

UNDERSTANDING SPATIAL AND TEMPORAL VARIABILITY OF WHEAT YIELD: AN INTEGRATED SYSTEM APPROACH

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ABSTRACT

Natural and acquired variability in production capacity or potential within a field causes uniform agronomic management practices for the field to be correct in some parts and inappropriate in others. To achieve the ultimate goal of sustainable cropping systems, variability must be considered both in space and time because the factors influencing crop yield have different spatial and temporal behavior. Determining the optimum prescription for a location within a field is challenging. Spatial variation in soil water and nitrogen are often the causes of crop yield spatial variability due to their influence on the uniformity of plant stand at emergence and for in-season stresses. The biggest challenge is that the plant response to variable management levels is often highly dependent upon the weather that occurs during the season. The objective of this study was to quantify the causes of yield variability in a 5 year study carried out in Southern Italy on wheat crop. Remote sensing imagery, field measurements on soil and crop variables, Electrical Resistivity Imaging were taken during the five growing seasons. A system approach was used to assess the long term impact of weather on previously identified management zones. The system approach integrated with remote sensing images and field data was able to explain that the causes of yield variability over space and time dealt with irregular distribution of rainfall which affect the amount of Nitrogen used by the crops.

Keywords: spatial and temporal variability, CCCI, SALUS, durum wheat yield

INTRODUCTION

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. 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 et al., 2002; Sadras et al., 2011). 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). The objective of this study was to quantify the causes of yield variability in a 5 year study carried out in Southern Italy on wheat crop.

METHODOLOGY

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 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 Figure 1. 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 et al, 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 Dirksen 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.

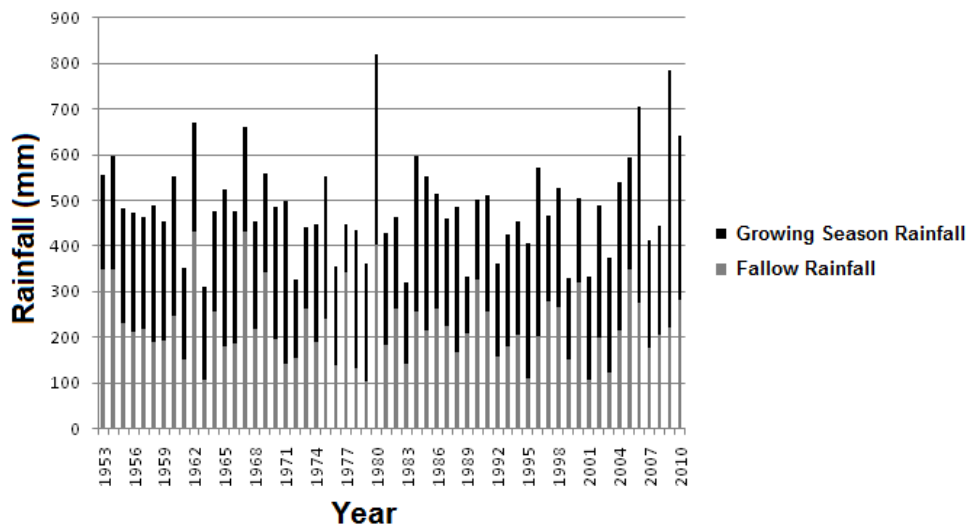


Figure 1. Mean rainfall in mm (bars) for the 58 studied years during the fallow period (June to November) and the growing season (December to May).

