Field Crops Research 177 (2015) 137–147

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Single and double crop systems in the Argentine Pampas: Environmental determinants of annual grain yield

José F. Andrade*, Emilio H. Satorre

IFEVA-Cátedra de Cerealicultura, Facultad de Agronomía, Universidad de Buenos Aires, CONICET, Avda. San Martín 4453, 1417 Buenos Aires, Argentina

ARTICLE INFO

Article history:
Received 6 October 2014
Received in revised form 16 March 2015
Accepted 16 March 2015

Keywords:
Double cropping
Maize
Rainfall
Soybean
Temperature
Wheat

ABSTRACT

New avenues are being explored to increase food production in the extensive agriculture of highly productive temperate regions. Intensifying the use of land by sequencing two crops in a season (double cropping) may enhance annual land productivity in relation to single annual crops. Single soybean (*Glycine max* L. Merr.) and maize (*Zea maize* L.) are widespread in the Argentine Pampas while wheat (*Triticum aestivum* L.)–soybean double crop system is the most common land-intensive cropping system. The possibility for expanding the double cropping system is large although it has received insufficient attention. The objectives of the present study were to (i) describe the association between major environmental variables and grain yield of wheat–soybean double crop, maize and soybean single crops and (ii) compare their annual grain yield over a wide range of environments as a basis to evaluate the possible contribution to productivity expected from wheat–soybean double crop compared with maize and soybean single crops. Yield data from farms widely distributed across the Argentine Pampas and meteorological information from 30 stations distributed in the region were recorded and analyzed. A five-year period of on-farm yields were obtained from 132 groups of farmers nested in 11 zones. Variables analyzed were crop grain yields, glucose equivalents grain yields, rainfall, temperature, radiation, and frost-free period. The ratio between radiation and temperature (photo-thermal quotient; PTQ) was also considered as a grain yield determinant for wheat. Mean daily temperature during crop reproductive stages was an important determinant of maximum yields for all crops as described by a boundary-function fit. The highest grain yields of maize and soybean were obtained at moderate summer temperatures (21.8–23.5 °C and 21.8–23.8 °C, respectively). Wheat maximum yields increased with low spring temperatures (<18.3 °C), following high photo-thermal quotients during reproductive stages. In contrast, the highest yields of double crop soybean were obtained at high summer temperatures (>21.2 °C), which were associated with extended frost free periods. High yields of the wheat–soybean double crop system were obtained with cool temperatures during spring combined with a relatively extended frost free period and substantial summer rainfall. On-farm yields below the boundary-function appeared associated to low rainfall scenarios, especially in double cropped soybean fields. The geographical patterns of yield for wheat–soybean double crop system tended to be similar to that of maize and soybean single crops. The most highly productive area for the three cropping systems evaluated was located in the center of the Argentine Pampas. However, wheat–soybean double crops were more productive than soybean at any site, but their yields were slightly lower than those of maize. In addition, the work helped to identify possible areas where wheat–soybean double crop system may give relative higher advantages; particularly, in some of the currently least productive areas. Since nowadays, almost 60% of the studied area is sown with single soybean, the results suggest that there is an effective possibility to have a substantial increase in on-farm productivity, while still producing soybean, simply by expanding the double crop system.

1. Introduction

There is consensus that most of the increase needed in food production in the next decades will come from currently exploited agricultural land (Hall and Richards, 2013). Genetically improved varieties and changes in farm management are therefore needed

Abbreviations: PTQ, photothermal quotient; PCA, principal component analysis; PCP, principal component.

* Corresponding author. Tel.: +54 11 4524 8039x31; fax: +54 11 4524 8053.
E-mail addresses: jandrade@agro.uba.ar (J.F. Andrade), satorre@agro.uba.ar (E.H. Satorre).

http://dx.doi.org/10.1016/j.fcr.2015.03.008
0378-4290/

to sustainably increase crop systems productivities, including more holistic and complex approaches to decision-making, processes and novel technologies (Satorre, 2000, 2012; Tilman et al., 2002). A relevant, but somewhat unexplored, alternative to achieve these goals is land use intensification. In highly productive temperate areas, the understanding of interactions among environmental factors that define yield variations of both intensified and non-intensified cropping systems is a necessary first step to identify and evaluate possibilities of expansion of land-intensive crop production systems.

Wheat, maize and soybean are among the main few crops on which a great part of world food supply relies (Bunting et al., 1982; http://www.fao.org). The Argentine Pampas is one of the most highly productive areas of food in the world (Loomis and Connor, 1992). Argentina currently contributes 20% of global soybean (*Glycine max* L. Merr.) production, and 2% of both maize (*Zea maize* L.) and wheat (*Triticum aestivum* L.) global production, and it is among the main exporters of grain and products from these crops in the world market. Since the early 90s, there was a significant increase in overall grain production and sown area in this region; i.e. total annual production has almost tripled, from 35 to almost 100 million tons and sown area has expanded from 20 to almost 35 million hectares since then. Wheat, maize and soybean alone explain more than 90% of that production. The area cropped with soybean covers more than 20 million hectares every year, which is approximately 60% of overall cropland in Argentina (http://www.fao.org; http://www.siia.gov.ar). This transformation was partially supported by the adoption of new technologies, such as no-tillage cropping, an increased use of new crop varieties (mostly transgenic), agrochemicals, and fertilizers (Satorre, 2012).

Although regional productivity has increased by expanding the cultivated area with grain crops and by intensifying the use of energy subsidies, the possibilities for continued expansion of croplands within the Argentine Pampas is being reduced. As a consequence, new production avenues are being explored by farmers as an adaptive response to increase productivity and profitability of land. During the last decades, innovative growers intensified the use of land by intercropping different species or by frequently sequencing two crops in a season, i.e. double cropping (Calviño and Monzon, 2009). Land use intensification can enhance annual land productivity because of an increment in resource capture in relation to single crops (Caviglia et al., 2004; Rao and Willey, 1983; Van Opstal et al., 2011), improving the ratio between seasonal grain yield and annual available resources. Due to the amount and distribution of annual rainfall and the extension of the frost free period, it is possible to cultivate a winter crop followed by a late summer crop in a year in almost the entire Argentine Pampas. In fact, wheat–soybean double crop has been extensively practiced since the late 80s and is still the most representative land intensive production system in this region (approximately 2.5 million hectares). However, the proportion of overall area under double cropping has been steadily reduced in the last 20 years, from an estimated 21% to 6.5% in the last year, showing that the increase of sown area was mainly supported by the expansion of single crops. The reduction (http://www.siia.gov.ar) in the area sown to wheat due to internal regulations of grain market and low relative grain prices have also led to a recently less intensified land use in the region. Despite the influence of political, economic or social reasons on the change of cropping systems, environmental factors are a crucial determinant of yield and yield variability. Knowing how these factors affect productivity at a regional scale may certainly help to conduct successful adaptive responses by farmers as grain demand increases.

Both single and double crop system performances are subject to the availability of resources like water and radiation and to the influence of other environmental factors, such as temperature (Asseng et al., 2011; Lobell and Field, 2007; Lobell et al., 2005, 2011; Wang et al., 2014). However, a differential response of each crop to environmental variations could be expected since optimal temperatures for maize and soybean growth are higher than that of wheat (Andrade et al., 1993; Larcher, 1980), whereas wheat is commonly grown under low vapor pressure deficit in the cool season (Satorre et al., 2004), and double cropped soybean is usually sown with low initial water in soil due to wheat previous consumption (Calviño et al., 2003). Analyzing on-farm crops at a regional scale could lead to better understanding of interactions among environmental factors that define crop yield variation. This is necessary to develop a deeper insight into crops performance and identify where land-intensive crop systems are actually better than single crops, as a basis to design and evaluate possibilities of expansion for more land-intensive crop production systems. Despite the fact that the Argentine Pampas appears as a homogeneous region, the influence of environmental factors on individual crop yields may be large and different among crops (Satorre, 2000; Satorre et al., 2004). Moreover, the influence of such factors is expected not only to differ among individual crops but also with respect to double crops. Double crops tend to use more resources than single crops, so we hypothesize that the geographical pattern of double crop yield will tend to be similar to that of the yield of the more productive crops in the region; i.e. being higher the productivity of the wheat–soybean double crop system where more resources and less limiting factors are present. However, since double crops use resources differently from single crops, it is expected that the pattern of relative advantages of double crops will differ from that of productivity from single crops.

The main objectives of this study were to (i) describe the association between major environmental variables and grain yield of wheat–soybean double crop, maize and soybean single crops and (ii) compare their annual grain yield over a wide range of environments as a basis to evaluate the possible contribution to productivity expected from wheat–soybean double crop compared with maize and soybean single crops. For this purpose, yield data from farms widely distributed across the Argentine Pampas and meteorological information were recorded and analyzed.

