DOES PASTURE LONGEVITY UNDER DIRECT GRAZING AFFECT FIELD-SCALE SORGHUM YIELD SPATIAL VARIABILITY IN CROP-PASTURE ROTATION SYSTEMS?

M.V. Pravia, J.A. Terra and A. Roel

National Institute of Agricultural Research- INIA
Treinta y Tres, Uruguay

ABSTRACT

Crop yield spatial variability is usually related to terrain attributes and soil properties. In pasture systems, soil properties are affected by animal grazing. However, soil and terrain attributes relation with crop yield variability has not been assessed in crop-pasture rotations. Landscape attribute and soil properties relation with sorghum (*Sorghum bicolor* L.) grain yield were evaluated at the field-scale under three crop-pasture rotation systems during three years in Uruguay: i) continuous cropping (CC): ryegrass (*Lolium multiflorum* Lam.)-sorghum-ryegrass-soybean (*Glycine max*); ii) short rotation (SR): 2yr grass/legume pasture- 2yr like CC; iii) long rotation (LR): 4yr grass/legume pasture- 2yr like CC. Sorghum and soybean grain were harvested, while ryegrass and perennial pastures were grazed with steers. Sorghum yield variation was registered with yield monitors, and field variation was assessed with intensive grid sampling for soil chemical analysis, terrain topographic attributes and soil electrical conductivity (EC); and analyzed for spatial autocorrelation. Relations between variables were analyzed with factor and regression analysis. No spatial autocorrelation was detected for any soil variable but EC. Terrain attributes and EC explained 77% of the site variation and determined 14-69% of yield variability. In 2005-06, yield spatial autocorrelation was not detected, and terrain attributes and EC relation with yield was weak (R^2=0.14 and 0.16 for CC and SR, and not significant for LR). However, in 2006-7 and 2007-08 dryer seasons, yield spatial dependence was strong (nugget/sill‹25%), with larger ranges in CC and SR than LR (165 vs 72m and 510 vs 125m, respectively). Terrain attributes relation with yield was stronger in SR than LR (R^2=0.46 vs 0.21; 0.69 vs 0.27 in 2006-07 and 2007-08, respectively). Sorghum yield spatial variability and its relation with soil and terrain attributes seem to be affected by previous pasture longevity. Grazing animal effects on soil-plant spatial variability should be further studied in crop-pasture rotations.

Keywords: sorghum, spatial autocorrelation, factor analysis, terrain attributes

INTRODUCTION

Soil properties and terrain attributes linked with water holding capacity and field-scale water regime are usually related to crop yield spatial variability (Kravchenko et al., 2003; Fraisse et al., 2001). Terrain attributes and grain yield data from multiple years could be used to identify and describe recurring spatial patterns in the fields to delineate management zones (Kaspar et al., 2003).

In the same way, in grazing systems, pasture yield and botanical composition are strongly influenced by rainfall distribution and topography (Marques da Silva et al., 2008). Moreover, direct grazing affects soil chemical and physical properties. Animal trampling compacts topsoil, reduces macroporosity at high stocking rates, increases soil bulk density and penetration resistance (Singleton and Addison, 1999; Kurz et al., 2006). Soil compaction limits root proliferation and leads to poor soil water utilization in deep soil layers (Martino, 2001). Excretal deposition near watering and resting areas concentrates soil content of N, P and K around these areas (West et al., 1989). This can increase soil nutrient losses in overland flow after grazing (Kurz et al., 2006).

There have been some efforts to study animal grazing preferences and its effects on soil nutrient distribution using GPS devices for animal tracking (Lamb et al., 2008; Dragamora et al, 2009). Research has focused on animal behavior and its consequences for pasture and livestock management. However, soil and terrain attributes relation with crop grain yield variability has not been assessed in crop-pasture rotations under grazing.

Crop-pasture rotations in Uruguay are traditional production systems (García-Préchac et al. 2004). The objective of this research was to determine the impact of soil landscape attributes on sorghum yield variability in three crop-pasture rotation systems under direct grazing.

MATERIALS AND METHODS

Site description and management practices

The field-scale study was conducted during 2005-06, 2006-07 and 2007-08 growing seasons at the 'Palo a Pique' experimental unit of the National Agricultural Research Institute (INIA) in Treinta y Tres, Uruguay (33°:15'36''S, 54°:29'26''W, 60-m elevation). Historical (1973-2008) mean annual rainfall and temperature at the site are 1375-mm and 16.6° C, respectively. According to the USDA-NRCS soil Taxonomy (Durán et al., 2005), soils were classified as Abruptic Argiaquolls and Oxyaquic Vertic Argiudolls (fine, smectitic and thermic) with an argillic horizon at 27-99 cm depth. The field had been under three contrasting no-till rotation systems since 1995 following regenerated native pasture vegetation.

