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Analysis of rainfall distribution on spatial and temporal patterns of wheat yield in Mediterranean environment

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ABSTRACT

Wheat yield production in Mediterranean environment is highly affected by rainfall and amount of soil water stored into the soil before and during the growing season. Agricultural fields have been always considered as uniform entities and managed accordingly. However, uniform agronomic management in fields where spatial variability is present, is economically and environmentally inefficient. The objectives of this study were to: (i) identify spatially and temporally stable areas throughout the field, (ii) understand the influence of fallow and growing season rainfall on spatial and temporal variability of wheat yield. The study was carried out on a 12 ha field located in Foggia, Southern Italy during five years wheat monoculture. One hundred geo-referenced points were sampled for deriving spatial maps of soil texture and organic carbon. Spatial maps of grain yield, normalized difference vegetation index (NDVI), soil electrical resistivity tomography (ERT) were collected non-destructively. Total growing season rainfall was correlated with grain yield after dividing it into long fallow (June–November), short fallow (September–November), growing season (December–May), vegetative (December–February), reproductive (March–May). The spatial maps were used to define spatial and temporal yield variability and to identify three stable zones within the field, "low yield stable" (LS), "average yield stable" (AS), "high yield stable" (HS). Long and short fallow rainfall was highly correlated with grain yield of HS zone with correlation coefficients ranging between 0.5 and 1. Growing season rainfall was mostly correlated with the AS zone. The crop response to rainfall was a result of dynamic interaction of spatial static properties such as soil texture, position in the landscape and dynamic properties (soil water content, infiltration and crop water use).

1. Introduction

Wheat yield production in Mediterranean environment is highly affected by rainfall and amount of soil water stored in the soil before the growing season and soil water availability during the growing season (Boyer, 1982; Unger et al., 2006). Since Mediterranean environments show high variability in rainfall patterns, the amount of initial soil water content can be as important as the growing season rainfall for establishing adequate levels of wheat yield (Angus et al., 1980; Sadras, 2002). Adequate rainfall before sowing provides proper condition for good seed germination and enough supply of water for later growth. A low rainfall and low soil water content at sowing slows or stops the process of germination reducing the percentage of germination hence planting density (Passioura, 2006). Asseng and Van Herwaarden (2003) reported that rapid plant establishment and early vigour are optimal for reaching adequate wheat yield. In fact, the amount of rain after sowing influences the production of roots, tillers and an adequate leaf area. Large values of leaf area index (LAI) obtained through better management and cultivars reduce soil evaporation and enhance transpiration increasing growth, dry matter production and water use efficiency (Acevedo et al., 1991; Richards, 2006; Ritchie and Basso, 2008). However, if plants used too much water before flowering and are too vigorous, a subsequent water stress caused by lower rainfall levels cause premature crop senescence and low yield or often poor quality grain, because plants set a large number of seeds but cannot produce enough carbohydrate to fill all of them (Van Herwaarden et al., 1998; Angus and van Herwaarden, 2001; Basso et al., 2011a,b). Wheat yield response to stored soil water varies according to the site and the soil type (Anderson, 2010). In the United States, it ranges between 4 and 9.5 kg ha^{-1} for mm of rain stored in the soil during low rainfall years and around 14 kg ha^{-1}

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in wet years (Norwood, 2000; Nielsen et al., 2002). In Australia the yield increase for each mm of available soil water at sowing ranges between 8 and 18 kg ha^{-1} (Kirkegaard et al., 2001; Sadras, 2002).

Agricultural fields have been always considered as uniform entities and managed accordingly. However, uniform agronomic management in fields where spatial variability is present, is economically and environmentally inefficient (Pierce and Nowak, 1999; Basso et al., 2011a). Alternative crop management is to divide the field areas of similar behavior, following several criteria based on technologies and principles that help to manage spatial and temporal variability. This will give farmers the chance to increase benefits by improving yield, reducing costs and minimizing environmental impact (Basso et al., 2011b).

In Mediterranean environments the benefit of managing the field in zones can only be achieved by dividing the fields in areas that are consistent in yield performance (Robertson et al., 2005). Wheat yield is spatially variable as a result of the interaction between static properties (factors affecting the yield at field scale). Yield maps produced by the yield monitor systems are evidence of the degree of within-field variability, and that patterns of yield variability within a field differ from year to year (Basso et al., 2009). Kaspar et al. (2003) related six years of corn yield data with soil attributes. They found that in four years, where rainfall was lower than the average, corn yield showed negative correlations with elevation, slope and soil curvature, and in the two years with abundant rainfall, the yield was positively correlated with those parameters. Kravchenko et al. (2005) found that the coefficient of variation increased in years with low rainfall (45%) and decreased in years with high rainfall (14%). Therefore, the effect of weather patterns on both crop growth and development and its interaction with soil type causes bias in the assessment of homogeneous management zones (Basso et al., 2009). The delineation of zones based on remotely sensed images confirms large differences in canopy growth that lead to yield variability (Basso et al., 2001; Basso et al., 2007). Such images taken during key growing stages might help to characterize the spatial variability of crops and delineate areas with similar response. Robertson et al. (2007) using spatial information from remote sensing and soil attributes at whole-farm and catchment scale showed the presence of spatial patterns of soil-landscape useful to identify areas with both low productivity and excessive nitrate leaching. The overlay of long-term yield spatial maps allows for the identification of stable zones, spatially and temporally, which is a fundamental prerequisite for adopting variable rate technologies (Basso et al., 2007).

In this study we hypothesized that in season rainfall distribution along with spatial variability of soil properties, mainly soil texture, soil depth and soil organic matter, affects the spatial and temporal patterns of wheat yield. The objectives of this study were to (i) analyze rainfall distribution for assessing spatially and temporally stable zones (ii) understand the influence of fallow and growing season rainfall on spatial and temporal variability of wheat yield.

2. Materials and methods

2.1. Site description and agronomic management

The study was carried out on a 12 ha field located in Foggia, Italy (41° 27′ 47″ N, 15° 30′ 24″ E; 80 m a.s.l.) during five years wheat monoculture (2005/06; 2006/07; 2007/08; 2008/09; 2009/10). The soil is a deep silty-clay Vertisol of alluvial origin, classified as fine mesic Typic, Chromoxerert (Soil Survey Staff, 1999).

The crop planted each year was durum wheat (*Triticum turgidum*, *var. Durum*) cultivar Duilio. Every season the seedbed was prepared in September with a minimum tillage (chisel plow) at a depth of 20 cm. The sowing was carried out for each of the five

Table 1
Monthly rainfall for the season 2005/06; 2006/07; 2007/08; 2008/09; 2009/10 and average rainfall for fallow period (June–November) and growing season (December–May). In this table is also reported the number of days in each month in which the rainfall (R) was greater than 15 mm.

	2005/06			2006/07			2007/08			2008/09			2009/10		
	Average R[a] (mm)	$5<R<15$[b] (# days)	$R>15$[c] (# days)	Average R (mm)	$5<R<15$ (# days)	$R>15$ (# days)	Average R (mm)	$5<R<15$ (# days)	$R>15$ (# days)	Average R (mm)	$5<R<15$ (# days)	$R>15$ (# days)	Average R (mm)	$5<R<15$ (# days)	$R>15$ (# days)
June	70	1	2	42	1	1	41	1	1	44	2	1	65	2	2
July	2	0	0	14	1	0	4	0	0	5	0	0	8	1	0
August	48	1	1	27	3	0	0	0	0	0	0	0	2	0	0
September	39	1	1	71	4	1	20	1	0	40	2	0	61	1	2
October	56	2	1	0	0	0	91	3	2	13	1	0	100	4	3
November	61	3	1	21	2	0	51	1	1	120	5	2	47	2	1
December	180	3	5	38	3	0	48	0	1	117	5	2	73	6	0
January	30	3	0	16	2	0	16	0	0	154	6	3	70	3	1
February	84	0	3	52	4	0	9	1	0	25	1	0	75	2	2
March	75	2	2	54	0	1	86	2	2	154	7	3	48	2	1
April	53	2	1	39	2	1	50	4	0	99	6	2	52	3	2
May	9	0	0	37	1	1	28	3	0	17	1	0	41	3	0
Tot[d]	706	18	17	413	23	5	444	16	7	785	36	13	643	27	14
FA[e]	275	8	6	176	11	2	207	6	4	221	10	3	283	10	8
GS[f]	432	10	11	237	12	3	237	10	3	564	26	10	360	17	6

[a] Average R = average rainfall.
[b] $5<R<15$ = days in which rainfall is between 5 and 15 mm.
[c] $R>15$ = days in which rainfall is higher than 15 mm.
[d] Tot = total rainfall (fallow + growing season).
[e] FA = fallow rainfall.
[f] GS = growing season rainfall.

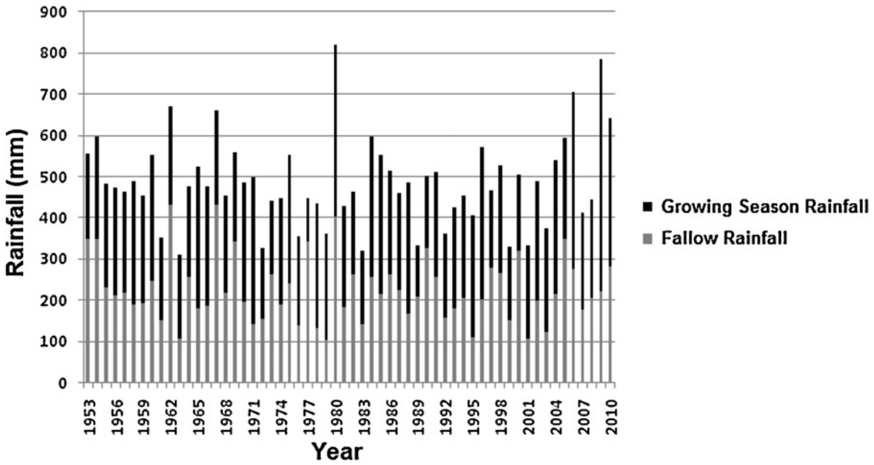


Fig. 1. Mean rainfall in mm (bars) for the 58 studied years during the fallow period (June–November) and the growing season (December–May).

years the first week of December at a depth of 5 cm with 17 cm distance between the rows and with a density of 400 plants m^{-2}. The nitrogen (N) fertilization consisted in two split applications, one at sowing with 25 kg N ha^{-1} as diammonium phosphate and another at tillering with 65 kg N ha^{-1}as urea. The crop was harvested between the second and the third week of June for the five years. Weather data were recorded by an on-site station for the last 58 years. Growing season rainfall and fallow rainfall from 1953 to 2010 are reported in Fig. 1. Detailed monthly rainfall average for the five growing seasons are reported in Table 1.

