* head blight and foliar diseases had an important impact on both treatments, particularly in cycle 2 phase 2 (Fig. 2).

Overall, at the crop sequence level, 97% of EI plots outyielded those of their FP counterparts (Fig. 3a). However, the impact of EI on individual crop grain yield as compared with FP was higher for maize than for wheat and negligible for soybean (Fig. 3b). Average accumulated grain yield differences between EI and FP were 273.6 g m^{-2} for maize, 69.0 g m^{-2} for wheat and -2.1 g m^{-2} for soybean. In fact, only 41% of soybean plots of EI outyielded FP treatment, whereas 72% of wheat plots and 97% of maize plots had higher grain yield in EI than in FP (Fig. 3b).

Accumulated grain yield expressed as glucose equivalent (Table 2) varied in a similar way than that expressed as the sum of grain mass of individual crops. These two ways of expressing yield were closely associated ($P < 0.0001$, $r = 0.99$, result not shown). The average contribution of maize was reduced from 56% to 51%, whereas the average contribution of soybean increased from 18% to 23% when accumulated yield was expressed as glucose equivalent. The average contribution of wheat did not differ between the two ways of yield expression.

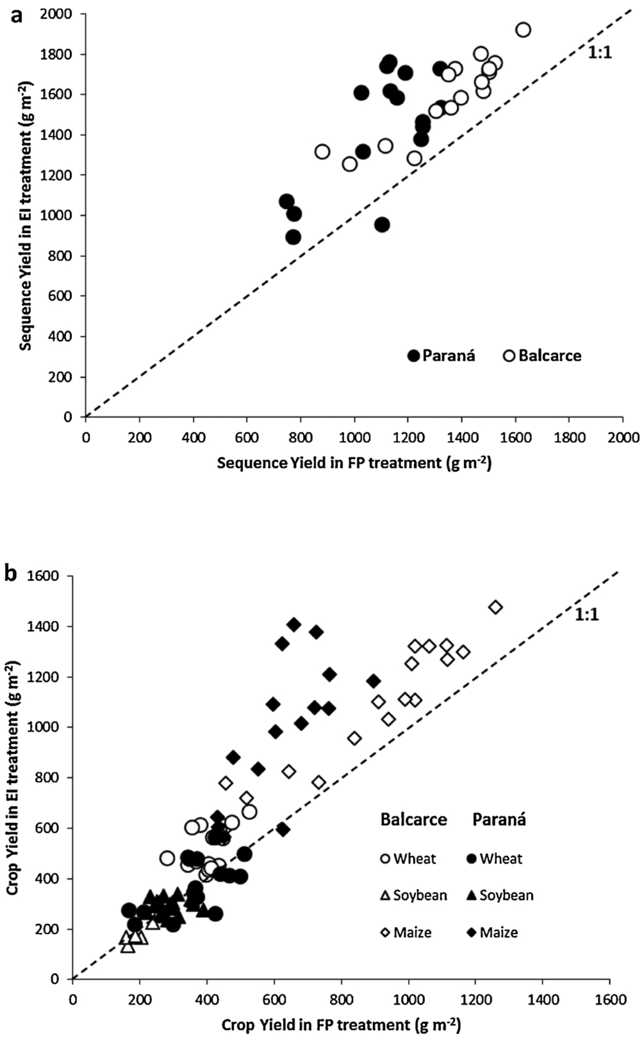

Fig. 3. Grain yields accumulated at the sequence level (a) and at the crop level (b) in ecological intensification (EI) vs. farmer practice (FP). Experiments were carried-out in two locations: Balcarce and Paraná (Argentina) during two consecutive cycles of the two phases of a wheat/soybean-maize cropping sequence. Dotted line represents the function $y = x$. Values of each replicate are shown. To convert g m^{-2} to kg ha^{-1} multiply by 10.

3.2. Resource productivity and its components

3.2.1. Water

Water productivity was affected by the same factors and interactions than accumulated grain yield (Table 3). Water productivity in EI was 24% higher than in FP. The magnitude of the increase was, on average, higher in Paraná than in Balcarce (29% vs. 19%). However, water productivity in Balcarce was 44% higher than in Paraná (Table 3), i.e. the impact of EI was higher in Paraná although with lower absolute values than in Balcarce. Average water productivity in Paraná was 0.64 g m^{-2} mm^{-1} in EI vs. 0.49 g m^{-2} mm^{-1} in FP whereas average water productivity in Balcarce was 0.88 g m^{-2} mm^{-1} in EI vs. 0.74 g m^{-2} mm^{-1} in FP.

Cumulative ET of the sequence did not differ between treatments and phases, but it was 14% higher, on average, in Paraná than in Balcarce because of a higher vapor pressure deficit in Paraná. Accordingly, water capture did not differ between the two treatments (Table 3), but water capture differed depending on locations and cycles. On average, water capture was 4% higher in cycle 1 (2009/10–2010/11) than in cycle 2 (2011/12–2012/13).