The experiment evaluated the field-scale impact of three soil use intensities (rotations) on sorghum grain yield during three seasons. These rotations were part of a long-term experiment that had been implemented for 10 years when the experiment started. Rotations were based on a sorghum- soybean (*Sorghum bicolor-Glycine max*) sequence crop stage rotating with a pasture stage for grazing of different length: 1) Continuous annual cropping (CC) with a winter cover of *Lolium multiflorum* Lam. for grazing; 2) Short rotation (SR): two years of pasture (mixture of *Trifolium pratense* L. and *Lolium multiflorum*) and two years like CC and; 3) Long rotation (LR): four years of pasture (mixture of *Dactylis glomerata*, *Trifolium repens* L. and *Lotus corniculatus* L) and two years like CC. After the perennial pasture stage, a winter cover of *Lolium multiflorum* planted for grazing was the first annual species of the cropping phase before sorghum. All rotation entry points were present each year, except for CC, which had only one field. The CC field was planted either by sorghum or soybean in alternated years according to the cropping sequence.

Sorghum (DK39) was planted using a 6 line no-till drill at 250,000 viable seeds ha^{-1} in 0.40m rows on 17 Nov 2005, 15 Nov 2006 and 7 Nov 2007. Fertilization at planting was done with 22.5 kg N. ha^{-1}, 45 kg P_2O_5. ha^{-1} and 22.5 kg K_2O. ha^{-1} in 2005-06, and 22.5 kg N. ha^{-1}, 57.5 kg P_2O_5.ha^{-1} in 2006-07 and 2007-08 seasons. Urea was broadcast at growing point differentiation stage on each season at a rate of 46 kg N.ha^{-1} spread on the soil surface. Sorghum grain was harvested between March 15th and April 15th in all seasons.

Data collection and measurements

Each field consisted of three blocks, according to the topographic positions: summit, middle slope and toeslope. Each block was divided in a grid of 40 cells per block (20m x 7m cells) evenly distributed in 8 strips along the slope. This grid was used for point sampling of soil properties and crop variables.

Soil samples (0.15-m depth) were taken each year before planting and analyzed for soil organic carbon (dry combustion and infrared detection), phosphorous (citric acid), and potassium (NH4OAc extraction and atomic absorption), according to the laboratory methods described by Burt (1996). Sampling sites were evenly distributed through cells one to five in a stratified systematic unaligned sampling design (Woolenhaupt et al., 1997) allowing one sample at each strip of the block.

Soil electrical conductivity surfaces of all sites at 0-30 cm (EC30) and 0-91-cm (EC91) depths were obtained with a Veris® Tech 3100 soil sensor (Veris Tech. Salina, KS) equipped with a DGPS. Topographic position and sampling points were georeferenced with a DGPS (Trimble AgGPS® 132).

Sorghum grain yield was recorded and geo-referenced across the fields using a combine equipped with a DGPS (Trimble AgGPS® 132) and an Ag Leader PF3000 yield monitor (Ag. Leader Tech. Inc., Ames, IA). An elevation map with one meter interval contour from a traditional topographic survey of the area was georeferenced with a DGPS (Trimble AgGPS® 124/132) using ArcView 3.2 software (ESRI, Redlands, CA). Elevation data was interpolated using punctual ordinary kriging to generate a digital elevation model (DEM) using GS+, v. 5.1 (Gamma Design Software, Plainwell, MI, USA). The DEM was converted to a 5-m grid using Spatial Analyst 2.0a (ESRI, Redlands, CA).

Topographic wetness index (TWI), Stream Power Index (SPI) and Length-Slope Factor (L-S factor) were secondary compound attributes calculated with ArcView. These attributes are important to assess potential soil moisture and potential erosion. Scripts used for these calculations were developed by Schmidt (2003), based on equations by Moore and Wilson (1992) and Moore et al. (1993).

The TWI is calculated from the specific catchment area of a point and the local slope gradient. It is based on the assumption that topography controls the movement of water in a sloped terrain, and thus the spatial pattern of soil moisture. High values are found in converging, flat terrain. Low values are typical for steep, diverging areas (Schmidt, 2003).

$TWI = \ln(As/\tan\beta)$

Where:

As= specific catchment area

β=Slope

The SPI is proportional to stream power, and it is a measure of the erosive power of overland flow (Moore et al., 1993).