2.2. Field measurements

One hundred georeferenced locations were selected randomly, on a grid based layout, so observations were evenly distributed on the investigated scene, using a simulated annealing approach (Van Groenigen and Stein, 1998; Cochran, 1977). This process solved the problem of finding a global minimum in the presence of several local minima.

Soil samples were taken, at each selected location, to 30 cm depth prior sowing in 2005 for determination of soil texture and soil organic matter. Sand, silt, and clay contents were determined with the hydrometer method (Klute and Dirkens, 1986). Soil electrical resistivity tomography (ERT) measurements were taken by the Automatic Resistivity Profiling, a multi-probes system mounted behind a four-wheeler motorbike; details about the ERT procedures are reported in Basso et al. (2010). The ERT was taken at three depths in the vertical dimension (0–50; 0–100 and 0–200 cm) and every 20 cm on the horizontal dimension.

Georeferenced yield data were recorded by a John Deere combine equipped with a yield monitor system (grain mass flow and moisture sensors). The data were acquired along 6 m wide parallel transects. Site coordinates for each yield measurement were determined with a differentially corrected (OMNISTAR signal) Trimble 132 receiver with centimeter accuracy. The SMS software version 3.0TM (AgLeaderTM Technology, Inc.) was used to read the raw yield data (expressed at 13.5% dry matter). The average distance between two successive acquisitions was about 2 m. After downloading, yield data were processed to eliminate unrealistic and outlier yield values lower than 0.5 t ha^{-1} and greater than 6 t ha^{-1}. The five years yield maps were obtained by plotting the yield data, elaborated by linear interpolation, at the nodes of a regular grid of 5 m spatial resolution. The yield maps were, then, georeferenced and recorded in UTM WGS 84 zone 33N. Geostatistical analyses were carried out using GS+ software v 5.3^{TM} (Gamma Design Software, 1999). A digital terrain model (DTM) of the studied area was extracted from Apulia Region DTM maps at the spatial resolution of 8 m (http://www.cartografico.puglia.it/portal/sit_cittadino/Documenti/DTM).

2.3. Remote sensing measurements

Remote sensing images were acquired from 2007 to 2010 to study the correlation between remotely sensed vegetation indices and wheat grain yield. During 2007 and 2008 airborne multispectral images (TerraSystem Srl., Viterbo, Italy) were acquired at the spatial resolution of 1 m with three spectral bands, Green, Red and Near InfraRed (NIR) region of the electromagnetic spectrum. Two images were acquired during both years in April and May. In 2009 and 2010 a time series of satellite images were acquired from RapidEye (www.rapideye.de) at the spatial resolution of 5 m and with five spectral band, Blue, Green, Red, Red-Edge and NIR region of the electromagnetic spectrum. The spectral bands were used to calculate the normalized difference vegetation index (NDVI, Rouse et al., 1974) as reported:

$$\text{NDVI} = \frac{(\text{NIR} - \text{RED})}{(\text{NIR} + \text{RED})} \quad (1)$$

where NIR was the wavelength in the near infrared portion of the spectrum (760–880 nm) and RED was the wavelength in the red portion of the spectrum (630–690). The remote sensing images were georeferenced and registered in UTM WGS 84 zone 33N.

2.4. Methodology for delineating homogeneous zone

The spatial variability of yield from 2006 to 2010 was analyzed by calculating the relative percentage difference of yield crop from the average yield level obtained within the field at each point mapped (Blackmore, 2000), according to the following equation:

$$\bar{y}_i = \frac{1}{n}\sum_{k=1}^{n}\left[\frac{y_{i,k} - \bar{y}_k}{\bar{y}_k} \times 100\right] \quad (2)$$

where n is the total number of studied years and $k = 1,\ldots,n$ is an integer corresponding to each year from 2005/06 to 2009/10 respectively, $\bar{y}_i$ is the average percentage difference at location i, $\bar{y}_k$ the average yield (kg ha^{-1}) obtained for the complete field at year k, $y_{i,k}$ the yield (kg ha^{-1}) monitored at location i at year k. The zones that show high values of $\bar{y}_i$ are associated to high yield, while the zones with low $\bar{y}_i$ values are defined as low yield zone.

Pringle et al. (2003) argued that to overcome the limits of the coefficient of variation the temporal variability of yield patterns, expressed as degree of stability, should be calculated as temporal variance (yield value recorded at each point mapped minus the field mean). Temporal variance calculation was based on the following equation (Blackmore et al., 2003):

$$\bar{\sigma}_i^2 = \frac{1}{n}\sum_{k=1}^{n}\left(y_{i,k} - \bar{y}_{i,n}\right)^2 \tag{3}$$

where $\bar{\sigma}_i^2$ is the temporal variance value at location i, $y_{i,k}$ the yield (kg ha^{-1}) monitored at location i at year k, $\bar{y}_{i,n}$ the average yield over the n years. The temporal variance may change considerably within a field by slightly changing the threshold used to determine the stable zone, as reported by Blackmore (2000).

To overcome the problem of threshold computation an unsupervised *k-means* clustering technique was applied to the spatial (Eq. (2)) and temporal (Eq. (3)) variability layers. The procedure follows a simple way to classify a given data set through a given number of clusters fixed a priori (Duda and Hart, 1993).

2.5. Correlation analysis

Once the homogeneous areas were identified with the procedure illustrated above, a correlation analysis was carried out between yield and rainfall. The total rainfall was divided into fallow and growing season rainfall. The fallow rainfall was sub-divided in two periods, long fallow (June–November), and short fallow (September–November). Growing season rainfall (December–May) was sub-divided into vegetative rainfall (December–February) that corresponds to the rainfall period from sowing to end of tillering, and reproductive rainfall (March–May) that is the rainfall period between stem elongation and maturation. These rainfall periods were correlated to grain yield of each zone through the Pearson's coefficients using calculated with Matlab7.7. Spatial maps were created using ArcGis10. Fig. 1 shows the long term meteorological data from 1953 to 2010. The long term rainfall pattern showed the presence of an extremely wet or dry year during the 5 studied years. Table 1 reports the last five years of weather data.

3. Results

3.1. Yield data

Spatial maps of wheat grain yield for the five years are reported in Fig. 2. Overall, wheat yield varied between 500 and 5000 kg ha^{-1}. In 2005/06, low yield production was recorded in the upper right area of the field and on transect that cuts diagonally the middle section of the field, while a higher yield was recorded in the lower part of the field. In 2006/07 grain yield was generally low throughout the field with average values of 1145 kg ha^{-1}, the transect area and the upper right portion showed higher yield than the rest of the field (Fig. 2b). In 2007/08 the upper right portion of the field showed a higher yield than the previous years. In 2008/09 and 2009/10 the spatial pattern of grain yield resembled the one observed in 2005/06, with the lower part of the field showing consistently higher yield values (Fig. 2d–e). In 2009/10 the yield along the transect area and in the upper right part of the field was higher than in 2008/09 and 2005/2006.

3.2. NDVI, soil texture and ERT data

Maps of remotely sensed NDVI are shown in Fig. 3a–d. The NDVI maps showed spatial patterns that are similar to the yield maps. During each experimental year, NDVI values were higher in the lower portion of the field. Because of the different satellite images spatial resolution and the different acquisition platform it was necessary to calibrate and correct the satellite images taking into account the atmospheric correction. The 2005/06 and 2006/2007 NDVI maps (1 m spatial resolution) were reported to the same spatial resolution of the satellite images by linear interpolation, at the nodes of a regular grid of 5 m spatial resolution. Fig. 3 shows the NDVI May images for the four experimental years. Images were acquired at the same phenological stages throughout the years. For the growing season 2006/07 the NDVI values showed the highest variability ranging between 0.06 and 0.66 (Fig. 3a). The spatial distribution of soil physical properties is shown in Fig. 4a–d. Clay content varied between 8 and 48% with high values in the bottom and mid portion of the field (Fig. 4a). Silt content varied between 34 and 54% and it was higher in the upper right portion of the field (Fig. 4c). Sand content showed a variation between 14.8 and 44.3% with higher values in the top portion of the field (Fig. 4c). Organic matter ranged from 1.6 to 2.3% with highest values in the top right portion of the field and the mid-lower left portion of the field (Fig. 4d).

