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Wheat yield response to spatially variable nitrogen fertilizer in Mediterranean environment

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ABSTRACT

Farmers obtain high yield when proper crop management is matched with favourable weather. Nitrogen (N) fertilization is an important agronomic management practice because it affects profitability and the environment. In rainfed environments, farmers generally apply uniform rates of N without taking into account the spatial variability of soil available water or nutrient availability. Uniform application of fertilizer can lead to over or under-fertilization, decreasing the efficiency of the fertilizer use. The objective of this study was to evaluate the impact of variable rate nitrogen fertilizer application on spatial and temporal patterns of wheat grain yield. The study was conducted during the 2008/2009 and 2009/10 growing seasons in a 12 ha field near Foggia, Italy. The crop planted each year was durum wheat (*Triticum durum*, Desf.) cultivar Duilio. The field was subdivided into two management zones High (H), and Average (A). Three N rates were identified using a crop model tested on the same field during a previous growing season. The N rates were: low N (T1: 30 kg N ha^{-1}), average N (T2: 70 kg N ha^{-1}), and high N (T3: 90 kg N ha^{-1}). The ANOVA test showed that there were no effects of the N levels for the first growing season for the H and A zone. For the 2009/10 growing season with higher rainfall there was a significant difference in grain yield for the A zone (2955 kg ha^{-1}), but not in the H zone (3970 kg ha^{-1}). This study demonstrates the optimal amount of N for a given management zone is not fixed but varies with the rainfall amount and distribution during the fallow and growing season.

1. Introduction

Nitrogen (N) fertilization is one of the most important agronomic management practices, yet the amount and timing of N remains a management challenge. Crops growing with N deficiency lose greenness, they are usually smaller with less biomass, and have reduced photosynthetic capacity resulting in poor yield and low protein content. It has been estimated that more than 50% of the human population relies on N fertilizers for food production (FAO, 2008). Their global demand has increased of about 7.3 million tons of N per year (IFAI, 2008). Proper N management is important for rainfed agriculture (annual rainfall between 200 and 600 mm). In rainfed environments, if N is available, crops can use much of the available soil water prior to anthesis, leaving the soil dry during the grain filling with resulting low yield and poor grain quality without adequate rainfall during the grain filling period. Soil water supply needs to be adequate before anthesis to develop a good canopy and grain set around anthesis, and during grain filling. Although wheat yield responds positively to soil water content, response will vary based on soil properties and rainfall distribution within the season (Norwood, 2000; Kirkegaard et al., 2001; Nielsen et al., 2002; Sadras, 2002; Anderson, 2010). In rainfed winter wheat areas, farmers generally apply uniform rates of N, with approximately 30% at sowing and 70% at the time of early stem elongation without taking into consideration the spatial variability of soil or rainfall distribution (Saseendran et al., 2004). This can lead to over- or under-fertilization, decreasing the efficiency of the fertilizer use (Mulla et al., 1992). Moreover, excessive N application will result in potential environmental impact due to nitrate leaching, ammonia volatilization, nitrous oxide emissions and soil acidification (Chen et al., 2008a,b; Li et al., 2008). In Germany, Ehlert et al., 2004 found that in variable rate N application, N fertilizer could be reduced by 12% without affecting wheat yield. Farmers can increase the efficiency of N fertilization, maximizing crop N uptake, and minimizing N losses by taking into account the spatial and temporal N need of the crop by dividing the field into homogenous zones of similar behaviour using geospatial technologies (Basso et al., 2011a,b). Robertson et al. (2005, 2007) found that the benefits of dividing the fields into homogenous zones can be achieved if the field zones are consistent in yield performance. Basso et al. (2012) defined three

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spatially and temporally stable zones by integrating spatial measurements of soil physical properties, five years of remotely sensed data and yield monitoring from 2006 to 2011 in the Mediterranean environment of Southern Italy. The interaction between the spatial variability of soil properties and the rainfall distribution affected the spatial and temporal variability of grain yield. Each zone had a different response to fallow and growing season rainfall. In the high yielding stable zones with high spatial and temporal stability, a high correlation between fallow rain and grain yield was observed, but this occurred only if the growing season rainfall was adequate. The average yield stable zones did not respond to fallow rain because of a shallow soil rooting depth and grain yield was more responsive if the growing season rainfall was not excessive.