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 meters wide parallel transects. 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 meter 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 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). Temporal variance calculation was based on the Blackmore et al. (2003). 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 and temporal 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). 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 to November), and short fallow (September to November). Growing season rainfall (December to May) was sub-divided into vegetative rainfall (December to February) that corresponds to the rainfall period from sowing to end of tillering, and reproductive rainfall (March to 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. During the last two experimental years (2009 and 2010), a variable rate nitrogen application was imposed as results of the simulation scenarios carried out by the SALUS model (Basso et al, 2010, 2011; 2012). The fertilization rates were: T1: 90 Kg/ha of N and 54 kg/ha P2O5; T2: 70 Kg/ha of N and 42 kg/ha P2O5; T3: 30 Kg/ha of N and 18 kg/ha P2O5. The fertilization consisted of a single field application in the middle of March (Fig. 2)

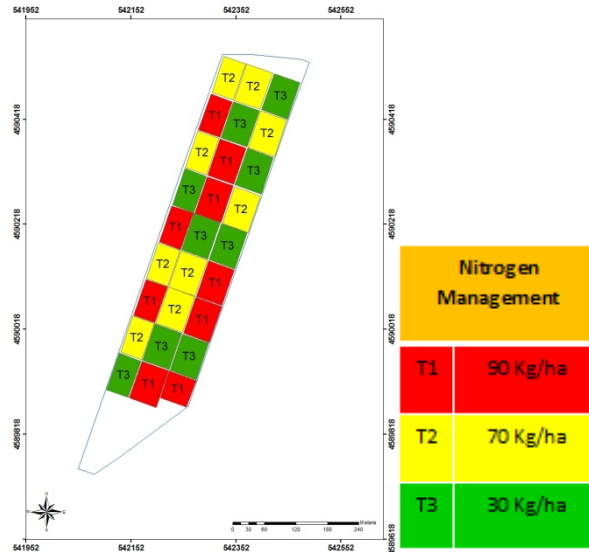


Figure 2. Variable Rate Nitrogen plots scheme applied in 2009 and 2010 in study site.

RESULTS AND DISCUSSION

Spatial maps of wheat grain yield for the five years are reported in Figure 3. 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, the transect area and the upper right portion showed higher yield than the rest of the field. 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. 3d-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.

