



Assessing benefits of land use intensification on extensive grain cropping systems of the Pampas

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ABSTRACT

A holistic approach in the design of cropping systems is essential to boost productivity in a sustainable manner. One of the most important decisions in the cropping system is the way that crops are organized in sequences, which is commonly oriented to obtain high yields and associated economic return while minimizing variability and risk. Increased cropping intensity based on sequenced winter/summer crops has proven to raise annual land productivity due to a larger utilization of environmental resources. In this study, we aim to compare a soybean monoculture sequence with more diverse and intensified crop rotations in terms of resource use, overall productivity, and economic return in four sites, along six years, exploring a relatively wide range of environmental conditions in the central area of the Argentine Pampas. Results showed that more intensified and diverse cropping sequences yielded 41–51% more, in average, than soybean monoculture, given that this latter crop makes use of available environmental resources only during summer. In addition, despite higher production cost when growing more diverse and intensified rotations, annual gross margin was 10–13% higher, in average, than soybean monoculture. According to our results, cropland intensification resulted in larger productive, economic, and environmental benefits. At this point, new alternative winter crops and intensified cropping systems may expand. However, to effectively promote such process in the Pampas, it appears that policy decision makers should target the development of new markets and create opportunities to use or sell the extra production.

1. Introduction

Global growing demand for agricultural products is challenging our capacity to increase food production in a sustainable manner. Crops worldwide have both expanded area and increased yields per unit area in the past decades to cope with this growing demand (Cassman and Grassini, 2020). Increasing yields per unit area has been based on a moderate increase of yield potential through genetically improved cultivars, as well as on larger amounts of inputs and technological innovations that have narrowed down the gap between the yield potential and the average farmer yield (Sadras et al., 2020). It is recognized that production increases should arise from yield increments at currently exploited agricultural lands in order to release pressure on uncultivated lands, which involves environmental concerns such as biodiversity loss and green-house gasses emission from land conversion among others (Cassman, 1999; Tilman et al., 2011; Andrade, 2020). However, given

the current rates of yield increase, there is skepticism on that crop genetic improvements and technological innovations will cope with food demand in the near future (Hall and Richards, 2013).

In this context, more holistic approaches are needed to stretch out cropping systems production capacity in a sustainable manner (Satorre, 2000, 2012; Andrade et al., 2015, 2017; Monzon et al., 2018; Andrade, 2020). The way that crops are organized in sequence, namely rotation, is one of the most important decisions in the cropping system design, which is commonly oriented to obtain high yields and associated economic return while minimizing yield variability and risk. Increased cropping intensity (*i.e.* number of crops per year) in rotations has proven to raise annual land productivity in many regions around the globe based on a larger utilization of available environmental resources (Trenbath, 1974; Caviglia et al., 2004; Graß et al., 2013; Andrade et al., 2015; Agus et al., 2019). In the Argentine Pampas, land use intensification takes places through double cropping (*i.e.* two crops in a year),

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which usually consists of a summer species grown late, as a second crop, after harvesting the cool-season crop (Calviño and Monzon, 2009; Andrade et al., 2015). In such temperate area, rainfed feasibility of this practice depends on the frost-free period extension and rainfall amount and distribution, as well as on the economic return of the second crop, which is typically reduced compared to the single full-season crop of the same species (Andrade et al., 2015).

Almost 90% of total harvested area with grain crops in Argentina (ca. 34 million ha) corresponds to soybean (54%), maize (20%), and wheat (16%) (2016–2019; FAOSTAT). In the Pampas region, these three crops are typically grown in a wheat/soybean double crop-maize-soybean sequence that vary depending on farmers' choice according to regional weather, soil, commodities price, and personal preferences -and sometimes include other summer crops such as sunflower or grain sorghum or winter crops like barley, rapeseed, or field pea. However, on one hand, relative higher prices and lower costs of producing soybean have pushed large extensions of agricultural land towards a soybean monoculture sequence, reducing the presence of cereal crops to less land and few years. On the other hand, most progressive farmers are eager to design more intensive and diverse crop sequences aiming for higher overall productivity, income, stability, and sustainability, especially if they own the land they produce on. In this study, we aim to compare the

typical crop rotation (TYP) indicated above against a soybean monoculture (SOY) and an intensified crop rotation (INT) in terms of resource use, overall productivity, and economic return for a relatively wide range of environmental conditions in the central area of the Argentine Pampas. For this purpose, a large scale on-farm research was set up during a six-year period.

2. Materials and methods

2.1. Experimental sites and environmental conditions

Four experiments were conducted along six years, from June 2014 to May 2020, in the Rolling Pampa, Argentina, under rainfed conditions. One experiment was close to San Pedro (34° 01' S; 59° 54' W), another in Pergamino (33° 55' S; 60° 23' W), and two next to Bragado ("I" and "II") (35° 01'; 60° 39') cities, in Buenos Aires province (Fig. 1). Soil pH ranged from 5.9 to 6.1 and topsoil organic matter from 2.6% to 3.9% (Supplementary Table S1). Soil texture differed among experiments, especially at 0.4–0.8 m depth, that define contrasting water storage capacities. Clay content in that layer is high in San Pedro (48% clay in Typic Argiudoll, Arrecifes series), intermediate in Pergamino (38% clay in Typic Argiudoll, Urquiza series), and low in Bragado (25% clay in