The increase in WUE by EI as compared with FP was consistent

Table 3
Total evapotranspiration (ET), water capture (WC), water use efficiency (WUE), and water productivity (WP) in two consecutive cycles of the two phases of a wheat/soybean-maize cropping sequence for two treatments: ecological intensification (EI) and average farmer practice (FP) in Balcarce and Paraná, Argentina. Variables were calculated the whole sequence duration, i.e. a cycle of 2 yr. Resource availability, i.e. rainfall during a cycle, can be estimated from the quotient between ET and WC. WP is obtained from the product between WC and WUE. Means are the average of four replicates.

Phase	Cycle	Treatment	ET mm	WC mm mm^{-1}	WUE g m^{-2} mm^{-1}	WP
					Balcarce	
I	1	EI	1015	0.58	1.68	0.97
		FP	1020	0.58	1.43	0.83
	2	EI	1234	0.66	1.30	0.85
		FP	1217	0.65	1.16	0.75
II	1	EI	1123	0.64	1.58	1.01
		FP	1114	0.63	1.31	0.83
	2	EI	946	0.50	1.38	0.69
		FP	963	0.51	1.09	0.56
					Paraná	
I	1	EI	1204	0.54	1.17	0.63
		FP	1232	0.56	0.97	0.54
	2	EI	1110	0.49	1.48	0.72
		FP	1115	0.49	1.04	0.51
II	1	EI	1198	0.54	1.41	0.76
		FP	1291	0.58	0.92	0.54
	2	EI	1337	0.59	0.74	0.44
		FP	1322	0.58	0.64	0.38

ANOVA

Source of variation	P- Value			
Treatment	0.0658	0.1248	< 0.0001	< 0.0001
Location	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Phase	0.0135	0.1744	< 0.0001	< 0.0001
Cycle	0.4218	< 0.0001	< 0.0001	< 0.0001
Treatment*Location	0.0514	0.0597	0.1200	0.6516
Treatment*Phase	0.2700	0.3170	0.4965	0.5623
Treatment*Cycle	0.0306	0.0597	0.1877	0.1944
Location*Phase	< 0.0001	< 0.0001	0.0002	0.9019
Location*Cycle	0.0292	0.0873	0.0074	0.0005
Phase*Cycle	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Treatment*Location*Phase	0.6680	0.5229	0.2161	0.3316
Treatment*Location*Cycle	0.0242	0.0106	0.7179	0.7347
Treatment*Phase*Cycle	0.5112	0.7838	0.0074	0.0048
Location*Phase*Cycle	< 0.0001	< 0.0001	< 0.0001	0.0991
Treatment*Location*Phase*Cycle	0.0238	0.0168	0.0001	0.0060

through all factors, with a similar extent to that recorded for water productivity. It was strongly associated ($R^2 = 85\%$, $P < 0.0001$) with WUE but not with water capture, i.e. most of the variation in water productivity was accounted for changes in WUE.

3.2.2. Radiation

On average, EI increased sequence radiation productivity by 23% as compared with FP. This significant effect ($P < 0.05$) of treatments ranged from 13% to 45% for the different combinations of location, phase and cycle (Table 4). Average radiation productivity in Paraná was 0.24 g MJ^{-1} in EI vs. 0.19 g MJ^{-1} in FP whereas average radiation productivity in Balcarce was 0.32 g MJ^{-1} in EI vs. 0.27 g MJ^{-1} in FP.

The cumulative IPAR of the sequence, in contrast with cumulative ET, was higher in EI (on average 5%) than in FP. Differences in cumulative IPAR between these two treatments were higher in Paraná than in Balcarce (7% vs 3%, $P < 0.0001$, Table 4), although cumulative IPAR was, on average, 46% higher in Balcarce than in Paraná ($P < 0.0001$). In fact, radiation capture was higher in Balcarce than in Paraná, i.e. the sequence captured 27% of incident PAR in Paraná and 46% in Balcarce (Table 4). Differences in radiation capture between treatments were significant although, on average, EI had only 5% higher radiation capture than FP ($P < 0.0001$).

Recorded differences in RUE between treatments averaged 18% (Table 4), with higher values in EI than in FP ($P < 0.0001$). Average RUE in Paraná was 0.87 g MJ^{-1} in EI vs. 0.72 g MJ^{-1} in FP (+21% higher in EI than in FP) whereas average RUE in Balcarce was 0.68 g MJ^{-1} in EI vs. 0.59 g MJ^{-1} in FP (+15% higher in EI than in FP).

Radiation productivity in Balcarce and Paraná was strongly associated with RUE ($R^2 = 0.89$, $P < 0.0006$ and $R^2 = 0.85$, $P < 0.002$, respectively). However, both the slope and the intercept of the regressions between these two variables differed ($P < 0.001$) between locations, i.e. at an equivalent value of RUE, radiation productivity was considerably higher in Balcarce than in Paraná. Radiation productivity also was associated, although to a lesser extent, with radiation capture ($R^2 = 0.57$, $P < 0.04$ in Balcarce and $R^2 = 0.70$, $P < 0.01$ in Paraná).