The spatial maps of the ERT at two different depths are shown in Fig. 5a–b. The resistivity results associate with soil texture analysis allowed for a better discrimination of areas within the field. The lower portion of the field showed a deep clay profile with no significant resistivity signals up to 100 cm, except for a few areas of the field with the presence of coarse fraction (small gravel and stones) in the first 50 cm (Fig. 5a). The upper portion of the field is characterized by a shallow clay profile followed by a compact layer of soil after the first 50 cm as shown by the ERT map (Fig. 5a–b). This zone has a shallower depth of exploitable soil volume due to shallower top layer. The DTM map showed that the field elevation varied between 79.8 m and 85.5 m with four distinct areas of different elevations with the upper portion of the field being on average 5.6 m lower than the higher point in the field, the latter located in the southern portion of the field (Fig. 6). The southern portion of the field showed an elevation ranging between 83.8 and 85.5 m, the mid lower portion between 82.5 and 83.8 m (Fig. 6). The mid-upper and upper portions (northern part) of the field have an elevation that ranged between 81.3 and 82.5 and 79.8 and 81.3, respectively (Fig. 6).

3.3. Delineation of spatial and temporal stable zones

The spatial stability map (determined by applying Eq. (2)) and the temporal stability map (obtained with $\sqrt{\bar{\sigma}_i^2}$ from Eq. (3)), are shown in Fig. 7a and b, respectively. The spatial variability ranged between −35 and 50 with high values in the mid-low portion of the field and low values in the bottom portion of the field (Fig. 7a). Temporal variability showed a range between 112 and 1400 (kg ha^{-1}), with high temporal variability in the northern part of the field and low at the southern part of the field (Fig. 7b). Spatial and temporal stable zones are shown in Fig. 7c. Four homogeneous zones were identified in the field; the first homogeneous zone has been defined as "Unstable" (U) since in this area the temporal stability values are the highest of the field and greater than 1000 kg ha^{-1} yr^{-1}. The remaining areas of the field have been divided into three stable zones over time. The first one was called "High yielding and Stable" (HS) and it is shown in red in Fig. 7c, the yellow zones in Fig. 4c was characterized by values of spatial stability close to 0, which is the case of small yield fluctuations around the yearly total average yield of the field. This area was defined as "Average yield and Stable zone" (AS) (Fig. 4c, yellow zone). The third zone, defined as "Low yield and stable" (LS) is a marginal part of the field, it includes the boundaries strips in the middle part of the field and

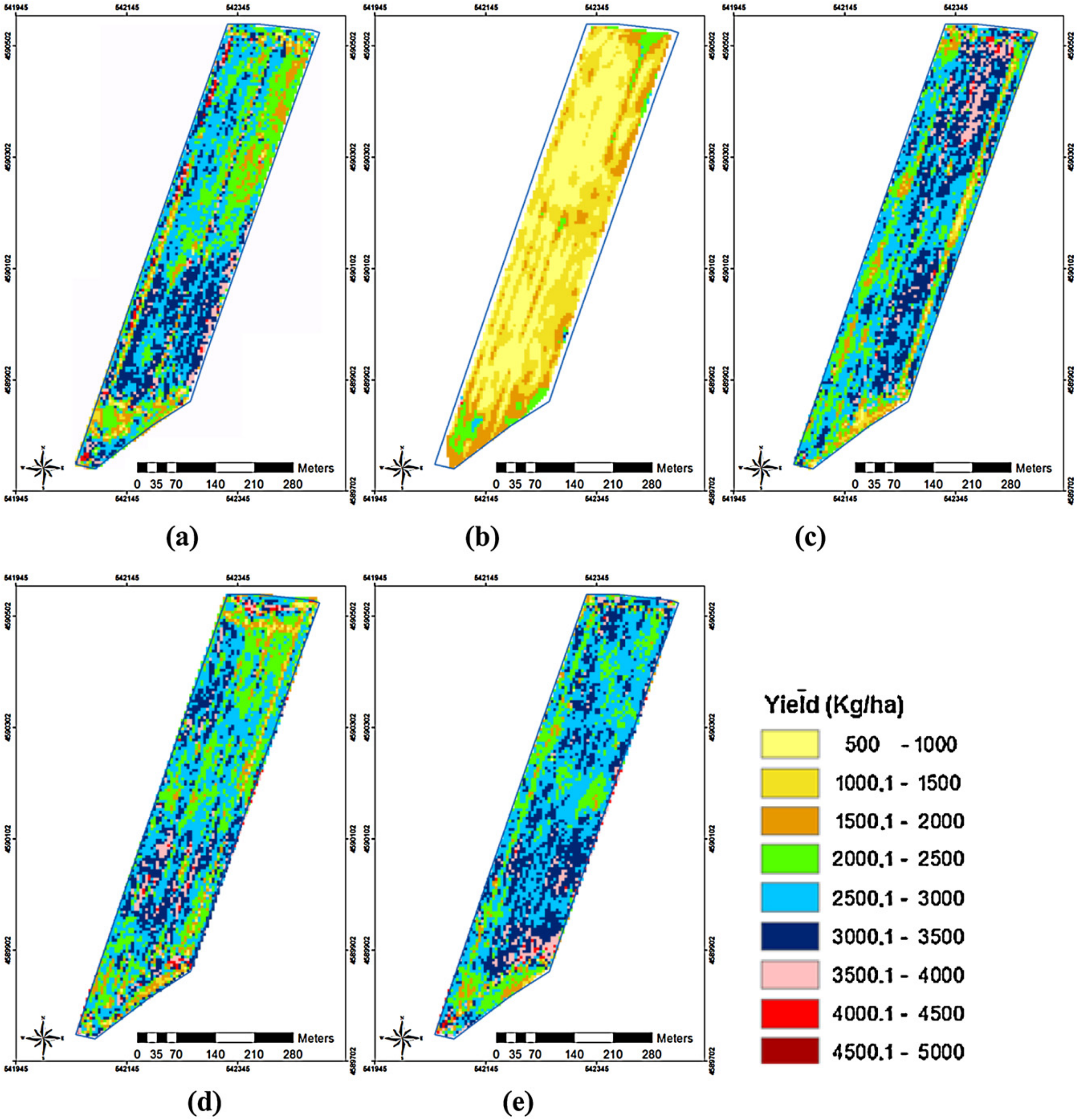


Fig. 2. Wheat grain yield maps (kg ha^{-1}) for the growing season 2005/06 (a); 2006/07 (b); 2007/08 (c); 2008/09 (d); 2009/10 (e).

Table 2
Average grain yield (kg ha^{-1}), standard deviation (Std) and coefficient of variation (CV) for the entire study field, for high stable (HS), average stable (AS), and low stable (LS) zone. The data are relative to each study year.

Season	Field			High stable zone			Average stable zone			Low stable zone		
	Yield (kg ha^{-1})	Std[a] (kg ha^{-1})	CV[b] (%)	Yield (kg ha^{-1})	Std (kg ha^{-1})	CV (%)	Yield (kg ha^{-1})	Std (kg ha^{-1})	CV (%)	Yield (kg ha^{-1})	Std (kg ha^{-1})	CV (%)
2005/06	2647	588.8	22	3136	430	14	2627	414	16	2093	537.63	26
2006/07	1145	470.9	41	1075	354	33	1067	428	40	1369	518.35	38
2007/08	2738	599.4	22	3044	397	13	2829	459	16	2154	584.43	27
2008/09	2661	575.1	22	3127	429	14	2632	418	16	2209	530.11	24
2009/10	2799	450.7	16	3130	326	10	2808	334	12	2366	392.75	17

[a] Std = standard deviation.
[b] CV = coefficient of variation.

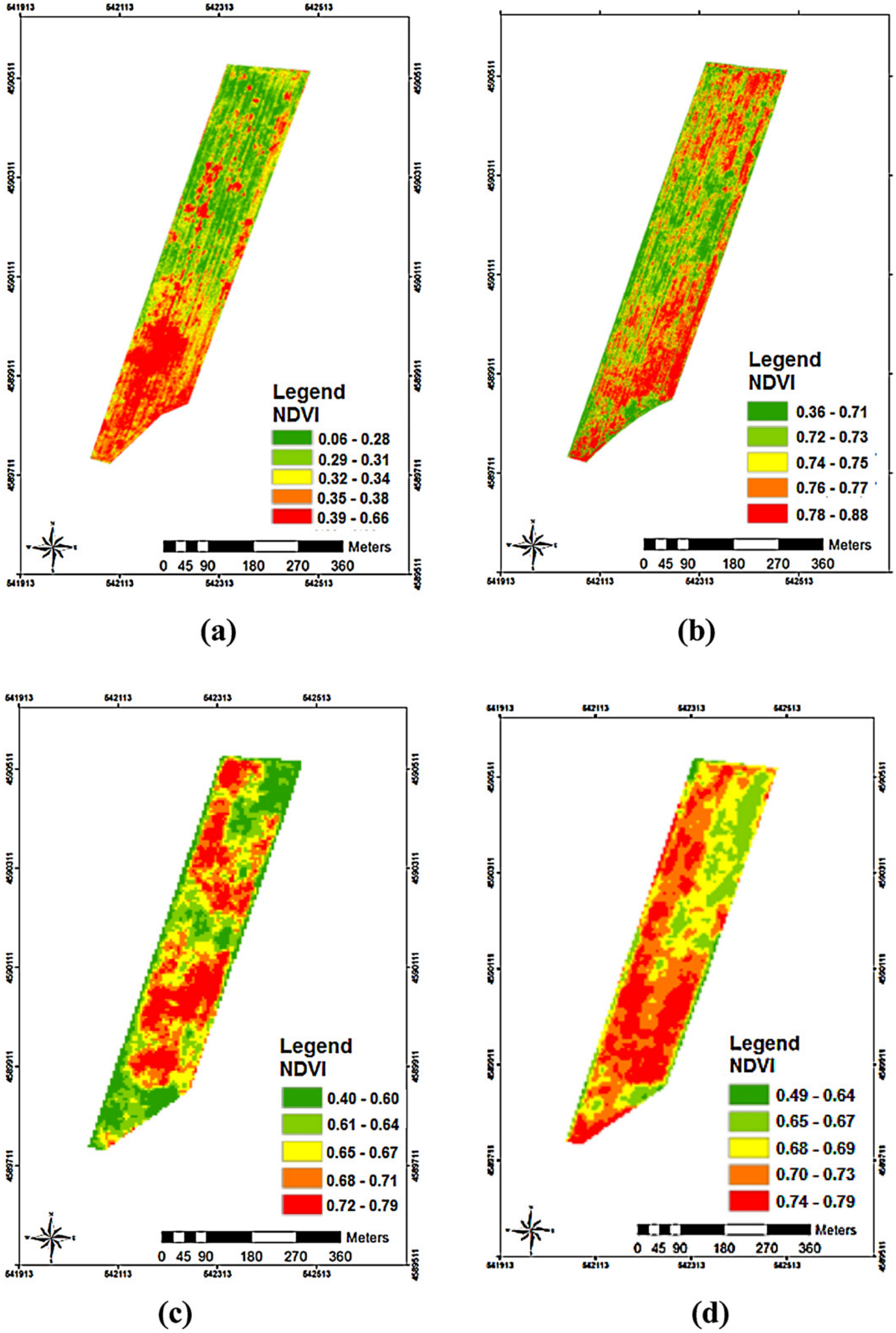


Fig. 3. Normalized difference vegetation index (NDVI) acquired in May 2007 (a), 2008 (b), 2009 (c), 2010 (d).