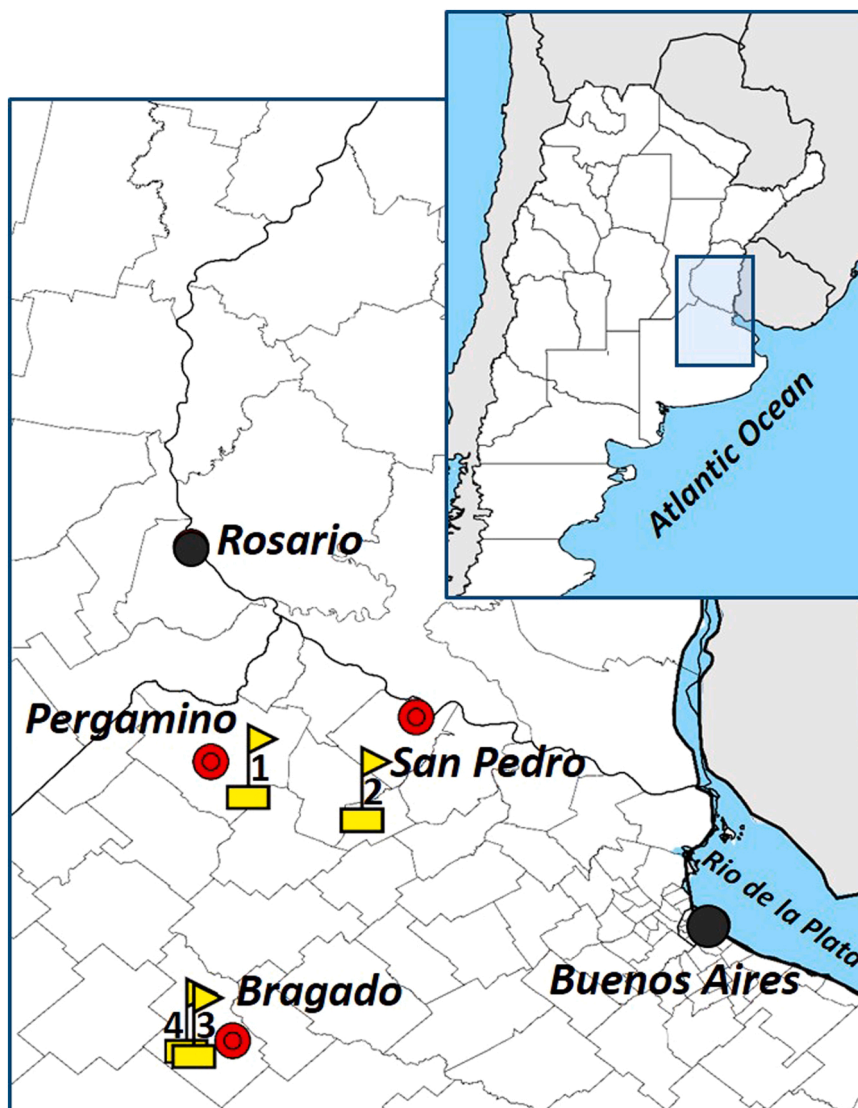


Fig. 1. Experimental sites (flags) and proximate main cities (red dots). Sites were named based on the proximate cities as follows: Pergamino (1), San Pedro (2), Bragado I (3), and Bragado II (4).

Typic Hapludoll, Bragado series (I) and 16% clay in Entic Hapludoll, Norumbega (II) series; INTA, 1989; <http://sisinta.inta.gov.ar/en/series>). Additionally, Bragado I and Pergamino often presented a water-table between 1.2 and 1.8 m depth.

Temperature and solar radiation during the six seasons were collected from meteorological stations close to the experimental sites (Servicio Meteorológico Nacional, 2021; Sistema de información y gestión agrometeorológica, 2021), except for solar radiation records at Pergamino that were obtained from NASA-POWER (2021). Rainfall data was measured at the experimental fields. Solar radiation and temperature presented the typical intra-annual oscillation from temperate regions. Mean summer temperature was among 23–25 °C while lowest mean temperature occurring during the winter season reached 10–12 °C for all sites, with Pergamino registering slightly lower mean temperatures during summer months (Fig. 2). Incoming solar photosynthetically

active radiation (PAR) followed a similar trend with largest values during summer in Bragado and Pergamino (Fig. 2). Inter-annual variation of mean temperature and PAR were relatively low for each location (CV<16%) and were similar to the historical averages. As expected, rainfall was low during winter and high during the spring-summer-early fall in all locations. However, rainfall inter-annual variability was large in all sites (average CV=73%). For example, total summer rainfall was considerably lower than historical records in San Pedro and Pergamino during the 2017/2018 and 2019/2020 summer seasons and in Bragado during the 2016/2017 and 2017/2018 summer seasons as well. Monthly averages for each site and year and the historical average values for rainfall, temperature, and incoming solar radiation can be found in Supplementary Table S2.

2.2. Experimental design and crop management

Three different crop sequences (treatments) were grown twice during the six seasons, covering two 3-yr cycles, from 2014/15–2019/20 season (Table 1). A completely randomized block design with two replicates was set on each site. On each one of the four locations, experiments consisted of 6 large plots, each 22 m wide and 200 m long (4400 m²). Widely used crop cultivars with high yield potential in the region were sown for each crop. Crops were planted with a no-till sowing system and sowing date, plant density, and row spacing used in the experiments were based on regional recommendations (Supplementary Table S3). Sowing date window across sites was June for wheat, July for field pea, October–November for soybean, and December for both double cropped soybean and maize. Maize single crop in TYP rotation was, however, flexible to be sown early in September–October or late in December depending on soil texture and expected rainfall during the season given that late planting provides yield stability in water-limited scenarios (Otegui et al., 2021) (Supplementary Table S3). Weeds, insects, and diseases were maintained below damage thresholds by applying chemical controls using a self-propelled sprayer when needed. Nutrient fertilization rates were set following the most common criteria among farmers in the region (see below).

2.3. Measurements and analyses

Aboveground biomass of every crop was estimated from three 1 m² samples in each plot at physiological maturity. Plants were cut at ground level, dried, and weighted. For grain yield determination, plots were harvested with a combine machine and then the grains were transferred to a hopper with scale to weight them. Crop yield was estimated as kilograms of dry grain per hectare (kg ha⁻¹) and converted to glucose-equivalent units per hectare (kg g.e. ha⁻¹) so yield from different crops species, with different energy concentration in grains, are expressed in the same units. A kg of glucose is equivalent to 0.83 kg of carbohydrates, 0.33 kg of lipids, or 0.41 kg of proteins (Penning de Vries et al., 1983). Based on seed composition described in many reports (Sinclair and de Wit, 1975; Watson and Ramstad, 1987; Gooding and Davies, 1997; Stone and Savin, 1999), we determined the value of glucose equivalent per kg of grain of wheat, field pea, maize, and soybean on 1.28, 1.26, 1.32, and 1.86 kg g.e. per kg of grain, respectively.

Solar radiation interception fraction was derived from NDVI measurements from Sentinel-2 images (10 m resolution). We only accounted pixels that were completely within the plot limits. NDVI values were obtained every 4–7 days from Auravant® (www.auravant.com). A linear relationship was assumed to associate NDVI with solar interception efficiency: lowest and highest NDVI values across the four sites were considered as 0 and 0.95 separately for each individual crop species and season [we confirmed at least one plot, at any location, reaching 0.95 with a photosynthetic photon flux portable sensible bar (<http://www.cavadevices.com>). NDVI data was only available for the second 3-yr cycle (2017/18–2019/20) so we estimated total PAR interception and the radiation use efficiency by each treatment for that period.