The interaction between rainfall, position in the landscape and soil properties is important when selecting the amount of N to apply at side-dressing to improve N use efficiency.

The hypothesis of this study was that wheat yield response to nitrogen fertilizer varies over space and time in predefined homogenous zones. The objective of this study was to evaluate the impact of variable rate nitrogen fertilizer application on spatial and temporal patterns of wheat grain 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 elev.) during two growing seasons 2008/2009 and 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 durum*, Desf.) cultivar Duilio. For each growing season the seedbed was prepared the first week of September with a minimum tillage (chisel plough) at a depth of 20 cm. The sowing was carried out in both 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 homogenous zones used in this study are described in Basso et al. (2012) and are High yield zone (H), Average yield zone (A). The zones were selected adopting a modified version of the methodology first reported by (Blackmore, 2000). Wheat yield spatial variability was analyzed, by calculating the relative percentage difference of yield crop from the average yield level obtained within the field at each point mapped. Overlaying the single map of the relative percentage difference created the final map of the zones with different yield levels. The temporal variability of yield patterns, expressed as degree of stability, was calculated as temporal variance (yield value recorded at each point mapped minus the field mean) according to the method proposed by Blackmore et al. (2003). By overlaying the map of relative percentage difference with the one of temporal variance, high and stable yield zones (H) were identified. Temporally stable and average yield were defined as A zones. The parts of the field characterized by unstable yield were classified as unstable (U) and were not considered in the analysis.

The amount of N fertilizer to apply in each zone was derived by using the SALUS crop simulation model over thirty years with weather and soil properties from the study site and following the same approach described by (Basso et al., 2010, 2011a,b). The model was tested using an independent dataset of grain yield from the growing season 2007/08 (Basso et al., 2010). The three N rates identified by the model were: low N rate (T1: 30 kg N ha^{-1}), average N rate (T2: 70 kg N ha^{-1}), and high N rate (T3: 90 kg N ha^{-1}). The most common N application in the study area is about 90 kg N ha^{-1} with 30% given at sowing and 70% at early stem elongation. The treatments were randomly distributed within each zone (Fig. 2). Fertilization consisted in two N split applications, one at sowing with 30 kg N ha^{-1} (representing 30% of the application) and the remaining 70% as a variable dose. The type of N fertilizer applied was ENTEC 25-15. The dates for the second N applications were 16 March 2009 and 17 March 2010. The field was divided into 27 regular and adjacent subareas (30 m × 10 m). Three plots were excluded from further analysis because in each plot there were the same number of pixels of A and H (Fig. 1b).

2.2. Field measurements

Grain yield was georeferenced using a yield monitor system (grain mass flow and moisture sensors). Site coordinates for each yield measurement were determined with a differentially corrected GPS (OMNISTAR signal) Trimble 132 receiver with 1 cm accuracy. The SMS software version 3.0TM (AgLeaderTM Technology, Inc.) was used to read the raw yield data (expressed at 13.5% dry matter). Yield data were then processed to eliminate outlier values lower than 500 kg ha^{-1} and greater than 7000 kg ha^{-1}. The yield maps were obtained by plotting the yield data, using linear interpolation, at the nodes of a regular grid of 5 m spatial resolution. The yield maps were georeferenced and recorded in UTM WGS 84 zone 33 N.