part of the triangular south-west area of the field. It is associated to high negative values of spatial stability, in this area the yield is lower than the average field yield. Table 2 shows the average grain yield, standard deviation and coefficient of variation, for the whole field and for each of the three zones. Grain yield for the whole field ranged between 1145 and 2799 kg ha^{-1}, and the coefficients of variation ranged between a minimum of 16 and a maximum of 41% which correspond to the 2006/07 yield, an extremely dry year with low yield (Tables 1 and 2). The standard deviation associated to each mean yield values are high because of the 1 m spatial resolution of the data acquisition. The AS zone produced alternately over the years, with yield fluctuating around the average total yield of the field. In addition, in this area the coefficients of variation are lower than the entire field except for the 2006/07 year (Table 2).

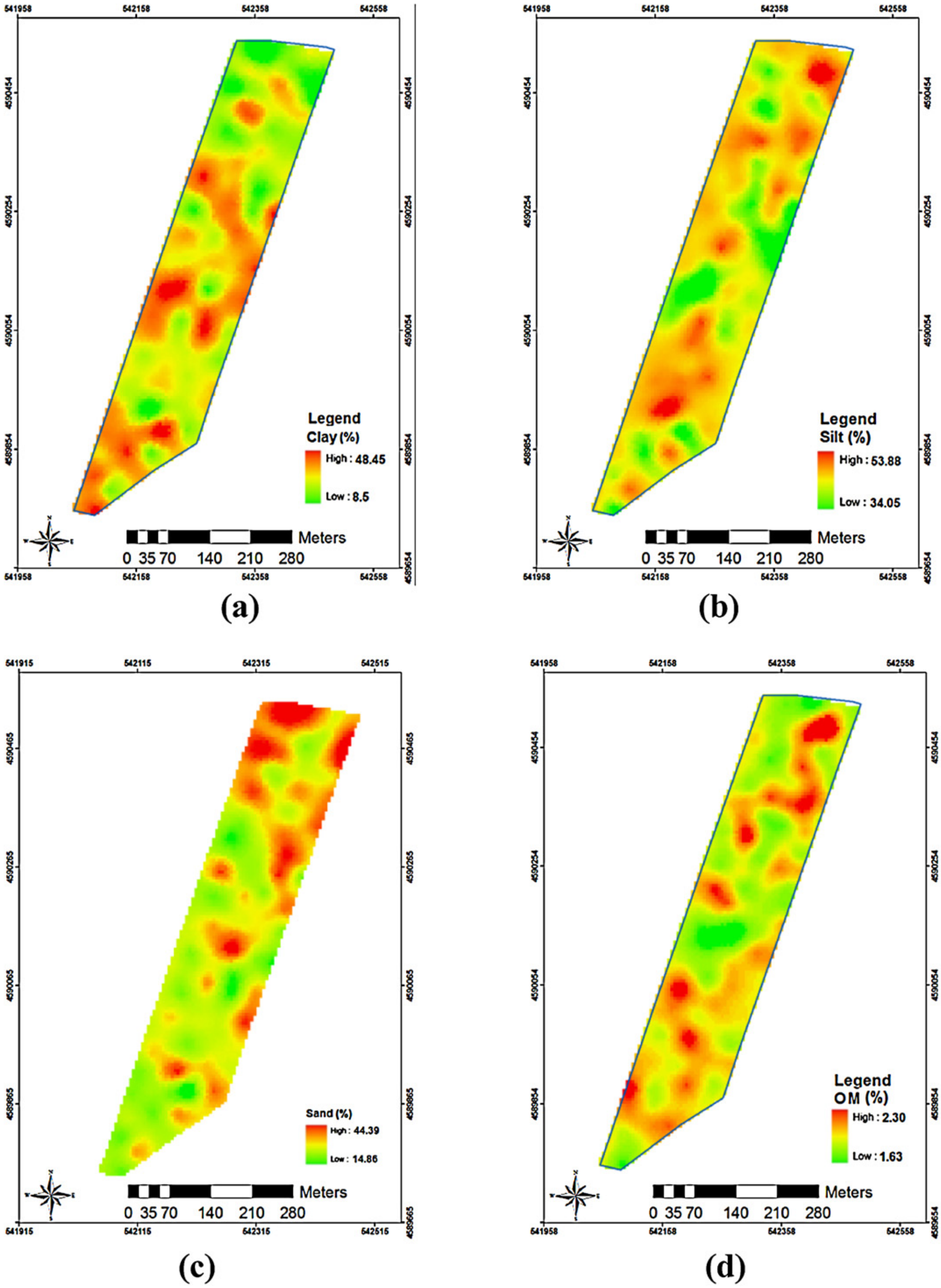


Fig. 4. Interpolated map of clay content (%) (a); silt content (%) (b); sand content (%) (c) and organic matter content (%) (d). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

The HS zone showed higher mean yields than the whole field for four growing season except the 2006/07, but also during this year it was very close to the mean yield of the whole field. For this area the coefficient of variation values were lower than the entire field (10–33%). The LS zone was characterized by lower yield than the field average except in 2006/07 when it was slightly higher (Table 2). The coefficients of variation associated to the mean yield of this area were higher than the entire field because boundaries areas are included in this zone (Fig. 7c–d). Fig. 8 shows the patterns of the relative yield differences (RYD) between average yield for the field and the yield of each of the three zones for the 5 growing seasons. The LS zone showed on average negative values of RYD meaning that the yield in this zone was always lower than the field average. In particular, the lowest RYD of −21% was measured in 2005/06 and the highest the subsequent year with an increase of 20% respect the field average (Fig. 8). HS is the zone that showed always the highest RYD except for the 2006/07 growing season where it produces around 6% less than the field average (Fig. 8). The AS zone showed an intermediate behavior between the LS and HS.

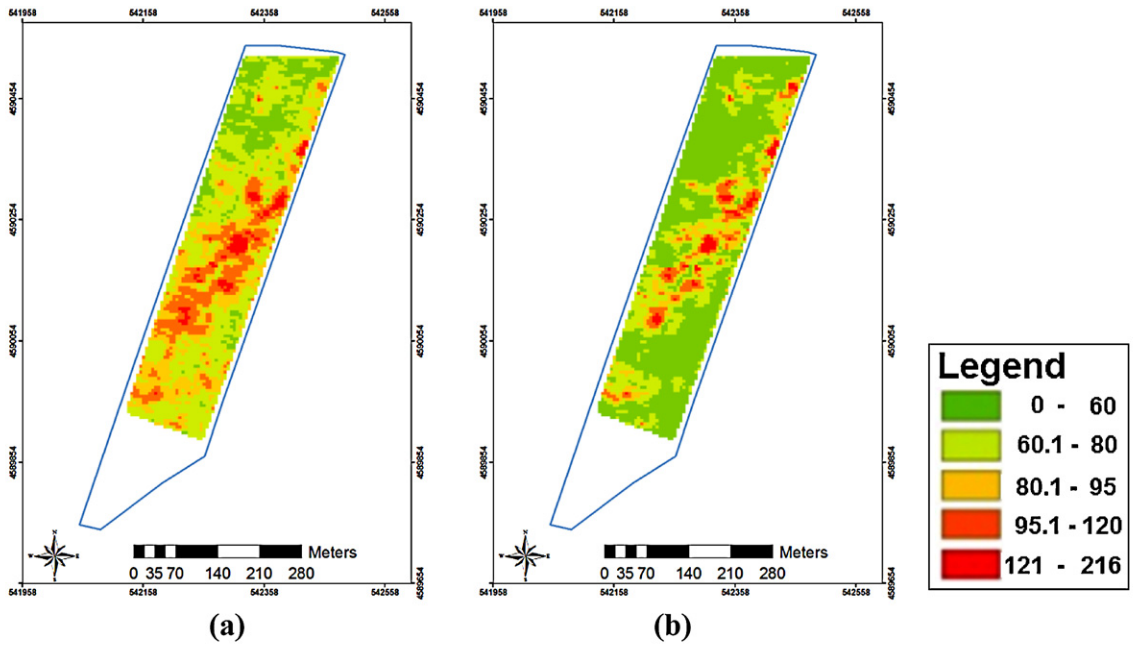


Fig. 5. Electrical resistivity tomography for two layers 0–50 cm (a); 0–100 cm (b).