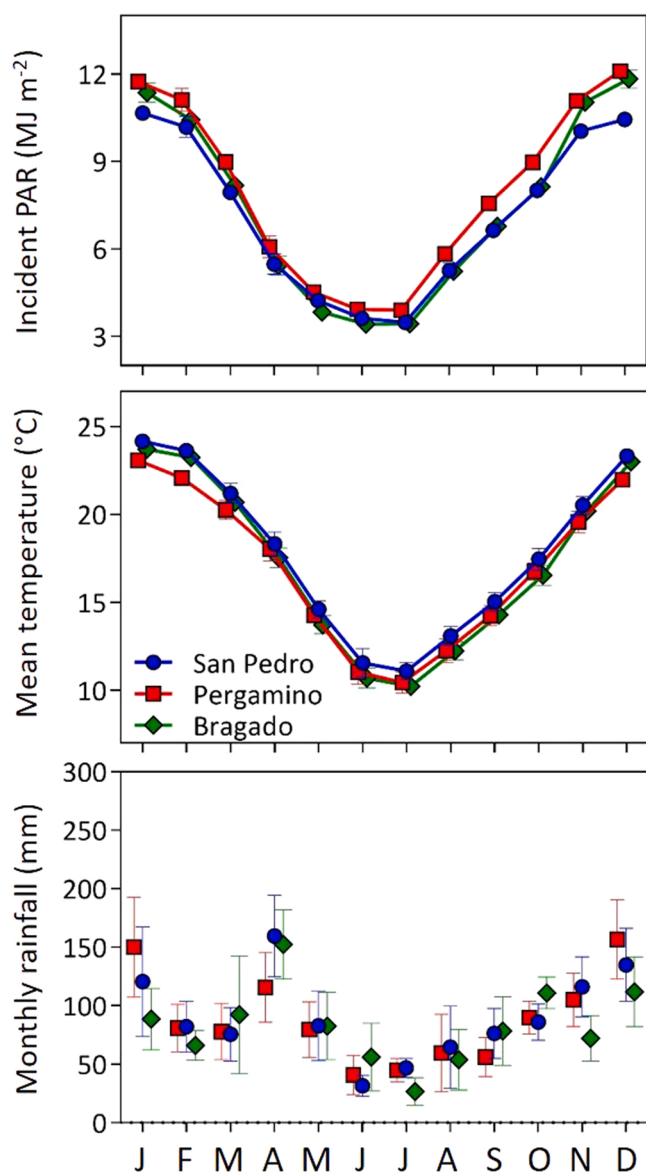


Fig. 2. Monthly average weather conditions in the four experimental sites across the six cropping seasons (2014/15–2019/20). Daily incident photosynthetically active radiation (PAR; MJ m⁻²), mean temperature (°C), and monthly cumulated rainfall (mm) are displayed in top, middle, and bottom panels, respectively. Standard errors are indicated with vertical lines. Separated data for each cropping season can be found in Supplementary Material (Supplementary Table S2).

Table 1

Crop rotations evaluated: Soybean monoculture (SOY), typical crop rotation (TYP), and intensified crop rotation (INT).

Treatment	Cycle 1			Cycle 2			Average crops year ⁻¹
	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	
SOY	Soybean	Soybean	Soybean	Soybean	Soybean	Soybean	1.00
TYP	Wheat/Soybean	Maize	Soybean	Wheat/Soybean	Maize	Soybean	1.33
INT	Wheat/Soybean	Field pea/Maize	Soybean	Wheat/Soybean	Field pea/Maize	Soybean	1.67

We used crop-specific water use efficiency (WUE) data on each location reported in previous field studies in nearby sites to indirectly estimate water evapotranspiration (Andrade et al., 2015). Depending on the location, the selected values were 26–35 kg of aboveground biomass produced per mm of evapotranspired water for wheat, 15–21 for soybean, 25–32 for maize, 19–27 for field pea, 10–14 for double cropped soybean, and 27–34 for double cropped maize (see Supplementary Table S4). Then, based on aboveground biomass produced by each crop in each sequence we calculated evapotranspiration at both individual crop and per 3-yr cycle at each location.

Similarly, partial N and P nutrient balance were estimated based on previously reported nutrient absorption per unit yield and nutrient proportion in grains as well as on fertilization amounts and estimation of biological N₂ fixation on each individual crop. A fixed ratio of absorbed nutrient was considered per Mg of grain harvested for each crop species. We used 30 kg N Mg⁻¹ and 4 kg P Mg⁻¹ for wheat, 75 and 6 for soybean, 47 and 4 for field pea, and 20 and 3.5 for maize as reported in previous studies (Dreccer et al., 2004). Similarly, we set fixed N and P harvest indexes based on previous estimations. We used 0.75 and 0.84 for soybean, 0.66 and 0.75 for wheat, 0.81 and 0.63 for field pea, and 0.66 and 0.75 for maize, respectively for N and P (Dreccer et al., 2004). Maize and wheat crops were fertilized with nitrogen (N) to reach 180–200 and 150–160 kg ha⁻¹ of total soil plus fertilizer available N, respectively, after N-NO₃ soil analysis (0–60 cm) immediately previous to sowing. On these crops, phosphorous fertilizer (P) was applied as reposition. Soils were not sampled prior to soybean nor field pea sowing. All legume seeds were inoculated with nitrogen-fixing bacteria (*Bradyrhizobium japonicum* for soybean and *Rhizobium leguminosarum biovar viceae* for field pea) and 10–14 kg P ha⁻¹ were applied according to expected yields at sowing except for double cropped soybeans that were not fertilized at all. Biological N₂ fixation was assumed to be 60% of total N in aboveground biomass of soybean and field pea crops (Salvagiotti et al., 2008). Additionally, we considered an extra 8% to account for N from biological N₂ fixation located in roots (Kehoe et al., 2019).

Given that crop rotation studies involve repeatedly sampling over time on the same plots, we assessed treatment effects on yield, carbon fixation, evapotranspiration, and partial nutrient balances using a multivariate analysis of variance (MANOVA). For each location, data were pooled within each cropping cycle and location and they were subjected to MANOVA, by using the rotation types and blocks as the randomized factors and the ‘cycle’ as the repeating factor (Cole and Grizzle, 1966; Piepho et al., 2004). Then, we run multiple comparison of means across treatments when significant effects were found (Hotelling-Bonferroni, $p < 0.05$) (Di Rienzo et al., 2020). A regular analysis of variance (ANOVA) was used to analyze treatment effects on solar radiation interception and use efficiency because data was available only for one 3-yr cycle. Additionally, an economic analysis was done considering average input prices for the period 2010–2020 (<http://www.crea.org.ar>). We computed all variable costs and incomes and calculated the gross margin annually and for each 3-yr crop sequence cycle.