$SPI = \ln(As * \tan\beta)$

Where:

As= specific catchment area

β=Slope

L-S Factor is a sediment transport capacity index, derived as a function of specific catchment area and slope by Moore and Wilson (1992). It gives a value for the water erosion potential relative to a slope of 22.13 m length and a slope angle of 5º.

$LS\ Factor = (m+1)(As/22.13)^m\ (\sin\beta/0.0896)^n$

With m=0.4 and n=1.3 for a slope length <100 and a slope angle <14º

Where:

As= specific catchment area

β=Slope

m=slope-length exponent in the LS factor in the USLE

n=slope-angle exponent in the LS factor in the USLE

Data analysis

Rotation effects

Yield was analyzed as a complete block design with three replications where the topographic zones were used as pseudo blocks. Data were analyzed using mixed models (Littell et al., 1996) performed with SAS software PROC MIXED (SAS Inst., Cary, NC). For the overall mixed model, rotation systems were considered as fixed effects, while year and blocks were considered as a random effect. An F statistic was used to determine the significance ($p \leq 0.05$) of the fixed effects for all analysis.

Spatial autocorrelation

Soil properties, terrain attributes and yield data were analyzed for spatial correlation and interpolated using GS+, v. 5.1. Spatial structure was characterized constructing sample semivariograms $\gamma(h)$ with field data. The sample semivariogram describes spatial dependence among samples as a function of separation distance h. It is computed as half the average squared difference between the components of data pairs (Goovaerts, 1999), according to the equation 1 (Wollenhaulpt et al., 1997):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (z_i - z_{i+h})^2 \qquad (1)$$

where N(h) is the number of data pairs at a separation distance h, and z_i and z_{i+h} are the sample property values at two locations separated by a distance h. Semivariograms often increase in value as separation distances increases, and level off to nearly constant value at large separation distances. In this study, sample semivariograms were fitted with spherical variogram models defined by equation 2.

$$\gamma(h)= C_0 + C_1 [1.5(h/a) – 0.5(h/a)3], \quad \text{if } h \leq a \qquad (2)$$
$$\gamma(h)= C_0 + C_1 , \quad \text{if } h > a$$

where: h= lag class interval, C0 = nugget variance, C1= structural variance a = range parameter.

Samples separated by distances closer than the range are spatially dependent, while those separated by greater distances are spatially independent. With a spherical model, spatial correlation exists if the range a is grater than zero (Bhatti et al., 1991). The value of the semivariogram at the range is called the sill and usually corresponds to the sample variance (C_1). The nugget represents the variance due to variability of samples at separation distances smaller than the closest sample spacing (Wollenhaupt et al., 1997). A property exhibiting no spatial correlation will be best modeled by a linear model in which the slope is zero. This is known as pure-nugget model (nugget/sill=1), indicating that variability is completely random (Bhatti et al., 1991).

Semivariance models were first selected by visual fit and the regression coefficient of determination. Adequacy of the chosen model was tested using the cross-validation technique, were each data-point is deleted one at a time and estimated by kriging based on the remaining data (Myers, 1991). After modeling spatial variation, spatial dependence was classified as strong, moderate of weak, based on nugget/sill ratio. Classification criteria was based on Cambardella et al. (1994), who suggested that a nugget/sill ratio <25% indicated strong dependence, between 25 and 75% indicated moderate dependence, and >75% indicated weak spatial dependence.

Relationship between variables

Factor analysis was used to reduce the dimensionality of soil properties and terrain attributes data. SAS FACTOR procedure was performed using the Principal Component method based on the correlation matrix, and Varimax orthogonal rotation (Khattree and Naik, 2000). As a result from this analysis, variables are grouped so that correlation is large between variables within the same group, but it is small between variables from different groups. Each group is represented by a new variable created from the variables in the group, defined by a common factor that makes them vary together within a field. These new variables are called latent variables or factors. Their interpretation is based on agronomic knowledge of potential reasons for the observed co-variation and subjective judgment is involved (Mallarino et al., 1999, Khattree and Naik, 2000). In this experiment, new variables with eigenvalues greater than 1 were interpreted as latent factors.

Scores were calculated for these latent factors in each of the 192 cells containing complete soil data. Then, latent factors were used as independent variables in a multiple regression equation, where yield variation respect to the treatment mean was the dependent variable. Regression statistical analysis was performed for each year*rotation combination using stepwise regression in SAS ($p < 0.05$) (Freund and Littell, 2000).