2.3. Statistical analysis

The N plots were large enough (about 300 m^2) to be treated as independent replications for statistical analysis using the conventional analysis of variance (ANOVA). The ANOVA was performed on the mean yield per plot values during both study years (2008/09 and 2009/2010) with a reference significance value of 0.05. The analysis was performed separately for the two homogenous zones. The ANOVA test was used to evaluate the influence of the homogenous zones on the relationship between N applied and grain yield. In the A zone, there were 14 plots of which 6 plots had T1, 5 plots T2, and 3 plots T3. In the H zone there were 2 plots with T1, 2 plots with T2, and 6 plots with T3. Since the T1 and T2 plots' distribution in H, the Kruskal–Wallis non-parametric test (Kruskal and Wallis, 1952) was used for testing if the plots originate from the same distribution. The model was evaluated using the root mean square error (RMSE):

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(Q_i - P_i)^2\right]^{1/2} \tag{1}$$

where Q_i is the observed value, P_i is the simulated value, and n is the number of pairs of measured and simulated values. In addition, the d-index or index of agreement (Willmott, 1982) which is a descriptive measure was calculated as follows:

$$d - index = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P'_i| + |O'_i|)^2}\right] \tag{2}$$

where n is the number of observed values, O_i is the observed values, P_i the simulated values, $P'_i = P_i - \hat{O}_1$ and $O'_1 = O'_1 - \hat{O}'_1$ ($\hat{O}_1$ is the average of the observations). The d-index values range between 0 (not good agreement) and 1 (good agreement).

For each of the two management zones and for the whole field the variability of grain yield was quantified using the coefficient of variation calculated for the 2008/09 and 2009/10 growing seasons. This variability was calculated using the average yields and standard deviations of the whole field, the H zone and the A zone as follows:

