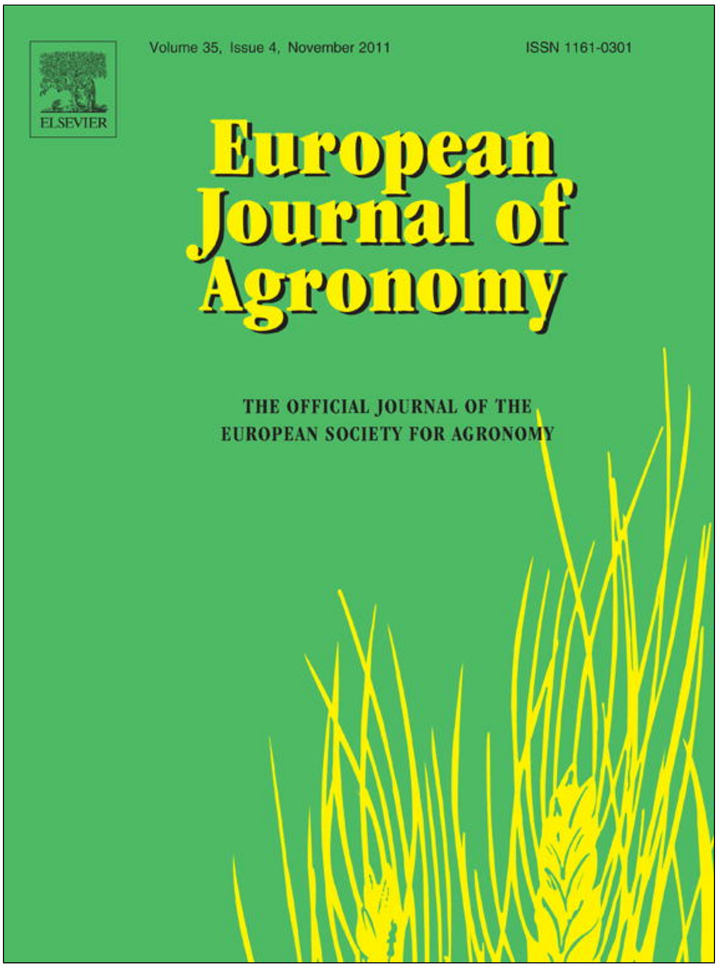
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Main edaphic and climatic variables explaining soybean yield in Argiudolls under no-tilled systems

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ABSTRACT

Argentina is an important producer of soybean (*Glycine max* L. Merr.), with 83% of the crop being cultivated under no tillage. Yield gaps of up to 2000 kg ha^{-1} are usually recorded in the main area, even between fields that are at a short distance. Soils are predominantly Argiudolls, with subsurface compacted layers (massive zones without visible macropores, termed delta clods, ΔM). The aims of this work were (i) to identify climatic variables and soil properties that explain seed yield variation in rainfed soybean growing in no-tilled Argiudolls; and (ii) to quantify the relative effect of those soil and climatic variables on field soybean yield. The database, which included 175 cases of soybean crops, was obtained from production fields during four crop seasons, covering a wide range of environmental and soil conditions. Multifactor linear regression was used to assess soybean yield variability and quantify the contribution of climatic and soil traits in the formation of grain yield. Threshold values, such as 180 mm of cumulative precipitation during the whole reproductive period and 200 mm of available soil water at sowing, separated different situations: (a) environments that were above those values, in which 48–51% of total yield variation was explained by mean daily temperate during seed set, cumulative solar radiation during seed filling, combined with soil variables, such as organic matter content and ΔM, or, alternatively, saturated hydraulic conductivity (K_{sat}); and (b) environments that were below the threshold values, in which precipitation during the whole reproductive period and ΔM or K_{sat} explained 72–88% of total soybean yield variation. Highest soybean yield values were always attained in fields under good soil physical conditions.