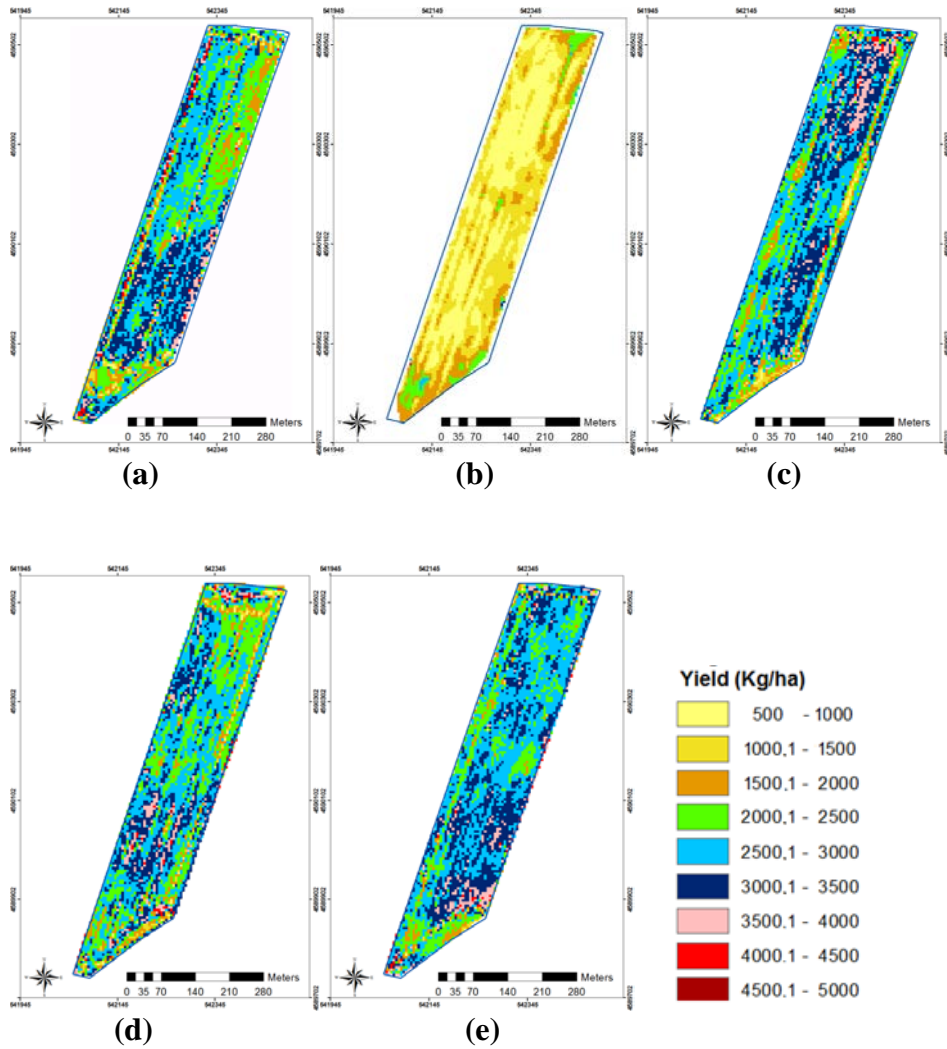


Figure 3. Wheat grain yield maps (kg ha^{-1}) for the growing season 2005/06 (a); 2006/07 (b); 2007/08 (c); 2008/09 (d); 2009/10 (e).

The spatial distribution of soil physical properties is shown in Figure 4a-d. Clay content varied between 8 to 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).

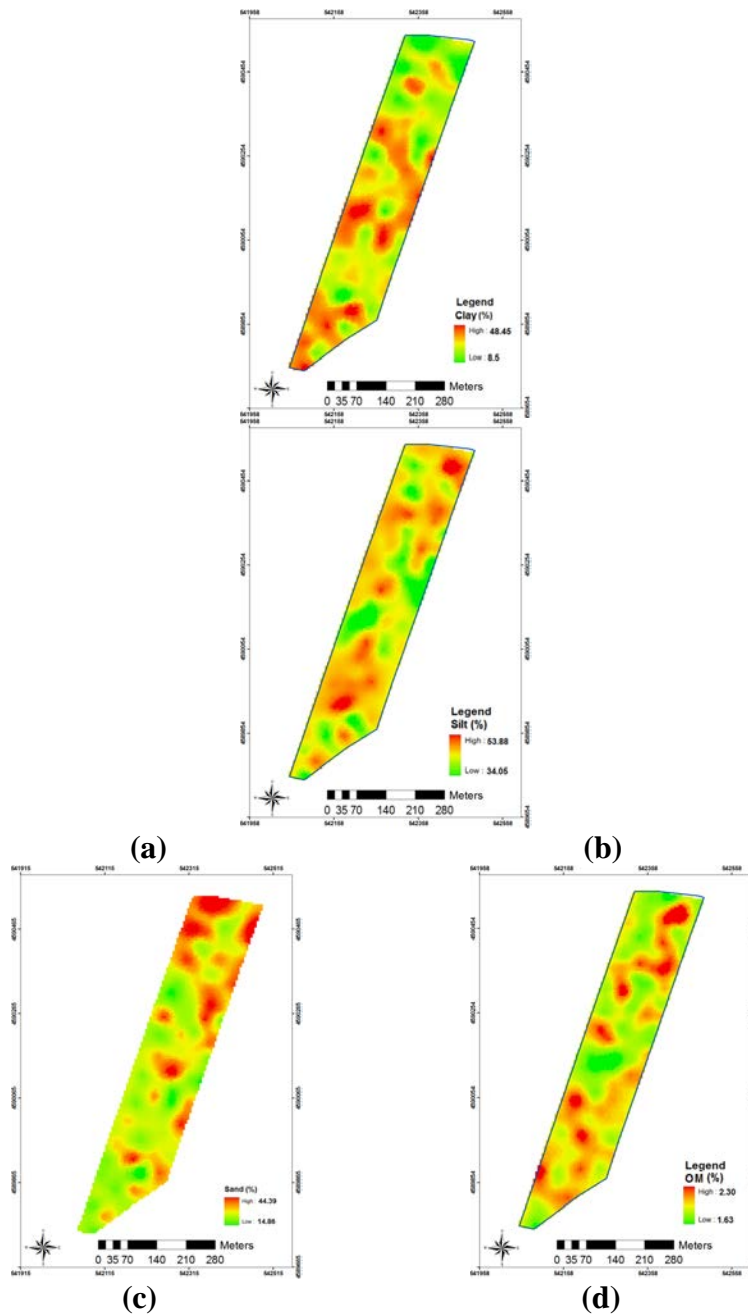


Figure 4. Interpolated map of clay content (%) (a); silt content (%) (b); sand content (%) (c) and organic matter content (%) (d).