$$CV \quad [\%] = \frac{\sigma}{\mu} \times 100 \tag{3}$$

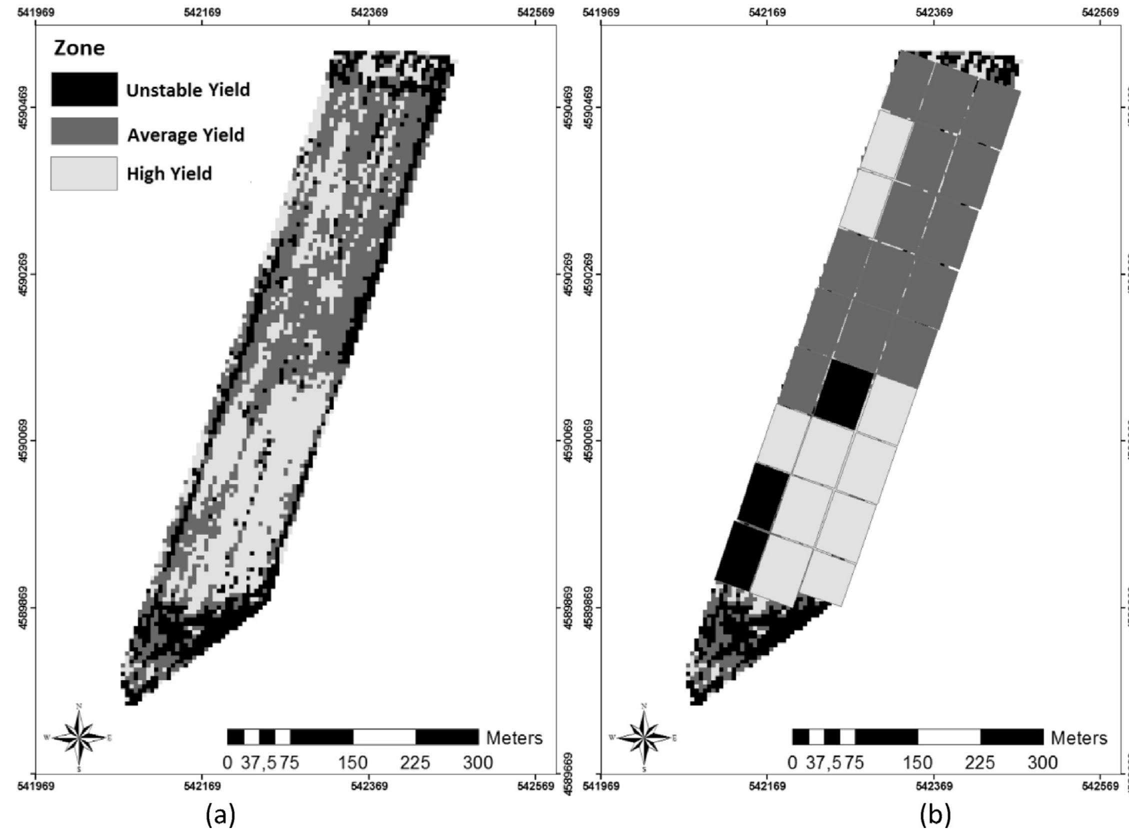

Fig. 1. (a) Spatial distribution of the homogeneous zones (adapted from Basso et al., 2012) and (b) plots of homogeneous zones, the black plots were excluded from the analysis because they had about the same number of pixels of Average (A) and High (H) zone.

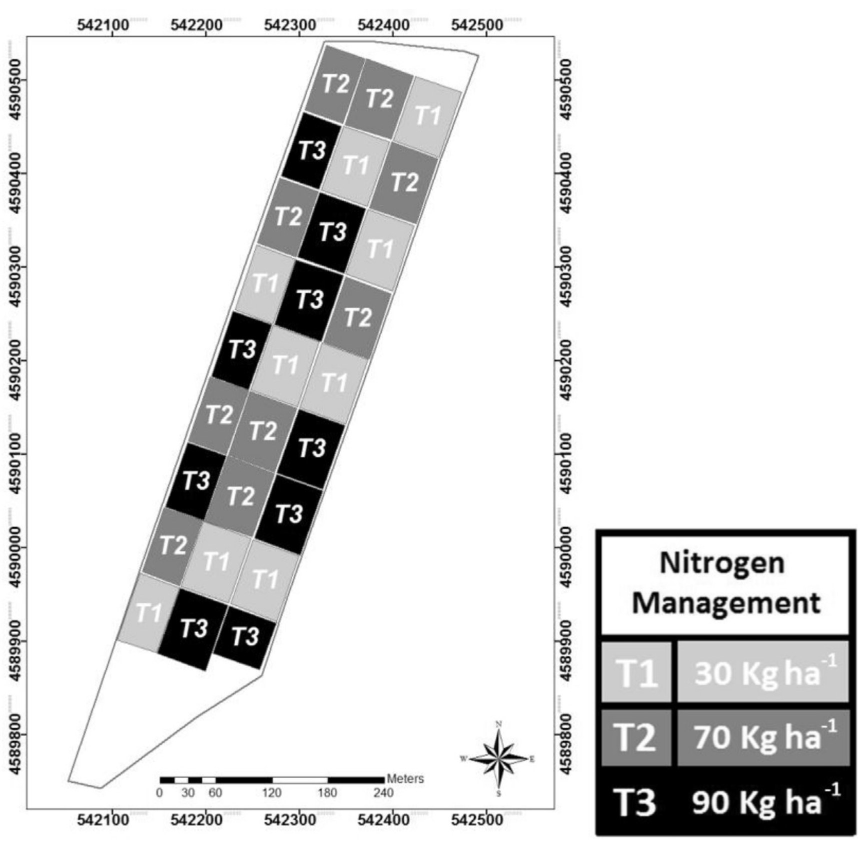

Fig. 2. Spatial distribution of the randomly determined N treatments for the growing seasons 2008/09 and 2009/10.

Table 1
Measured and simulated yield (kg ha^{-1}), standard deviation, root mean square error, and *d*-index for the whole field, the Average zone (A), and the High zone (H) for the growing season 2007–2008.