2. Materials and methods

The studied area covered most of the Argentine Pampas, from 30° to 39°S and from 58° to 65°W. Soils, weather and agricultural management vary greatly across the region. The annual mean temperature ranges from 14 °C to 17 °C in the southern and northern regions, respectively. Annual rainfall varies between 600 and 1000 mm, increasing from south-west to north-east. The most frequently cropped soils in this region are Mollisols, with prevalence of the Typic Argiudoll (Hall et al., 1992; Satorre, 2000). Soils are either sandy or clayey in the north, sandy in the south-west, and loamy or clayey in the south-east (Dardanelli et al., 2004; Hall et al., 1992). In this last area, soils are shallow because of the presence of a petrocalcic horizon (Pazos and Mestelan, 2002).

In Argentina, the private farmer's association AACREA (Argentine Association of Agricultural Experimentation Consortiums; http://www.crea.org.ar) is one of the main sources of information on major cropping systems at on-farm level. In AACREA, professional consultants advise groups of 8–12 farmers (a CREA group) on the basis of both on-farm trials and records of crop, soil, weather and economic data. Along the past 15 years the association, which presently incorporates approximately 3000 farmers and 200 professional consultants, has developed a comprehensive database on local cropping systems that has been instrumental in the analysis of current and novel production techniques (Menéndez and Satorre, 2007; Mercau et al., 2001, 2007).

Table 1
Latitude (°S), longitude (°W), main soil type (Hall et al., 1992; Pazos and Mestelan, 2002), grain yield of maize, soybean, wheat and double cropped soybean, expressed as kilograms of grain per hectare, and double crop relative grain glucose-equivalent yields for 11 zones of the Argentine Pampas. Grain yield data is presented as the average for the period 2003–2008. Relative area cropped with maize, soybean and wheat is indicated between brackets (%), and the percentage of wheat harvest area cultivated with double cropped soybean is also indicated. W–S DC: wheat–soybean double crop. W–S DC/maize: ratio between wheat–soybean double crop and maize yields; W–S DC/soybean: ratio between wheat–soybean double crop and soybean yields.

Zone	*n*	Lat (°S)	Lon (°W)	Main soil type	Grain yield (kg ha^{-1})				Relative grain yield	
					Maize	Soybean	Wheat	DC soybean	W–S DC/maize	W–S DC/soybean
COR	28	31.0	63.8	Typic Haplustoll	6832 (26)	2443 (47)	1877 (27)	2153 (88)	0.72	1.44
SFC	30	31.4	61.6	Typic Argiudoll	5838 (24)	2141 (46)	2173 (30)	1926 (100)	0.87	1.79
LIS	54	32.0	59.1	Vertic Argiudoll	5507 (21)	2041 (64)	2929 (15)	1821 (100)	1.00[a]	1.82
SSF	64	33.2	61.9	Typic Argiudoll	8261 (25)	3099 (45)	3331 (30)	2377 (100)	0.80	1.52
CEN	43	33.5	64.0	Entic Hapludoll	6733 (31)	2869 (50)	2418 (19)	2324 (87)	0.86	1.40
NBA	33	34.3	60.5	Typic Argiudoll	7671 (27)	3121 (45)	3730 (28)	2190 (100)	0.89	1.53
OAR	53	35.7	63.4	Entic Haplustoll	6061 (29)	2408 (56)	2626 (15)	1997 (59)	0.88	1.57
OES	51	35.7	61.9	Entic Hapludoll	7605 (23)	2758 (55)	3540 (22)	2078 (93)	0.84	1.65
SUE	62	36.2	58.9	Entic Hapludoll	6439 (17)	2390 (55)	3626 (28)	1801 (100)	0.92	1.78
SUO	34	37.6	60.9	Entic Haplustoll	4332 (8)	1820 (28)	2396 (64)	1085 (11)	1.11[a]	1.60
MYS	57	37.9	59.4	Petrocalcic Argiudoll	6139 (8)	2145 (38)	3662 (54)	1030 (61)	0.86	1.69
SE		0.14	0.15		271.4	93.4	172.0	93.3	0.049	0.090
DF		508	508		489	488	452	425	401	406

SE: standard error; DF: degrees of freedom.
[a] Quotient non-statistically different from 1 (confidence interval: 95%).

On-farm yield data for rainfed maize, soybean, wheat and double cropped soybean were obtained from AACREA records. More than 110,000 field crops nested in 132 CREA groups were included in the analysis. Yield records distributions were explored to eliminate aberrant values and then data analysis was carried out with the average yield of every crop for each CREA group by season to reduce the impact of individual values and obtained a robust and adequate estimate for the scale intended. The data series was restricted to 5 seasons (2003–2008) to allow for a reasonable range of weather conditions while meeting the assumption of unchanged technology (Calviño and Sadras, 1999). Results of crops by CREA groups and seasons were then organized in 11 zones (Table 1 and Fig. 1), initially established by AACREA, on the basis of agro-ecological similarities. Ideally a 132 × 5 average yield data base should be used for each crop if sown in all CREA groups; in some cases, a CREA group did not sow a crop in a particular season and the total number of data used may slightly differed in particular comparisons.

Characterizing soils at an on-farm level is very difficult in the Argentine Pampas, since they are usually presented as soil complexes in the field. For this reason main soil types will be indicated (Table 1) but not used as a determining variable in this paper.

Variables analyzed were crop grain yields, rainfall, temperature, radiation, and frost-free period. Meteorological variables were obtained from 30 stations distributed in the region. The ratio between radiation and temperature (photo-thermal quotient; PTQ) was also considered as a grain yield determinant for wheat (Magrin

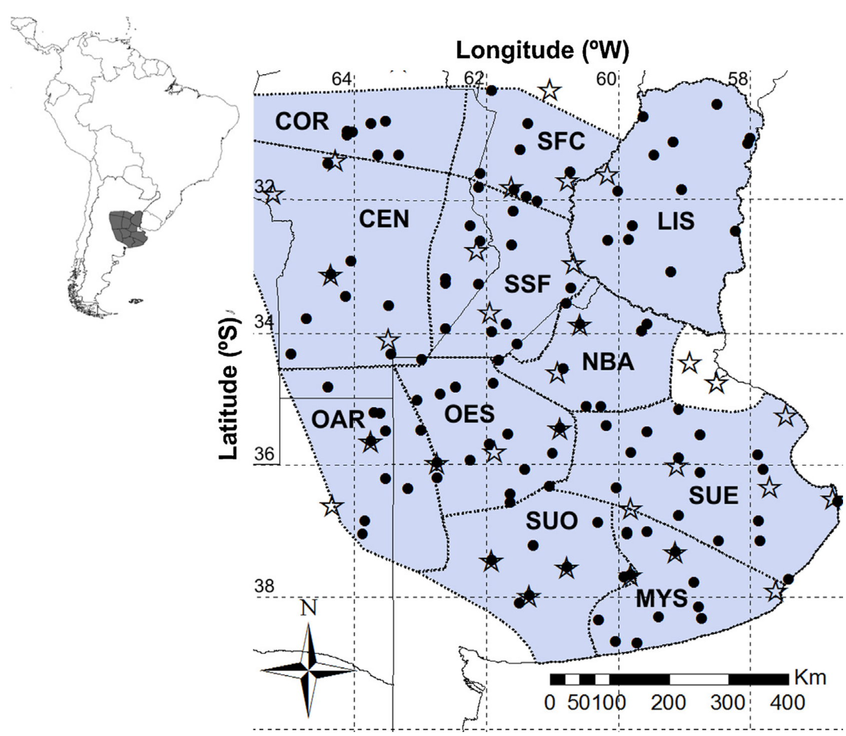

Fig. 1. Zones evaluated within the Argentine Pampas: Córdoba (COR), Santa Fe Centro (SFC), Litoral Sur (LIS), Centro (CEN), Sur de Santa Fe (SSF), Norte de Buenos Aires (NBA), Oeste Arenoso (OAR), Oeste (OES), Sudeste (SUE), Sudoeste (SUO) and Mar y Sierras (MYS), bounded by dotted lines, and spatial distribution of CREA groups (black dots) and meteorological stations (stars).

Table 2
Average records of rainfall during each crop growth stage, frost-free period (FFP), mean daily summer radiation, summer temperature and spring photo-thermal quotient (PTQ) for 11 CREA zones of the Argentine Pampas during the period 2003–2008.