RESULTS AND DISCUSSION

Rainfall

Precipitation amount and distribution differed considerably during the three seasons (Table 1). In 2005-06 no rains were registered from planting until the growing point differentiation stage, but well distributed rains during the growing point differentiation-soft dough stages (310 mm). In 2006-07 rainfall between planting-soft dough stages was only 185 mm. In 2007-08 events of rain and low temperature that followed planting delayed crop emergence in all treatments. Rains occurred at the stage of 6-8 leaves (160mm), but were low during bloom and grain filling stages (92mm).

Soil properties

Cropping systems that included perennial pastures had a significantly greater soil organic carbon content than CC ($p < 0.05$) in 2005-06 (14.2 vs 15.9 and 17.8 g. kg^{-1} average values for CC vs SR and LR, respectively) (Table 2). Rotations with perennial pastures phase of four years had a significantly greater organic carbon content than rotations including shorter perennial pastures (18.7 vs 16.3 g. kg-1 in 2005-06, 18.3 vs 16.5 g. kg-1 in 2006-07 and 16.4 vs 14.9 g. kg-1 in 2007-08 for LR vs SR, respectively). This was in agreement with results from a long term experiment in Uruguay, where crop rotations including pastures recovered most soil organic carbon lost by plowing during the cropping phase (García-Préchac et al. 2004). These results suggest that for Uruguayan Arguidolls, perennial pastures rotating with crops are necessary to preserve soil organic C even under no-tillage.

Table 1. Accumulated rain (mm) during each sorghum development stage since fallow until harvesting for the three seasons evaluated.

	Season		
Stage of sorghum development	2005-06	2006-07	2007-08
	--------------Rainfall (mm) ----------		
Fallow- Planting	110	53	221
Planting-Growing point differentiation	0	64	81
Growing point differentiation-Boot stage	141	54	160

Boot stage-Half bloom	79	23	62
Half bloom-Soft dough	90	44	30
Hard dough-Maturity	50	92	148
Maturity-Harvest	36	132	46

Table 2. Effect of 12 years of three crop-pasture rotation systems with different pastures duration on soil chemical properties (0.15 cm) in a no-till experiment in Uruguay.

	Org. C -g.kg^{-1}-			P(citric) -µg P/g-			K -meq/100g-		
	Year‡			Year‡			Year‡		
Rotation†	2006	2007	2008	2006	2007	2008	2006	2007	2008
LR	18.7a	18.3a	16.4a	10.8c	10.9b	14.8b	0.24a	0.22b	0.25a
SR	16.3b	16.5b	14.9b	13.8b	12.4a	16.0b	0.22b	0.24a	0.20b
CC	13.6c	--	14.8b	21.3a	--	25.1a	0.18c	--	0.24a

† Continuous cropping (CC): ryegrass-sorghum-ryegrass-soybeans; Short Rotation: two years idem CC and two years perennial pasture; Long Rotation (LR): two years idem CC and four years perennial pasture;

‡ Least square means followed by the same letter within a column are not significantly different at P ≤ 0.05 level.

Grain yield

Grain yield observed in each season was related to accumulated precipitation during the most water demanding crop development stages. The highest yield (8.15 Mg.ha^{-1}) was observed in 2005-06, when 310 mm of rain were accumulated from growing point differentiation until soft dough stages (Table 1). In 2006-07 yield was 43% lower than in 2005-06, and rainfall during these critical stages was 121 mm. In 2007-08 crop productivity was 26% lower than in 2005-06 and 252 mm of rainfall occurred in the same period (Table 3). These results emphasize the concept that water availability is the most important factor influencing grain yield in rainfed crops in Uruguay.

No consistent effect of soil use intensity was observed on grain yield over seasons (Table 3). Under favorable rainfall regime (in 2005-06); the highest yield was observed in CC and the lowest in LR (8.6 vs 7.74 Mg.ha^{-1}). Meanwhile, a slight tendency to higher yield was observed in SR respect to LR (8.12 vs y 7.74 Mg.ha^{-1}). In 2006-07, no differences in yield were observed between SR and LR. Finally, in 2007-08 no differences between rotations were detected at $p<0.05$, however, a strong trend to higher yield was observed in SR ($p<0.1$) compared with LR and CC (15 and 23%, respectively).

Table 3. Rotation systems and year effects on sorghum yield in a field-scale experiment in Uruguay.