	Grain yield				RMSE	*d*-index
	Observed		Simulated			
	Mean	Std. dev.	Mean	Std. dev		
Field	3517	241.92	3953	190.24	151	0.87
A	2955	236.63	2904	185.79	171	0.82
H	3970	198.37	3948	170.87	136	0.84

where σ is the standard deviation of the yield (kg ha^{-1}), and μ is the mean of the yield (kg ha^{-1}). ANOVA analysis was performed in Matlab software (MATLAB®, R2011b).

3. Results

Results of the model testing are shown in Table 1. The grain yield data are from an independent dataset from the growing season 2007/08. The RMSE was 163.5 kg ha^{-1} and the *d*-index 0.80 (Table 1). Fallow and growing season rainfall for the growing seasons 2008/09 and 2009/10 are shown in Fig. 3. Fallow rainfall (September–November) was 172 mm for 2008/09 and 207 mm for 2009/10. The total growing season rainfall (December–May) was 564 mm and 360 mm for the growing season 2008/09 and 2009/10, respectively (Fig. 3). The partition of the growing season rain into monthly values were higher in the 2008/2009 season except February and May when were higher for the 2009/10 growing season.

The spatial variability of grain yield for the two growing seasons is shown in Fig. 4a–b. Overall, wheat yields varied between 500 and 5000 kg ha^{-1} with an average yield of 3000 kg ha^{-1} and 3500 kg ha^{-1} for the growing season 2008/09 and 2009/10, respectively. Grain yield within each N treatment varied spatially within the field and within each management zone. For the first growing season the 30 N and 70 N treatments had yield values ranging between 2150 and 3200 kg ha^{-1} and 90 N treatments had yield values ranging between 2500 and 3200 kg ha^{-1} (Fig. 4c). In the second season grain yields within each plot were higher than the first season, with 30 N yields ranging between 2400 and 3100 kg ha^{-1}, 70 N between 2650 and 3000 kg ha^{-1}, and 90 N ranging between 2650 and 3400 kg ha^{-1} (Fig. 4d). Some of the N plots had no increase or decrease in yield between the two seasons. For example, 30 N, 70 N and 90 N located on the left-mid portion of the field had similar yields for both years, while the same plots located in the right bottom-mid portion of the field had an increase in yield from the

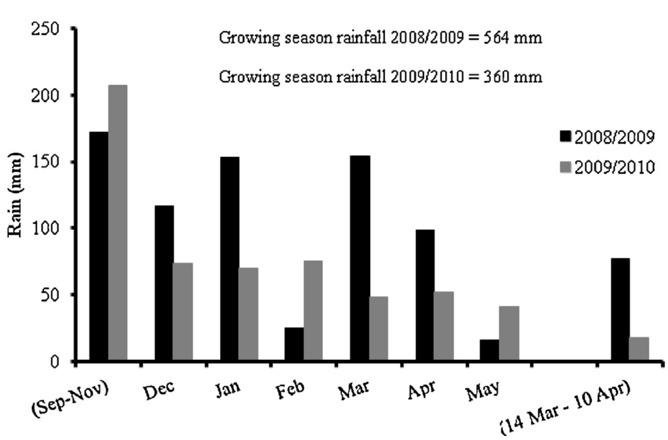

Fig. 3. Fallow (September–November) rainfall, monthly rainfall, and rainfall between the second N application for the growing season 2008/09 and 2009/10.

first to the second growing season (Fig. 4c–d). In the H zone the 30 N and 90 N yields for the second growing season had the same yield range (Fig. 4d) demonstrating that 30 N was sufficient for this zone.