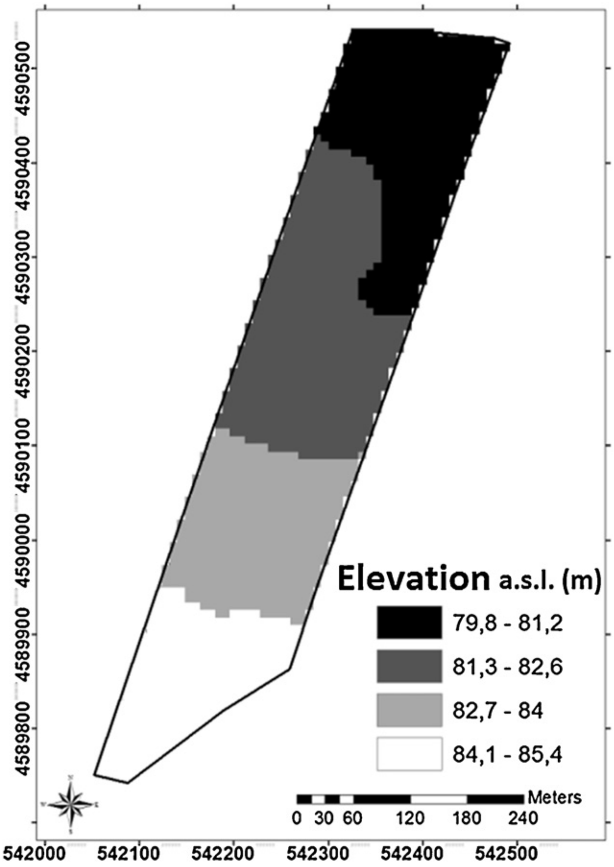
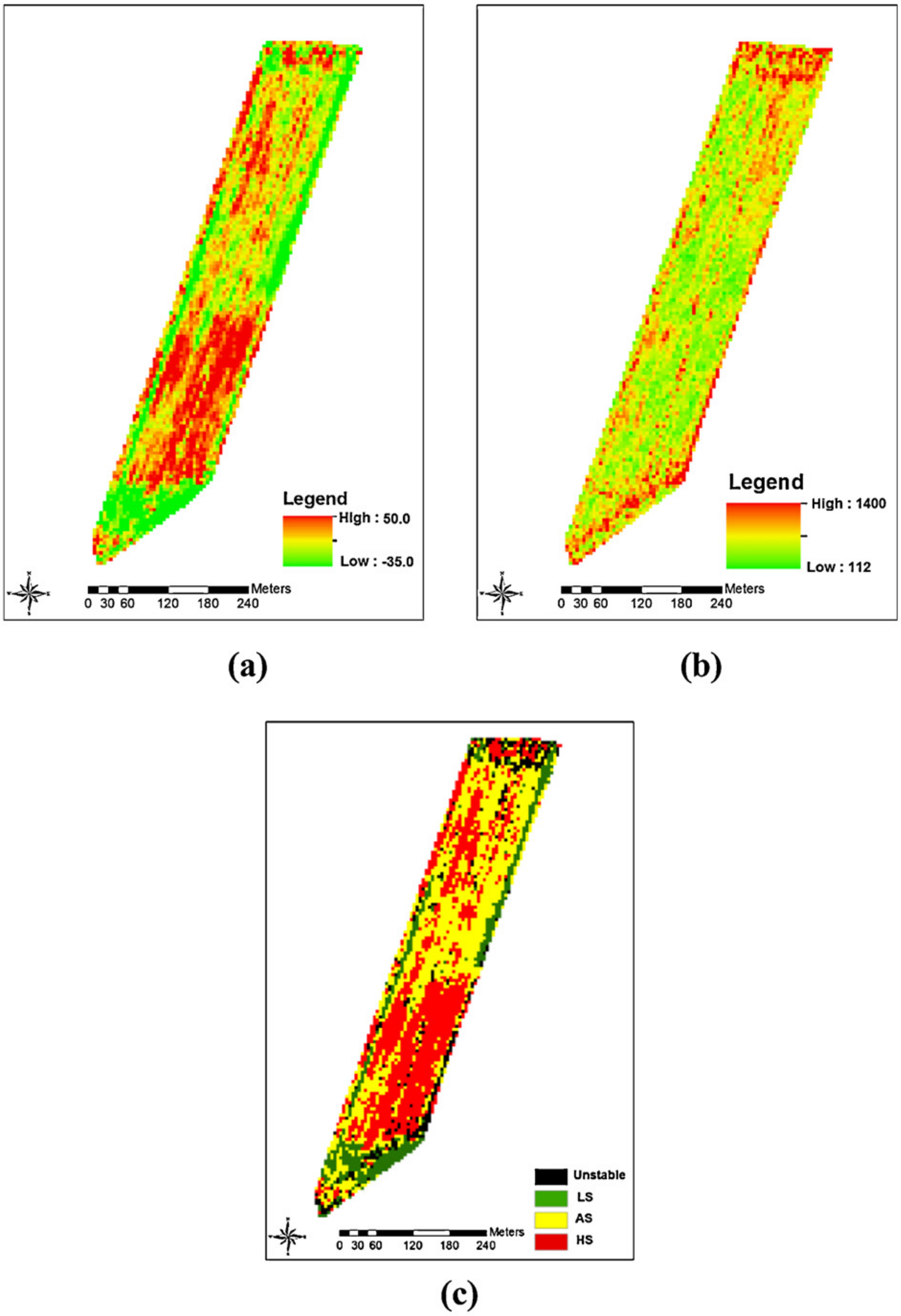


Fig. 6. Digital elevation model of the study field.

3.4. Rainfall patterns and correlation analyses

The total rainfall distribution over 58 years of recorded weather data is highly variable with the highest total rainfall recorded for 1980 and the lowest for 1963 (Fig. 1). Growing season rainfall was lowest in 1977 with just around 100 mm and was highest in 2009 with 564 mm. Fallow rainfall was lowest in 1963 and highest in 1980 with 100 mm and 400 mm, respectively (Fig. 1). The five years of experimental data recorded high rainfall variability and included the wettest growing season recorded in 58 years and one of the driest growing seasons. Rainfall varied from a minimum value of 412 mm for the growing season 2006/07 to a maximum of 785 mm for the growing season 2008/09 (Table 1). The long fallow rainfall (June–November) showed lower values for the growing season 2006/07 with 176 mm and a maximum of 283 mm for 2009/10 (Table 1). The growing season rainfall (December–May) showed a minimum value of 237 mm for the growing seasons 2006/07 and a maximum of 564 mm for 2008/09 (Table 1). Figs. 9 and 10 show the Pearson correlation coefficient maps between total rainfall, long fallow rainfall, growing season rainfall and yield for the five study years. By removing the driest and the wettest years, the correlation values for each map were found highly significant with *p*-values greater than 0.005. Fig. 9a shows the Pearson correlation coefficient map between total rainfall and yield. Overall, total rainfall showed higher correlation in the HS zone, and part of the AS zone. Higher correlation coefficient was observed throughout the field except for some negative coefficient of correlation at the top right portion of the field in the AS zone (Fig. 9a). Long fallow rainfall showed higher correlation coefficients for the three zones but also negative coefficient in the LS zone and top right portion of the AS zone, with most of field having an r ranging between 0.5 and 1 (Fig. 9b). Growing season rainfall and grain yield showed areas of negative correlation with coefficients varying between 0.5 and -1 (Fig. 9c). The growing season rainfall had high positive coefficients only for the HS, while these values where prevalently low in the AS zone (Fig. 9c). Fig. 9d shows the correlation coefficients between long fallow rain and grain yield obtained by removing from the analysis both the extremely dry (2006/07) and extremely wet (2009/10) years. The removal of these two growing season caused an improvement of the correlation between the AS zone and some pixels of the LS zone and the grain yield. Overall, the coefficient of correlation increased negatively from 0.2 to -0.8 (Fig. 9d). Fig. 9e shows the correlation coefficient of the growing season rainfall (by eliminating the dry and wet years) and the grain yield. Overall, the negative



(a)

(b)

(c)

Fig. 7. Spatial stability map of grain yield obtained from Eq. (2) (a); temporal stability of grain yield obtained from the square root of Eq. (3) values (b); homogeneous zones map obtained from the first two maps (c).

correlation between yield and rainfall for the AS zone increased from very low correlation values to a range between −0.7 and −1.0 (Fig. 9e). Fig. 10a–c shows the correlation between grain yield and total, long fallow, growing season rainfall when only the driest year was excluded from the analysis. Fig. 10d–f depicts the correlation between grain yield and total, long fallow, growing season rainfall when the wettest year was excluded. In general, the removal of the driest year from the correlation analysis causes the correlation to decrease for the three rainfall periods (total, long fallow, growing). The HS zone shows the highest positive correlation coefficients between grain yield and total rainfall in some areas (the red pixel in figure) and some areas in which the correlation values are very low while there are negative values of correlation in the AS zone (Fig. 10a). In the AS higher coefficients of correlations, ranging between −0.5 and −0.7 where obtained for the long fallow rainfall and growing season rainfall (Fig. 10b–c). On the other hand, in the HS zone growing season rainfall shows higher positive coefficients of correlations (Fig. 10b–c). When the wettest growing season is removed the overall correlations improve for all the three zones ranging between 0.3 and 1 for the total, long fallow and growing season rainfall (Fig. 10d–f). Table 3 shows the correlation coefficients for the three different zones between grain yield and rainfall for the 5 growing season (All – 5 years), 4 years from whit the exclusion of the dry year (No Dry – 4 years), 3 years with the exclusion of the wettest and dries years (No Dry No Wet – 3 years). This analysis is performed for the total rain, long fallow (June–November), short fallow (September–November), growing season rainfall (December–May), growing season vegetative