Zone	Rainfall (mm)				FFP (days)	Summer radiation (MJ m^{-2})	Summer temperature (°C)	Spring PTQ (MJ m^{-2} °C^{-1})
	Maize	Soybean	Wheat	DC soybean				
COR	466	540	205	518	297	20.3	22.2	0.98
SFC	474	546	309	547	264	22.2	23.8	1.04
LIS	541	567	528	508	273	21.3	24.2	1.05
SSF	438	517	271	504	235	20.9	22.5	1.09
CEN	484	567	252	546	251	21.0	22.0	1.11
NBA	484	536	393	457	244	20.6	22.3	1.12
OAR	460	485	300	448	221	22.0	23.1	1.16
OES	520	559	359	499	247	21.3	22.1	1.20
SUE	433	488	405	411	217	20.4	20.5	1.21
SUO	425	459	357	361	203	20.3	20.2	1.36
MYS	372	433	372	355	201	20.6	21.0	1.14
SE	20.6	23.5	20.6	27.7	7.1	0.34	0.27	0.017
DF	403	385	409	382	332	226	332	226

SE: standard error; DF: degrees of freedom.

et al., 1993; Menéndez and Satorre, 2007). Since wheat phenology commonly differs among locations, an overall spring photothermal quotient (PTQ) was obtained to analyze the effect on grain yield (Fischer, 1985; Savin and Slafer, 1991). The spring PTQ was computed as the ratio between daily mean incident solar radiation and air temperature for the period between 21st September and 21st December to assure that wheat critical periods are considered in the spring PTQ for any crop management and location within the studied area, while keeping reasonable variability for a regional study.

Latitude and longitude of each CREA group were determined by the central position of the individual farm locations to geo-reference each data point. Daily incident global radiation, daily temperature, and frost-free period were obtained from INTA (National Institute of Agricultural Technology; http://www.inta.gob.ar) meteorological records, while rainfall data for each CREA group were obtained from a database provided by SMN (National Meteorological Service; http://www.smn.gov.ar). The nearest SMN or INTA meteorological station within a 60-km range was used for each CREA group. Rainfall during the period September–January was assumed relevant for maize, from October to February for sole soybean, from May to November for wheat, and from December to March for double cropped soybean crops (Satorre et al., 2004).

Crop yield was expressed as kilograms of dry grain per hectare (kg ha^{-1}; Table 1) and in glucose-equivalent terms, i.e. expressed as kilograms of glucose equivalent per hectare (kg g.e. ha^{-1}) to compare crops and cropping systems with different grain composition. Glucose equivalent is the amount of glucose necessary to produce a kg of grain, something which depends on grain chemical composition. Penning de Vries et al. (1983) established that 1 kg of glucose is equivalent to 0.83 kg of carbohydrates, 0.33 kg of lipids or 0.41 kg of proteins. Many reports describe wheat, maize and soybean grain composition (e.g. Gooding and Davies, 1997; Stone and Savin, 1999; Watson and Ramstad, 1987; Weilenmann de Tau and Suárez, 1998), allowing to determine an equivalent value of glucose per kg of grain for each crop. It was determined as 1.28, 1.32 and 1.86 kg g.e. per kg of wheat, maize and soybean grain, respectively. Grain yields are presented as kilograms per hectare in Table 1, and then transformed to glucose equivalent units. Relative grain yields were obtained as the quotient between wheat–soybean double crop grain glucose-equivalent yield and maize or soybean grain glucose-equivalent yield as single crops. The quotients were calculated only for those CREA groups that grew both cropping systems in a year. Hereinafter, we will refer to grain glucose-equivalent yield as grain yield.

Variables were grouped by zone and analyzed using descriptive statistics and Student's *t*-test for comparison of means. Tables 1 and 2 summarize the grain yield of all crops and environmental variables analyzed in this work as the average of the 5 years considered for each zone. Additionally, Table 1 presents the main soil type for each zone but, as mentioned before, this is not considered for further analysis. Finally, the influence of overlapping between the growing periods of the crops on their yield correlation was analyzed. The overlapping period between two crops was estimated as the number of days when both crops are growing simultaneously divided by the number of days when at least one crop is growing, using average emergence and maturity dates for the region (Satorre et al., 2004). The entire data set was subjected to principal component analysis (PCA) and Pearson correlation analysis (Di Rienzo et al., 2011) to describe zones and investigate the association between environmental factors and crop yields.

Temperature effects on maximum grain yield were determined by boundary-function analysis. First, temperature records were ordered from the lowest to the highest. Maximum yields out of 20 consecutive temperature records were used to build the boundary-function by regression analysis, which was used as an indicator of potential on-farm grain yield (van Ittersum et al., 2013). After that, the relative distance (%) of each yield record to the boundary-function line was calculated. Then, rainfall records were also ordered from the lowest to the highest and clustered in groups of 20 consecutive records. Finally, average relative yield distances were correlated with the average rainfall values of each cluster.

Spatial analysis patterns of average yields from each CREA group were explored using Kriging ordinary method (Wackernagel, 2003), whereas parameters for spherical variograms were estimated with R statistical software (v 2.2.0, R Development Core Team, 2008).

3. Results

3.1. Major environmental effects on crop grain yields

Principal components (PC) 1 and 2 explained 64.3% of total data variability (Fig. 2). A positive correlation between two variables establishes that zones prone to high values for a variable also present high values for the other. On the contrary, a negative correlation between two variables means that zones with high values for a variable present low values for the other. For these reasons, in multivariate analysis (Fig. 2), vectors of positively correlated variables conformed angles close to 0°, whereas negatively correlated variables conformed angles close to 180°, while linearly uncorrelated variables tend to present angles close to 90°.

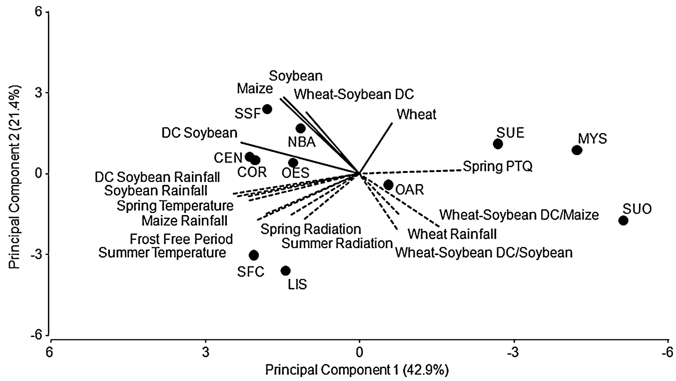

Fig. 2. Result of principal component analysis: eleven zones (MYS, SUO, SUE, LIS, NBA, OES, OAR, SFC, SSF, CEN and COR) represented as dots and ordered according to crop system productivities and environmental variables (vectors). Near dots correspond to similar zones for the studied variables, while distant dots represent dissimilarity between zones. Discontinuous vectors represent autovectors for each environmental variable [rainfall, temperature, radiation and spring photothermal quotient (PTQ)]. Continuous vectors represent autovectors for each crop yield [maize, soybean, wheat, double cropped (DC) soybean and wheat–soybean double crop (DC) grain yield and double crop relative yield against maize and soybean as single crops].

On the one hand, for the wheat crop, grain yield, spring PTQ, wheat rainfall, and double crop grain yield relative to those of single crops were positively associated by values on PC 1. Negative associations of wheat yield were mainly related to spring temperature. When considering the yield of single summer crops and the double crop system (which were strongly correlated), summer rainfall, frost free period, and spring temperature were positively correlated on PC 1. On the other hand, positive values of PC 2 corresponded to high grain yield of wheat, but it was also associated with high maize, soybean and wheat–soybean double crop yields; while negative values of this component were associated with high double crop yield relative to those of single crops (Fig. 2).

Based on Pearson linear correlation analysis (Table 3), double cropped soybean and wheat, separately, linearly responded to temperature during their reproductive stages (r = 0.30 and −0.44, respectively; $p < 0.001$). Moreover, the grain yields of these crops were highly correlated with other environmental variables partially associated with temperature. Wheat grain yield was positively correlated with spring PTQ (r = 0.43, $p < 0.001$), while grain yield of double cropped soybean was associated with the frost free period (r = 0.43, $p < 0.001$). In contrast, maize and soybean yields were not linearly associated with changes in mean summer temperature ($p > 0.05$).

The boundary-function analysis performed on the association between mean daily temperature during the reproductive stages and grain yield showed differences among crops (Fig. 3). The highest estimated potential yields, i.e. maximum yields for wheat were obtained with mean daily spring temperatures below 18.3 °C, whereas the double cropped soybean highest yields occurred with summer mean daily temperatures above 21.2 °C (Fig. 3). The boundary analysis performed on maize and soybean single crops showed that the highest grain yields were reached in a narrow range of moderate mean daily summer temperatures (21.8–23.5 °C and 21.8–23.8 °C, respectively), and that low and high mean temperatures had detrimental effects on the possibilities to reach high grain yields on these crops (Fig. 3).

According to Pearson correlation analysis, rainfall during the crop cycle was also a determinant of maize, soybean and wheat yields (r = 0.29, 0.30 and 0.36, respectively; $p < 0.001$), but it had a much stronger effect on double cropped soybean grain yield (r = 0.51; $p < 0.001$; Table 3). The average relative yield distance to the estimated potential was reduced as rainfall during crop growth cycle increased (Fig. 4). For double cropped soybean, average yield distance was reduced approximately 10% per every 100 mm of rainfall increase up to 600 mm. However, maize and soybean average relative yield distances were reduced at a rate of 4.4 and 2.8% per 100 mm of rainfall increase, respectively. Wheat average relative yield distance presented a bi-linear response to rainfall; yield distances to potential tended to be independent of rainfall above 378 mm rainfall in the crop cycle. Results pointed out that, even at the highest rainfall records, average relative yield distance to the estimated potentials were never less than 15% for any crop.