3.3. Partial N productivity, N utilization efficiency and partial N balance

The N rate was higher in EI than in FP, depending on the available soil N and target yield in each situation. In Balcarce, total N rate applied in a cycle of the sequence ranged from 14.3 to 21.9 g N m^{-2} for EI and from 9.7 to 18.2 g N m^{-2} for FP (on average, 18–47% higher in EI than in FP), whereas in Paraná, this variable ranged from 14.8 to 21.2 g N m^{-2} for EI and from 10.1 to 12.6 g N m^{-2} for FP (on average, 41–110% higher in EI than in FP).

N uptake by maize and wheat was higher in EI than in FP for all combinations of factors, except for phase II cycle 1 in Paraná. On average, N uptake was 23% higher in Paraná than in Balcarce. Remarkably, N utilization efficiency remained noticeably higher in EI as compared with FP, even though when N uptake was higher in EI than

Table 4

Total intercepted photosynthetically active radiation (IPAR), radiation capture (RC), radiation use efficiency (RUE), and radiation productivity (RP) in two consecutive cycles of the two phases of a wheat/soybean-maize cropping sequence for two treatments: ecological intensification (EI) and average farmer practice (FP) in Balcarce and Paraná, Argentina. Variables were calculated for the whole sequence duration, i.e. a cycle of 2 yr. Resource availability, i.e. incident PAR during a cycle, can be estimated from the quotient between IPAR and RC. RP is obtained from the product between RC and RUE. Means are the average of four replicates.

Phase	Cycle	Treatment	IPAR	RC	RUE	RP
			MJ m^{-2}	MJ MJ^{-1}	g MJ^{-1}	
				Balcarce		
I	1	EI	2326	0.47	0.73	0.34
		FP	2265	0.46	0.65	0.30
	2	EI	2460	0.51	0.65	0.33
		FP	2405	0.49	0.59	0.29
II	1	EI	2421	0.49	0.73	0.36
		FP	2290	0.46	0.64	0.30
	2	EI	2098	0.43	0.62	0.27
		FP	2074	0.43	0.51	0.22
				Paraná		
I	1	EI	1773	0.30	0.79	0.24
		FP	1647	0.28	0.73	0.21
	2	EI	1752	0.29	0.94	0.27
		FP	1633	0.27	0.71	0.19
II	1	EI	1618	0.28	1.04	0.29
		FP	1505	0.26	0.79	0.20
	2	EI	1370	0.23	0.72	0.16
		FP	1288	0.21	0.66	0.14

ANOVA

Source of variation	P- Value			
Treatment	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Location	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Phase	< 0.0001	< 0.0001	0.4839	< 0.0001
Cycle	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Treatment*Location	0.0412	0.1605	0.0202	0.5646
Treatment*Phase	0.8918	0.9676	0.4186	0.5555
Treatment*Cycle	0.0688	0.0294	0.7402	0.2706
Location*Phase	< 0.0001	0.0003	0.1213	0.7705
Location*Cycle	0.0055	< 0.0001	0.601	0.6249
Phase*Cycle	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Treatment*Location*Phase	0.2682	0.2285	0.7374	0.3415
Treatment*Location*Cycle	0.3613	0.2795	0.779	0.9646
Treatment*Phase*Cycle	0.1279	0.0752	0.0051	0.0048
Location*Phase*Cycle	< 0.0001	< 0.0001	< 0.0001	0.1165
Treatment*Location*Phase*Cycle	0.3351	0.2135	0.0004	0.0049

in FP in most situations (Table 5). The amount of N removed in wheat and maize grains, i.e. N exported outside the system, was 17% higher ($P < 0.001$) in EI than in FP.

Partial factor productivity of applied N, considering maize and wheat, was affected by treatments in a variable extent depending on the particular combination of factors, and it ranged from 35 to 127 g grain per g applied N. Partial factor productivity of applied N was higher in FP than in EI only in Paraná in Phase I cycle 1 (+32%) and Phase II cycle 2 (+78%), and in Balcarce in Phase I cycle 1 (+22%) and Phase II cycle 1 (+25%), without significant differences between treatments in the other combinations of factors. The partial nutrient balance ranged from 0.67 to 1.64 g N removed per g applied N at Balcarce and from 0.56 to 1.59 g N removed per g applied N at Paraná. The balance was improved in EI compared with FP in almost all situations, which was strongly related to the increase in N rates. Averages for EI and FP were of 0.98 and 1.13 g N removed per g applied N for Balcarce and 0.97 and 1.26 g N removed per g applied N for Paraná, respectively.