The spatial maps of the ERT at two different depths are shown in Figures 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 to 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 to 82.5 and 79.8 and 81.3, respectively (Fig. 6).

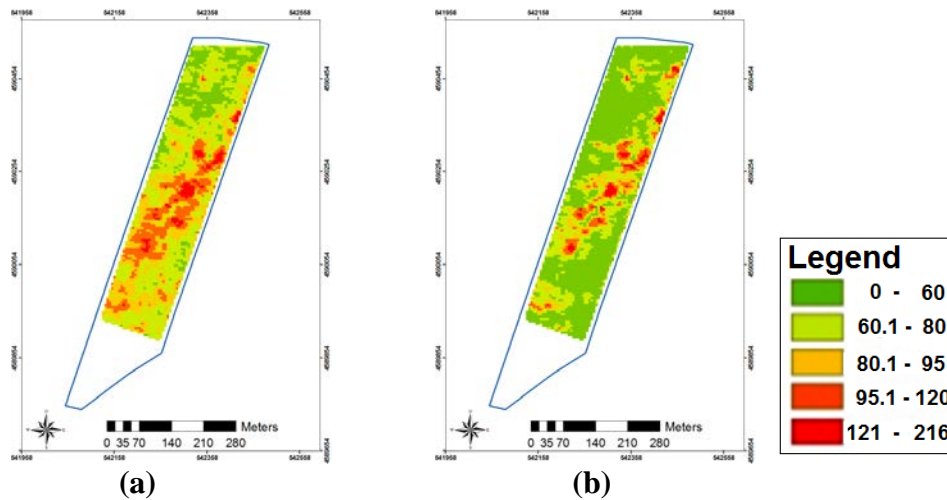


Figure 5. Electrical Resistivity Tomography for 0-50 cm (a); 0-100 cm (b).

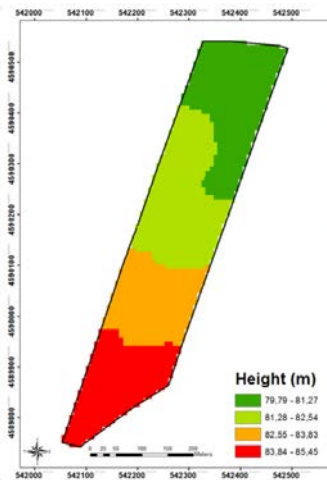


Figure 6. Digital Terrain Model of the study field.

Maps of remotely sensed NDVI are shown in Figure 7a-d, while in figure 8 are shown the NDRE maps. The NDVI maps showed spatial patterns that are similar to the yield maps. During each experimental year, NDRE values were higher in the lower portion of the field. An ANOVA analysis was performed on 2009 and 2010 yield data to evaluate the effectiveness of the Nitrogen rates application. During 2009, from the ANOVA analysis, no correlation was found between Nitrogen rates and yield (or the estimated N uptake) in both AS and HS zones. In

2010, a significant correlation was found between yield and N rates in the AS zone (significance value =0.018) .