Results of the ANOVA analysis for the first growing season showed non-significant effect of the N levels on grain yield at $p < 0.05$, but in the second season there was a significant N response on the yield. The ANOVA test was used for each management zone analyzed separately. The A zone in the first growing season had no N treatment effect on grain yield [$F(2,12) = 0.23$, p-value = 0.798] while there was a significant N effect on grain yield for the second season [$F(2,12) = 6.98$, p-value = 0.01). In the H zone the Kruskal–Wallis non-parametric test showed no significant effects of N treatments on grain yield for both growing seasons [$F(2,7) = 0.52$, p-value = 0.61 for 2008/09; $F(2,7) = 1.18$, p-value = 0.36 for 2009/10].

The CV for the first growing season was 22% for the whole field, 14% for the H zone and 16% for the A zone. In the second year, it was lower, with 16, 10, 12% for the whole field, H, and A, respectively.

The grain yield measured for each N treatment, each management zone, and for the two growing seasons are shown in Fig. 5. Overall, there was a large variability in yield response between the treatments within each zone and between the years. In the first year the grain yield in the A zone ranged between [1]2177 kg ha^{-1} and 2566 kg ha^{-1} for T1, between 2335 kg ha^{-1} and 2863 kg ha^{-1} for T2 and between 2587 kg ha^{-1} and 2656 kg ha^{-} for T3. For the same year the H zone grain yield was 3167 kg ha^{-} for T1, 2800 kg ha^{-1} and 3000 kg ha^{-1} for T2, and between 2561 kg ha^{-1} and 3098 kg ha^{-} for T3. In the first growing season the maximum yields for the H were higher for the T1 lower N rate of T3 than for the T3 but the differences were not statistically different (Table 1). In the second season T3 produced higher yields than the previous growing season with H having the higher yields. T1 treatment had higher yield for the H zone but they were not statistically different (Table 1). In both zones the T2 treatment had little variation in the range of the measured yield (Fig. 5).

4. Discussion

Results of this study complement a previous study for the same field (Basso et al., 2012). The CV% values and spatial yield variability (Fig. 4) of the present study agree with the results of Basso et al. (2012) in Table 1. The earlier study highlighted the importance of fallow and growing season rainfall and stored soil water content at the time of second N application on spatial and temporal variability of wheat yields. It also demonstrated the interaction between rainfall and spatial distribution of soil properties within each uniform management zone.

The lack of any significant correlation between yield and the N treatments for each of the uniform zone (Fig. 5) can be explained by the patterns of the fallow and growing season rainfall and for the spatial soil properties of each uniform zone analyzed in Basso et al. (2012). In wet years the whole field requires less N because of water logging in the low elevation zones of the field (Basso et al., 2012) negatively influences the plant population stand. A poor wheat stand will take put a lower amount of N. The 2008/09 growing season rainfall was 204 mm higher than the 2009/10 season; therefore the benefits of stored water prior to sowing (fallow rain) was less evident. The H zone has a deeper soil profile for root growth and uptake (Basso et al., 2012). This allows more rainfall to be stored during fallow and usually has a positive influence on grain yield. Information in Figs. 4d–c and 5 shows that the yield in the T3 and T1 treatments in the lower right portion of the field are not different. This suggests that in the lower portion of the field the lower amount of N (T1) would be adequate