3.2. Comparative analysis of crop yields

Grain yields of soybean and maize were highly correlated ($p < 0.001$; Fig. 5b). In addition, grain yields of wheat plus double cropped soybean were strongly correlated with soybean and maize grain yields ($p < 0.001$; Fig. 5a and c), although the correlation between wheat and double cropped soybean was not significant (p = 0.471; Fig. 5d). Pairing all possible crop combinations, it was found that correlation between crop yields (r) increased as the overlapping of crop system growing periods increased, regardless of species composition (Fig. 6).

In terms of overall relative productivity, maize was the most productive crop. The slope of regressions forced through 0:0 in Fig. 5 indicates that the glucose-equivalent grain yield per unit area of maize was 92% greater than that of soybean (Fig. 5b), whereas wheat–soybean double crop yielded 59% more than soybean, but only 15% less than maize (Fig. 5a and c).

Table 3
Pearson correlation coefficients among crop productivities and environmental variables analyzed. PTQ: spring phothermal quotient; DC: double cropped.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Maize rainfall (mm)	1.00														
2	Soybean rainfall (mm)	0.86	1.00													
3	Wheat rainfall (mm)	0.42	0.21	1.00												
4	DC soybean rainfall (mm)	0.62	0.81	−0.08	1.00											
5	Frost free period (days)	0.34	0.31	−0.06	0.34	1.00										
6	Spring radiation (MJ m^{-2} d^{-1})	−0.08	−0.12	−0.08	−0.04	−0.23	1.00									
7	Summer radiation (MJ m^{-2} d^{-1})	−0.15	−0.15	−0.04	−0.15	0.00	0.48	1.00								
8	Spring temperature (°C)	0.32	0.35	−0.25	0.45	0.49	0.34	0.31	1.00							
9	Summer temperature (°C)	0.23	0.14	0.03	0.16	0.35	0.48	0.44	0.78	1.00						
10	Spring PTQ (MJ m^{-2} °C^{-1})	−0.38	−0.45	0.08	−0.45	−0.35	0.24	−0.04	−0.83	−0.48	1.00					
11	Maize yield (kg g.e. ha^{-1})	0.29	0.36	−0.05	0.37	0.19	−0.09	−0.21	0.09	−0.10	−0.06	1.00				
12	Soybean yield (kg g.e. ha^{-1})	0.25	0.30	−0.12	0.33	0.10	0.05	−0.23	0.10	−0.08	0.04	0.77	1.00			
13	Wheat yield (kg g.e. ha^{-1})	−0.05	−0.05	0.36	−0.18	−0.25	−0.01	−0.13	−0.44	−0.23	0.43	0.38	0.35	1.00		
14	DC soybean yield (kg g.e. ha^{-1})	0.42	0.49	−0.19	0.51	0.43	0.14	−0.07	0.52	0.30	−0.33	0.54	0.66	−0.04	1.00	
15	Wheat–soybean DC yield (kg g.e. ha^{-1})	0.25	0.29	0.13	0.22	0.11	0.10	−0.14	0.04	0.04	0.12	0.65	0.70	0.72	0.67	1.00

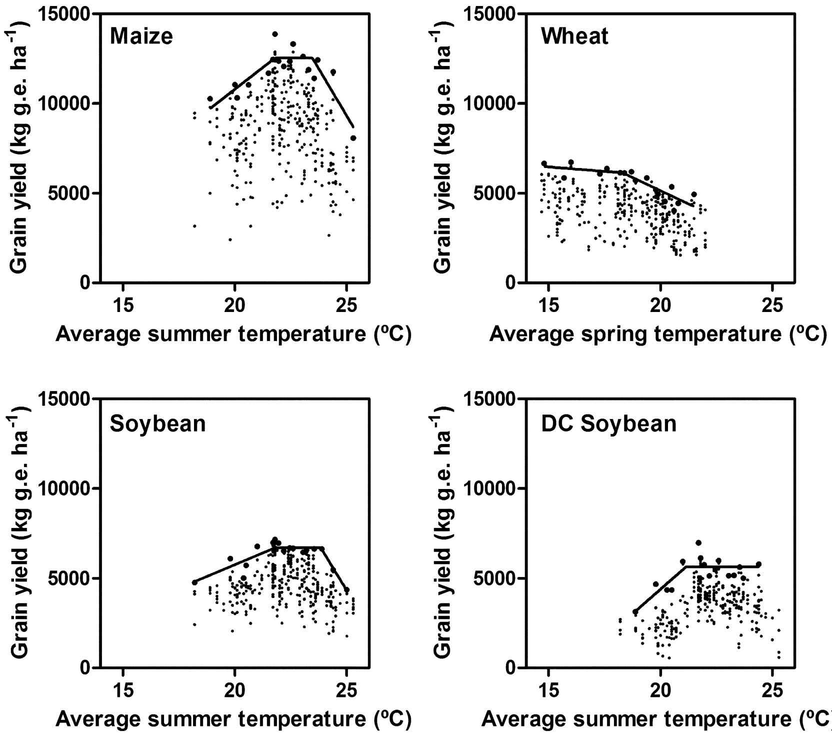

Fig. 3. Crop systems annual grain yields for each CREA group per season, expressed as kilograms of glucose equivalent per hectare, as a function of mean daily temperature during spring (wheat) or summer (double cropped soybean, single soybean and maize). Boundary-function line is an indicator of potential grain yield, which was estimated by regression analysis of the maximum values out of every 20 consecutive temperature records after ordering all temperature data from the lowest to the highest records. Maize: $y = -8637 + 970.9x$ (if $x < 21.8$); $y = 12{,}529$ (if $21.8 <= x <= 23.5$); $y = 12{,}529 - 2099 * (x - 23.5)$ (if $x > 23.5$). Soybean: $y = -4798 + 527.5x$ (if $x < 21.8$); $y = 6702$ (if $21.8 <= x <= 23.8$); $y = 6702 - 2050 * (x - 23.8)$ (if $x > 23.8$). Wheat: $y = 7945 - 99.2x$ (if $x <= 18.3$); $y = 6130 - 588.5 * (x - 18.3)$ (if $x > 18.3$). Double cropped soybean: $y = -17{,}470 + 1092x$ (if $x <= 21.2$); $y = 5637$ (if $21.2 <= x <= 24.4$).

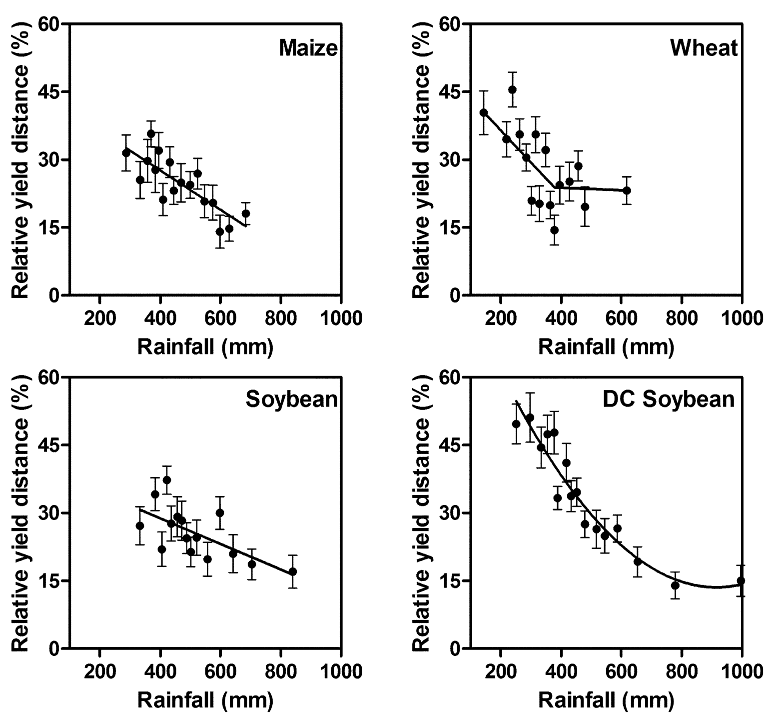

Fig. 4. Relative yield distance (%) to the boundary-function in Fig. 3 as a function of rainfall (mm) during the growing period of maize ($R^2 = 0.65$), wheat ($R^2 = 0.53$), single soybean ($R^2 = 0.43$), and double cropped (DC) soybean ($R^2 = 0.92$). Rainfall data was previously ordered from the lowest to the highest and clustered in groups of 20 consecutive records. Average values of rainfall and relative yield distance of each cluster were used in the analysis. Bars indicate standard error of means.