Partial factor productivity of applied N was negatively related to N rate (Fig. 4). In Balcarce, partial factor productivity of applied N linearly decreased by 6.1 g grain per g N applied per each additional unit of N rate (g N m^{-2}) whereas in Paraná partial factor productivity of applied N decreased in a similar way only when N rates were higher than 15 g N m^{-2}. In addition, higher N rates in EI than in FP decreased partial factor productivity of applied N (Fig. 5). In fact, an increase of 1% in N rate in EI respect to FP led to a reduction of 0.51% in partial factor productivity of applied N ($R^2 = 0.76$, $P < 0.006$). However, the decrease in partial factor productivity of applied N was proportionally lower than the increase in N rate (Fig. 5). Remarkably, the increment in N rate in EI respect to FP led to an average increase in N utilization efficiency by 4% in Balcarce and by 30% in Paraná (Fig. 5). Accumulated grain yield of the crop sequence was closely related to N utilization efficiency ($R^2 = 0.77$; $P < 0.004$ for Balcarce; $R^2 = 0.87$; $P < 0.0008$ for Paraná).

4. Discussion

To face up the main challenge of agriculture for the next years, i.e. satisfy the increasing global demand using the same or less land area, there is a need to increase resource and input productivity at the cropping systems level with a low environmental impact (Andrade, 2016; Cassman, 2017). Previous research had mainly focused on the effect of EI concepts on yield and, to a lesser extent, on some environmental impact variables at the crop level (e.g. Gehring et al., 2013; Zhao et al., 2016). In this work, we have addressed at the crop sequence level the productivity of water, radiation and N, a key step towards an ecological intensification (Cassman, 2017). Although this approach has been successfully used in our region to compare agricultural systems with different cropping intensity (Caviglia et al., 2004;

Table 5

Total N rate (N rate), total N uptake (N_{upt}), exported N (ExpN), partial factor productivity of applied N (PFPN), N utilization efficiency ($N_{ut}E$) for grain yield, and partial N balance (PNB) in two consecutive cycles of the two phases of a wheat/soybean-maize cropping sequence for two treatments: ecological intensification (EI) and average farmer practice (FP) in Balcarce and Paraná, Argentina. Variables were calculated for the whole sequence duration, i.e. 2 yr, considering only wheat and maize crops, as neutral N balance for the soybean crop was assumed. Means are the average of four replicates. To convert g m^{-2} to kg ha^{-1} multiply by 10.

Phase	Cycle	Treatment	N rate	N_{upt}	ExpN	PFPN	$N_{ut}E$	PNB
				g m^{-2}		g grain. g N^{-1}		g Exp N. g N $rate^{-1}$
						Balcarce		
I	1	EI	14.3	27	19.3	104	54	1.35
		FP	9.7	22	15.9	127	56	1.64
	2	EI	21.9	24	16.4	62	58	0.76
		FP	18.1	21	15.4	64	55	0.85
II	1	EI	18.5	29	20.6	88	56	1.12
		FP	13.0	26	17.8	100	51	1.37
	2	EI	21.4	22	15.0	49	48	0.70
		FP	18.2	17	12.2	44	46	0.67
						Paraná		
I	1	EI	19.6	25	16.3	60	47	0.84
		FP	12.6	23	15.1	72	39	1.20
	2	EI	14.8	36	23.3	94	39	1.59
		FP	10.5	29	16.8	91	32	1.61
II	1	EI	18.4	28	16.7	77	50	0.91
		FP	12.6	30	15.3	73	30	1.21
	2	EI	21.2	32	11.6	35	23	0.56
		FP	10.1	29	10.4	59	21	1.02

ANOVA

Source of variation	P- Value					
Treatment	< 0.0001	< 0.0001	< 0.0001	0.0001	< 0.0001	< 0.0001
Location	< 0.0001	< 0.0001	0.0335	< 0.0001	< 0.0001	0.0847
Phase	< 0.0001	0.2221	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Cycle	< 0.0001	0.5846	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Treatment*Location	< 0.0001	0.2524	0.9305	0.8171	0.0002	0.0513
Treatment*Phase	< 0.0004	0.1411	0.2365	0.5735	0.0398	0.4055
Treatment*Cycle	0.7901	0.1068	0.0566	0.1092	0.0112	0.0184
Location*Phase	0.1487	0.2509	< 0.0001	0.856	0.1032	0.0062
Location*Cycle	< 0.0001	< 0.0001	0.0002	< 0.0001	< 0.0001	< 0.0001
Phase*Cycle	0.6828	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Treatment*Location*Phase	0.0013	0.142	0.0573	0.0492	0.7795	0.0492
Treatment*Location*Cycle	0.0005	0.0209	0.0237	0.0009	0.0031	0.2942
Treatment*Phase*Cycle	0.0001	0.2696	0.3282	0.0028	0.0009	0.1259
Location*Phase*Cycle	< 0.0001	0.4076	0.0017	< 0.0001	0.3207	< 0.0001
Treatment*Location*Phase*Cycle	< 0.0001	0.5388	0.021	0.0097	0.1353	0.0369

Van Opstal et al., 2011; Andrade et al., 2015; Ojeda et al., 2018), it has not been yet used to assess the effect of EI concepts on accumulated grain yield and resource productivity.