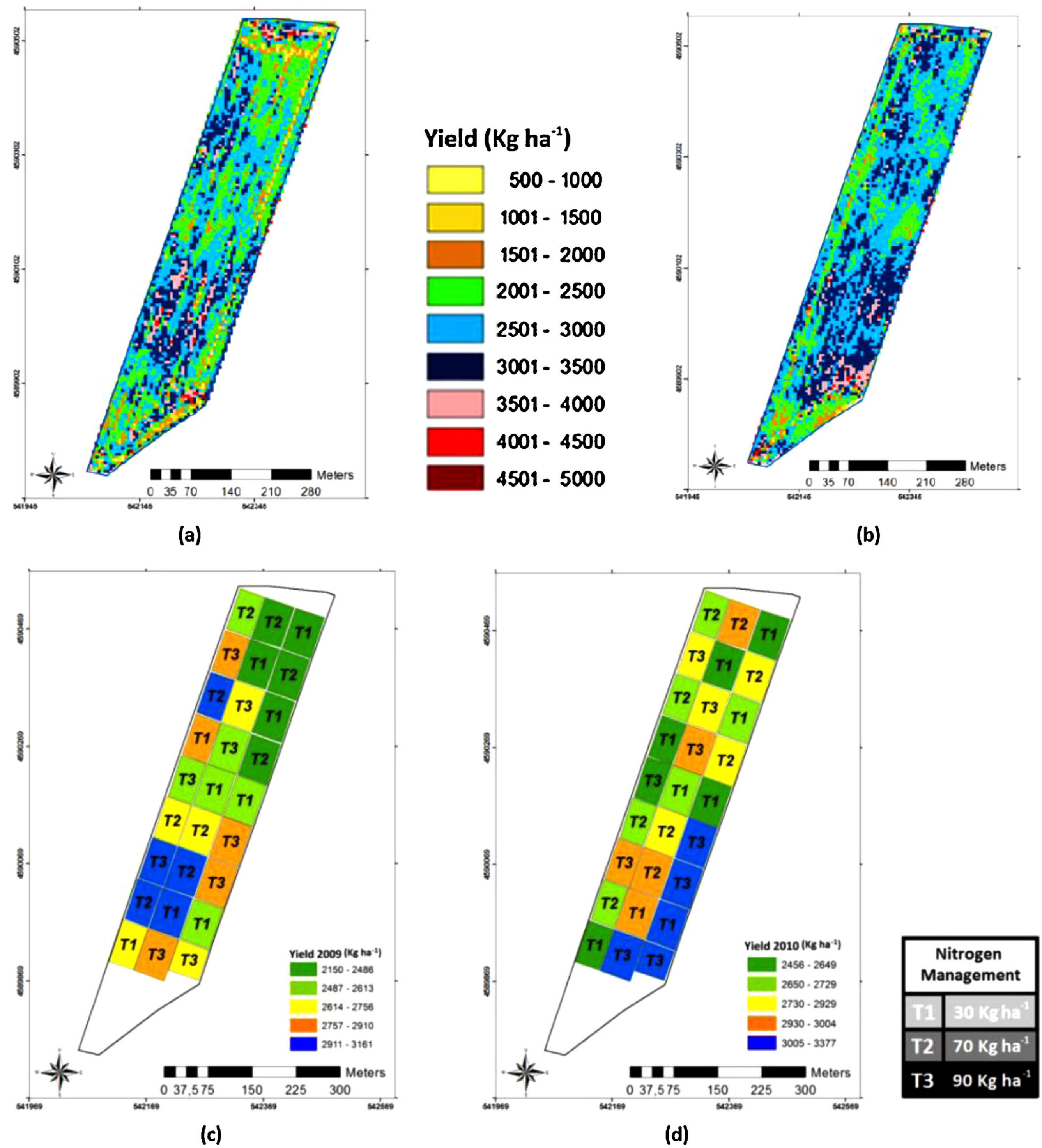

Fig. 4. (a) Spatial distribution of grain yield (kg ha^{-1}) for the growing season 2008/09 and (b) Spatial distribution of grain yield (kg ha^{-1}) for the growing season 2009/10; (c) grain yield for each N plot for the growing season 2008/09 growing season, and (d) grain yield for each N plot for the growing season the 2009/10 growing season.

in years where the rainfall up to the second N application is similar to the ones observed in this study for both growing season. Thus the H zone will have little advantage from high fertilization rates because of the high content in organic matter (>2%) and the deeper exploitable root zone (Basso et al., 2012). Overall, this result agrees with the findings of Basso et al. (2010) that for this type environment, lower N fertilization rate is sufficient to meet crop N demands, but this amount is dictated by the spatial soil properties.