	Growing season		
Rotation	2005-6†	2006-7†	2007-8†
	---Mg.ha^{-1}---		
Continuous Cropping	8.60 b	--	5.49 a
Short Rotation	8.12 ab	4.76 a	6.77 a
Long Rotation	7.74 a	4.52 a	5.88 a
Mean‡	8.15 C	4.64 A	6.05 B

†Least square means values followed by the same letter within a column are not significantly different at P ≤ 0.05 level

‡Least square means values followed by the same captial letter within a row are not significantly different at $P \leq 0.05$ level

Yield spatial structure

Yield spatial structure was affected by season and rotation. In 2005-06, spatial autocorrelation was not detected, while in 2006-7 and 2007-08 strong spatial dependence was detected in all rotations (Fig.1).

Semivariograms for all rotations in 2005-06 showed pure nugget effect. In 2006-07 season, yield data from LR and SR had a nugget/sill=1.3% and 21.4%, respectively. Among rotations, LR showed smaller spatial correlation range (72 vs 165m in SR). In 2007-08, yield spatial correlation was stronger than in 2006-07 in all rotations; with grater nugget/sill ratios (0.1, 0.5 and 0.4% for LR, RC and CC, respectively) and larger spatial correlation ranges. Autocorrelation range was similar in SR and CC, but larger than in LR (510m vs 125m, respectively).

Temporal variation between seasons was associated to differences in accumulated rainfall (Table 1). Temporal variation in water availability affected yield spatial variability. While in 2005-06 favorable rainfall conditions did not restrict yield potential and masked spatial patterns; drought and intermediate rainfall in the second and third growing seasons let the crop performance show dependence on field attributes.

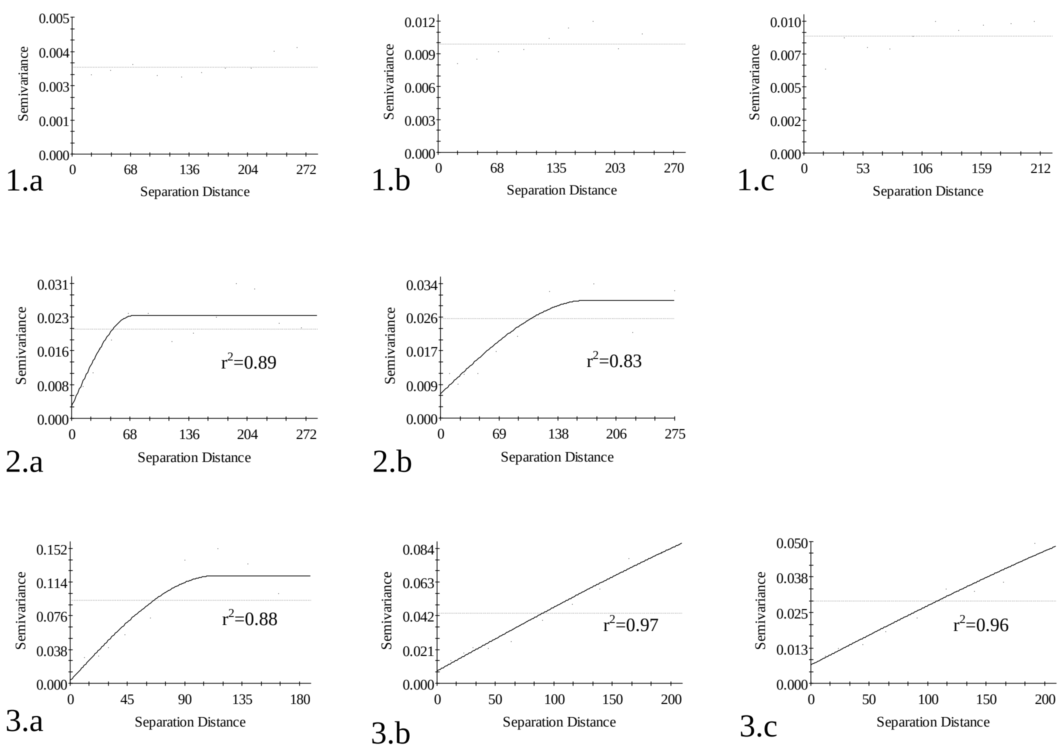

Fig.1. Isotropic semivariograms for sorghum grain yield Normalized residuals; 1. 2005-06, 2. 2005-06 and 3. 2005-06 growing season; a. After long term pasture. b. After short term pasture. c. In continuous cropping system.

