ASSESSMENT OF CLIMATE VARIABILITY ON OPTIMAL NITROGEN FERTILIZER RATES FOR PRECISION AGRICULTURE

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ABSTRACT

Wheat yield and protein content are spatially variable due to inherent spatial variability of factors affecting yield at field scale. In Mediterranean environments yield variability is often caused by the irregular weather pattern, particularly rainfall and by position on the landscape. The magnitude of this variability is a good indication of the suitability of implementing a spatially variable management plan. Crop simulation models have the potential to integrate the effects of temporal and multiple stress interaction on crop growth under different environmental and management conditions. The strength of these models is their ability to account for stress by simulating the temporal interaction of stress on plant growth each day during the season. The objective of paper is to illustrate a methodology that allows for the selection of optimal nitrogen fertilizer rates to be applied spatially on previously identified management zones through crop simulation modeling. An analysis was carried out to assess the effects of climate variability in selecting variable rates nitrogen. The integration of yield maps, remote sensing imagery, ground truth measurements, electrical resistivity imaging allowed for the identifications of three distinct management zones based on their ability to produce yield and their stability over time. After validating the SALUS model, we simulated 7 N rates from 0 to 180 kg N/ha with a 30 kg N/ha increment. The model results illustrate the different N responses for each of the zone. The analysis allowed us to identify the optimal N rate for each of the zone based on agronomic, economic and environmental sustainability of N management. The model provided excellent results when compared to the measured data; it also showed to be a valuable tool that would help farmer reduce their economic risk and environmental impact related to N fertilization.

Keywords: Simulation Models, Wheat, Variable Rate Nitrogen, Management Zones, Precision Agriculture

INTRODUCTION

Appropriate nitrogen management is one of the main challenges of agriculture production and for the environment. Raun and Johnson (1999) stated that Nitrogen Use Efficiency (NUE) defined as the amount of N used for producing grains, might be as low as 33% for cereals and that an increase of 1% in NUE would lead to a global savings of $234 million U.S. dollars. Under field conditions N losses are mainly due to volatilization of NH_3 from leaves of N-rich plants, soil denitrification and nitrates leaching (Raun and Johnson, 1999). Therefore to reduce such losses a better and more efficient way of applying N is necessary.

From an economic point of view the optimal Nitrogen (N) fertilizer amount should be the rate at which the farmer’s financial return is maximized and it known as Economic Optimum Rate (EOR). The optimal N amount (N_{opt}) varies between cultivar, site location and between years (Samborski et al., 2009), for the same field cropped with the same cultivar the N_{opt} is not constant across the field because of the spatial variability of crop growing conditions and soil properties (Pierce and Novak, 1999).

Understanding the N fertilization efficiency might require the availability of long-term studies, because few years of field experiments might not reflect the potential crop response, due to variation in growing season rainfall. Process-oriented crop growth models can be useful to simulate the long-term effects of water and N stresses and their temporal interactions on daily crop growth and development rates through the growing season (Batchelor et al., 2002; Basso et al., 2007). They have been extensively validated and applied under a wide range of environmental conditions (Singh, 1985; Carberry et al., 1989; Jagtap et al., 1993; Kiniry et al., 1997; Garrison et al., 1999; Miao, et al., 2006; Basso et al., 2007, 2009; Senthilkumar et al., 2009).

Crop simulation models have the potential to integrate the effects of temporal and multiple stresses interaction on crop growth under different environmental and management conditions (Basso et al., 2001). The strength of these models is their ability to account for stress by simulating the temporal interaction of stress on plant growth each day during the season (Batchelor et al., 2002). However, crop simulation models cannot simulate every position in the field because of the costs associated with gathering data and the availability of detailed inputs. As a consequence, delineating zones within the field of similar crop response may provide the right amount of data to execute the model (Basso et al., 2007). Various authors have proposed criteria for the delineation of management zones (Mulla, 1991; Fleming et al., 2001; Ferguson et al., 2004; Schepers et al., 2004; Chang et al., 2004; Inman et al., 2005: Franzen et al., 2002; Basso et al., 2009).

The objective of this paper is to present a procedure that allows for the selection of optimal nitrogen fertilizer rates to be applied spatially on previously identified management zones through crop simulation modelling.

METHODOLOGY

Site Description

The study was carried out on a 10 ha field with rolling landscape, located in the S. Agata delle Tremiti, Serracapriola (FG) (41° 48’ 46” N , 15° 93’ 99” E; 40 m a.s.l.), Foggia –Italy, during 7 crop seasons of wheat monoculture (from 2001/02 to 2008/09). The field is characterized by 3 different yielding zones (Basso et al., 2009) and soil type (Figure 1):

1. a high yielding zone (High Yield Zone) with silty loam soil, 1.3% organic carbon (OC), 150 mm m^{-1} of potential extractable soil water (PESW);
2. a medium yielding zone (Medium Yield Zone) with a sandy loam soil and 1.2% (OC), 130 mm m^{-1} PESW;
3. a low yielding zone (Low Yield Zone) with coarse and stony soil, 100 mm m^{-1} of PESW, even though this area has a shallow soil (60 cm) reducing further the PESW to only 60 mm.