4.1. Accumulated grain yield of sequence and individual crop yields

The impact of EI on accumulated grain yield in relation to FP was noticeably high, varying from 13% to 42%, according to the considered combination of location, phase and cycle (Fig. 3a). Although the impact of EI at the crop level has been widely documented (e.g. Gehring et al., 2013; Zhao et al., 2016), there are few reports at the crop sequence level (e.g. Seben Junior et al., 2016; Theisen et al., 2017; Monzon et al., 2018). Hence, this research provided a quantitative evidence of the attainable benefits of EI in terms of accumulated grain yield of a sequence (Fig. 3a, Table 2).

The contribution of each crop to accumulated grain yield of the sequence was evaluated to detect the impact of EI at the individual crop level (Fig. 3a). Maize had the most important contribution to the accumulated grain yield of the crop sequence, irrespective of the treatment (Fig. 2). These results evidenced the crucial role of maize in the variations of the accumulated grain yield of this crop sequence. In the FP treatment, on the other hand, the variations in accumulated grain yield of the crop sequence were also related to the variations in wheat grain yield. The higher wheat contribution in Balcarce than in Paraná (28 vs. 25%, $P < 0.05$) is attributable to the contrasting differences in the photothermal environment between the two locations (Magrin et al., 1993). The role of wheat in the crop sequence in conferring stability and as an important contributor to accumulated grain yield of several crop sequences in the region of Balcarce has been more deeply discussed elsewhere (Caviglia et al., 2013).

The contribution of soybean to the accumulated grain yield of the crop sequence was low (on average 16% for EI and 20% for FP), and was unrelated to the accumulated grain yield of the crop sequence. As it was anticipated, the contribution of soybean to the accumulated grain yield of the crop sequence was higher in Paraná (on average 21%) than in Balcarce (on average 16%) because of unfavorable growing conditions for soybean as a second crop in the southern location (Calviño et al., 2003).

Treatments had a negligible impact on soybean grain yield because they only differed in the genotype choice in Paraná. The impact of agronomic practices on soybean as a second crop in the Argentinean Pampas is usually low. Moreover, the yield gap between water limited yield potential and actual yield has been reported as higher in soybean as a second than as a single crop (Di Mauro et al., 2018). As indicated previously, advancing sowing date and increasing P fertilization are the main practices to closing the yield gap in double cropped soybean yield. In our experiments, however, there were no differences in soybean sowing date between treatments and P fertilization was not required in the EI treatments.

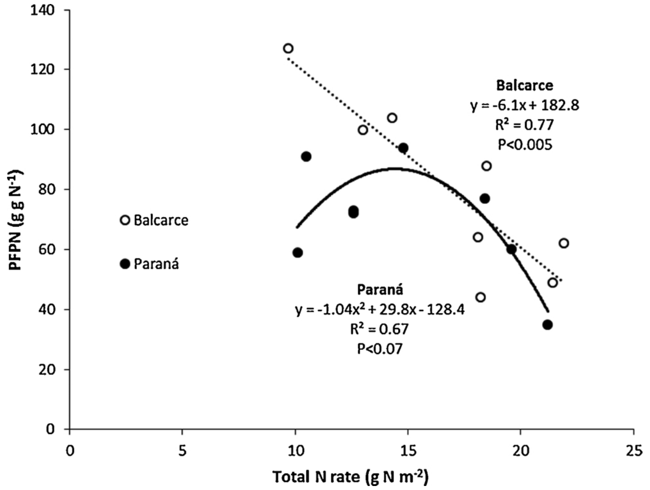

Fig. 4. Partial factor productivity of applied N (PFPN) as a function of the total N rate added in a cycle of a wheat/soybean-maize crop sequence. Experiments were carried-out in two locations: Balcarce and Paraná (Argentina) during two consecutive cycles of the two phases of the sequence. Values are the average of four replicates. To convert g m^{-2} to kg ha^{-1} multiply by 10.

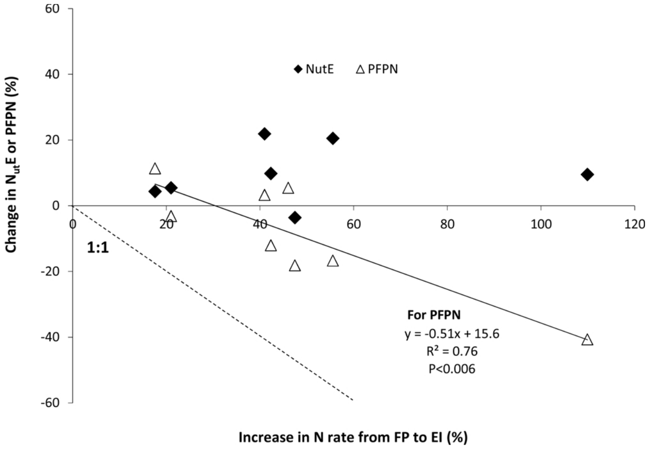

Fig. 5. Change in factor productivity of applied N (PFPN) and N utilization efficiency (NutE) in ecological intensification treatment (EI) in relation to the farmer average practice treatment (FP) as a function of the relative increase in the N rate, i.e. the increase in N rate from FP to EI. Experiments were carried-out in two locations: Balcarce and Paraná (Argentina) during two consecutive cycles of the two phases of a wheat/ soybean sequence. Values are derived from the average of four replicates for each treatment. To convert g m^{-2} to kg ha^{-1} multiply by 10.