3. Results

3.1. Cumulated grain yield and solar radiation use

SOY glucose yield equivalent was the lowest in all sites. Considering 3-yr cycles as a unit of analysis, TYP yielded 41% more (range from 20%

to 63%) than SOY across all site by cycle combinations ($p < 0.001$; Fig. 3). Roughly, two thirds of this yield difference could be attributable to the second year of each cycle, when a maize crop was grown in TYP, and the remaining difference to the wheat/soybean double crop grown during the first season as compared with full season soybeans grown every year in SOY sequence. Additionally, in five out of eight site by cycle combinations, INT yielded more than TYP ($p < 0.05$) with an overall difference of 7% (range from –5% to 17%) as a consequence of a low-to moderate contribution of field pea in the second year, of each cycle, to overall yield (Fig. 3).

Lower productivity in SOY rotation is a consequence of full season soybeans making use of incoming solar radiation only during summer, while TYP and INT increased solar radiation interception through double cropping, extending the cropping season and incorporating a more efficient crop species such as maize (Fig. 4). Additionally, INT increased solar radiation interception due to field pea/maize double crop when compared to the single maize from TYP and increased both interception and use efficiency when compared with the full season soybeans from SOY sequence (Fig. 5). Overall, SOY intercepted 29% of total incident PAR along the second 3-yr cycle while TYP and INT intercepted 34% and 38%, respectively (Fig. 4). Conversion efficiency of PAR into yield (*i.e.* intercepted radiation use efficiency, RUE) was significantly lower in SOY (average of 0.85 g g.e. MJ⁻¹; $p < 0.05$) than in either TYP or INT (average of 1.06 and 1.04 g g.e. MJ⁻¹, respectively). Increasing PAR interception was associated with larger grain equivalent productivity across sites and treatments ($p < 0.001$), being SOY the rotation with the lowest PAR interception and also lowest RUE (Fig. 5; $p < 0.05$).

3.2. Biomass production and water use

Total aboveground carbon fixation in SOY was, in average, equivalent to 57% (range of 48–63) and 51% (42–58) of that fixed by TYP and INT sequences, respectively ($p < 0.05$; Table 2). There were significant differences in total carbon fixed between INT and TYP crop sequences in five site by cycle combinations, where carbon fixation difference was equivalent to 1.0 Mg ha⁻¹ y⁻¹ ($p < 0.05$). In San Pedro, differences between INT and TYP were found to be about half of that and non-significant ($p > 0.05$; Table 2).

Evapotranspiration estimations based on aboveground biomass also showed significant differences among treatments, with increasing water use as crop intensity increased. In average, across the four sites, water evapotranspiration increased from 1608 mm (range of 1189–2071) (SOY) to 2470 mm (2036–2970) (INT), which represent 55% and 83% of total rainfall amount per each 3-yr cycle, respectively ($p < 0.05$; Table 2, Supplementary Fig. S1). Main differences among cropping systems are explained by the differential water use estimated in single versus double cropping. Full season soybean crops evapotranspired an average of 530 mm (range 334–780), maize 773 mm (645–890), wheat/soybean double crop 969 mm (627–1260), and field pea/maize double crop 959 mm (746–1302) (Supplementary Fig. S1).

3.3. Characterization of N and P partial balances

The estimated partial N balance showed a negative trend in all sites and treatments (Table 2; Supplementary Fig. S2). SOY presented the largest N negative balance in every site, with an average 3-yr rate going from around –100 kg ha⁻¹ in Pergamino and Bragado I to ca. –70 kg

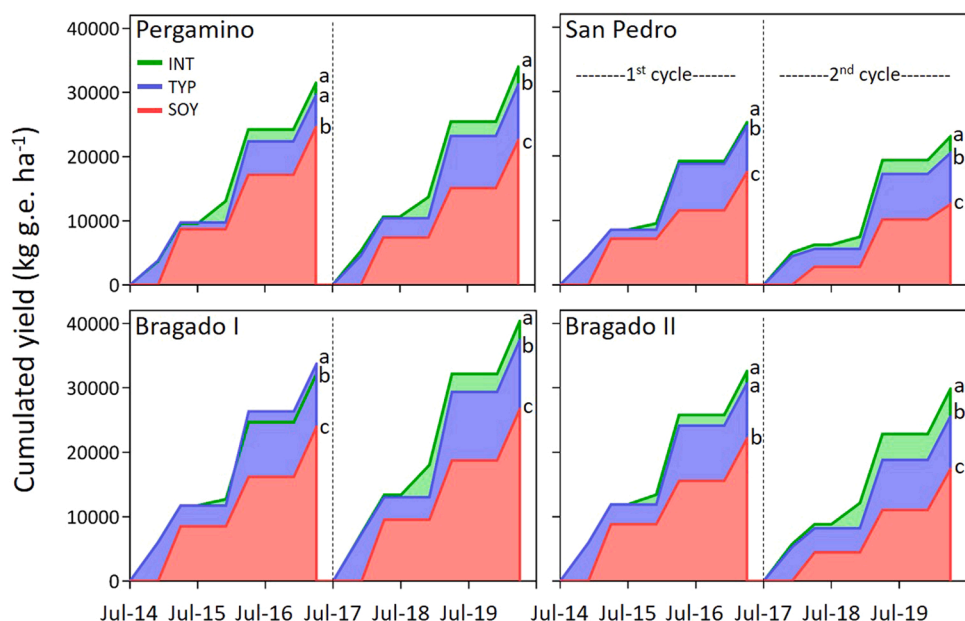


Fig. 3. Cumulated glucose equivalent yield (kg g.e. ha^{-1}). Results are shown for each combination of site and 3-yr rotation cycle [first (2014/15–2016/17) and second (2017/18–2019/20)] at four sites. Soybean monoculture (SOY) is shown in red, typical rotation (TYP) in blue, and the intensified rotation (INT) in green. Treatment, cycle, and treatment by cycle effects were statistically significant in all cases (MANOVA; $p < 0.001$). Different letters indicate significant yield differences among treatment within each cycle and each site (Hotelling-Bonferroni; $p < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