1. Introduction

Argentina is an important soybean producer and the leading exporter of soybean oil and oilseed-derived protein meal (WASDE, 2010). Eighty-three percent of the crop is grown under no tillage (Argentine Association of farmers using no-tillage, AAPRESID, personal communication), a system that has proven successful, especially due to greater soil water storage (Panigatti et al., 2001; Fabrizzi et al., 2005; Álvarez and Steinbach, 2009). However, soil compaction and the consequent loss of macroporosity mainly due to wheel traffic is one of the limiting factors of no tillage in intensive agriculture (Hamza and Anderson, 2005; Botta et al., 2007). Several studies have reported the soil characteristics affected by management practices under continuous agriculture (such as rotations and tillage systems) that play an important role in determining crop yield (Lipiec et al., 2003; De Bie, 2004; So et al., 2009). However, soil properties should also be analyzed in relation to climatic variables (Grassini et al., 2009), because the combination of both factors determines different environments for the crops, generating important yield variability. Consequently, yields obtained in the main cropped area in Argentina exhibit a high inter-annual variation, with gaps that can exceed 2000 kg ha^{-1}, even in production fields that are at short distances or use the same soil management system (Bacigaluppo et al., 2009). Identifying the edaphic and climatic factors that most influence final crop yield contributes to the selection of management techniques needed to attain stable yields across space and time. The effect of stress factors during the critical crop period (seed set) on soybean yield determination (Board et al., 1995; Jiang and Egli, 1995) and the influence of sowing date (Martignone et al., 2006) and the genotypes used in different

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Abbreviations: MG, maturity groups; OM, organic matter; B2t depth, depth to B2t horizon; ΔM, delta clods; CS, compacted soil layers; SAW, soil available water at sowing; K_{sat}, saturated hydraulic conductivity; R2, full flowering; R5, start of seed filling; R7, physiological maturity; Tm, mean daily air temperature; Rs, cumulative global solar radiation; Phot, mean daily photoperiod; pp, cumulative precipitations; IR2, canopy cover at R2; IR5, canopy cover at R5; SW, individual seed weight; SN, seed number; G, genotype; E, environment.

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crop areas in Argentina (Fuentes, 2009) are well known aspects in soybean production. However, the numerous correlations between environmental resources, such as solar radiation, precipitations and temperature and their interaction with soil limiting factors (low hydraulic conductivity, soil physical impedance) and soybean yield in production fields under no till in Argiudoll soils have not been documented for the main soybean cropped area in Argentina.

The effect of environment has been shown to account for most of the variations in seed yield (Salado Navarro et al., 2006; Zheng et al., 2009; Anderson, 2010) as well as of variations in seed oil and proteins (Dardanelli et al., 2006; Carrera et al., 2009). The effect of one or several stress factors and their interactions on crop growth and development are usually evaluated using experimental assays under highly controlled experimental conditions. However, under field conditions crop yield is the result of complex temporal and non-controlled interactions occurring during the crop cycle that determine the crop response to several, likely simultaneous, stresses. Seed yield will depend on the duration of each limiting process, on the crop phenological stage at which these processes occur, and on other factors that are difficult to control altogether in experimental assays (Batchelor et al., 2002). Hence, to explain growth and development variability and therefore crop yield variability, observational studies conducted in production fields are needed to perform multidimensional analyses and explore interactions as they occur under field conditions.

The aims of this study were (i) to identify climatic variables and soil properties that explain seed yield variation in rainfed soybean growing in no-tilled Argiudolls; and (ii) to quantify the relative effect of those soil and climatic variables on field soybean yield.

2. Materials and methods

2.1. Data set

Data were collected from soybean production fields under no-tilled, rainfed conditions, in four crop seasons (2001/02 to 2004/05). The study area (Latitude 32°25′S to 33°48′S; Longitude 60°20′W to 62°00′W) includes approximately 1,570,000 ha of the Argentine Pampas region. The soil origin is loessic sediments mainly of silt-loam texture (Mosconi et al., 1981). All the soils from the study area are genetically similar, belong to the Great group of Argiudolls and vary only at the series level (Table 1).