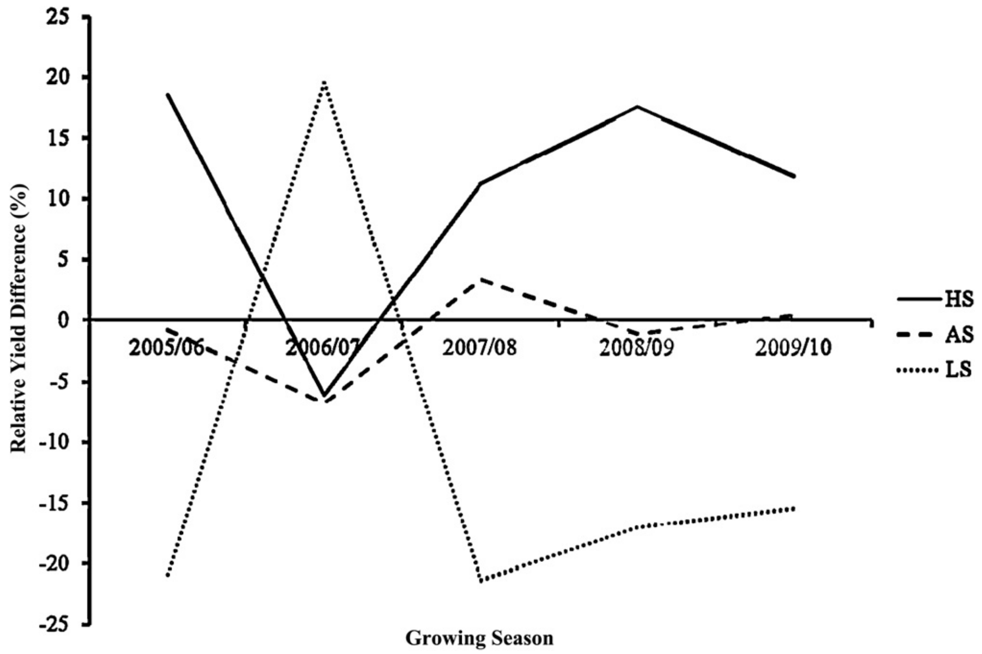


Fig. 8. Relative yield difference (%) between the average field yield and the yield of each zone for the 5 growing seasons.

rainfall (December–February) and growing season reproductive rainfall (March–May).

This analysis was performed on the basis of the one hundred georeferenced sample points. A buffer zone of 3 pixel diameter around each point was considered. Each point was ascribed to the most frequent class (LS, AS, HS) present in the neighborhood and the mean yield of this pixel was associated to the relative sample point. The points for which it was not possible to identify the assignment of classes, because the neighborhood contains mixed class pixels or it was equally divided between two classes, were excluded from the analysis. For the 5 years, the correlation between yield and short fallow rainfall showed the highest coefficients with 0.70 for the LS, 0.79 for the AS and 0.87 for the HS. The exclusion of the wettest year (not reported in Table 3) showed not very significant differences with the previous case, for the LS zone an increase in long and short fallow rainfall correlation coefficient and small decreases in growing season rainfall coefficient was recorded. In the AS zone there was an increase of long and short fallow coefficients and in the AS, as in HS, zone an increasing in growing season reproductive rainfall-yield correlation coefficients was obtained (0.62 for AS and 0.58 for HS). The exclusion of the driest year causes the relationship between rain and yield decreases for the three zones and become not significant for the AS zone. LS yield is correlated with the short fallow rainfall (0.54), while AS yield is negatively correlated with growing season rain (0.47) and vegetative rainfall (0.58). The HS yield shows a low correlation with total fallow rainfall (Table 3). When both the wettest and driest years are removed, the LS yield is still correlated with the total and short fallow rainfall (0.58), while the AS yield is negatively correlated with growing season (0.45) and vegetative rainfall (0.51) and positively correlated (0.62) to growing season reproductive rainfall.

Table 3

Correlation coefficients (R^2) between grain yield and rainfall for the 2005/06, 2006/07, 2007/08, 2008/09, and 2009/10 for the low stable (LS), average stable (AS) and high stable (HS) zones. The total rainfall period was divided into long fallow, short fallow, growing season, vegetative period, and reproductive period. The correlations were obtained considering all the five years (All – 5 years), without the driest (No Dry – 4 years) and wettest years (No Dry-No Wet – 3 years). At the apex of the correlation coefficients are reported the corresponding *p*-values, n.s. means not significant (*p*-value > 0.05).

Correlation coefficients	Total rainfall	Long fallow rainfall	Short fallow rainfall (September–November)	Growing season rainfall	Vegetative growing season (December–February)	Reproductive growing season (March–May)
5 Years						
LS	0.58***	0.54**	0.70***	0.50**	0.48**	0.35*
AS	0.49***	0.56***	0.79***	0.40***	0.35***	0.33***
HS	0.68***	0.66***	0.87***	0.64***	0.65***	0.37***
4 Years						
LS	0.32 n.s.	0.21 n.s.	0.54*	0.28 n.s	0.27 n.s	0.18 n.s
AS	−0.31*	−0.16 n.s.	0.08 n.s.	−0.47*	−0.58*	0.02 n.s.
HS	0.04 n.s.	0.03 n.s.	0.30**	0.03 n.s.	−0.01 n.s.	0.08 n.s.
3 Years						
LS	0.34 n.s.	0.49*	0.58**	0.26 n.s.	0.26 n.s.	−0.23 n.s.
AS	−0.38*	−0.22 n.s	0.09 n.s	−0.45**	−0.51**	0.62*
HS	−0.03 n.s.	0.09 n.s.	0.36**	−0.08 n.s.	−0.07 n.s.	0.01 n.s.

n.s., not significant.

** $p < 0.01$.

*** $p < 0.005$.

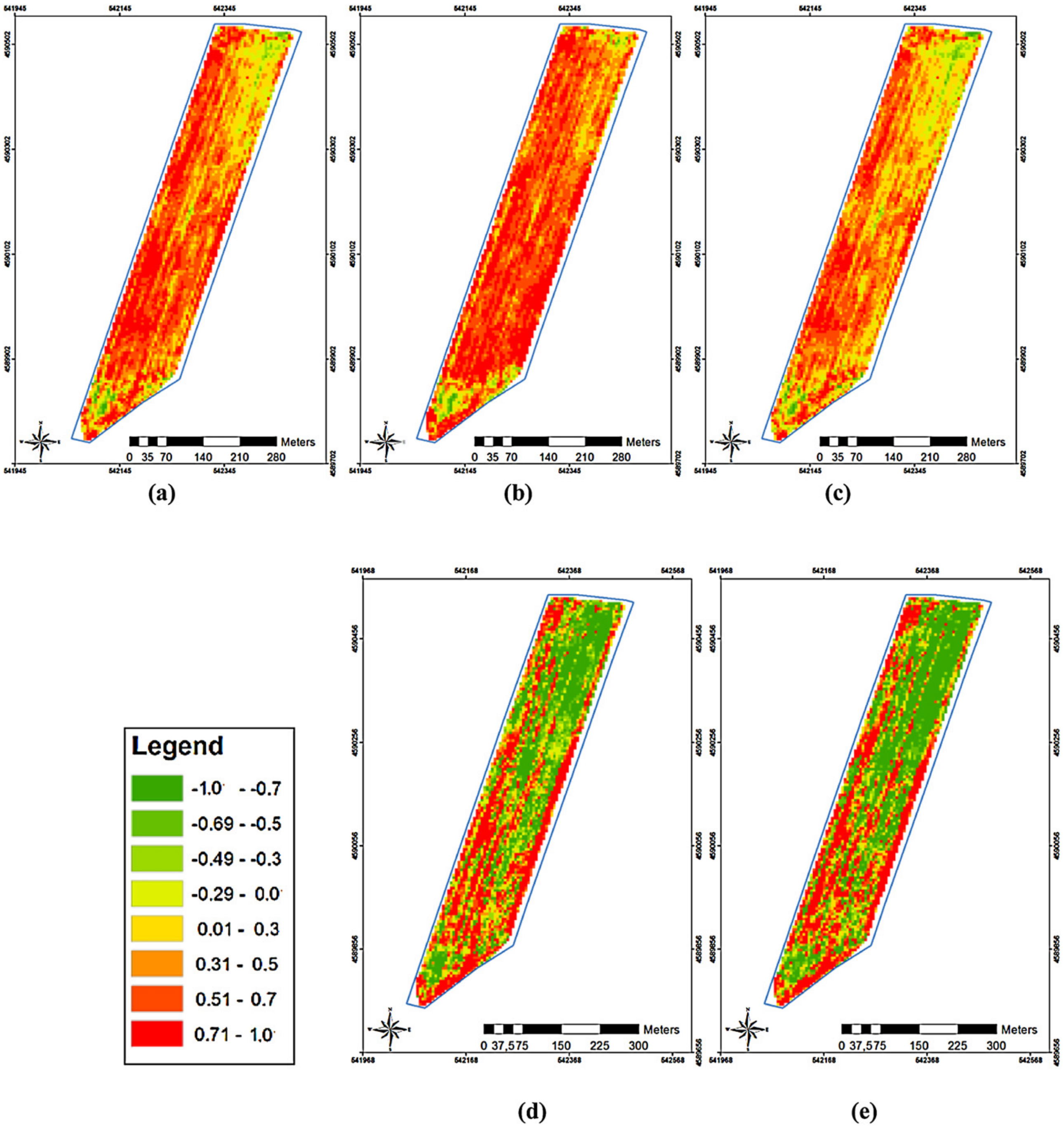


Fig. 9. Spatial correlation map between yield and total rainfall (a); spatial correlation map between grain yield and long fallow (b); spatial correlation map between grain yield and growing season rain (c); spatial correlation map between grain yield and fallow excluding the wettest year (2008/09) and the driest year (2006/07) (d); spatial correlation map between grain yield and growing season rain excluding the wettest year (2008/09) and the driest year (2006/07) (e).