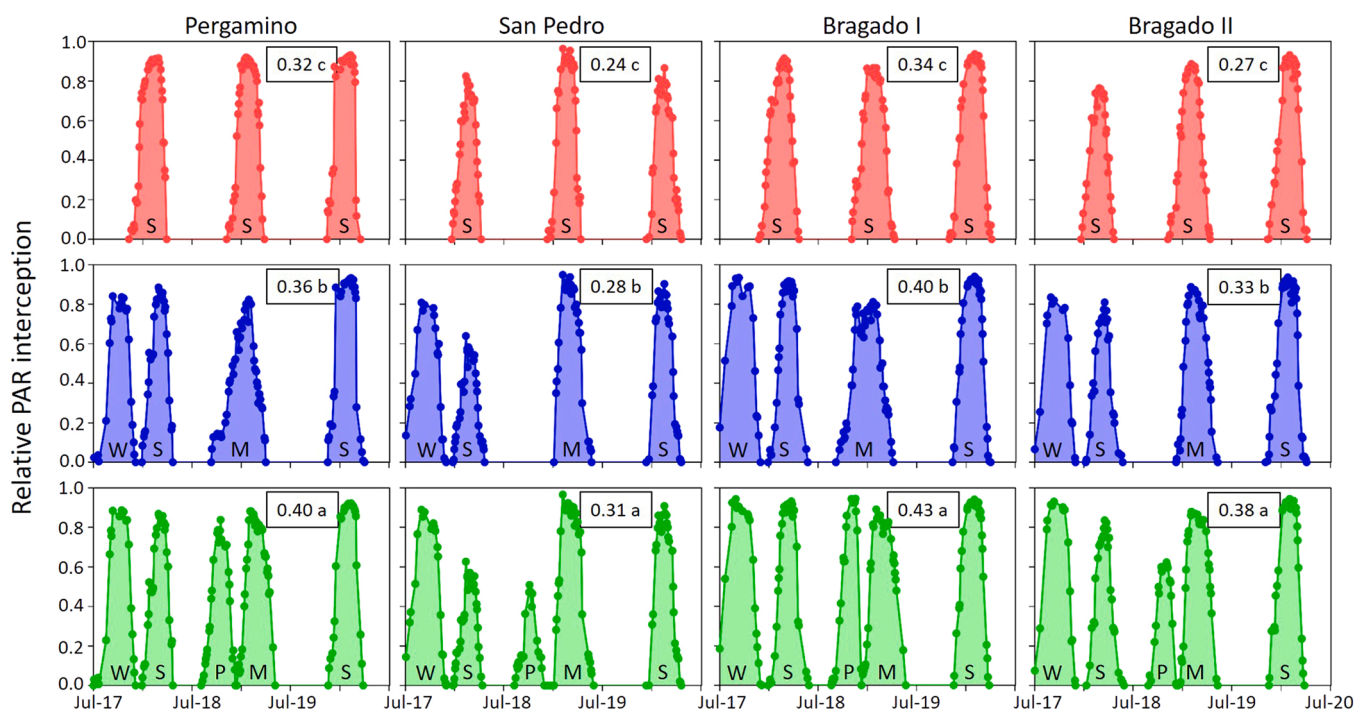


Fig. 4. Relative solar photosynthetically active radiation (PAR) interception dynamic for the second 3-yr rotation cycle (2017/18–2019/20). Soybean monoculture (SOY), typical rotation (TYP), and intensified rotation (INT) are displayed in top, middle, and bottom panels, respectively, for each of the four experimental sites. Overall interception efficiency is shown as inset in each panel. S: soybean; W: wheat; M: maize; P: field pea. Different letters indicate significant differences among treatments within each site (LSD; $p < 0.05$).

ha^{-1} in San Pedro and Bragado II. These negative trends were approximately two-fold larger than the rates shown by INT and TYP treatments. In contrast, estimated partial P balance for TYP and INT ranged from neutral (Pergamino and Bragado I) to slightly positive ($\text{ca. } +18 \text{ kg ha}^{-1}$ per 3-yr cycle in San Pedro and Bragado II), while in SOY sequence it ranged from neutral (San Pedro and Bragado II) to negative ($\text{ca. } -27 \text{ kg ha}^{-1}$ per 3-yr cycle in Pergamino and Bragado I) (Table 2; Supplementary Fig. S3).

3.4. Economic analysis

Average TYP and INT gross margins were 10% and 13% higher than SOY across sites. In the least productive sites (San Pedro and Bragado II), soybean monoculture (SOY) exhibited large inter-annual variability as consequence of extreme low incomes that increase the likelihood of not covering the value of rented land (if applicable) or even increasing the possibility of obtaining negative gross margins (Fig. 6). However, in highly productive environments (Pergamino and Bragado I), SOY exhibited similar lower limit annual margins as TYP and INT rotations

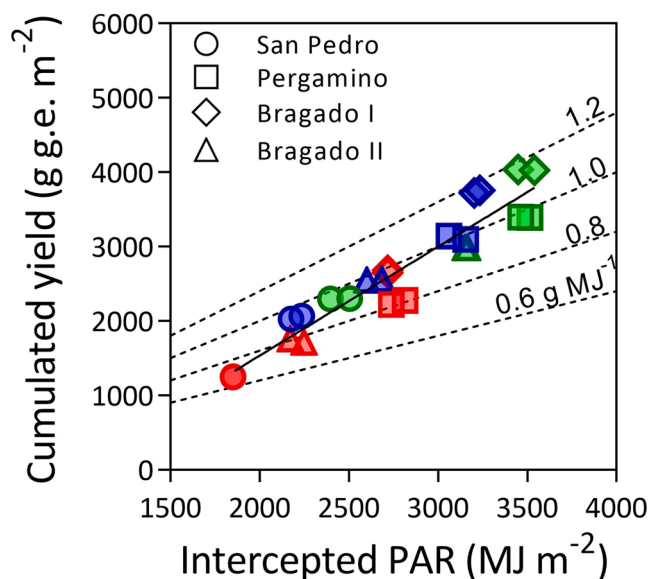


Fig. 5. Cumulated yield (g m^{-2} in glucose equivalent units) for the second 3-yr cycle (2017/18–2019/20) as a function of total intercepted PAR in the same period for every site, treatment, and replicate. Soybean monoculture (SOY) is shown in red, typical rotation (TYP) in blue, and the intensified rotation (INT) in green. Radiation use efficiency reference values are shown as dotted lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

but showed a limited capacity to achieve high margins in favorable rainy years (Fig. 6). Additional income compared to SOY on each 3-yr cycle was US\$ 189 (63 yr^{-1}) and US\$ 246 (82 yr^{-1}) per ha for TYP and INT in average across sites. As a counterpart, money investment needed was higher in TYP and INT than in SOY. The direct costs to run a SOY sequence was US\$ 1167 ha^{-1} per each 3-yr cycle (US\$ 389 $\text{ha}^{-1} \text{ yr}^{-1}$) as compared with TYP and INT sequences with average costs of US\$ 1662 (+42%) and US\$ 1935 ha^{-1} (+66%), respectively. Main additional expenses from increasing cropping intensity in TYP and INT treatments were due to more frequent labor activities, hybrid maize seeds, and fertilizer applied in wheat and maize when compared to the SOY sequence.