The climate is temperate and sub-humid, with suitable cropping period for soybean between September and April. Mean annual precipitation is 1052 mm (series 1951–2009), with a high inter-annual variation ranging between 465 and 1862 mm (Agrometeorological Station of INTA Oliveros Experimental Station, 32°33′54″S, 60°51′31″W, 26 m a.s.l.). Rainfall regime tends to be monsoonal, with 70% of rainfall concentrated between October and March (Mosconi et al., 1981).The base for statistical evaluation was a high number of observations made on 33 production fields in the years 2001–2005. Thirty-three sites were selected at different localities, with a 3–60-year range of continuous agriculture, 1–15 years of no-tillage and different previous crops: soybean, maize and wheat/soybean. The production fields were sown with soybean, on different dates between October 14 and November 30, which is considered the optimum sowing period in the region. In all the selected sites, soil phosphorous content down to 20 cm-depth was above 13 ppm, the threshold above which this nutrient is not limiting (Ferraris et al., 2002). Weeds, pests and diseases were chemically controlled following the guidelines or recommendations for the region. Each site was divided into plots of ca. 1000 m^{-2} (observational unit). Data were collected from the plots, which were sown with three soybean genotypes of different maturity groups (MG) that are widely used in the region: DM 4800 RR (MG IV), A 5520 RG (MG V), and A 6040 RG (MG VI). Because of the differences in cycle length among genotypes, we were able to explore different windows to study climatic effects, resulting in a wide range of environmental variations. Thus, 70 environments defined by the combination of the factors site and genotype were generated, i.e., for a single crop season and site, plots with different genotypes were treated as different environments. Therefore, we enlarged the data variability by growing three soybean varieties, differing in the length of the growing period. Due to this approach, the stages of plant development were evidenced in different calendar days and were characterized by different weather conditions. The total number of observational units was 175 since in each environment we collected 2–3 replicates (Table 2). Complementary to the production field data, for variance component estimation we used another database of soybean yield records from a network of soybean comparative assays of INTA conducted in the same areas and crop seasons as the present study, which included yields of varieties of MG III–VI (Bodrero et al., 2002, 2003, 2004, 2005).

2.2. Variables recorded

2.2.1. Soil variables

The following variables were considered: organic matter (OM) for the 0–20 cm layer; depth to B2t horizon (B2t depth) – B2t being an argillic subsurface horizon formed by clay movements caused by illuviation and clay formation in situ (Dardanelli et al., 2003); delta clods (ΔM) and compacted soil layers (CS); soil available water at sowing (SAW) and saturated hydraulic conductivity (K_{sat}). To determine OM at sowing, a sample of 0–20 cm layer (A horizon), composed of 15 subsamples, was taken with a borer (15 mm diameter). Organic carbon content was determined using the Walkley Black oxidation method and quantification by titration (Jackson, 1964). Results were expressed as percentage of OM.

To determine B2t depth a side view (210 cm long and 70 cm deep) was set across the rows. On one of its walls, soil horizons were identified and vertical distance was measured in cm, from the surface ground to the beginning of B2 argillic horizon. ΔM and CS were determined on the same side view using the cultural profile method (Manichon, 1987). On one of the walls, only the sectors of soils corresponding to the "delta massive" structural state were delimited. This state is typically a single structural element with smooth breaking surface, no visible porosity (absence of macroporosity) and high cohesion. Delta massive structure was expressed as %ΔM, and was calculated as the proportion of area of the delta clods relative to the total area of horizons A + B1 (De Battista et al., 1994; Richard et al., 1999). Percentage of surface compacted layer (%CS) was calculated as the proportion of length of ΔM relative to the total profile length (Gerster et al., 2002) (Fig. 1).

SAW was determined as the available water at sowing (in mm) down to 2 m in depth. SAW was calculated from data of volumetric soil water content at each horizon as the difference between the observed volumetric water content and that of the lower limit (Ritchie, 1981), multiplied by horizon depth. Lower limit was previously established for each soil series of the plots under study (Andriani, 2000a). Measurements of volumetric water content were recorded with a neutron probe model Troxler 4302. Hydraulic conductivity was measured at field saturation using disc permeameters (Perroux and White, 1988).

2.2.2. Environmental variables

To construct environmental variables meteorological data were combined with phenological data. Temperature, global solar radiation and photoperiod data were daily recorded at the Agrometeorological Station of INTA Oliveros Experimental Station (32°33′54″S, 60°51′31″W, 26 m a.s.l.). This station is located at up to 60 km away from each of the study plots. Given that the

Table 1
Example of analytical data of the profile of a typic Argiudoll (Maciel series). Textural components are expressed in percentage.

	Horizons						
	A1	B1	B21t	B22t	B23t	B3	C1
Depth (cm)	0–25	25–37	37–51	51–85	85–112	112–147	147–240
Clay < 2μ	21.5	29.0	48.5	49.0	40.5	33.0	31.5
Silt 2–50μ	74.5	69.5	49	49	58	63.5	65.5
Sand 50–250μ	3.4	1.7	1.9	2.0	1.6	3.2	3.1

Table 2
Genotypes and sites defining 70 crop environments and 175 observational units.