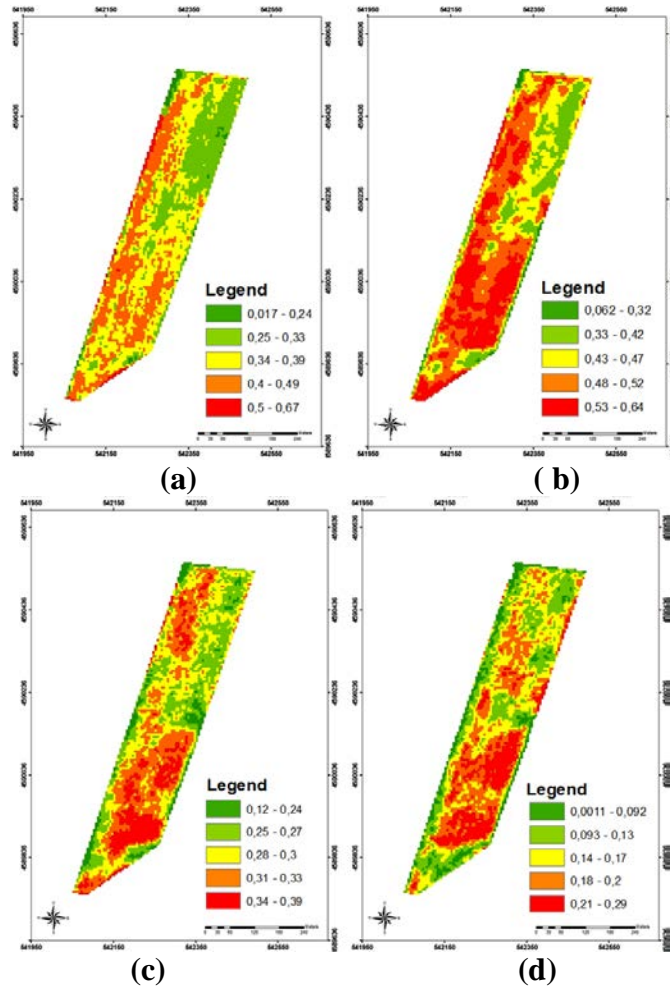
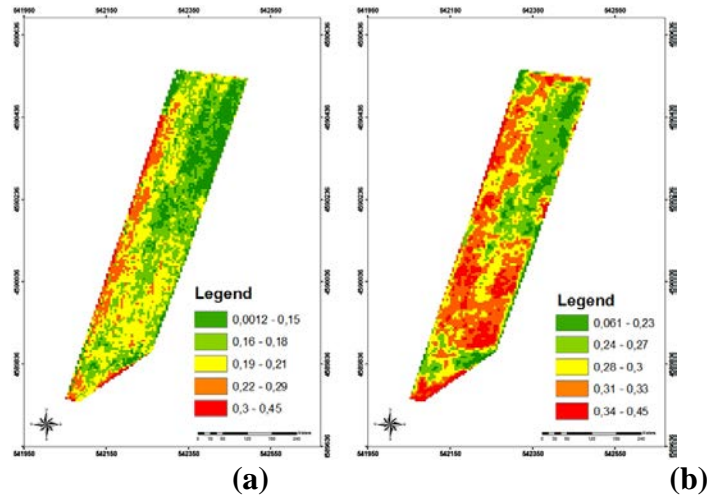


Figure 6. NDVI maps of 14 March (a), 7 April (b), 26 April (c) and 24 May (d) 2010.