4. Discussion

This study shows how increasing crop intensity can raise agricultural systems productivity and economic return across a range of environmental conditions for the Rolling Pampas. Increased productivity was based on a larger use of available resources such as solar radiation and water, which confirms previous insights on land use intensification where single and double cropping were characterized (Caviglia et al., 2004; Andrade et al., 2015). Here, we extended the period of analysis along six years to assess benefits derived from double cropping when designing more intensive crop rotations that are suitable to be applied in large-scale commercial fields. One limitation of this study was the lack of contemporary presence of all phases of each crop rotation in the same year, which is useful to determine the effect of crop by weather interaction (Cochran, 1939). However, we focused our analysis on the crop rotation cycle and, indeed, we evaluated two 3-yr cycles to account for temporal variation in weather. In addition, we explored the influence of spatial variation in weather and soil by setting experiments in four key sites to be representative of most usual environments in the studied area. Thus, rotation cycles were exposed to a relatively wide range of conditions due to temporal and spatial variability. The inclusion of all phases of each rotation every year would have implied to more than double the number of plots at the cost of reducing the number of experiments and/or plot size to keep trials manageable and within budget, losing

Table 2 Average above-ground carbon fixation (Mg ha^{-1}), evapotranspiration (mm), N balance (kg ha^{-1}), and P balance (kg ha^{-1}) estimations for each treatment and site per 3-yr cycle. Carbon was assumed to be 40% of biomass for all crop species. Standard errors are shown between brackets. Treatment, cycle, and treatment by cycle effects were significant across all sites ($p < 0.001$) as determined by Wilks statistics calculated through multivariate analysis of variance (MANOVA). At each location, different letters indicate significant differences among treatments within each cycle (Hotelling-Bonferroni, $p < 0.05$).

	San Pedro		Pergamino		Bragado I		Bragado II	
	Cycle 1		Cycle 2		Cycle 1		Cycle 2	
Carbon fixation (Mg ha^{-1})								
SOY	10.3 (0.0)	b	13.7 (0.1)	c	13.3 (0.4)	c	12.1 (0.1)	c
TYP	17.6 (0.1)	a	21.6 (0.0)	b	24.5 (0.0)	b	22.0 (0.3)	b
INT	18.1 (0.0)	a	23.4 (0.1)	a	23.4 (0.5)	a	23.7 (0.2)	a
Evapotranspiration (mm)								
SOY	1710 (7)	b	2071 (22)	b	1570 (44)	b	1429 (33)	c
TYP	2123 (21)	a	2671 (11)	ab	2408 (4)	a	2205 (19)	b
INT	2189 (0)	a	2824 (13)	a	2352 (57)	a	2383 (9)	a
N balance (kg ha^{-1})								
SOY	-71.7 (0.2)	b	-101.0 (1.4)	b	-98.4 (0.7)	c	-90.8 (2.2)	b
TYP	-16.3 (0.9)	a	-30.3 (0.4)	a	-65.4 (0.2)	a	-37.8 (1.5)	a
INT	-17.1 (0.4)	a	-34.6 (0.3)	ab	-45.6 (1.0)	a	-49.4 (1.2)	a
P balance (kg ha^{-1})								
SOY	-12.0 (0.2)	c	-32.4 (0.9)	c	-12.3 (0.5)	c	-7.2 (1.5)	c
TYP	0.7 (0.1)	b	-1.7 (0.6)	b	24.0 (0.3)	b	30.6 (0.4)	b
INT	11.0 (0.1)	a	5.8 (0.4)	a	40.7 (0.2)	a	40.3 (0.1)	a

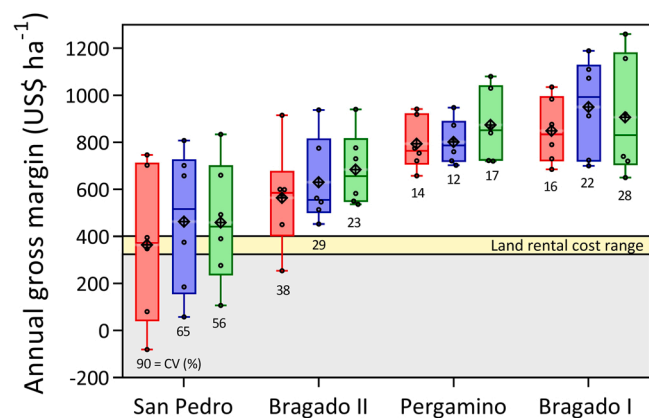


Fig. 6. Annual gross margins (US\$ ha⁻¹) for the six years (dots) at four sites and three crop sequences. Boxes indicate percentiles 25, 50 and 75. Whiskers indicate the maximum to minimum range. Average values are shown as diamonds. Soybean monoculture (SOY) is shown in red, typical rotation (TYP) in blue, and the intensified (INT) rotation in green. The land rental values range across sites and years is also presented. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

both representativeness of commercial fields and regional coverage.

In a region with a mean annual rainfall of about 1000 mm (Hall et al., 1992; Supplementary Table S2), cultivation of single summer crops such in soybean monoculture schemes result in a sub-utilization of this resource which may derive into temporal water excess and soil erosion (Nosetto et al., 2012; Nosetto et al., 2015) Basche and DeLonge, 2017; Caviglia, 2020). Here we showed how cropping system intensification in the Pampas closed this gap between water availability and utilization, allowing for larger use of other available resource such as incoming solar radiation while enhancing overall productivity (Figs. 3–5). Besides water and solar radiation sub-utilization, soybean monoculture holds onto many years with negative nutrient balances which add up to significant nutrient losses in the six-year period studied (Table 2; Supplementary Figs. S2 and S3). Crop rotation with cereals in more intensified schemes presented better nutrient balances, which tends to reduce soil mining by adding larger quantities of N and P through fertilization into the system. Moreover, the combination of winter and summer legumes N-fixation and low C/N ratio in residues tend to boost soil biological activity and cereal crops growth and yield in the rotation (Andrade et al., 2017; D'Acunto et al., 2018). By these means, legumes contribute to develop the smallest fraction of organic matter in the soils releasing large quantities of nitrogen to feed the crop plants.