Site	Crop season	Plots: genotype – maturity group			Number of environments	Number of observational units
		DM 4800 MG IV	A 5520 MG V	A 6040 MG VI		
1	2001/02	3	3	3	3	9
2	2001/02	3	3	3	3	9
3	2001/02	3	3	3	3	9
4	2001/02	2	2	2	3	6
5	2001/02	2	2	2	3	6
6	2002/03	3	3	3	3	9
7	2002/03	3	3	3	3	9
8	2002/03	3	3	3	3	9
9	2002/03	3	3	3	3	9
10	2002/03	3	3	3	3	9
11	2002/03	3	3		2	6
12	2002/03	2	2	2	3	6
13	2002/03	2	2		2	4
14	2003/04		3		1	3
15	2003/04	3	3		2	6
16	2003/04	3	3		2	6
17	2003/04	2	2		2	4
18	2003/04	2	2		2	4
19	2003/04	3			1	3
20	2003/04	3			1	3
21	2003/04	3	3		2	6
22	2004/05	2	2		2	4
23	2004/05	2	2		2	4
24	2004/05	2	2		2	4
25	2004/05	2	2		2	4
26	2004/05	2	2		2	4
27	2004/05	2	2		2	4
28	2004/05	2	2		2	4
29	2004/05	2	2		2	4
30	2004/05	2			1	2
31	2004/05	2			1	2
32	2004/05	2			1	2
33	2004/05	2			1	2
Total					70	175

Numbers in genotypes rows represent the number of observational units in each of the 70 environments (non-empty cells).

region under study is flat and far from mountains, we considered that the values recorded for the variables constructed can be extrapolated to all the study plots. Daily precipitations were recorded at each plot during the crop season. Furthermore, dates of occurrence of crop phenological stages were determined: emergence (E), full flowering (R2), start of seed filling (R5), physiological maturity (R7) and full maturity (R8), following the scale of Fehr and Caviness (1977). To construct environmental variables, the

Fig. 1. Example of cultural profile for soil structural status diagnosis.

crop cycle was divided into three crop subperiods: (1) vegetative subperiod: from emergence to full flowering (E–R2); (2) seed set subperiod: from full flowering to beginning of seed filling (R2–R5), (3) seed filling subperiod: from beginning of seed filling to physiological maturity (R5–R7). For each subperiod, the following parameters were calculated: mean daily air temperature (T_m, °C) as the average of daily maximum and minimum temperatures, cumulative global solar radiation (R_s, MJ m^{-2}), and cumulative precipitations (pp, mm). Mean daily photoperiod (Phot, h) was obtained as the arithmetic mean of values recorded in each subperiod. For each environmental variable, subscripts 1, 2 and 3 identified each crop subperiod (i.e. R_{s3} was cumulative solar radiation for the seed filling subperiod).

2.2.3. Crop variables

Canopy cover was measured at R2 and R5 (indirect method to estimate crop intercepted radiation), as described by Adams and Arkin (1977) (IR2, IR5). All measurements were performed at about midday. At R8 seeds were manually harvested from a 10-m^{-2} surface at each plot. Seed yield, expressed at 13.5% moisture (Yield) and seed yield components were determined: individual seed weight (SW), obtained from the weight of five samples of 200 seeds each, and seed number m^{-2} (SN), calculated as yield (g m^{-2}) divided by individual seed weight (g).

2.3. Data analysis

To show the relative importance of genotype (G), environment (E) and their interaction (G × E) to explain yield variations in each crop season, variance components were estimated fitting a linear mixed model in Proc Mixed of SAS version 9.1 using yield records from the network of soybean comparative assays of INTA conducted in the same areas and crop seasons as the present study.

Correlations between variables were analyzed by simple Pearson correlation coefficients. Multiple linear regression models were fitted both to the original data and the logarithmically transformed data to account for possible non-linear relationships. For the multiple linear regression, partial residuals for yield were obtained and graphed according to each variable involved. If there was a linear relationship between partial residuals and a predictor variable, then it was assumed that the predictor might be a useful component in the linear model. Multifactor linear regression was enough to model relationships between climatic variables and soil properties accounting for yield variations, except for the relationship between yield and pp and SAW. Non-linear relationships were found between pp/SAW and yield, suggesting the need to fit different linear models to different water availability conditions. Best-fit linear regression models under different conditions were selected by the backward process of variable selection (Draper and Smith, 1998). The predictive power of each fitted model was evaluated based on the square root of the mean square prediction error (RMSPE), expressed as the percentage of average yield observed, (%RMSPE). RMSPE were obtained by cross validation using the leave one out iterative procedure (i.e., leaving one observation out of the fitting and using it as validation of the model fitted with the other n-1 data). The analyses were performed with the statistical software InfoStat (2008).