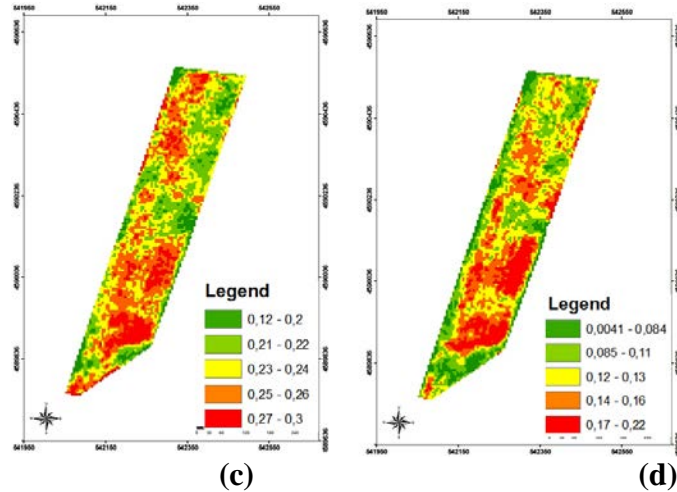
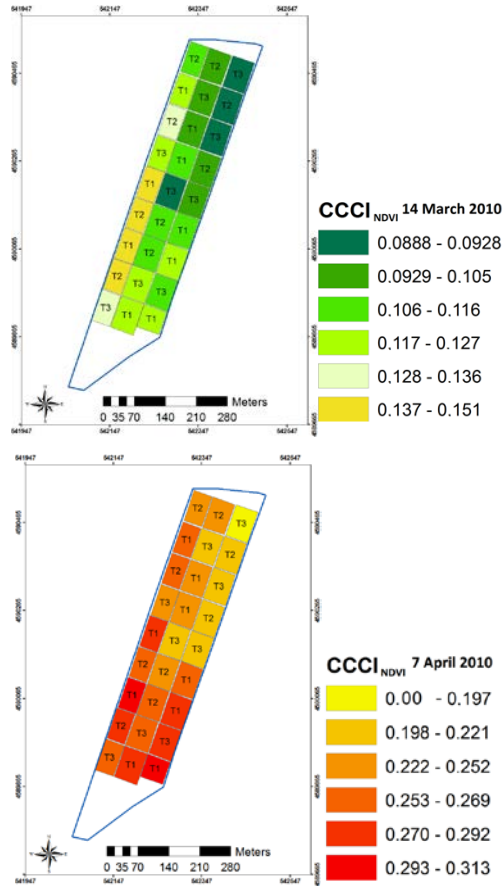


Figure 7. NDRE maps of 14 March (a), 7 April (b), 26 April (c) and 24 May (d) 2010.

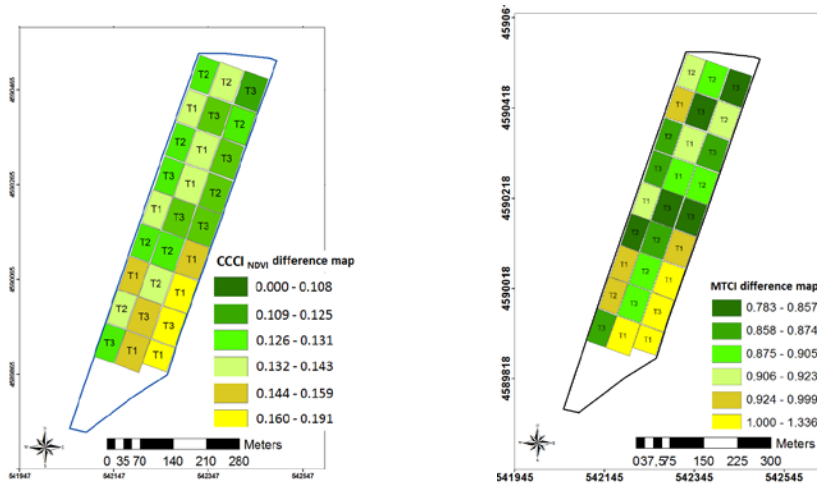
In figure 8 a and b are shown the CCCI maps of March and April 2010. The difference map of $CCCI_{NDVI}$ and MTCI indices are reported in figure 9. The ANOVA analysis was performed on the difference vegetation indices and the nitrogen rates considering the two stable zone (HS and AS) that were found prevalent inside each plot. In 2009 no consistence correlation was found between vegetation indices and N rates for both AS and HS zone, while in 2010 only two indices were found significantly (at a significance level < 0.01) related to nitrogen treatment in the AS zone: $CCCI_{NDVI}$ (Significance=0.007) and MTCI (Significance=0.004).



(a)

(b)

Figure 8. CCCI maps of 14 March (a) and 7 April 2010 (b).