Even though the increases in costs at higher crop intensities, farmers still appear to be rewarded with larger margins and yield stability (Fig. 6). However, for the past 20 years soybean has dominated the landscapes of the Argentine pampas, covering 54% of total harvested area with annual crops. Besides the fact that soybean suited well the temperate conditions of the Pampas, high adoption rate by farmers was due to a combination of high relative soybean price and low production costs and effective developed technologies that simplified farm activities such as no-till sowing and use of glyphosate-resistant cultivars (Satorre, 2005). Of these interacting factors, current dominance of soybean is mostly explained by the lower investment needed compared with other crops. Soybean predominance is even larger in rented fields, where farmers are eager to shrink expenses due to the additional land rental cost. In addition, rental time span in the Pampas is often one year long which reduces farmer interest on projecting integrated rotation schemes with mid or long-term objectives regarding cropping system sustainability such as soil conservation (Caviglia, 2020). This is of vital importance for the region, especially if one considers that rented land accounts for 30–55% of total area sown with annual crops in the most

important provinces for grain production systems (Bisang, 2020).

Current crop intensification index for the Pampas is around 1.20 crops per year, mostly relying in summer crops (Satorre and Andrade, 2021). According to our results, moving to a 1.33 land intensification index based in winter/summer crops or even close to 1.66 would mean a larger production of grain equivalent yield with economic, productive, and environmental benefits. However, crop sequence intensification beyond 1.33 may rely on non-traditional crops (such as field pea in this work). Lack of market for the alternative winter crops can become a more restrictive factor than any ecological or technological limitation. At this point, land intensification in the Pampas appears to depend on policy decision makers and the development of new markets and commercial opportunities in order to sell the extra production.

CRediT authorship contribution statement

José F. Andrade: Conceptualization, Investigation, Data curation, Formal analysis, Writing – review and editing. **Matías Ermácora:** Conceptualization, Investigation, Resources, Review and editing. **Emilio H. Satorre:** Conceptualization and Visualization, Funding acquisition, Review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2022.126484.

References

- Agus, F., Andrade, J.F., Rattalino Edreira, J.I., Deng, N., Purwantomo, D.K., Agustiani, N., Aristya, V.E., Batubara, S.F., Hosang, E.Y., Krisnadi, L.Y., Makka, A., Samijan, Cenacchi, N., Wiebe, K., Grassini, P., 2019. Yield gaps in intensive rice-maize cropping sequences in the humid tropics of Indonesia. *Field Crops Res.* 237, 12–22. <https://doi.org/10.1016/j.fcr.2019.04.006>.
- Andrade, F.H., 2020. *Los desafíos de la agricultura global*. Ediciones INTA, Argentina.
- Andrade, J.F., Poggio, S.L., Ermácora, M., Satorre, E.H., 2015. Productivity and resource use in intensified cropping systems in the Rolling Pampa. *Argent. Eur. J. Agron.* 67, 37–51. <https://doi.org/10.1016/j.eja.2015.03.001>.
- Andrade, J.F., Poggio, S.L., Ermácora, M., Satorre, E.H., 2017. Land use intensification in the Rolling Pampa. In: *Eur. J. Agron.* 82, diversifying crop sequences to increase grain yields and resource use, Argentina, pp. 1–10. <https://doi.org/10.1016/j.eja.2016.09.013>.
- Basche, A.D., DeLonge, M., 2017. The impact of continuous living cover on soil hydrologic properties: a meta-analysis. *Soil Sci. Soc. Am. J.* 81, 1179–1190. <https://doi.org/10.2136/sssaj2017.03.0077>.
- Bisang, R., 2020. Las transformaciones de la agricultura en los últimos años. *Cienc. Hoy* 19, 45–49.
- Calviño, P., Monzon, J., 2009. Farming systems of Argentina: yield constraints and risk management. *Crop Physiology: Applications for Genetic Improvement and Agronomy*, 51. Elsevier Academic Press, San Diego, California, p. 70.
- Cassman, K.G., 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. *Proc. Natl. Acad. Sci. U. S. A.* 96, 5952–5959. <https://doi.org/10.1073/pnas.96.11.5952>.
- Cassman, K.G., Grassini, P., 2020. A global perspective on sustainable intensification research. *Nat. Sustain.* 3, 262–268. <https://doi.org/10.1038/s41893-020-0507-8>.
- Caviglia, O., 2020. Cultivos de servicios e intensificación. In: Satorre, E.H. (Ed.), *Sistemas Productivos Sostenibles: bases y experiencias para repensar el modelo de producción agrícola y su relación con la ganadería*. Asociación Argentina de Consorcios