Spatial variability of soil properties, terrain attributes and relation with yield

Soil chemical properties showed no significant spatial autocorrelation at the site for any rotation*year combination. Semivariance was not successfully modeled as a function of distance for organic carbon, phosphorous or potassium soil content. Then, no homogeneous zones for N, P or K could be outlined based on the soil sampling grid used. Spatial variability of soil properties has been extensively reported for different cropping systems around the world (Kerry and Oliver, 2004, Kravchenko et al., 2006). However, few reports were found in pasture systems (West, 1989, Su et. al., 2006, Zhao et al., 2007), and no reports were found that consider crop-pasture rotation systems under direct grazing, which are traditional in Uruguay.

Nutrient redistribution dynamics through animal feces and urine is widely known in pasture systems. The stock camping activities of grazing animals result in an increase of fertility and biological activity in soils from camp areas at the expense of these properties on the main grazing areas (West et al., 1989; Iyyemperumal et al., 2007). The interaction between these nutrient redistribution effects of grazing animals with soil chemical nutrients spatial patterns occurring in crop-pasture rotation systems has not been assessed. In this context, the fact that no spatial structure was detected in soil chemical properties in our experiment using an intense sampling grid suggests that such interactions should be further investigated.

Soil apparent electrical conductivity measurements identified a zone of high values in the CC rotation field (Fig.2a). Considering the known relation between EC values and soil salinity (Corwin and Lesch, 2005a and b), this may identify a patch of saline soil in the field. Elevation at the experimental site ranged from 47.8 to 61.6 m (Fig.2b). Fields were situated transversing the topography gradient, thus every terrain condition was present in each year-rotation combination. The TWI maps indicated zones of high potential of soil moisture (high TWI) and zones that dry up first (lower TWI) (Fig.2d). Experimental fields had similar TWI, ranging between 7.6-10.2, with the higher values at the summit. The SPI and LS-Factor maps showed areas of essentially no risk of erosion (SPI and LS-factor =0.0-0.2) representing a minor area in the experimental fields, dominated by zones with higher erosion potential (SPI > 0.44 and LS-Factor >0.50) (Fig.2e and 4f). High elevation areas consisted of flat summits with high TWI and low SPI and LS-Factor scores, corresponding with poorly drained patches in the fields, and Argiaquolls mapping position (Fig. 4c). Middle and toeslope topographic positions had moderate slope, and consequently better drainage that corresponds to moderate TWI, and higher SPI and LS-Factor, but also determining higher risk of erosion (Fig.2 d, e and f), that corresponded to soil classification mapping positions of Argiudolls (Fig.2c).