3. Results

The variance component analysis shows that the site effect accounted for 74%, 61%, 82%, and 62% of yield variation in the 2001/02, 2002/03, 2003/04 and 2004/05 crop seasons, respectively. The environment was the principal factor explaining yield variation with effect magnitude several times greater than the genotype effects (Table 3). Moreover, within sites the environmental variability was increased by growing soybean varieties differing in length of the vegetative cycle used to calculate environmental and crop variables.

Table 3
Effects (expressed in percentage) of sites, genotype and their interaction on variations in yield of soybean grown under no-till conditions in Argiudolls from Argentina.

Crop season	E	G	G × E
2001/02	74	15	11
2002/03	61	13	26
2003/04	82	9	9
2004/05	62	18	20

E: site (environment); G: genotype; G × E: site × genotype.

Mean, maximum and minimum values of the recorded soil variables exhibited wide variation ranges (Table 4). Minimum ΔM and CS values equal to zero indicate that some sites did not have physical impedance problems.

Most of the environmental variables (Table 5) also showed a wide range of values, especially regarding precipitations and cumulative global solar radiation. Cumulative precipitations during the crop season ranged between 264 and 831 mm, suggesting water deficit in some environments. This variation range is a consequence of the important variability typical of the climate in the Pampas region (Hall et al., 1992).

Regarding crop variables (Table 6), yield obtained in the different environments ranged between 2060 and 4580 kg ha^{-1}; seed number was the yield component with the greatest variation. The variability observed in crop variables is consistent with variability observed in climate and soil.

The correlation coefficients between yield and soil variables (Table 7) showed that yield was negatively associated with ΔM and CS and positively correlated with K_{sat} and OM. In addition, K_{sat} was negatively correlated with ΔM and CS, suggesting the convenience of evaluating alternative regression models (one with ΔM or CS and another with K_{sat} as explanatory variable) because the inclusion of these variables in a single explanatory linear model would be redundant.

Correlations between yield and environmental variables in subperiod 2 and 3 are presented in Table 8, except for pp, in which a single variable was analyzed (pp_{2+3} or pp in the whole reproductive period). Positive and statistically significant linear correlations of yield with T_{m2} and R_{s3}, as well as with $Phot_2$ and $Phot_3$ are shown. No linear correlation was found with pp_{2+3}. As expected, radiation, photoperiod and temperature were frequently correlated.

All correlation coefficients between yield and other crop variables were statistically significant (Table 9). Yield was correlated with SN and the latter with IR5, a variable that results from leaf development until the end of subperiod 2. In the logarithmic scale, the reported correlations were also significant (data not shown).

Based on the above mentioned variable correlations, different regression models were fitted, each of them based on a group of both edaphic and climatic variables; the groups were selected in such a way that variables in a group were weakly correlated to avoid multicollinearity problems and obtain parsimonious models of practical utility.

The analysis of partial residuals of the full regression model (model with all predictors after selection to avoid multicollinearity) showed that the relation between yield and cumulative precipitation in the reproductive period (pp_{2+3}) had a different behaviour at a threshold value of 180 mm (Figure 2). Below that threshold, the relation between partial residuals and pp_{2+3} showed a significant positive linear response (Regression coefficient = 19 kg ha^{-1}, $p < 0.0001$), which was not observed at values above the threshold of 180 mm ($p > 0.05$). The non-linear relationship was also observed with SAW at a threshold of 200 mm (data not shown). Graphs of

Table 4
Data characterization according to soil variables.

Variables	Mean	Minimum	Maximum	SD
SAW (mm)	256	127	382	61
OM (%)	3.03	2.23	3.55	0.35
B2t depth (cm)	25.8	14.7	33.3	3.7
ΔM (%)	22	0	54	15
CS (%)	57	0	93	20
K_{sat} (cm h^{-1})	6.7×10^{-4}	2.6×10^{-4}	1.5×10^{-3}	2.7×10^{-4}

SAW: soil available water content at sowing down to 2 m-depth; OM: organic matter; B2tdepth: depth of textural B2 horizon; ΔM: delta clods; CS: compacted soil layer; K_{sat}: saturated hydraulic conductivity.

Table 5
Data characterization according to environmental variables.