The climate of the area was characterized by an average annual rainfall of about 400 mm. The annual average maximum temperature was 18 °C, with a minimum of 6 °C.

The sampling scheme was made by adopting a 25m x 25m grid. There were 25 sampling points, which were identified using of a DGPS (Trimble AgGPS 114). The points were located at the nodes of the grid and measurements were taken on the point of sampling at three different distances from the node (1, 3 and 5 m). A Digital Elevation Model (DEM) was obtained using the DGPS a resolution of 5 m^2 and with cm level DGPS accuracy.

Agronomic management

The crop planted was durum wheat (*Triticum Durum*, Desf.) cultivar ‘Quadrato’ for the first 3 crop seasons, then Ciccio and Simeto for the rest of the crop seasons. For all crop seasons the seedbed was prepared in September with a plough at a depth of 30 cm. The sowing was made in December at depth of 5 cm and 17 cm distance between the rows. 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. Weed control was accomplished using RoundUp (Glifosate) and Topik + Sound (2.4D+ CLODIFOP + Metosulan) for all crop seasons. The crop was harvested always around the first decade of June.

Soil Sampling

The soil samples were taken in November 2001 prior planting to determine the soil chemical properties to use as input in the simulation model. Four depths were sampled with an increment of 15 cm up to a total depth of 60 cm. Soil texture was determined using the hydrometer method (Klute, 1986), Organic Carbon (C) was measured using the Walkley-Black method (Walkley and Black, 1934), total N was determined using Kjedahl method, K exchangeable, cation exchange capacity (CEC) and P exchangeable were determined with the Olsen method. Soil water content was measured using the gravimetric method every three weeks for the sampling points selected every 20 cm increment to a total depth of 60 cm (where possible). The sampling points located at the top of the hill side did not allow reaching the depth of 60 cm, therefore the total depth of those sampling points reach a maximum of 40 cm.

Yield monitoring

Yield data were recorded by using a *New Holland* TX 64 combine equipped with a yield monitor system (grain mass flow and moisture sensors). Site coordinates for each yield measurement were determined with a differentially-corrected (*OMNISTAR* signal) Trimble 132 receiver. The SMS software version 3.0™ (*AgLeader Tecnology*, Inc.) was used to read the row yield data (expressed at 14% dried matter). Yield data semivariograms were created using GS+ software version 5.3™ (*Gamma Design Software*, 1999).

Crop model description

Simulation runs were performed using the SALUS model for wheat (Basso et al., 2006: Senthilkumar et al., 2009). The model is process-oriented model that simulate plant growth and development responses to environmental conditions (soil and weather), genetics and management strategies.

The weather data used by the model included daily values of incoming solar radiation (MJ m^{-2} day^{-1}), maximum and minimum temperature (°C) and rainfall (mm). The measured weather was providing by the meteorological station located near the experimental field. Soil input data (sand, silt, and clay content, bulk density, organic carbon and water limits) were determined from soil samples collected at the 25 locations (see paragraph 2.3). Soil water limits were calculated using the procedure suggested by Ritchie et al. (1999). The soil water limit used to execute the model varied spatially using site-specific input according to the observed data of soil texture, soil depth, coarse fraction and initial soil water content. The model performance was evaluated using the root mean square error (RMSE). The simulated yields were compared with the measured yield for the study site. An additional validation was carried out using the long term yield data collected at variety trails experiment of the CRA Cereal Institute since 1976.

Procedure for selecting optimal N fertilizer rates

We selected 7 nitrogen (N) fertilizer rates (0, 30, 60, 90, 120, 150, 180 kg N ha-1) to simulate the impact of N fertilizer on yield, leaching, and net economic return for 56 years of available weather record. The model quantifies the effect of climate variability of temporal variation of yield, and environmental impact. We simulated the selected N rates for the previously identified management zones (Basso et al., 2009). We assessed the spatial and temporal variability of yield, leaching and nitrogen marginal values using the simulated cumulative probability analysis. We simulated the 7 N fertilizer rates for 56 years of available weather record for the site. We then chose the best N fertilizer rate for each of the zone based on the yield response to N, marginal value and amount of nitrate leaching.

RESULTS AND DISCUSSION

The validation of measured and simulated yield for the 56 years was shown in Figure 2. The RMSE was 320 kg ha^{-1} demonstrating the reliability of the model used for this study.