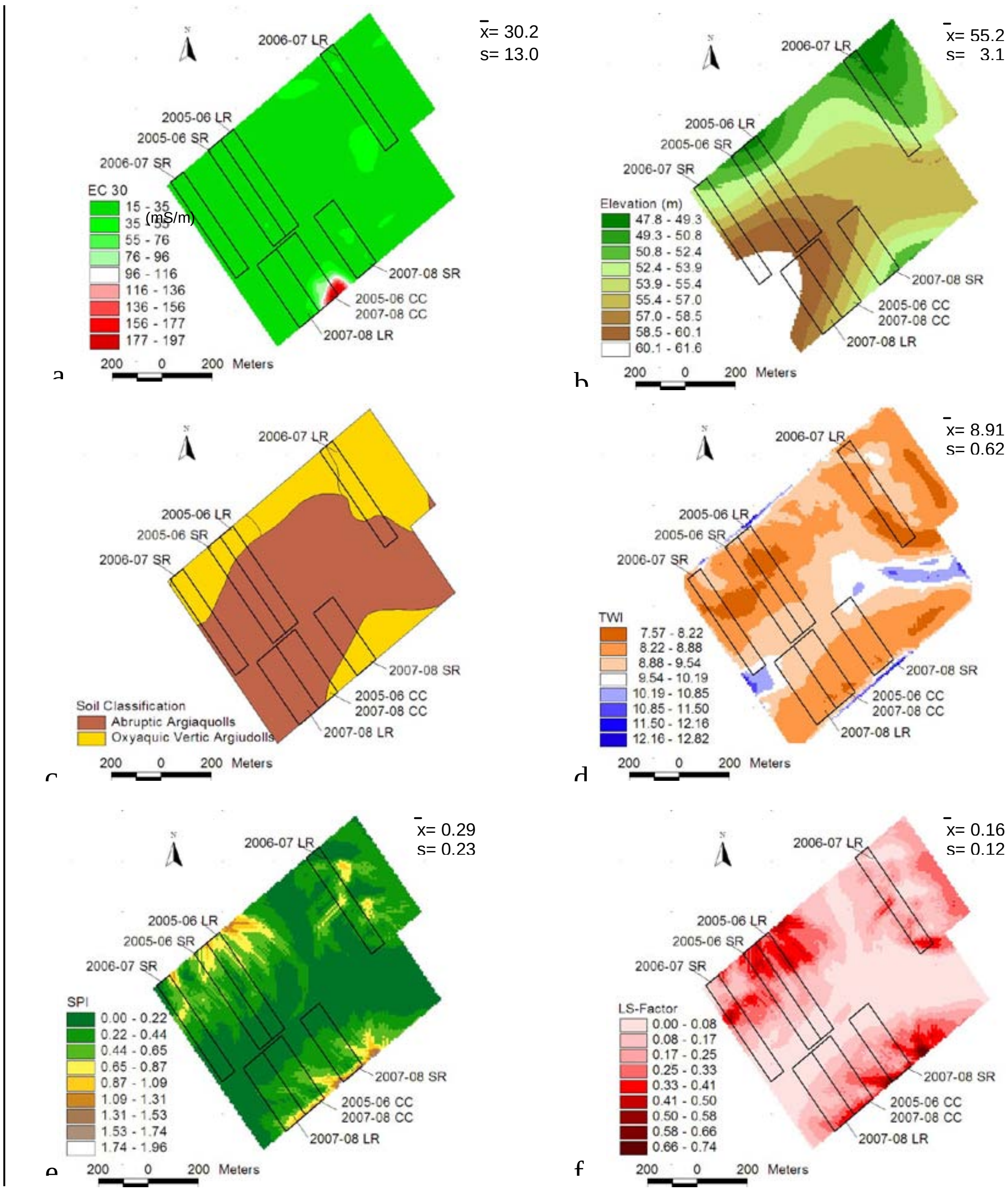

Fig.2. Terrain attributes and soil classification at the experimental site for eight year*rotation combination. (a) Electrical Conductivity at 30cm depth (EC 30), (b) Soil classification, (c) Elevation, (d) Topographic Wetness index (TWI), (e) Stream Power index (SPI), and (f) Length-Slope Factor (SL-Factor).

Integrating soil properties and terrain attributes in the factor analysis resulted in four latent factors with eigenvalues grater than 1, which explained 77% of the experimental site variation (Table 4). The first factor revealed that variation was grouped in the first place by terrain attributes associated to field drainage and risk of erosion. It was named "Drainage", and it explained 25% of total variation.

Table 4. Rotated latent factors names, loadings and variance explained for measured soil properties and terrain attributes in a field scale experiment in Uruguay.

Latent factor number and name	Factor 1- Drainage	Factor 2- Salinity	Factor 3- Texture	Factor 4- Textural differentiation	Total
	--------------------Coefficients--------------------				
Elevation	-0.74	0.17	-0.04	0.30	
TWI	**-0.86**	-0.13	-0.03	-0.10	
SPI	**0.84**	0.09	-0.02	-0.14	
L-S	**0.95**	0.09	0.00	-0.02	
EC 30	0.20	**0.87**	-0.06	-0.38	
EC 30-91	0.15	**0.88**	-0.15	0.30	
EC0-91 /EC30	-0.12	-0.17	0.01	**0.92**	
pH	0.21	**0.82**	-0.04	-0.33	
OrgC.	0.29	-0.52	0.61	-0.19	
P	-0.39	0.63	-0.09	0.00	
K	0.07	-0.06	0.63	-0.34	
Sand	0.20	-0.04	**-0.81**	-0.21	
Clay	0.06	-0.15	**0.89**	0.08	
Eigenvalue	3.29	2.97	2.25	1.51	10.02
Variance explained	0.25	0.23	0.17	0.12	0.77

Shallow and deep soil EC and pH were the major components of the second factor, which explained 23% of the variation. Given the known relationship between these variables and soil salinity (Corwin and Lesch, 2005a and b), this factor was named “Salinity”.

The third factor was associated to clay levels, and was named “texture”. The forth latent factor was associated to deep/shallow EC ratio, probably indicating the degree of clay concentration of the argillic horizon respect to the soil superficial horizon, and was named “textural differentiation”.

Latent factors explaining most of the field variation were determined by variables showing similar mapping to soil classification. Variables with greatest influence on the first latent factor had contrasting mapping areas at the summit, and middle and toe slope areas, consistent with soil classification mapping units of Argiaquolls and Argiudolls (Fig.2). None of the latent factors explaining most of the field variation was determined by soil nutrients. This may indicate that soil variation is not determined by the effect of a few variables but by complex interactions between them, that were better identified by the assessment of terrain attributes than by nutrient chemical analysis alone.