4.2. Radiation and water productivity

The variations in water productivity and radiation productivity were mainly driven by variations in resource use efficiency, i.e. WUE and RUE, rather than in resource capture, i.e. WC and RC (Tables 3 and 4). In fact, there were important differences in accumulated grain yield of the crop sequence but small differences in resource capture between treatments (Fig. 6). As a consequence, the higher resource productivity in EI than in FP can be attributed to improvements in resource use efficiency. Although the isolated effect of single agronomic practices involved in EI (such as proper management practices for fertilization, superior genotypes managed with the suited plant density, proper row spacing) on water and radiation use efficiency has been previously documented (e.g. Caviglia and Sadras, 2001 for N in wheat; Hernández et al., 2015 for plant density and N rate in maize and Barbieri et al., 2012 for row spacing in maize), the impact of combing these practices has been less explored in the literature.

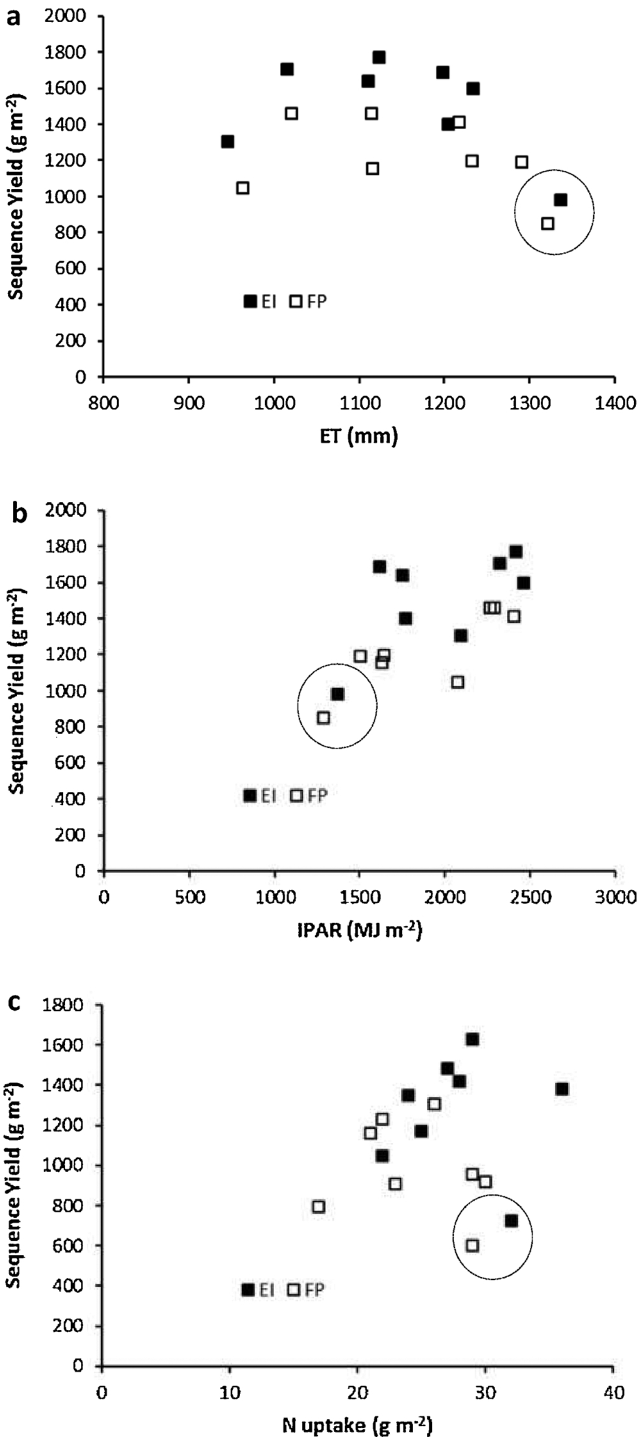

Fig. 6. Sequence yield as a function of (a) crop evapotranspiration (ET), (b) intercepted photosynthetically active radiation (IPAR) or (c) crop N uptake for the ecological intensification (EI) and the average farmer practice (FP) treatments. Values within dotted circles represent sequence yield of cycle 2 phase 2 at Paraná, which were low in spite of high ET and N uptake (see text for further details). Experiments were carried-out in two locations: Balcarce and Paraná (Argentina) during two consecutive cycles of the two phases of a wheat/soybean-maize crop sequence. Soybean data were excluded from Fig. 6c. To convert g m^{-2} to kg ha^{-1} multiply by 10.