The cumulative probability distribution of the simulated yield showed the different effect of N on each of the zones (Basso et al., 2009). The High Yield Zone (HYZ) demonstrated to be more responsive to the N fertilizer supply with a significant increase in the 90 kg N/ha compared to greater amount that did not increase yield substantially. The Medium Yield Zone (MYZ) showed an increase from 30 to 60, demonstrating that from 60 onward the N addition does not guarantee a greater yield. Low Yield Zone (LYZ) does not show any difference in yield increase after 30 kg N/ha.

Average Grain yield for the three management zones at different N rates is showed in Fig 4. The High Yield Zone (HYZ) showed the highest yield for all the N rates; in the HYZ the maximum yield was obtained with 150 N (4100 kg/ha) even though the difference with from 90 Kg N/ha are nearly insignificant. For the Medium Yield Zone (MYZ) the highest yield was obtained with 90 N (2800 kg/ha) while for the Low Yield Zone (LYZ) the same yield of 1900 kg/ha was obtained with either 60 or 90 N.

The net revenue calculated as difference between the current grain price and the global costs (operation plus materials), achieved at the different N rates is showed in Fig. 5. For the HYZ the maximum economical return was achieved at 150 N, but again the difference with the lower rates are very small, suggesting that the same income can be obtained with lower N but at the same we save N fertilizer that is a potential threat to the groundwater through the leaching processes. For the MYZ and LYZ the highest profit was obtained with 90 Kg N/ha and 60 Kg N/ha, respectively.

Figure 6 shows that the marginal return of N on grain yield decreased as the N rates increased. The additional 30 kg N/ha added from the 30 N showed a diminishing marginal return for all the three zones. The difference in output for the HYZ was 13.6 € kg $N^{-1}$for the first 30 kg N/ha, 2.2 € kg N^{-1} for the additional 30 kg N/ha, and 0.46 € kg N^{-1} for the last two N increases. For the MYZ the marginal return was 5.6 € kg N^{-1} for the first 30 kg N/ha, 3.06 € kg N^{-1} for the 60 N, -1.2 and -0.4 € kg N^{-1} for the last two N increases. For the LYZ the only positive marginal return was for the first 30 kg N/ha applied (2.2 € kg N^{-1}). It dropped to -0.4 and -1.26 € kg N^{-1} for the subsequent N increases.

The N leaching for the three zones at different N rates showed that the leaching increased as the N rate increased, with the highest values of N leached obtained for the 180 N. However, from the analysis of the 56 years long-term simulations for each area, the cumulative probability function showed that higher N leaching were obtained for the LYZ and the MYZ, while lower N leaching were observed for the HYZ. This might be due to the best utilization of mineral N from crop growing in the HYZ respect to the other two management areas. In the LYZ highest N value leached was obtained for the 120, 150 and 180 N, while for the MYZ the values of N leached were close for all the N levels.

The increase of grain yield for each unit of N applied as a function of changes in N leaching for each unit of N applied showed that for the HYZ the 150 kg N/ha maximized the yield increase as function of N leached, while for MYZ and LYZ was 90 and 60, respectively.

When the net revenue is plotted against N leaching the profitability and the environmental impact of the fertilization management for HYZ respect to MYZ and LYZ is showed (Fig.7). In fact, as supported by the marginal return, each increase of 30 N units does not increase significantly the net revenue after 90, 60 and 90 for HYZ, MYZ and LYZ respectively. To note that the LYZ showed a negative value for 30 kg N/ha because it is necessary to increase the N supply to have a marginal net return. After 60 kg N/ha, there is a negative impact on the environment with no increase in net marginal return. The MYZ showed a negative profit at lower N rates, with increase in revenue at higher N rates, but at a certain environmental costs, since it shows the highest N leaching rates. The LYZ is the more sensitive zone for a fertilizer management, because most of the N rates will not increase the net revenue for that area and only two N rates showed to be economic viable solution, with 60 N the optimum rate for such zone.

One of the most important issues arising from the management of N fertilization for precision agriculture is environmental protection (Pierce and Novak, 1999). The use of crop simulation models, which integrate the effects of complex multiple stresses in a temporal way, allow for a complete understanding of the interaction of the climate and soil effects on crop growth and yield. Sadler et al. (2000) concluded that the application of simulation models to site-specific management is still limited, because models are often not developed or tested for application where there is a certain amount of variability. However, Basso et al. (2007; 2009) showed that crop models were able to simulate yield in a spatial context in a field where a certain degree of variability existed.