Variables	Mean	Minimum	Maximum	SD
R_{s1} MJ (m^{-2})	1065	655	1493	239
R_{s2} MJ (m^{-2})	831	549	1183	120
R_{s3} MJ (m^{-2})	779	570	1362	128
T_{m1} (°C)	23.3	20.3	25.6	0.9
T_{m2} (°C)	24.6	22.9	26.3	0.8
T_{m3} (°C)	23.4	20.2	25.9	1.2
Phot$_1$ (hs)	15.1	14.4	15.2	0.2
Phot$_2$ (hs)	14.7	14.2	15.2	0.2
Phot$_3$ (hs)	13.6	12.9	14.6	0.4
pp$_1$ (mm)	220	60	421	92
pp$_2$ (mm)	130	8	253	59
pp$_3$ (mm)	177	9	412	91
pp$_{2+3}$ (mm)	307	107	532	95
pp$_{cycle}$ (mm)	527	264	831	142

R_s: cumulated global solar radiation; T_m: mean temperature; Phot: photoperiod; pp: precipitations.
1: E–R2; 2: R2–R5; 3: R5–R7.

Table 6
Data characterization according to crop variables.

Variables	Mean	Minimum	Maximum	SD
IR2 (%)	85	36	99	14
IR5 (%)	97	60	99	5
Yield (kg ha^{-1})	3372	2060	4580	606
SW (g)	0.153	0.114	0.183	0.017
SN (m^{-2})	2210	1345	3011	354

IR2: canopy cover at R2; IR5: canopy cover at R5; SW: individual seed weight; SN: seed number.

Table 7
Pearson correlation coefficients of grain yield and soil variables.

	Yield	OM	B2tdepth	K_{sat}	ΔM	CS
Yield	1					
OM	0.36[*]	1				
B2tdepth	−0,05	0,13	1			
K_{sat}	0.44[*]	0.32[*]	0.29[*]	1		
ΔM	−0.53[*]	−0.13	−0.02	−0.63[*]	1	
CS	−0.43[*]	−0.06	−0.05	−0.71[*]	0.74[*]	1

[*] Significant at $\alpha = 0.05$
OM: organic matter; B2tdepth: depth of textural B2 horizon; K_{sat}: saturated hydraulic conductivity; ΔM: delta clods; CS: compacted soil layer.

Table 8
Pearson correlation coefficients of grain yield and environmental variables.

	Yield	pp$_{2+3}$	T_{m2}	T_{m3}	R_{s2}	R_{s3}	Phot$_2$	Phot$_3$
Yield	1							
pp$_{2+3}$	0.06	1						
T_{m2}	0.25[*]	−0.26[*]	1					
T_{m3}	−0.14	−0.33[*]	−0.12	1				
R_{s2}	0.13	−0.23[*]	0.03	0.62[*]	1			
R_{s3}	0.15[*]	0.06	−0.10	0.21[*]	0.54[*]	1		
Phot$_2$	0.31[*]	0.06	0.24[*]	0.28[*]	0.62[*]	0.67[*]	1	
Phot$_3$	0.21[*]	−0.06	0.20[*]	0.41[*]	0.63[*]	0.74[*]	0.92[*]	1

[*] Significant at $\alpha = 0.05$.
pp: precipitations; T_m: mean temperature; R_s: cumulated global solar radiation; Phot: photoperiod.
2: R2–R5; 3: R5–R7.

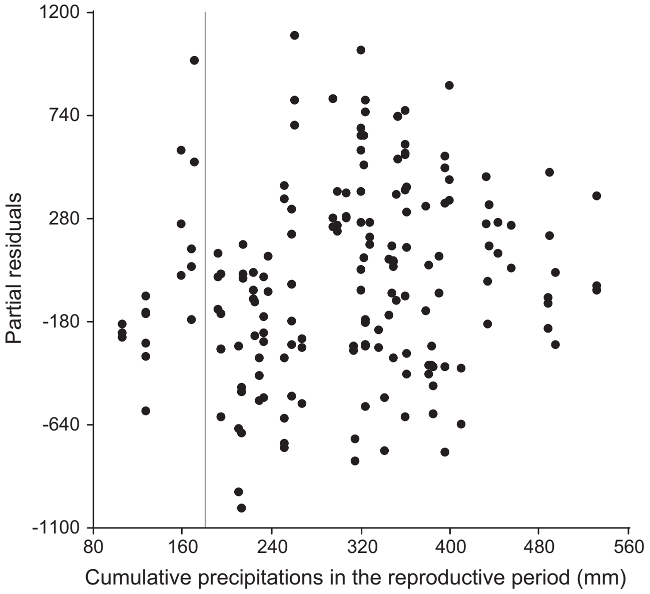

Fig. 2. Relation between partial residuals for yield and cumulative precipitations in the reproductive period.

partial residuals for the remaining predictive variables suggested a linear behaviour within the range of values recorded.