EI improved more WUE (26%) than RUE (17%) as compared with FP. In fact, EI improved only scarcely (< 5%) radiation capture (Table 4) or did not significantly affect water capture as compared with FP (Table 3). These results evidenced that the agronomical practices used in FP were enough to allow the crops to expand their structures, i.e. leaf and roots, needed to capture these resources to a similar extent than in EI. The different nature of water and radiation may, however, explain the lower proportion of radiation captured from the annual offer as compared with water (0.37 vs 0.57, respectively) (Tables 3 and 4). In fact, water is a resource that can be stored in the soil profile during fallow periods or during the periods with low crop ability to capture this resource, i.e. initial growing stages or crop senescence (Goudriaan and Monteith, 1990). On the other hand, solar radiation is received as a flux of non-storable resource, which can be captured by green organs only when they are displayed. Thus, the different nature of these resources not only allows a higher capture of the annual offer of water than of radiation but also allows to minimize the differences in water capture between treatments (Table 3). Thus, our results indicate that EI is a more reliable strategy to increase radiation than water capture at the crop sequence level.

Water and radiation productivities were higher in Balcarce than in Paraná (Tables 3 and 4). The impact of the two components of resource productivity, i.e. resource capture and resource use efficiency, was quite different between these two locations. In spite of the lower RUE in Balcarce than in Paraná, radiation productivity in EI was 42% higher in Balcarce (Tables 3 and 4), because of a dramatically higher radiation capture (73%). The higher cumulative IPAR in Balcarce than in Paraná (Table 4) was mainly related to: i) the longer growing cycle of wheat and maize and, ii) the better matching between incident PAR and the PAR interception in wheat. These are two important insights derived from this work that can be useful to improve radiation capture and radiation productivity at the crop sequence level in other locations. Contrarily, WUE in Balcarce was higher than in Paraná as well as water capture (only 10% higher), which led to a 44% higher WP.

The higher vapor pressure deficit (VPD) in Paraná than in Balcarce underlies the recorded differences in WUE between these two locations, a result already reported for wheat (Abbate et al., 2004). On the other hand, the lower RUE in Balcarce than in Paraná is probably related to the lower mean temperature, which may have affected the RUE of maize, the main crop in the sequence, as reported by Andrade et al. (1993).

The average values of water productivity in the FP treatment, 0.74 g $m^{-2} mm^{-1}$ in Balcarce and 0.49 g $m^{-2} mm^{-1}$ in Paraná, outyielded by far the average for Argentina farmers (estimated at 0.35 g $m^{-2} mm^{-1}$, based on grain yield data from Estimaciones Agrícolas, 2018) in spite of equivalent input levels. These substantial differences can be attributed, at least in part, to the higher proportion of the maize when compared to Argentina (0.50 vs 0.15, Estimaciones Agrícolas, 2018), and to the lower cropping intensity level (< 1.15 crops per year, Estimaciones Agrícolas, 2018) in the sequences of the farmers as compared with the higher cropping intensity of the sequence in our experiments (1.5 crops per year). Although other agronomical and site factors such as soil quality, climatic conditions, accurate and timely management, and others, are also involved in the higher water productivity of FP as compared with the national average, these results provide a rough estimation of the potential improvement in water productivity by increasing cropping intensity, since the input levels are equivalent.

EI demonstrated, therefore, a high potential to increase water and radiation productivity mainly through high resource use efficiency at the crop sequence level (Table 2 and 3, Fig. 6). For further improvements in resource capture, others agronomic practices should be added to EI, such as the increase of cropping intensity and the selection of the crop cycle length to better match the resource offer with the capture, especially for radiation which is received as a continuous flux.

4.3. Nitrogen productivity

Despite N rates were, on average, 48% higher in EI than in FP, N utilization efficiency was higher (+18%, on average) in EI across all situations, i.e. the combination of location, cycle and phase (Table 5). The higher N utilization efficiency in EI with respect to FP was reflected by the more than proportional increase in accumulated grain yield than in N uptake (Fig. 6), i.e. on average, accumulated grain yield of wheat and maize increased by 45% and N uptake by 13% in EI respect to FP. This result is in contrast with most of the literature regarding N fertilization, which refers a negative relationship between N rate and N utilization efficiency, mainly in regions that use high N fertilization rates (Moll et al., 1982; Qiao et al., 2012; Fixen et al., 2015; Yan et al., 2016; Omonode et al., 2017). The complex nature of the experimental approach used in our work, which included the comparison of treatments differing in several management factors surely underlies this result. In fact, the increase in N rate in EI was complemented with crop management improvements that included superior genotypes, an optimal plant density, precise timing and amount of applied inputs (see Table 1). Results of a similar experiment has been reported, although at a single crop level, for maize in China where, however, the N rate in the EI treatment was lower than in FP (Zhao et al., 2016).