4. Discussion

The spatial variability of soil properties and the distribution of the rainfall influenced both the spatial and temporal variability of grain yield. The use of spatial yield maps allowed the identification of three spatial and temporal stable zones and one unstable zone. The ERT map was useful for determining spatial variability of soil properties non-destructively. Results from this study agree with the findings of Basso et al. (2010) that used such technique to discriminate soil physical properties between tillage systems. The ERT map shows in the AS zone the presence of high resistance, which is due to a shallow and compacted clay layer followed by compacted coarse and fine sand and stones. This has an important implication in terms of water stored into the soil during the fallow period or growing season, and in terms of rooting depth. The subdivision of the field into three stable zones agrees with the findings of Robertson et al. (2007), which found that the use of only three management zones is common amongst farmers that adopt precision agriculture, regardless of the farm's dimension. They concluded that dividing the field into more zones cause a diminishing net economic returns as a response to an attempt to extract more information, requiring also more management time and analysis.

The growing season rainfall for 2006/07 was one of the lowest of the 58 years weather data (Fig. 1) and for the same growing

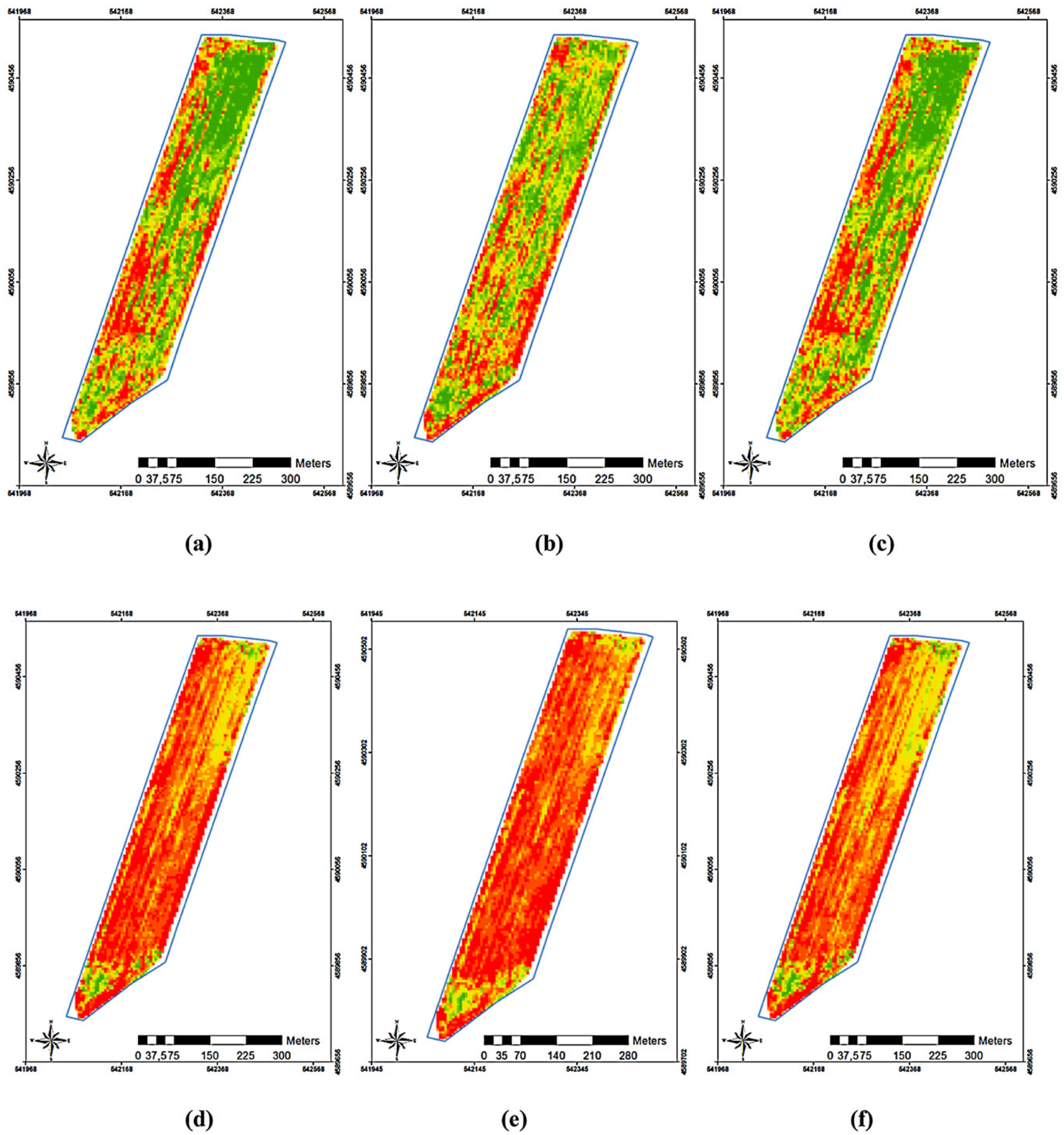


Fig. 10. Spatial correlation map between grain yield and total rainfall excluding the driest year (2006/07) (a); spatial correlation map between grain yield and fallow rainfall excluding the driest year (2006/07) (b); spatial correlation map between grain yield and growing season rainfall excluding the driest year (2006/07) (c); spatial correlation map between grain yield and total rainfall excluding the wettest year (2008/09) (d); spatial correlation map between grain yield and fallow rainfall excluding the wettest year (2008/09) (e); spatial correlation map between grain yield and growing season rainfall excluding the wettest year (2008/09) (f).

season fallow rainfall was also the lowest recorded for the five years of study (Table 1). The balance between fallow rain and growing season rainfall plays an important role in determining grain yield. The amount of rain stored in the short fallow period (September–November) was an important factor affecting the spatial and temporal variability of wheat yield. Sadras et al. (2012) have demonstrated that there are no beneficial effects of the long fallows water storage and concluded that the benefits of fallow rainfall declined with the increase of seasonal rainfall. Crops that rely on fallow rainfall lose much less in soil evaporation during the growing season, although evaporative losses before sowing could be significant (Hatfield et al., 2001). The importance of rainfall during short fallow was particularly evident for two consecutive years, the 2006/07 and 2007/08. The former, had 92 mm of short fallow rainfall, the growing season rainfall was very low (93 mm as shown in Table 1) during March and April 2007, with 54 mm in the month of March, with a single rain event greater than 15 mm and none between 5 and 15 mm, while the total growing season rainfall was of 237 mm. The 2007/08 year had the same amount of growing season rainfall (237 mm) but well distributed during the season and 162 mm of fallow rainfall (Table 1). The yield produced in 2007/08 was 1693 kg ha^{-1} higher than the previous year. O'Leary and Connor (1997) demonstrated that stubble retentions and tillage systems influence the amount of fallow water stored in soils and therefore final yield. However, Sadras et al. (2012) demonstrated that stubble retention was not important in capturing the gains of summer rainfall but was more important for soil stability.

The effect of rainfall variability between and within the years on grain yield is also evident when the zones are considered. By removing the driest year from the analysis, the correlation between short fallow rain and yield decreased for all zones and become not significant for AS zone. The LS zone was less influenced by either the wettest and driest year (Table 3). The relative yield differences (Fig. 8) between the zones and the average field yield can be explained by the interaction of rainfall and the spatial distribution of soil properties and root downward movement and water uptake in the soil layers. Exploitable soil volume by the roots varied spatially across the field and within each zone as shown by the ERT (Fig. 5a–b). Spatial patterns in soil resistivity provided information on soil variability due to inherent geo-pedogenetic soil processes (Hagrey, 2007). In the HS zone, where there is low resistivity, the deeper exploitable soil profile allowed for a greater amount of rainfall to be stored during the fallow period and to show significant relationship between rainfall and grain yield for the fallow period (Fig. 9b). Fallow season rainfall stored into the soil allowed the crop to use it as need for the growth, producing more biomass and accumulating more carbohydrates into the stems. At anthesis, the stem weight is proportional to grain number (Fisher, 1985) and with more carbohydrates in the stem, the crop is expected to have higher yields. In 2006/07 (driest fallow) the HS zone does not have enough water stored into the soil prior sowing affecting plant establishment, and later in the season crop nitrogen uptake. Between stem elongation and anthesis, the driest year showed the lowest amount of rainfall (Table 1), the low amount of fallow and growing season rain causes a shortage of nitrogen uptake between these two growth stages (when stored soil water before sowing would maximize the uptake of nitrogen) that will cause a reduction of crop growth rates and grain number per unit crop growth causing a reduction in grain yield (Fisher, 1985; Sadras et al., 2012).

The AS zone does not respond to fallow rainfall (neither short nor long) because the soil has higher clay content in the first 50 cm followed by a compacted layer of stones as highlighted from the ERT map (Fig. 5) as the central transect was an old creek bed. The upper right area is mainly characterized by high resistivity through the soil profile, with high silt and coarse sand fraction. Moreover, there is a soil slope in the direction of the upper right corner of the field as shown in the digital elevation model (DEM) (Fig. 6). All these factors affect the lower soil water storage due to shallow profile. The AS zones produced higher yield in 2007/08 and 2009/10 when the rain in the growing season is well distributed. In 2007/08 during the first three month of growing season period, the total rain was of 73 mm (Table 1) with only one day in which the rain level was higher than 15 mm and the water storage during the previous three month fallow period (161 mm) was not excessive or limited. The yield of this area was satisfactorily also in 2009/10 during this year the first growing season three month period rainfall was 218 mm with 3 days in which the rain level was higher than 15 mm. This rainfall level was higher than 2007/08, but lower than 2005/06 and 2008/09 years when during December, January and February the rainfall was of about 295 mm. As shown in Table 1 the rainfall level during the months of March and April were also optimal.