Latent factors relation with yield was affected by season and rotation. Results varied from no significant association detected, to a maximum Pearson correlation coefficient of 0.79 (Table 5).

In the 2005-06 season, no consistent association was found between any of the latent factors and yield. Rainfall conditions determined high yield with random spatial distribution (Fig.1) that was not significantly associated with field properties (Table 5).

Table 5. Regression statistics form stepwise procedure estimating yield as a function of latent factors, for each year - rotation combination evaluated.

				Regression estimates		Model		
Year	Rotation†	Latent Factor	Pearson r	Parameter	Partial R^2	Intercept	R^2	P
2005-06	CC	2-Salinity	-0.39	-252	0.16	8808	0.16	0.0574
	SR	2-Salinity	-0.37	-697	0.14	7927	0.14	0.0732
	LR		ns				ns	
2006-07	SR	1-Drainage	0.58	479	0.34	4686	0.46	0.0016
		3-Texture	-0.28	-583	0.12			
	LR	1- Drainage	0.45	737	0.21	4137	0.21	0.0343
2007-08	CC	2-Salinity	-0.77	-569	0.59	5995	0.59	0.0001
	SR	4-Textural differentiation	0.79	1087	0.63	6783	0.69	<.0001
		3-Texture	-0.48	-455	0.06			
	LR	3-Texture	0.52	933	0.27	6361	0.27	0.0093

† Continuous cropping (CC): ryegrass-sorghum-ryegrass-soybeans; Short Rotation (SR): two years idem CC and two years perennial pasture; Long Rotation (LR): two years idem CC and four years perennial pasture.

Drought in 2006-07 increased crop dependence on soil attributes, and yield spatial autocorrelation was detected (Fig.1), while latent factors were significantly associated with yield (Table 5). "Drainage" latent factor was positively correlated with yield in both SR and LR (r2=0.58 and 0.45, respectively). Argiudoll mapped areas were located on medium and toe-slope areas with low TWI and high SPI and LS-factor values (Fig.2), which were major components of "Drainage" latent factor. This suggests Argiudolls were associated to higher yields than Argiaquolls.

In 2007-08, most of yield variation in SR was explained by "Textural differentiation" (r=0.79 and partial R^2=0.63). "Salinity" was negatively correlated with CC yield (r=-0.77) and "Texture" was correlated with LR yield (r=0.52). Latent factors in 2007-08 season explained 69%, 59% and 27% of yield variation in SR, CC and LR, respectively. These relations were stronger than the ones found in the 2006-07 season, where 34 and 21% of the yield variability was explained for SR and LR, respectively. Average rainfall conditions in 2007-08 season determined greater crop yield than in 2006-07, stronger yield spatial variability detected (Fig.1), and also stronger association between yield and latent factors than in 2005-06 and 2006-07 (Table 5). When soil water availability was not as limiting as in 2006-07, crop productivity probably depended on other soil properties as well, and expressed these differences in soil properties in grain yield. These results agree with Kravchenko et al. (2003), who reported that the range of significant spatial correlations between yield and soil EC and topographic attributes was related to precipitation data.

Latent factors relation with yield was stronger in SR than in LR in both seasons (R^2= 0.46 vs 0.21 and 0.69 vs 0.27 for SR vs LR in 2006-07 and 2007-08, respectively), agreeing with larger spatial autocorrelation range of yields on SR relative to LR in those seasons (165 vs 72m and 510 vs 125m, respectively) (Fig.1). These results suggest that pasture phase duration in the system may have affected yield spatial dependence and its relation with soil and terrain attributes. Therefore nutrient spatial distribution through grazing animals on the pasture phase should be studied.

CONCLUSIONS

Temporal variation associated with differences in seasonal rainfall was the first factor determining yield, its spatial variation, and its relation with soil and terrain attributes. Soil water availability and its distribution through landscape are major determinants of sorghum grain yield in rainfed crop-pasture systems of Uruguay.

Soil nutrients showed no spatial autocorrelation, implying that no homogeneous zones could be delimited in terms of soil nutrient availability at the sampling intensity used in this study.

Field variation was mostly explained by terrain attributes and EC, rather than by soil chemical properties. None of the latent factors explaining most of the field variation was determined by soil nutrients. Terrain attributes and EC explained 77% of the site variation and determined 14-69% of yield variability.

Sorghum yield spatial variability and its relation with soil and terrain attributes seem to be affected by previous pasture longevity. Data suggest that grazing effects on soil dynamics impact yield spatial patterns in crop-pasture rotations. These findings set new challenges for precision agriculture research.

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