- Regionales de Experimentación Agrícola (AACREA). Ciudad Autónoma de Buenos Aires, Argentina.
- Caviglia, O., Sadras, V., Andrade, F., 2004. Intensification of agriculture in the south-eastern Pampas: i. capture and efficiency in the use of water and radiation in double-cropped wheat-soybean. *Field Crops Res.* 87, 117–129. <https://doi.org/10.1016/j.fcr.2003.10.002>.
- Cochran, W.G., 1939. Long-term agricultural experiments. *Suppl. J. R. Stat. Soc.* 6, 104–148. <https://doi.org/10.2307/2983686>.
- Cole, J.W.L., Grizzle, J.E., 1966. Applications of multivariate analysis of variance to repeated measurements experiments. *Biometrics* 810–828. <https://doi.org/10.2307/2528076>.
- D'Acunato, L., Andrade, J.F., Poggio, S.L., Semmartin, M., 2018. Diversifying crop rotation increased metabolic soil diversity and activity of the microbial community. *Agric. Ecosyst. Environ.* 257, 159–164. <https://doi.org/10.1016/j.agee.2018.02.011>.
- Di Rienzo J.A., Casanoves F., Balzarini M.G., Gonzalez L., Tablada M., Robledo C.W. InfoStat versión 2020. Centro de Transferencia InfoStat, FCA, Universidad Nacional de Córdoba, Argentina. URL (<http://www.infostat.com.ar>).
- Dreccer, M.F., Ruiz, R.A., Maddonni, G.A., Satorre, E.H., 2004. Bases Ecológicas de la nutrición de los cultivos de grano. In: Satorre, E.H., Benez Arnold, R.L., Slafer, G.A., de la Fuente, E.B., Miralles, D.J., Otegui, M.E., Savin, R. (Eds.), *Producción de Granos, Bases funcionales para su manejo*. Editorial Facultad de Agronomía, Universidad de Buenos Aires, Argentina, pp. 479–497.
- Gooding, M.J., Davies, W.P., 1997. *Wheat Production and Utilization: Systems, Quality and the Environment*. Cab International, p. 355.
- Graß, R., Heuser, F., Stülpnagel, R., Piepho, H.P., Wachendorf, M., 2013. Energy crop production in double-cropping systems: results from an experiment at seven sites. *Eur. J. Agron.* 51, 120–129. <https://doi.org/10.1016/j.eja.2013.08.004>.
- Hall, A.J., Richards, R.A., 2013. Prognosis for genetic improvement of yield potential and water-limited yield of major grain crops. *Field Crops Res.* 143, 18–33. <https://doi.org/10.1016/j.fcr.2012.05.014>.
- Hall, A.J., Rebella, C.M., Ghersa, C.M., Culot, J.Ph., 1992. Field-crop systems of the Pampas. In: Pearson, C.J. (Ed.), *Field Crop Ecosystems Series: Ecosystems of the World*. Elsevier Science Publishers B.V., Amsterdam, pp. 413–450.
- INTA, 1989. Mapa de Suelos de la Provincia de Buenos Aires. 525 pp.
- Kehoe, E., Rubio, G., Salvagiotti, F., 2019. Contribución de las raíces y la fijación biológica al balance de Nitrógeno en soja. *Mercosoja*, 5 pp. (available at (<http://www.mercosoja2019.org.ar/trabajos-presentados/>)).
- Monzon, J.P., Calviño, P.A., Sadras, V.O., Zubiaurre, J.B., Andrade, F.H., 2018. Precision agriculture based on crop physiological principles improves whole-farm yield and profit: a case study. *Eur. J. Agron.* 99, 62–71. <https://doi.org/10.1016/j.eja.2018.06.011>.
- NASA, Prediction of Worldwide Energy Resources; (<https://power.larc.nasa.gov/>). Last access June 2021.
- Nosetto, M.D., Jobbágy, E.G., Brizuela, A.B., Jackson, R.B., et al., 2012. The hydrologic consequences of land cover change in central Argentina. *Agric. Ecosyst. Environ.* 154, 2–11. <https://doi.org/10.1016/j.agee.2011.01.008>.
- Nosetto, M.D., Paez, R.A., Ballesteros, S.I., Jobbágy, E.G., 2015. Higher water-table levels and flooding risk under grain vs. livestock production systems in the subhumid plains of the Pampas. *Agric. Ecosyst. Environ.* 206, 60–70. <https://doi.org/10.1016/j.agee.2015.03.009>.
- Otegui, M.E., Riglos, M., Mercu, J.L., 2021. Genetically modified maize hybrids and delayed sowing reduced drought effects across a rainfall gradient in temperate Argentina. *J. Exp. Bot.* 72, 5180–5188. <https://doi.org/10.1093/jxb/erab139>.
- Penning de Vries, F.W.T., Van Laar, H.H., Chardon, M.C.M., 1983. Bioenergetics of growth of seeds, fruits, and storage organs. In: Smith, W.H., Banta, S.J. (Eds.), *Productivity of field crops under different environments*. IRRI, Los Baños, The Philippines, pp. 37–59.
- Piepho, H.P., Büchse, A., Richter, C., 2004. A mixed modelling approach for randomized experiments with repeated measures. *J. Agron. Crop Sci.* 190, 230–247. <https://doi.org/10.1111/j.1439-037X.2004.00097.x>.
- Sadras, V., Alston, J., Aphalo, P., Connor, D., Denison, R.F., Fischer, T., Gray, R., Hayman, P., Kirkegaard, J., Kirchmann, H., Kropff, M., Lafitte, H.R., Langridge, P., Lenne, J., Mínguez, M.I., Passioura, J., Porter, J.R., Reeves, T., Rodriguez, D., Ryan, M., Villalobos, F.J., Wood, D., 2020. Making science more effective for agriculture. *Advances in Agronomy*. Academic Press Inc, pp. 153–177. <https://doi.org/10.1016/bs.agron.2020.05.003>.
- Salvagiotti, F., Cassman, K.G., Specht, J.E., Walters, D.T., Weiss, A., Dobermann, A., 2008. Nitrogen uptake, fixation and response to fertilizer N in soybeans: a review. *Field Crops Res.* 108, 1–13. <https://doi.org/10.1016/j.fcr.2008.03.001>.
- Satorre, E.H., 2000. Production systems in the Argentine Pampas and their ecological impact. In: Solbrig, O.T., Paarlberg, R., di Castri, F. (Eds.), *Globalization and the Rural Environment*. Harvard University Press, Cambridge, MA, pp. 81–101.
- Satorre, E.H., 2005. Cambios tecnológicos en la agricultura argentina actual. *Cienc. Hoy* 15, 24–31.
- Satorre, E.H., 2012. In: Araus, Slafer (Ed.), *Recent changes in Pampas agriculture: possible new avenues to cope global change challenges*. *Crop Stress Management and Climate Change*. CABI Series No. 2, pp. 47–57.
- Satorre, E.H., Andrade, F.H., 2021. Cambios Productivos y tecnológicos de la agricultura extensiva argentina en los últimos quince años. *Cienc. Hoy* 29, 19–27.
- Servicio Meteorológico Nacional; (<https://www.smn.gov.ar/>). Last access: June 2021.
- Sinclair, T., de Wit, C.T., 1975. Photosynthate and nitrogen requirements for seed production by various crops. *Science* 189, 565–567.
- Sistema de información y gestión agrometeorológica, INTA; Last access June 2021.
- Stone, P.J., Savin, R., 1999. Grain quality and its physiological determinants. In: Satorre, E.H., Slafer, G.A. (Eds.), *Wheat: Ecology and Physiology of Yield Determination*. Food Products Press, New York, USA, pp. 85–120.
- Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. U. S. A.* 108, 20260–20264. <https://doi.org/10.1073/pnas.1116437108>.
- Trenbath, B.R., 1974. Biomass productivity of mixtures. *Advances in agronomy*, 26, 177–210. [https://doi.org/10.1016/S0065-2113\(08\)60871-8](https://doi.org/10.1016/S0065-2113(08)60871-8).
- Watson, S.A., Ramstad, P.E., 1987. Structure and composition. In: Watson, S.A., Ramstad, P.E. (Eds.), *Corn: Chemistry and technology*. American Association of Cereal Chemists, Minnesota, USA, pp. 53–82.