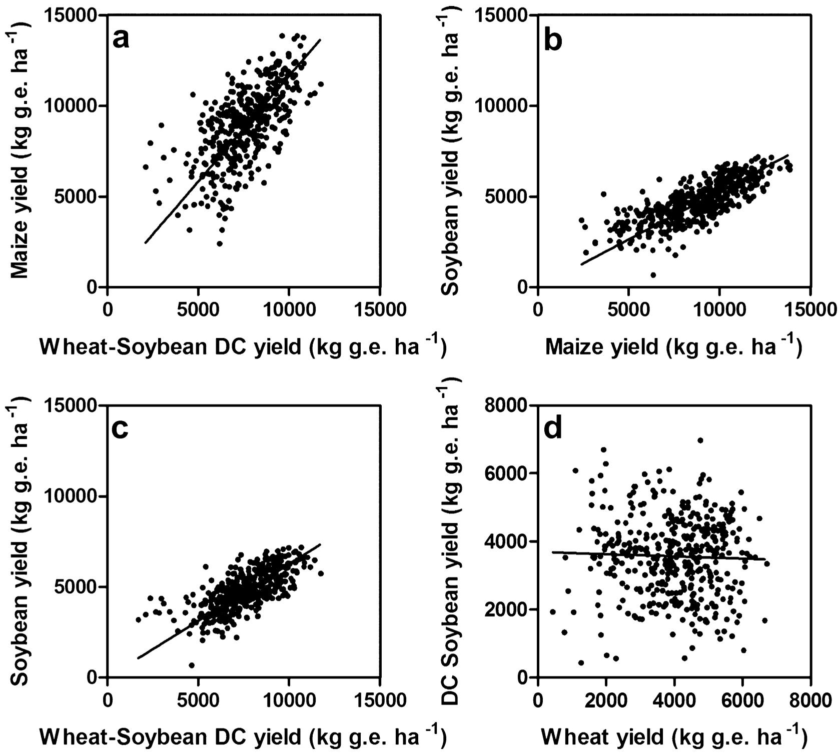

Fig. 5. Crop yields correlations (forced to 0:0) between (a) wheat–soybean double crop (DC) and maize yields ($m = 1.17$; $R^2 = 0.35$; $p < 0.0001$); (b) maize and soybean yields ($m = 0.53$; $R^2 = 0.52$; $p < 0.0001$); (c) wheat–soybean double crop and soybean yields ($m = 0.63$; $R^2 = 0.43$, $p < 0.0001$); and (d) wheat and double cropped soybean yields ($m = -0.04$; $R^2 = 0.00$; $p = 0.4713$). Yields of each CREA group per season were included, and are expressed as kilograms of glucose equivalent per hectare (kg g.e. ha^{-1}).

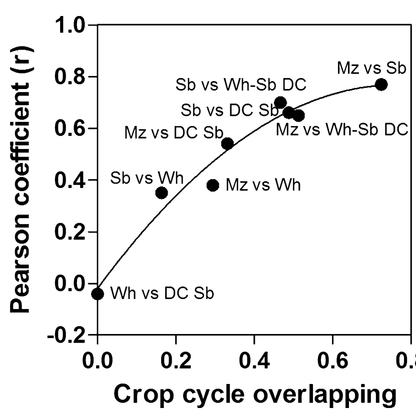

Fig. 6. Pearson correlation coefficient of grain yields, presented in Table 3, as a function of crop cycle overlapping ($y = -0.02 + 2.06x - 1.35x^2$; $R^2 = 0.96$). The overlapping period is the number of days when both crops are growing divided by the number of days when at least one of them is growing. Associations among maize (Mz), soybean (Sb), double cropped soybean (DC Sb), wheat (Wh) and wheat–soybean double crop (Wh–Sb DC) systems were included.

3.3. Grain yield spatial patterns

Latitude was an important determinant of the variability of crop yields within the region since it was closely correlated with environmental factors. Increases in latitude were negatively associated with average daily temperature (Fig. 7c and d) and frost-free period (Fig. 7b), but positively correlated with average spring PTQ (Fig. 7a).

The spatial patterns of the average grain yield highlighted the existence of important intra-region variability (Fig. 8). Wheat average yields were the highest toward the south-east. On the contrary, double cropped soybean yield increased toward the north-west. In spite of spatial differences between wheat and double cropped soybean, overall productivity pattern of wheat–soybean double crop was similar to those of maize and soybean single crops; i.e. areas with the highest productivity were located in the center of the region while the least productive areas were radially distributed around the edges of the region (Fig. 8).

Single soybean yields were lower than those obtained by growing wheat–soybean double crop in all zones [confidence interval (CI): 95%; Table 1 and Fig. 8]; however, wheat–soybean double crop yields were never higher than those of maize single crop (CI: 95%; Table 1 and Fig. 8). Moreover, double crop yields relative to those of single summer crops appeared to increase toward less productive environments; i.e. in the north-eastern zones (LIS and SFC) and the southern zones (SUO and MYS; Figs. 8 and 9).

4. Discussion

4.1. Major environmental factors and grain yield

Rainfall and temperature were the main environmental factors affecting crop grain yields (Tables 1–3 and Figs. 2–4). Rainfall and crop water availability are among the most important limiting factors in rainfed cropping systems around the world (Bunting et al., 1982; Hall et al., 1992); whereas temperature is known as a universal determining factor of crop potential grain yield (van Ittersum and Rabbinge, 1997). Both factors explained an important part of intraregional yields of the various crop systems studied; while for this data set, daily incident radiation presented low variation within the region during the period analyzed (Table 2).

In a mostly large flat area as the Argentine Pampas, it is expected that temperature variation follows major geographical patterns (for example, latitude; Fig. 7) while rainfall will be exposed to a large inter-annual variability (Hall et al., 1992; Podestá et al., 1999; Prohaska, 1976). Also, water may be stored in the soil, so that growing season rainfall does not necessarily indicate the amount of water available for the crops. Unlike previous research works that

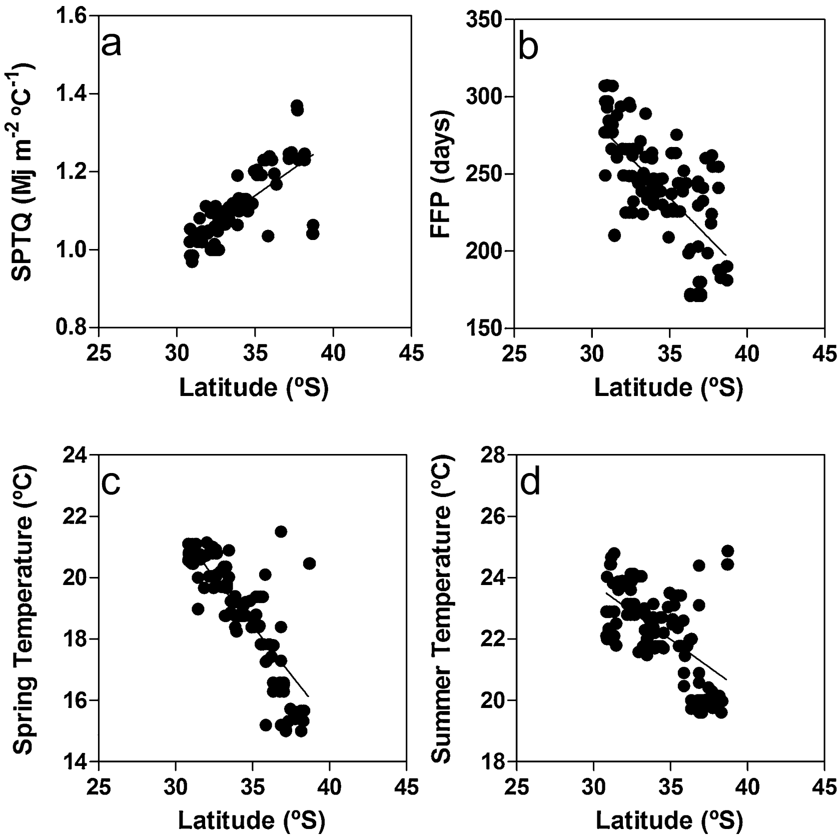

Fig. 7. Spring photothermal quotient (SPTQ; $m = 0.28$; $R^2 = 0.54$; $p < 0.0001$), frost free period (FFP; $m = -10.3$; $R^2 = 0.49$; $p < 0.0001$), spring ($m = -0.64$; $R^2 = 0.63$; $p < 0.0001$) and summer ($m = -0.36$; $R^2 = 0.34$; $p < 0.0001$) mean daily temperatures of each CREA group as a function of latitude (°S). Average records for the period 2003–2008 were used in the analysis.

implemented crop simulation models (Asseng et al., 2011; Lobell et al., 2005; Magrin et al., 1997), in this work the temperature effect on crops was first determined with a boundary-function analysis of maximum yields under presumably no-limiting situations, and then rainfall effects were studied with the distance of data to that boundary.