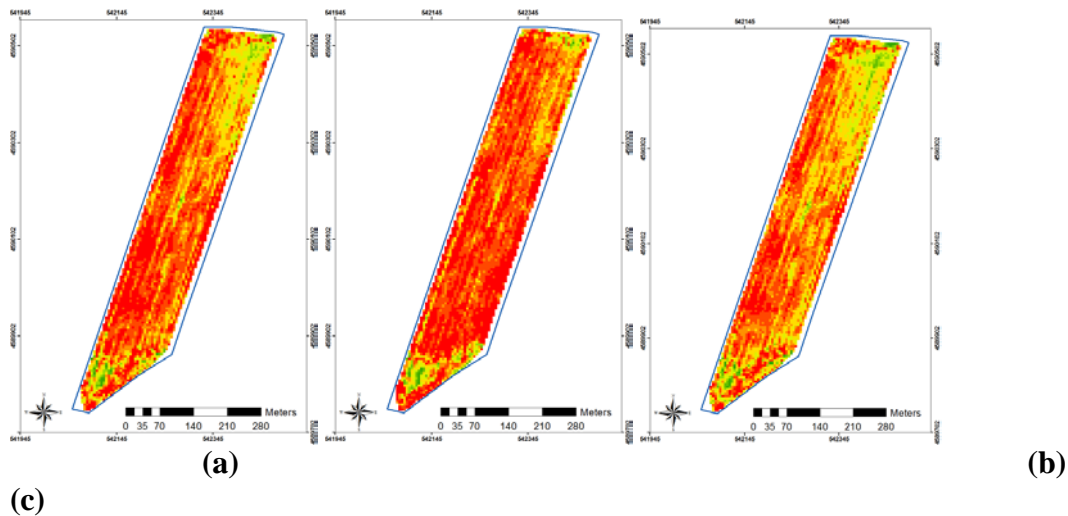


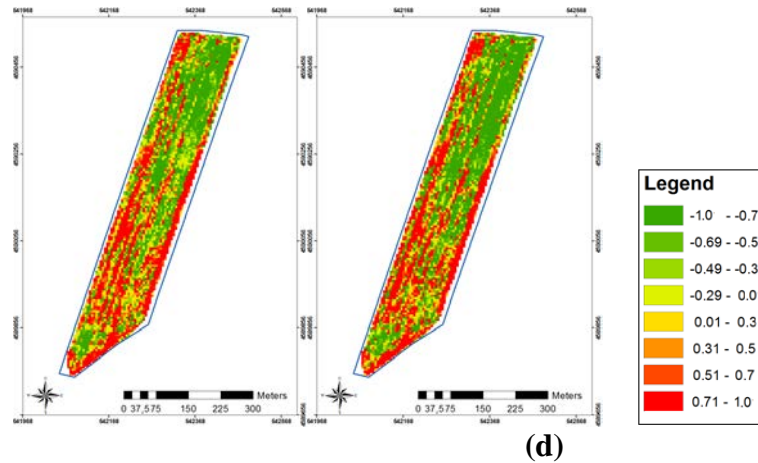
(a)

(b)

Figure 9. Difference map between CCCI_{NDVI} of April and March (a) and difference map between MTCI of April and March (b).

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. The growing season rainfall (Dec to May) showed a minimum value of 237 mm for the growing seasons 2006/07 and a maximum of 564 mm for 2008/09 (Tab. 1). Figure 10 shows the Pearson correlation coefficient maps between total rainfall, long fallow rainfall, growing season rainfall and yield for the five study years. 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. 10a). 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. 10b). Growing season rainfall and grain yield showed areas of negative correlation with coefficients varying between 0.5 and -1 (Fig 10c). The growing season rainfall had high positive coefficients only for the HS, while these values were prevalently low in the AS zone (Fig.10c). Figure 10d 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. 10d). Figure 10e shows the correlation coefficient of the growing season rainfall (by eliminating the dry and wet years) and the grain yield. Overall, the negative 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. 10e).





(e)
Figure 10. 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).

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 (Tab. 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.

CONCLUSION

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 side-dressing 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 should be reduced in low laying area, while increased in N responsive area.

6. References

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