The increase in N rate is often not encouraged in high-input agroecosystems as those of USA (Fixen et al., 2015; Omonode et al., 2017), Europe (Oenema et al., 2011) and some regions of Asia (Liu et al., 2008; Chen et al., 2011), because of important environmental consequences of N losses (Cassman et al.;, 2002; Ladha et al., 2016). The increase on N rates could be really critical, however, in medium- or low-input agroecosystems as the Argentinean Pampas, in order to improve use efficiency of other resources such as water and radiation. Despite of the increase in fertilizer use in the Pampas along the last 20 years, N consumption is still considered low to medium (Norton et al., 2015; García and González Sanjuan, 2016). Our results evidenced that in a medium-input system, EI allowed to reach high yield, N utilization efficiency, radiation productivity and water productivity with a less than proportional reduction in partial factor productivity of applied N than the increase in N rate. However, it should be noted that the higher N rate in EI than in FP was accompanied by a target set of improved agronomic practices (Table 1).

Average N rates applied to wheat and maize and estimated partial nutrient balance for N and partial factor productivity of applied N in Argentina are similar to those applied to the FP treatment at Paraná and Balcarce (Table 5) (Fertilizar, 2017; García and Salvagiotti, 2009). Under these conditions, a large portion of N removed in grains is putatively supplied through soil organic matter mineralization. Our results evidenced a positive impact of EI on partial N balance (Table 5) as compared with FP (average increase of 23%). Moreover, the used N rates allowed a balance close to neutral (average of 0.93 for EI). In fact, considering the relationship between N Input – N Output and Output N proposed by Norton et al. (2015), EI is in a situation of “Farmer wins, Environment wins” and our FP treatments are in the situation of “Farmer loses, Environment loses”, which is coincident with the average estimation for Argentina. Similarly, following Davidson et al. (2016), EI is close to the situation of “Food security wins, Environment wins”, but FP aligns with “Food security wins, Environment loses – soil degradation”.

It should be noted, however, that the contribution of N biological fixation from soybean was not accounted in our partial N balance. Likewise, focus of N management to reach a neutral apparent balance may not be most proper target for EI, since its aim is to increase yield levels and resource use efficiency while reducing environmental impact (Cassman, 2017). Thus, a better quantification of contribution of N biological fixation and a proper choice of yield target to decide N rates can be useful to design N management practices to include in EI. Accordingly, Cassman (2017) has proposed the use of target yield of 75–85% of water limited yield potential (Y_w), which is compatible with the yield used herein to decide N rates.

Our values of partial factor productivity of applied N were generally higher than the range reported by Ladha et al. (2016) for cereals in several regions. This discrepancy cannot be attributed to low N rates in our experiments. In fact, our average partial factor productivity of applied N was 75 g grain g N^{-1} with an average N rate of 16 g N m^{-2} per cycle, whereas Ladha et al. (2016) reported an average partial factor productivity of applied N of 58 g grain g N^{-1} with an average N rate of 12 g N m^{-2}.

On the other hand, partial factor productivity of applied N was linearly reduced with the increase of the N rate in EI (Fig. 5) in coincidence with most of the literature (Chen et al., 2011; Guo et al., 2016). The reduction in partial factor productivity of applied N, however, was low as compared with previous studies (Fixen et al., 2015; Guo et al., 2016). Again, the combination of management practices in EI (Table 1) prevented large reductions in partial factor productivity of applied N observed when N rate is the only single studied factor (Fixen et al., 2015; Guo et al., 2016). Thus, our results showed that the challenge to reach high yields with an increase in the N utilization efficiency could be achieved in a medium-input system by applying a target set of agronomic practices, which included an increase in the N rate in EI.

5. Conclusions

Maize grain yield accounted for most of the variation of the accumulated grain yield of the crop sequence, in EI as well as in FP, contributing 41–64% to the accumulated grain yield of the crop sequence. Although the contribution of wheat and soybean to the accumulated grain yield of the crop sequence was similar, wheat grain yield variations accounted for the variations in accumulated grain yield of the crop sequence, but only in FP treatment.

Water and radiation productivities were higher in EI than in FP, mainly because of increases in resource use efficiencies, i.e. water and radiation use efficiencies. Although to a limited extent (~5%, on average), EI also increased radiation capture as compared with FP whereas water capture remained unaffected by treatments.

In spite of the lower radiation use efficiency, resource productivity was higher in Balcarce than in Paraná, because radiation capture was proportionally higher in the former location. On the other hand, water productivity was higher in Balcarce than in Paraná mainly because of a higher water use efficiency.

EI reduced the partial factor productivity of applied N but improved the partial N balance as compared with FP. The reduction in partial factor productivity of applied N was less than proportional to the increases in N rates. Moreover, the higher N rates in EI with respect to FP not only did not reduce N utilization efficiency but also increased this variable (+17%) across almost all situations. The combination of agronomical practices in EI, including higher plant densities, superior genotypes and improved fertilizer management, were involved in preventing large reductions in partial factor productivity of applied N and in increasing N utilization efficiency associated with a high N rate.

Our results showed that the challenge to reach high yields with an increase in the N utilization efficiency, radiation productivity and water productivity in a medium-input system could be achieved by applying a set of agronomical practices, which include an increase in the N rate, the use of higher plant densities and superior genotypes compared with FP.

This work evidenced several benefits of EI as compared with FP on grain production and resource productivity through a novel approach, which not only included the evaluation of key resources at a time but also the focus at the crop sequence level.

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