Therefore, four scenarios were generated to analyze yield in linear relation to soil-climate variables: (i) $pp_{2+3} \leq 180$ mm; (ii) $pp_{2+3} > 180$ mm; (iii) SAW ≤ 200 mm; (iv) SAW > 200 mm. The statistics of the models obtained are shown in Table 10.

Under limited water availability conditions (models i and iii), variables associated with infiltration and water availability to the crop explained yield variation. By contrast, under favourable water conditions, the variables OM, T_{m2} and R_{s3} contributed significantly to the models. In all cases, the variables related to soil physical condition (ΔM or K_{sat}) were present in the selected models that best explained soybean yield variability in the production fields.

4. Discussion

Yield variations in soybean cultivated under no tillage in Argiudolls can be explained by soil variables, such as ΔM, K_{sat}, and OM content, and by climate variables, such as precipitations, temperature, and cumulative solar radiation. Soil variables can be recorded before crop sowing and, although climate variables are not available beforehand, historical records can be used to simulate scenarios or make forecasts for a given crop season.

The results obtained in the present work suggest that prediction of soybean yield can be improved in environments of low water availability (Table 10). These results are in agreement with findings reported in a similar work conducted by Yang et al. (2003), who observed that productivity index used to estimate yield was more accurate in relatively dry periods, probably due to other edaphic and climatic factors that are involved in humid periods, such as aeration, temperature and solar radiation.

Table 9
Pearson correlation coefficients of grain yield and crop variables.

	Yield	IR2	IR5	SN	SW
Yield	1				
IR2	0.31*	1			
IR5	0.50*	0.51*	1		
SN	0.80*	0.49*	0.53*	1	
SW	0.47*	−0.22*	0.04	−0.15*	1

* Significant at $\alpha = 0.05$

IR2: canopy cover at R2; IR5: canopy cover at R5; SN: seed number; SW: individual seed weight.

The highest yields were always recorded in environments with good soil physical conditions, reflected in high saturated hydraulic conductivity or low presence of delta clods in the profile. Hence, soil impedances would not only affect incorporation of water to the profile but also crop root growth and functioning, nutrient availability, aeration and gas diffusion, as previously documented (Lipiec et al., 2003; Taboada and Alvarez, 2008; So et al., 2009).

The presence of light soil zones, cracks or channels generated by the mesofauna in a compacted soil layer can have a very important effect on root penetration, but a limited effect on mean values of soil physical variables indicative of that compaction. Therefore, simple variables, such as bulk density or soil resistance, might be insufficient to make a good characterization of soil structure if considered individually (Tardieu, 1994). Taboada and Micucci (2002) observed that alterations in plant root growth and proliferation in the soil profile due to impedances reduce water and nutrient uptake. The response is not uniform; in a dry year, root penetration is impeded by high compacted soil resistance; thus, roots cannot explore deeper layers from where they might absorb water (Andriani, 2000b). In very humid years, although roots can penetrate the compacted layers, the absence of macropores in these densified horizons leads to an anoxic state that also affects crop growth. Gerster and Bacigaluppo (2004), Botta et al. (2007), and Imvinkelried et al. (2010) found up to 29% reductions in soybean yield due to a negative effect of soil compaction induced by wheel traffic.

The predictive capability of saturated hydraulic conductivity can be attributed to the influence of macropore continuity on that variable, which would facilitate diagnosis of the soil status (Strudley et al., 2008; So et al., 2009). According to Lipiec et al. (2003), hydraulic conductivity is an important parameter that should be considered in models in which soil physical conditions are simulated to predict the effects of compaction on crop growth and yield. This parameter, an indicator of the stability and continuity of the pore system, is important for the distribution of roots in the soil profile.

Furthermore, in environments of high water availability ($pp_{2+3} > 180$ mm or SAW > 200 mm) increased crop yields were obtained when, besides cultivating the crop in soils of good physical conditions, the highest T_m values were recorded in the subperiod 2 and the highest R_s values in subperiod 3. In agreement with the present results, in an evaluation of late-sown soybean, Calviño et al. (2003) obtained two models that explained 82% and 79% of soybean yield, with mean temperature in the R1–R5 period and cumulative radiation in the R5–R7 period as some of the explanatory variables of these models, respectively.