4.1.1. Temperature effect on crop yields

The boundary-function analysis indicated that the highest yields for maize or soybean were obtained at moderate temperatures (Fig. 3). On the one hand, below the optimal range of temperature, yields decreased because of low radiation use efficiency (Andrade et al., 1992; Larcher, 1980; Magrin et al., 1997), and due the concomitant reduction of the frost free period (Fig. 7; Wang et al., 2007, 2014) which implies the use of short cycle cultivars and more risk of crop damage by the direct effect of low temperature (Baker et al., 1989; Boote et al., 2005; Kurosaki and Yumoto, 2003; Ohnishi et al., 2010). On the other hand, exceeding the optimal range of temperature also reduced maize and soybean maximum yields since developmental periods are reduced and, hence, the intercepted radiation (Andrade et al., 1996; Andrade and Sadras, 2000). Other authors have found similar patterns analyzing climate change effect on maize and soybean yields in temperate areas of United States, Africa and China (Lobell and Asner, 2003; Lobell et al., 2011; Wang et al., 2014).

Unlike single summer crops, the highest wheat yields were achieved under low spring temperatures (<18.3 °C; Fig. 3b), following high spring photothermal quotients (PTQ; Fig. 2 and Table 3; Magrin et al., 1993; Menéndez and Satorre, 2007). It is recognized that high temperatures during the growing season reduce grain yield of wheat crops under field conditions (Asseng et al., 2004; Evans et al., 1975; Lobell and Ortiz-Monasterio, 2007; Manderscheid et al., 2003). This behavior reflected the strong influence of latitude on wheat productivity (Table 3).

On the contrary, double cropped soybean maximum yields decreased in cool environments (summer daily temperature <21.2 °C), with larger detrimental effects of low temperatures than those on single soybean crops. The reason is that late sowing dates of double cropped soybean, after wheat harvest, exposed it to low temperatures toward the end of the summer season when yield is determined (Calviño et al., 2003; Monzon et al., 2007). Moreover, wheat harvest commonly occurs later in cool (southern) than in warm (northern) environments, increasing the sowing delay of double cropped soybean.

4.1.2. Rainfall effect on crop yields

Rainfall effect on grain yields was statistically significant for all crops (Table 3). Moreover, the variability of yields found for all crops at any temperature was highly explained by rainfall. As expected, all crops reduced the relative yield distance to the estimated potential yield with increasing rainfall (Fig. 4). However, double cropped soybean yields were more affected by scarce rainfall scenarios than any other crop, possibly because stored soil water at wheat harvest is usually low (Hamblin and Tennant, 1987) and the double cropped soybean tend to be immediately sown after the previous crop harvest. In contrast, the yield response to rainfall was the lowest for wheat crops, which are cultivated during the cool season with low water demand and frequently large amounts of soil water stored (Dardanelli et al., 2004).

Large variability was found for the correlations between rainfall and the gap between the actual yields and the estimated potentials

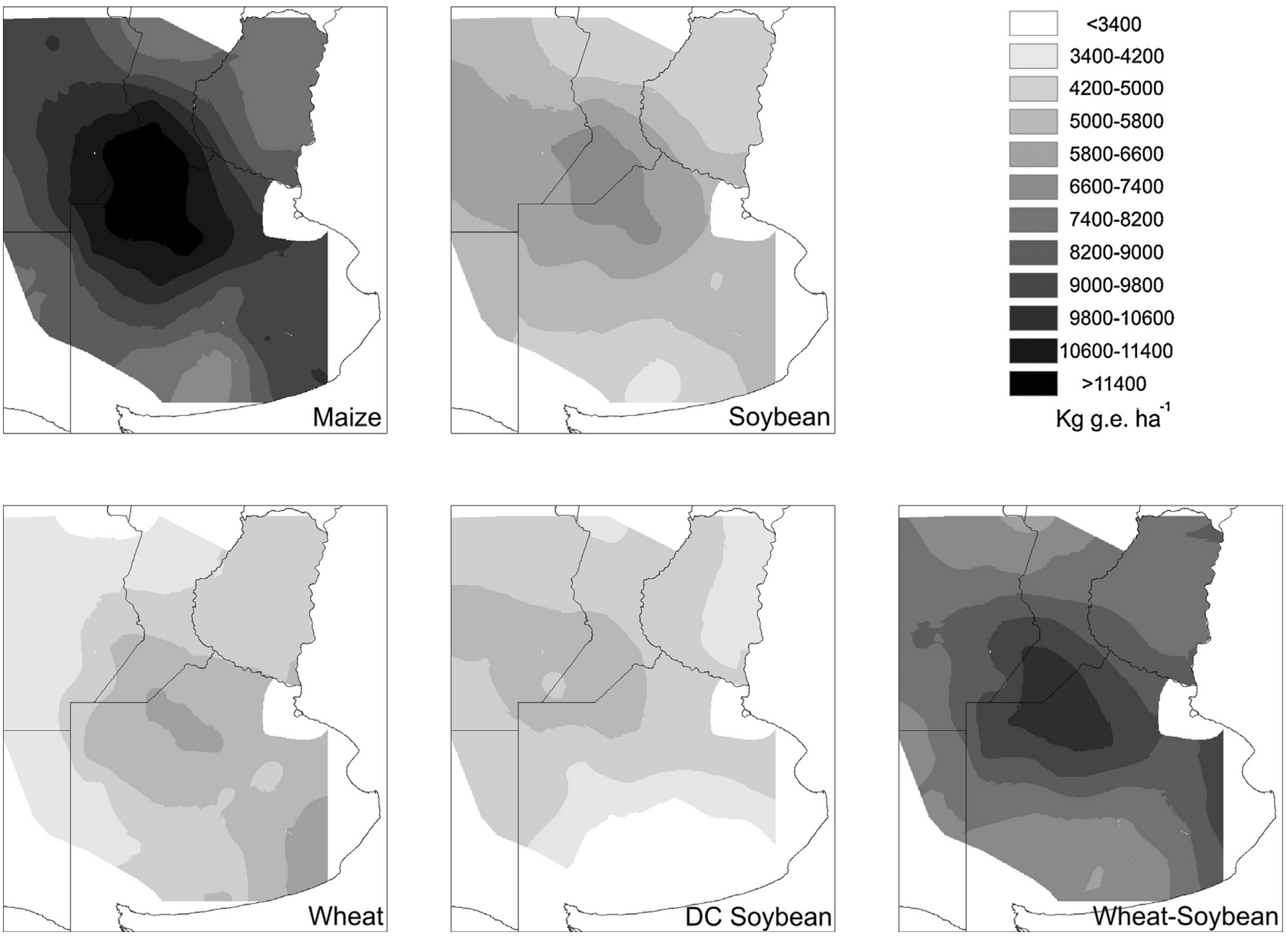

Fig. 8. Crop systems average grain yields spatial distribution (Kriging ordinary method), expressed as kilograms of glucose equivalents per hectare, in the Argentine Pampas for the period 2003–2008. Increasing productivity pattern goes from light colored areas to dark colored areas.

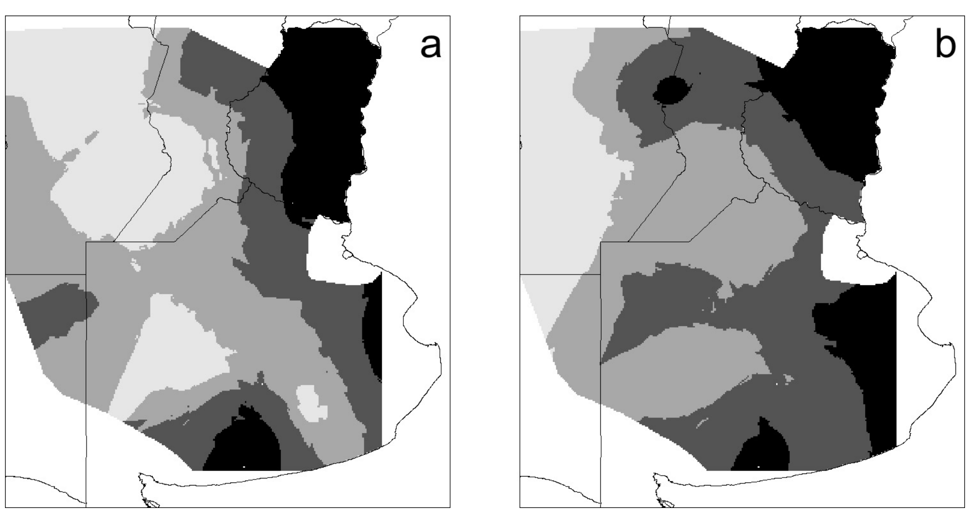

Fig. 9. Wheat–soybean double crop relative yield to those of (a) maize and (b) soybean single crops (Kriging ordinary method), as the average for the period 2003–2008. Relative yield quartiles (*Q*) are indicated with different colors. Increasing relative yield pattern goes from light colored areas to dark colored areas. Quartiles for the ratio between the double crop and maize: 1°*Q* = 0.74–0.83; 2°*Q* = 0.83–0.88; 3°*Q* = 0.88–0.94; 4°*Q* = 0.94–1.04. Quartiles for the ratio between the double crop and soybean: 1°*Q* = 1.31–1.48; 2°*Q* = 1.48–1.61; 3°*Q* = 1.61–1.74; 4°*Q* = 1.74–1.92.

for each temperature record (Fig. 4). This may be due to the fact that water condition for crops is not only determined by rainfall. Initial water available in soil, effective infiltration, soil water retention capacity, vapor pressure deficit, and specific moment of water stress relative to critical period of yield determination in each crop also influences the crop response.