The lack of response of yield to N treatments for the whole field in 2008/09 is also related to the high amount of rainfall. During the month of December, the 116 mm of rainfall caused water logging in the low elevation zones of the field; moreover 77 mm rain fell between the second N application (16 March) and 25 days later (April 10) (Fig. 3). The high rainfall in a short time could cause N leaching, especially for the T2 and T3 treatments. Basso et al. (2012) found that in the A zone there is a negative correlation between grain yield and growing season rainfall because of water

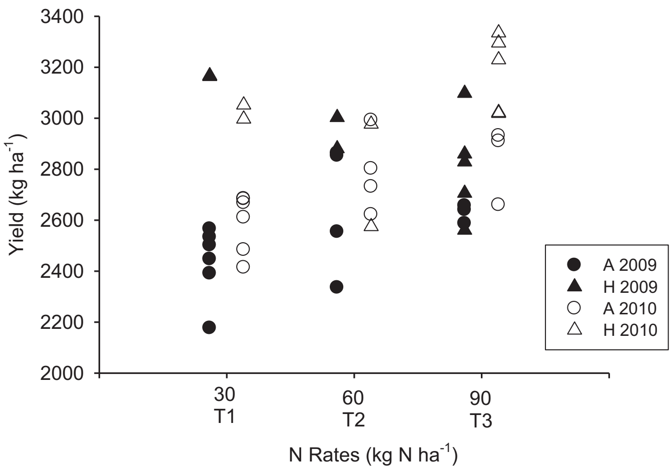

Fig. 5. Measured grain yield for the all treatment for the 2008/2009 (closed triangles) and 2009/2010 (open triangles) growing seasons.

logging in this depression area (Basso et al., 2012). In the H zone high N fertilization will not always result in higher yields as shown in Fig. 4d for the mid-portion of the field where T1 treatments show the same yield levels as T2. The July–September fallow period rainfall was higher in 2009/10 than the previous growing season, thus the benefits of stored water prior to sowing was beneficial for apparently causing low yield variability within the field as shown from Fig. 5. Our findings agree with those of Sadras et al. (2012) who demonstrated that July–September fallow (approximately 60 days before sowing) water storage had more benefits on grain yield than July–December fallow (time between the previous harvest and before the next sowing) water storage and the benefits of fallow rain declined as within season rainfall increased.

The A zone had a response to N for the 2009/10 growing season mainly because the entire zone did not respond to fallow rainfall owing to its soil physical properties (Table 1 and Fig. 4d). The soil has higher clay content in the upper 50 cm over a compacted layer of soil and stones because the central transect was an old creek bed (Basso et al., 2012). The upper right area soil profile had a high electrical resistivity with high silt and coarse sand fraction and a descending slope in the direction of the upper right corner of the field shown Basso et al. (2012) in Fig. 5 of that paper. These factors contribute to the lower soil water storage in the shallow profile and contribute to a response to different N levels (Basso et al., 2012) due to different amount of water available to plants and root exploitable profile which will determine the amount of N uptake. The knowledge of spatial variability of plant extractable soil water during the off-season, at planting and at side dressing is crucial to optimize nitrogen fertilizer. Such knowledge can be obtained through a validated simulation approach using long-term weather records.

In conclusion, this study demonstrates how the amount of N needed for spatially variable fields is not fixed but varies with the rainfall amount and distribution of rainfall within the fallow period and growing season as well as the stored soil water at the time of the spring N fertilizer application. Within each defined somewhat uniform management zone there is an appropriate amount of N for optimum grain yield within the confines of the uncertainty of spatial and temporal variability. The study showed experimentally that N fertilizer can be reduced without compromising yield, and with the consequent advantage of reducing nitrous oxide emission. The simulation of the soil water balance in each zone and the rainfall distribution can be used to make tactical decisions regarding the N fertilizer management, thus providing the opportunity to increase profitability and decrease N losses as demonstrated in Basso et al. (2011a,b, 2012). Thus, this type of management strategy can be adopted in fields where spatial variability exists.

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