High correlation was observed, throughout the field and only some negative correlation at the top right portion of the field in the AS zone (Fig. 9a). Negative correlation mean that the increase in rainfall causes a yield decrease due to water logging as results of the position in the landscape and the lower elevation. By removing the driest year (2006/07) this zone shows a negative correlation with the growing season vegetative rainfall, and a not significant correlation with the reproductive growing season rainfall. When the wettest year was removed from the correlation analysis, the negative coefficients become lower for vegetative growing season rainfall, while the correlation coefficient for the reproductive period becomes significant, high and positive.

The correlation between grain yield and long fallow rainfall showed a stronger correlation respect to the total rainfall and yield. Long fallow rainfall showed higher correlation coefficients for the three zones but also negative correlation coefficients in the LS zone and top right portion of the AS zone, with most of field having a correlation coefficients ranging between 0.5 and 1 (Fig. 9b).

5. Conclusions

In conclusion, the spatial variability of soil properties and the distribution of the rainfall affect both the spatial and temporal variability of grain yield. Spatial and temporal analysis of yield maps allowed for the identification of three spatially and temporally stable zones and one unstable zone. Short fallow rainfall was an important factor affecting the spatial and temporal variability of wheat yield. Based on the rainfall analysis carried out in this research, N fertilizer management must take in consideration the amount of precipitation that fell till march (time when sidedressing N fertilizer is applied) especially for the low laying area of the field due to the high risk of water logging in wet years, confirmed by the low or negative correlation with rainfall. In the wet years, N fertilizer application should be reduced in low laying area.

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References

Acevedo, E., Craufurd, P.Q., Austin, R.B., Perez-Marco, P., 1991. Traits associated with high yield in barley in low rainfall environments. Journal of Agricultural Science 116, 23–36.

Anderson, W.K., 2010. Closing the gap between actual and potential yield of rainfed wheat. The impacts of environment, management and cultivar. Field Crop Research 116, 14–22.

Angus, J.F., Nix, H.A., Russell, J.S., Kruizinga, J.E., 1980. Water use, growth and yield of wheat in a subtropical environment. Australian Journal of Agricultural Research 31, 873–886.

Angus, J.F., van Herwaarden, A.F., 2001. Increasing water use and water use efficiency in dryland wheat. Agronomy Journal 93, 290–298.

Asseng, S., Van Herwaarden, A.F., 2003. Analysis of the benefits to wheat yield from assimilates stored prior to grain filling in a range of environments. Plant and Soil 256, 217–229.

Basso, B., Ritchie, J.T., Pierce, F.J., Braga, R.P., Jones, J.W., 2001. Spatial validation of crop models for precision agriculture. Agricultural Systems 68, 97–112.

Basso, B., Bertocco, M., Sartori, L., Martin, E.C., 2007. Analysing the effects of climate variability on spatial pattern of yield in a maize–wheat–soybean rotation. European Journal of Agronomy 26, 82–91.

Basso, B., Cammarano, D., Chen, D., Cafiero, G., Amato, M., Bitella, G., Rossi, R., Basso, F., 2009. Landscape position and precipitation effects on spatial variability of wheat yield and grain protein in Southern Italy. Journal of Agronomy and Crop Science 195, 301–312.

Basso, B., Amato, M., Bitella, G., Rossi, R., Kravchenko, A., Sartori, L., Carvahlo, L.M., Gomes, J., 2010. Two-dimensional spatial and temporal variation of soil physical properties in tillage systems using electrical resistivity tomography. Agronomy Journal 102, 440–449.

Basso, B., Ritchie, J.T., Cammarano, D., Sartori, L., 2011a. A strategic and tactical management approach to select optimal N fertilizer rates for wheat in a spatially variable field. European Journal of Agronomy 35, 215–222.

Basso, B., Sartori, L., Bertocco, M., Cammarano, D., Grace, P.R., 2011b. Economic and environmental evaluation of site-specific tillage in a maize crop in NE Italy. European Journal of Agronomy 35, 83–92.

Blackmore, B.S., 2000. The interpretation of trends from multiple yield maps. Computers and Electronics in Agriculture 26, 37–51.

Blackmore, S., Godwin, R.J., Fountas, S., 2003. The analysis of spatial and temporal trends in yield map data over six years. Biosystems Engineering 84, 455–466.

Boyer, J.S., 1982. Plant productivity and environment. Science 218, 443–448.

Cochran, W.G., 1977. Sampling Techniques. Wiley & Sons, p. 428.

Duda, R., Hart, P.E., 1993. Pattern Classification and Scene Analysis. Wiley, New York.

Fisher, R.A., 1985. Number of kernels in wheat crops and the influence of solar radiation and temperature. Journal of Agricultural Science 105, 447–461.

Gamma Design Software, 1999. GS+: Geostatistics for the Environmental Sciences, v 3.5. Gamma Design Software, Plainwell, MI.

Hagrey, S.A., 2007. Geophysical imaging of root-zone, trunk, and moisture heterogeneity. Journal of Experimental Botany 58, 839–854.

Hatfield, J.L., Sauer, T.J., Pruegerm, J.H., 2001. Managing soils to achieve greater water use efficiency: a review. Agronomy Journal 93, 271–280.

Kaspar, T.C., Colvin, T.S., Jaynes, D.B., Karlen, D.L., James, D.E., Meek, D.W., 2003. Relationship between six years of corn yields and terrain attributes. Precision Agriculture 4, 87–101.

Kirkegaard, J.A., Howe, G.N., Pitson, G.,2001. Agronomic interactions between drought and crop sequence "Science and technology: delivering results for agriculture". In: Proceedings of the 10th Australian Agronomy Conference. Australian Society of Agronomy, Hobart, Australia, www.regional.org.au/au/asa/2001/4/c/kirkegaard1.htm.

Klute, A., Dirkens, C., 1986. Hydraulic conductivity and diffusivity: laboratory methods. In: Klute, A. (Ed.), Methods of Soil Analysis: Part 1. Physical and Mineralogical Methods. , 2nd ed. ASA, Madison, WI, p. 687-734.

Kravchenko, A.N., Robertson, G.P., Thelen, K.D., Harwood, R.R., 2005. Management, topographical, and weather effects on spatial variability of crop grain yields. Agronomy Journal 97, 514–523.

Nielsen, D.C., Vigil, M.F., Anderson, R.L., Bowman, R.A., Benjamin, J.G., Halvorson, A.D., 2002. Cropping system influence on planting water content and yield of winter wheat. Agronomy Journal 94, 962–967.

Norwood, C.A., 2000. Dryland winter wheat as affected by previous crops. Agronomy Journal 92, 121–127.

O'Leary, G.J., Connor, D.J., 1997. Stubble retention and tillage in a semi-arid environment: 1. Soil water accumulation during fallow. Field Crops Research 52, 209–219.

Passioura, J., 2006. Increasing crop productivity when water is scarce – from breeding to field management. Agricultural Water Management 80, 176–196.

Pierce, F.J., Nowak, P., 1999. Aspects of precision agriculture. Advances in Agronomy 67, 1–85.

Pringle, M.J., McBratney, A.B., Whelan, B.M., Taylor, J.A., 2003. A preliminary approach to assessing the opportunity for site-specific crop management in a field, using yield monitor data. Agricultural Systems 76, 273–292.

Richards, R.A., 2006. Physiological traits used in the breeding of new cultivars for water scarce environments. Agricultural Water Management 80, 197–211.

Ritchie, J.T., Basso, B., 2008. Water use efficiency is not constant when crop water supply is adequate or fixed: the role of agronomic management. European Journal of Agronomy 28, 273–281.

Robertson, M., Isbister, B., Maling, I., Oliver, Y., Wong, M., Adams, M., Bowden, B., Tozer, P., 2005. Managing spatial and seasonal variability within field can improve the profitability of WA grain production. In: Turner, N., Acuna, T. (Eds.), Groundbreaking Stuff. Proceedings of the 13th Australian Agronomy Conference. 10–14 September 2006 Perth, Western Australia.

Robertson, M., Isbister, M., Maling, I., Oliver, Y., Wong, M., Adams, M., Bowden, B., Tozer, P., 2007. Opportunities and constraints for managing within-field spatial variability in Western Australian grain production. Field Crops Research 104, 60–67.

Rouse, J.W., Haas, R.H., Schell, J.A., Deering, D.W., 1974. Monitoring vegetation systems in the Great Plains with ERTS. In: Third ERTS Symp., NASA SP-351 1, pp. 309–317.

Sadras, V.O., 2002. Interaction between rainfall and nitrogen fertilisation of wheat in environments prone to terminal drought: economic and environmental risk analysis. Field Crops Research 77, 201–215.

Sadras, V.O., Lawson, C., Hooper, P., McDonald, G., 2012. Contribution of summer rainfall and nitrogen to the yield and water use efficiency of wheat in Mediterranean-type environments of South Australia. European Journal of Agronomy 36, 41–54.

Soil Survey Staff, 1999. Soil Taxonomy, second edition. USDA, National natural resources Conservation Service, Washington, DC.

Unger, P.W., Payne, W.A., Peterson, G.A., 2006. Water conservation and efficient use. In: Peterson, G.A., Unger, P.W., Payne, W.A. (Eds.), Dryland Agriculture. Agronomy Monograph 23. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, Wisconsin, USA, pp. 39–86.

Van Groenigen, J.W., Stein, A., 1998. Constrained optimization of spatial sampling using continuous simulated annealing. Journal of Environmental Quality 27, 1078–1086.

Van Herwaarden, A.F., Angus, J.F., Richards, R.A., Farquhar, G.D., 1998. Hayingoff, the negative grain yield response of dryland wheat to nitrogen fertiliser. II. Carbohydrate and protein dynamics. Australian Journal of Agricultural Research 49, 1083–1093.