Unexpectedly, when large amount of water was available there was still approximately 15% of average yield distance to the boundary-function line. This, pointed out the importance of others factors such as unexplored thermal conditions (due to temperature amplitude and frost) or crop management (due to nutrient deficiencies, biotic stresses, etc.), or technology. However, this result was consistent with previous investigations on yield gaps in the Argentine Pampas (Aramburu Merlos et al., 2014; Monzon et al., 2013).

4.2. Comparative grain yields

Grain yield of maize and soybean single crops were highly correlated because of their similar optimal thermal requirements and crop growing periods (Figs. 3, 5b and 6). Wheat and double cropped soybean explored different yield determining periods. No crop cycle overlapping (Fig. 6) and large dependence of double cropped soybean on climatic conditions after wheat maturity determined a low correlation between these crop yields in the whole region (Figs. 2 and 5d). Although this may be interpreted as a possible way to obtain more yield stability, when overall productivity is considered (wheat + double cropped soybean) high correlations were found with either single maize or soybean yields (Table 3; Figs. 2, 5a and c), since overall growth cycles are greatly overlapped (Fig. 6).

When trying to achieve the highest possible yield with wheat–soybean double crop, factors tended to counterbalance in the region: spring cool environments potentially allow the highest grain yield for wheat (Table 3; Figs. 2 and 3), but they reduce the frost free period (Fig. 7) increasing the risk of detrimental effects on double cropped soybean toward the end of the summer season (Calviño et al., 2003). On the contrary, spring temperatures are high in the north of the region, and wheat yields tend to be low but, summer temperatures are high and frost free periods are long allowing for good double cropped soybean yields. Moreover, substantial summer rainfall is required to compensate the low initial soil water availability under the double cropped soybean.

4.3. Spatial patterns of crop grain yields

When feasibility and productivity of crop systems is considered, the results obtained showed that temperature is a crucial factor. As expected from Figs. 3 and 7, the highest average yields of summer crops tended to concentrate in the central portion of the region, while the highest average yields of wheat crops were found in the southern part of the region (Fig 8). The frost free period and temperature increased northwards (Fig. 7), which led to high double cropped soybean average yields to the north (Fig. 8). The interaction of major controlling factors for summer crops (frost free period, temperature and rainfall) and winter crops (temperature, spring PTQ and rainfall) determined a consistent productivity pattern for maize, soybean and wheat–soybean double crop (Fig. 8). The radial pattern observed (Fig. 8) may be attributed to the interaction of temperature and crop water availability (considering rainfall and stored water). Rainfall decreases from north-east to south-west but the deep, loamy, more productive soils are found in the central part of the region (Table 1; Hall et al., 1992). Since wheat–soybean double crops demand large amounts of resources and yields were highly correlated to summer crop yields, the overall pattern of productivity was similar to that of the summer single crops (Fig. 8).

Summer single crops and wheat–soybean double crop differed in average grain yields, in spite of similar spatial patterns. Productivity of maize and wheat–soybean double crop exceeded that of single soybean in the entire region. Maize is commonly more efficient than soybean in the use of intercepted radiation because of its C4 metabolism, absence of symbiotic energy costs and lower canopy light extinction coefficient (Hesketh, 1963); whereas double cropping increases the resource capture in comparison with single soybean crops (Andrade et al., 2015; Caviglia et al., 2004; Van Opstal et al., 2011). In terms of glucose-equivalent productivity, the results evidenced great opportunities to the expansion of maize and double crop production systems in the region. This alone, may greatly increase grain yield productivity in the region. Moreover, differently to what was expected, relative contributions and opportunities of double cropping may be greater in some of the presently considered marginal areas of the region.

Double crop relative yields increased toward less productive zones in the north-east, following the historical greater annual isohyets pattern (Hall et al., 1992). Only 15% of the analyzed cropland was cultivated with double crops in LIS during the studied period by CREA farmers (Table 1), indicating that possibilities of expansion of land intensive systems are likely to take place in those areas. In addition, high relative yields were also registered in the south as a consequence of increasing wheat yields and decreasing summer crop yields. Expansion possibilities, however, are subjected to market prices and trade policies, which in fact have been reducing the wheat sown area in Argentina during the past 5 years, as mentioned in Section 1.

Regional studies such as the one presented here, do not consider individual interactions among crop genotype, environment and management which may greatly modified the yields at a field level. However, average yield values and environmental variables were useful to point out the relative influence of major determinants of crop success and to draw the variability pattern of productivity in the region from on-farm yields and present technologies. Such an analysis may be used as a first step to evaluate new avenues for the development of presumably more productive systems including different grain crops or new crop managements and technologies, with similar or different analytical techniques, in this and other regions.

5. Conclusions

This work implemented a simple and innovative analysis to determine the effect of several environmental factors on the grain yield of the main cropping systems of the Argentine Pampas, analyzing complex interactions inherent to large-scale rainfed productions systems. In the analysis, maximum yields of all crops were associated with temperature and actual yields were greatly related to rainfall. A differential response of each crop to environmental variations was found although regional yield pattern was similar among maize, soybean and wheat–soybean double crop systems. However, across the region, single maize yields were the highest and soybean yields the lowest. Wheat–soybean double crops were more productive than soybean at any site, but their yields were slightly lower than those of maize. Wheat–soybean double crops were then feasible in any part of the studied area. Since at present almost 60% of the studied area is sown with single soybean crops, the results suggest that there is an effective possibility to have a substantial increase in on-farm productivity, while still producing soybean, simply by expanding the double crop system (an already proven technology). In addition, the work helped to identify possible areas where wheat–soybean double crop system may give relative higher advantages; particularly, in some of the presently least productive areas.

Acknowledgements

The authors thank AACREA and SMN for providing the dataset, Lic M. Lopez and Dr J.I. Rattalino Edreira because of their collaboration in dataset analysis. Drs F.H. Andrade, F. Bert, A. Hall, J.P. Monzon, and S.L. Poggio provided critical reviews of earlier versions of this paper. Comments made by the reviewers greatly help to improve the paper. JFA and EHS are members of CONICET (National Research Council), Argentina.

References

Andrade, F.H., Uhart, S.A., Arguissain, G.G., Ruiz, R.A., 1992. Radiation use efficiency of maize grown in a cool area. Field Crops Res. 28, 345–354.

Andrade, F.H., Uhart, S.A., Cirilo, A., 1993. Temperature affects radiation use efficiency in maize. Field Crops Res. 32, 17–25.

Andrade, F.H., Cirilo, A.G., Uhart, S., Otegui, M., 1996. Ecofisiología del Cultivo de Maíz. Editorial La Barrosa-EEA Balcarce. CERBAS, INTA-FCACERBAS, INTA-FCA, UNMP.

Andrade, F.H., Sadras, V., 2000. Bases para el manejo del maíz, el girasol y la soja. Ed. Médica Panamericana S.A., 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, Argentina. Eur. J. Agron., http://dx.doi.org/10.1016/j.eja.2015.03.001.

Aramburu Merlos, F., Monzon, J.P., Grassini, P., Andrade, F.H., 2014. Potential for Crop Production Increase in Argentina through Closure of Existing Yield Gaps , ASA-CSSA-SSSA, Long Beach, CA, 2–5 November 2014, pp. 235–236.

Asseng, S., Jamieson, P.D., Kimball, B., Pinter, P., Sayre, K., Bowden, J.W., Howden, S.M., 2004. Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric CO_2. Field Crops Res. 85, 85–102.

Asseng, S., Foster, I.A.N., Turner, N.C., 2011. The impact of temperature variability on wheat yields. Global Change Biol. 17, 997–1012.

Baker, J.T., Allen, L.H., Boote, K.J., Jones, P., Jones, J.W., 1989. Response of soybean to air temperature and carbon dioxide concentration. Crop Sci. 29, 98–105.

Boote, K.J., Allen, L.H., Prasad, P.V., Baker, J.T., Gesch, R.W., Snyder, A.M., Thomas, J.M., 2005. Elevated temperature and CO_2 impacts on pollination, reproductive growth, and yield of several globally important crops. J. Agric. Meteorol. 60, 469–474.