Temperature and solar radiation, along with water, are the principal agro-meteorological variables regulating metabolic processes in plants (Cárcova et al., 2003). Production of dry matter depends on the plant's ability to intercept solar radiation and, through photosynthesis, transform it into metabolic energy. Mean daily temperature in the R2–R5 subperiod could have been associated with leaf expansion, as can be inferred from the significant correlation between T_{m2} and IR5 under non-limiting water conditions ($r = 0.18$, $p = 0.03$). This association shows that T_{m2} was positively correlated with canopy cover at R5, a greater cover being an indicator of greater leaf area, which allows the plant to intercept a higher percentage of solar radiation. The greater cover of the crop at that phenological stage was also positively associated with seed number. Soybean yield formation can be thought of in terms of yield components, such as seed number and seed size. Quijano et al. (1999) determined that the critical period for seed establishment includes the 20-day interval prior to the start of R5 stage. Hence, to

Table 10
Coefficients of regression and statistics obtained from linear explanatory models for soybean yield in production fields under different values of cumulative precipitation in the reproductive period or soil water availability at sowing.

Model	n	R^2	Variable	Coefficient	p Value	Mallows Cp	RMSE (kg ha^{-1})	Error (%)
i ($pp_{2+3} \leq 180$)	17	0.88	Constant	892	0.0627		±285	±9
			ΔM	−14	0.0036	13.46		
			pp_{2+3}	19	<0.0001	54.06		
iia ($pp_{2+3} > 180$)	158	0.48	Constant	−4320	0.0003		±453	±13
			OM	435	<0.0001	25.93		
			ΔM	−21	<0.0001	75.29		
			T_{m2}	244	<0.0001	33.74		
			R_{s3}	1.03	0.0001	19.94		
iib ($pp_{2+3} > 180$)	158	0.40	Constant	−5491	<0.0001		±493	±14
			OM	332	0.0020	13.85		
			K_{sat}	985276	<0.0001	41.66		
			T_{m2}	266	<0.0001	33.56		
			R_{s3}	0.86	0.0023	13.56		
iii (SAW ≤200 mm)	12	0.72	Constant	2003	<0.0001		±378	±12
			K_{sat}	2331982	0.0004	25.02		
iv (SAW>200 mm)	163	0.51	Constant	−4581	0.0001		±443	±13
			OM	423	<0.0001	27.22		
			ΔM	−22	<0.0001	97.42		
			T_{m2}	252	<0.0001	38.24		
			R_{s3}	1.21	0.0001	25.47		

SAW: soil available water content at sowing down to 2 m-depth; OM: organic matter; ΔM: delta clods; K_{sat}: saturated hydraulic conductivity; R_s: cumulated global solar radiation; T_m: mean temperature; pp_{2+3}: precipitations R2–R7.

obtain an increased number of seeds, a maximum radiation intercept before the start of such critical period is necessary.

On the other hand, our study showed a close association between solar radiation available during seed filling and SW ($r = 0.45$, $p < 0.0001$). Results reported by Egli (1997) and Proulx and Naeve (2009) show that a decrease in solar radiation by shading during the R5–R7 period reduces soybean yield, affecting not only individual seed weight but also seed number. Shading generated stress by reducing photosynthesis and assimilating supplies to the seed during seed filling. Overall, although the inferences made in the present work have the limitations characteristic of observational studies, they can be useful for future experimental studies to elucidate with greater precision the interactions between climatic and soil factors that restrict soybean productivity under no tillage system.

5. Conclusions

Soil and climate variables were identified and used to construct robust explanatory models of the variation in soybean yield under no tillage systems. These models included a low number of variables under relatively dry conditions (scarce soil water availability at sowing or scarce precipitations during the reproductive period), which were related to precipitation during the reproductive period and physical factors limiting water uptake and root penetration in the soil. Under higher water supply conditions, the variables related to soil impedance also explained soybean yield variations, along with (i) temperature during the early reproductive period, which is determinant of the degree of crop cover and the latter, in turn, determines seed number and (ii) cumulative solar radiation in the late reproductive period, influencing seed weight. Therefore, in all the situations analyzed, soil structural condition was important to explain variations in crop yield.

Thus, the simple models obtained in this study were able to capture the main sources of variation in soybean crop yield under continuous no tillage on Argiudolls. They can be used to estimate crop yield including a few variables accessible to growers, such as ΔM or K_{sat}, OM, precipitation, mean temperature and cumulative solar radiation.

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