Bunting, A.H., Dennett, M.D., Elston, J., Speed, C.B., 1982. Climate and crop distribution. In: Blaxter, K.L., Fowden, L. (Eds.), Food, Nutrition and Climate. Applied Science Publisher, London, pp. 43–78.

Calviño, P., Sadras, V.O., 1999. Interannual variation in soybean yield: interaction among rainfall, soil depth and crop management. Field Crops Res. 63, 237–246.

Calviño, P., Sadras, V.O., Andrade, F.H., 2003. Quantification of environmental and management effects on the yield of late-sown soybean. Field Crops Res. 83, 67–77.

Calviño, P., Monzon, J., 2009. Farming Systems of Argentina: Yield Constraints and Risk Management. Crop Physiology: Applications for Genetic Improvement and Agronomy, vol. 51. Elsevier Academic Press, San Diego, CA, pp. 70.

Caviglia, O.P., Sadras, V.O., Andrade, F.H., 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.

Dardanelli, J., Collino, D., Otegui, M.O., Sadras, V.O., 2004. Bases funcionales para el manejo del agua en los cultivos de grano. In: Satorre, E.H., Benech 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, Buenos Aires, pp. 375–440.

Di Rienzo, J.A., Casanoves, F., Balzarini, M.G., Gonzalez, L., Tablada, M., Robledo, C.W., 2011. InfoStat versión 2011. Grupo InfoStat, FCA, Universidad Nacional de Córdoba, Argentina http://www.infostat.com.ar

Evans, L.T., Wardlaw, I.F., Fischer, R.A., 1975. Wheat. In: Evans, L.T. (Ed.), Crop Physiology: Some Case Histories. Camb. University Press, pp. 101–149.

Fischer, R.A., 1985. Number of kernel in wheat crops and the influence of solar radiation and temperature. J. Agric. Sci. 105, 447–461.

Gooding, M.J., Davies, W.P., 1997. The Production and Utilization of Wheat, System, Quality and the Environment. CAB International, Wallingford, Oxford, UK.

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.

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.

Hamblin, A.P., Tennant, D., 1987. Root length density and water uptake in cereals and grain legumes: how well are they correlated. Crop Pasture Sci. 38, 513–527.

Hesketh, J., 1963. Limitations to photosynthesis responsible for differences among species. Crop Sci. 3, 493–496.

Kurosaki, H., Yumoto, S., 2003. Effects of low temperature and shading during flowering on the yield components in soybeans. Plant Prod. Sci. 6, 17–23.

Larcher, W., 1980. Physiological Plant Ecology. Springer-Verlag, Berlin Heidelberg, New York.

Lobell, D.B., Asner, G.P., 2003. Climate and management contributions to recent trends in US agricultural yields. Science 299, 1032.

Lobell, D.B., Ortiz-Monasterio, J.I., Asner, G.P., Matson, P.A., Naylor, R.L., Falcon, W.P., 2005. Analysis of wheat yield and climatic trends in Mexico. Field Crops Res. 94, 250–256.

Lobell, D.B., Ortiz-Monasterio, J.I., 2007. Impacts of day versus night temperatures on spring wheat yields. Agron. J. 99, 469–477.

Lobell, D.B., Field, C.B., 2007. Global scale climate-crop yield relationships and the impacts of recent warming. Environ. Res. Lett. 2, 014002.

Lobell, D.B., Bänziger, M., Magorokosho, C., Vivek, B., 2011. Nonlinear heat effects on African maize as evidenced by historical yield trials. Nat. Clim. Change 1, 42–45.

Loomis, R.S., Connor, D.J., 1992. Crop Ecology: Productivity and Management in Agricultural Systems. Cambridge University Press, Melksham, Great Britain.

Magrin, G.O., Hall, A.J., Baldy, C.H., Grondona, M.O., 1993. Spatial and interannual variations in the photothermal quotient: implications for the potential kernel number of wheat crops in Argentina. Agric. Forest Meteorol. 67, 29–41.

Magrin, G.O., Travasso, M.I., Diaz, R.A., Rodriguez, R.O., 1997. Vulnerability of the agricultural systems of Argentina to climate change. Clim. Res. 9, 31–36.

Manderscheid, R., Burkart, S., Bramm, A., Weigel, H.J., 2003. Effect of CO_2 enrichment on growth and daily radiation use efficiency of wheat in relation to temperature and growth stage. Eur. J. Agron. 19, 411–425.

Menéndez, F.J., Satorre, E.H., 2007. Evaluating wheat yield potential determination in the Argentine Pampas. Agric. Syst. 95, 1–10.

Mercau, J.L., Sadras, V.O., Satorre, E.H., Messina, C., Balbi, C., Uribelarrea, M., Hall, A.J., 2001. On-farm assessment of regional and seasonal variation in sunflower yield in Argentina. Agric. Syst. 67, 83–103.

Mercau, J.L., Dardanelli, J.L., Collino, D.J., Andriani, J.M., Irigoyen, A., Satorre, E.H., 2007. Predicting on-farm soybean yields in the pampas using CROPGRO-soybean. Field Crops Res. 100, 200–209.

Monzon, J.P., Aramburu Merlos, F., Mercau, J.L., Taboada, M., Andrade, F.H., Hall, A.J., Jobaggy, E., Cassman, K.G., Grassini, P., 2013. Magnitude and variability of maize, wheat, and soybean yield gaps in Argentina. In: American Society of Agronomy International Annual Meeting, Tampa, FL, USA, 3–6 November 2013.

Monzon, J.P., Sadras, V.O., Abbate, P.A., Caviglia, O.P., 2007. Modelling management strategies for wheat–soybean double crops in the south-eastern Pampas. Field Crops Res. 101, 44–52.

Ohnishi, S., Miyoshi, T., Shirai, S., 2010. Low temperature stress at different flower developmental stages affects pollen development, pollination, and pod set in soybean. Environ. Exp. Bot. 69, 56–62.

Pazos, M.S., Mestelan, S., 2002. Classification of udolls with caliche at variable depth. Buenos Aires province – Argentina. Soil Sci. Soc. Am. J. 66, 1256–1264.

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.

Podestá, G.P., Messina, C.D., Grondona, M.O., Magrin, G.O., 1999. Associations between grain crop yields in central-eastern Argentina and El Niño-Southern Oscillation. J. Appl. Meteorol. 38, 1488–1498.

Prohaska, F., 1976. The climate of Argentina, Paraguay and Uruguay. In: Schwerdtfeger, W. (Ed.), Climates of Central and South America. World Survey of Climatology, vol. 12. Elsevier, Amsterdam, pp. 13–112.

R Development Core Team, 2008. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rao, M.R., Willey, R.W., 1983. Effects of genotype in cereal/pigeonpea intercropping on the alfisols of the semi-arid tropics of India. Exp. Agric. 19, 67–78.

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., 2012. Recent changes in Pampean agriculture: possible new avenues to cope global change challenges. In: Slafer, Araus (Ed.), Crop Stress Management and Climate Change; CABI Series No. 2, pp. 47–57.

Satorre, E.H., Benech Arnold, R.L., Slafer, G.A., de la Fuente, E.B., Miralles, D.J., Otegui, M.E., Savin, R., 2004. Producción de granos, bases funcionales para su manejo. Editorial Facultad de Agronomía, Buenos Aires.

Savin, R., Slafer, G.A., 1991. Shading effects on the yield of an Argentinean wheat cultivar. J. Agric. Sci. 116, 1–7.

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. Haworth Press Inc., New York, USA, pp. 85–120.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677.

van Ittersum, M.K., Rabbinge, R., 1997. Concepts in production ecology for analysis and quantification of agricultural input–output combinations. Field Crops Res. 52, 197–208.

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—a review. Field Crops Res. 143, 4–17.

Van Opstal, N.V., Caviglia, O.P., Melchiori, R.J.M., 2011. Water and solar radiation productivity of double-crops in a humid temperate area. Aust. J. Crop Sci. 5, 1760–1766.

Wackernagel, H., 2003. Multivariate Geostatistics: An Introduction with Applications. Springer-Verlag, Berlin.

Wang, Z., Song, K., Li, X., Zhang, B., Liu, D., 2007. Effects of climate change on yield of maize in maize zone of Songnen Plain in the past 40 years. J. Arid Land Resour. Environ. 21, 112–117.

Wang, X., Peng, L., Zhang, X., Yin, G., Zhao, C., Piao, S., 2014. Divergence of climate impacts on maize yield in Northeast China. Agric. Ecosyst. Environ. 196, 51–58.

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.

Weilenmann de Tau, M.E., Suárez, J.C., 1998. Soja. In: Aguirrezábal, L.A., Andrade, F.H. (Eds.), Calidad industrial de productos agrícolas. Bases ecofisiológicas, genéticas y de manejo agronómico. Edición de la Facultad de Ciencias Agrarias de la Universidad Nacional de Mar del Plata y de INTA Balcarce, pp. 197–230.