CONCLUSIONS

This study has demonstrated that once the management zones have been well defined, crop models can be useful tools in selecting the most sustainable N management from the agronomic, economic and environmental point of view. Models help finding the best management option regarding the N rate that will maximize farmer’s economical return and reducing the risk of environmental pollution. In fact, the N rates were different among the zone, with 90-120 kg N/ha being the best rate for the HYZ, 90 kg N/ha for the MYZ and 60 kg N/ha for the LYZ; further increase in N rates for the MYZ and LYZ would have not cause any yield increase. The best rates for the zones were not identified only by choosing the rate that maximize yield, but the one that will decrease the cost and the environmental impact, and from the analysis of the marginal net return, the net revenue vs. leaching and the NUE. For example for the HYZ results might suggest that 150 N would have been the optimal rate in terms of yield, but the analysis accounting for environmental impact and marginal value of N suggested that the rate between 90 and 120 kg N/ha should be the quantity of fertilizer applied to this area, versus 90 and 60 for the MYZ and LYZ.

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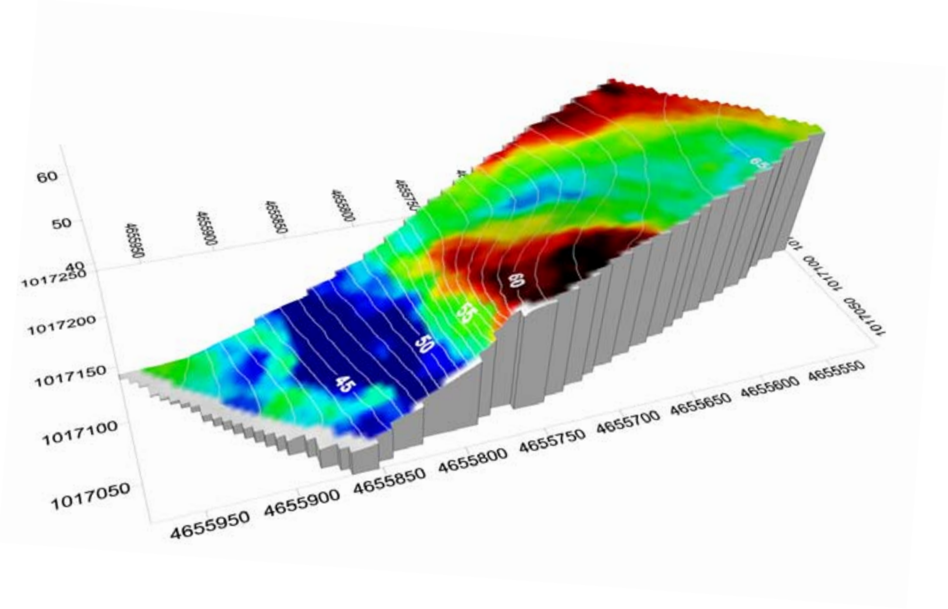

Figure 1. Interpolated map of the Automatic restivity profiling (ARP) for the 0-50 cm soil layer.

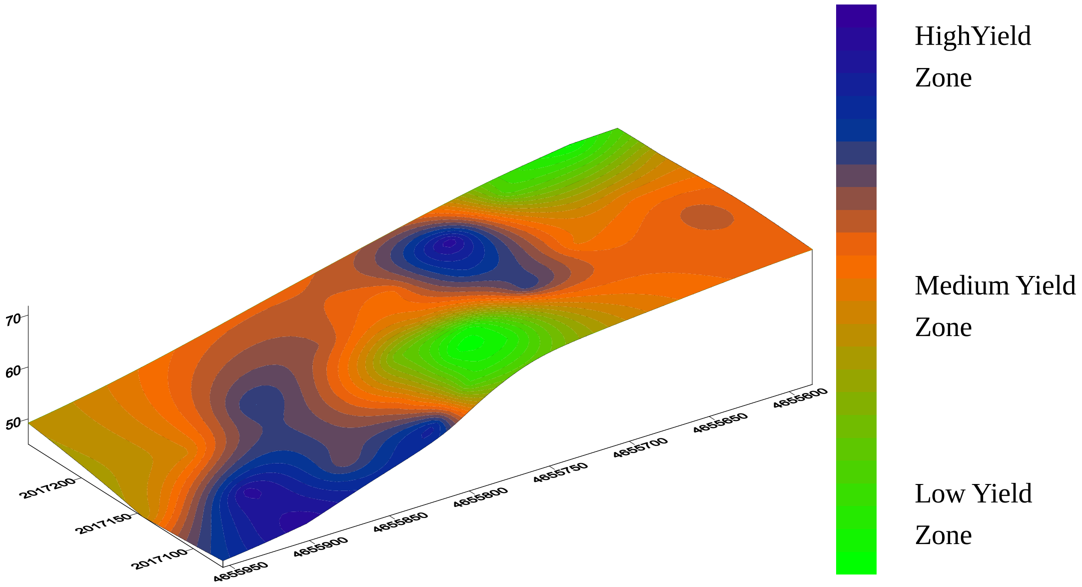

Figure 2. Maps of the three management zones. High Yield Zone; Medium Yield Zone, Low Yield Zone (Basso et al., 2009).

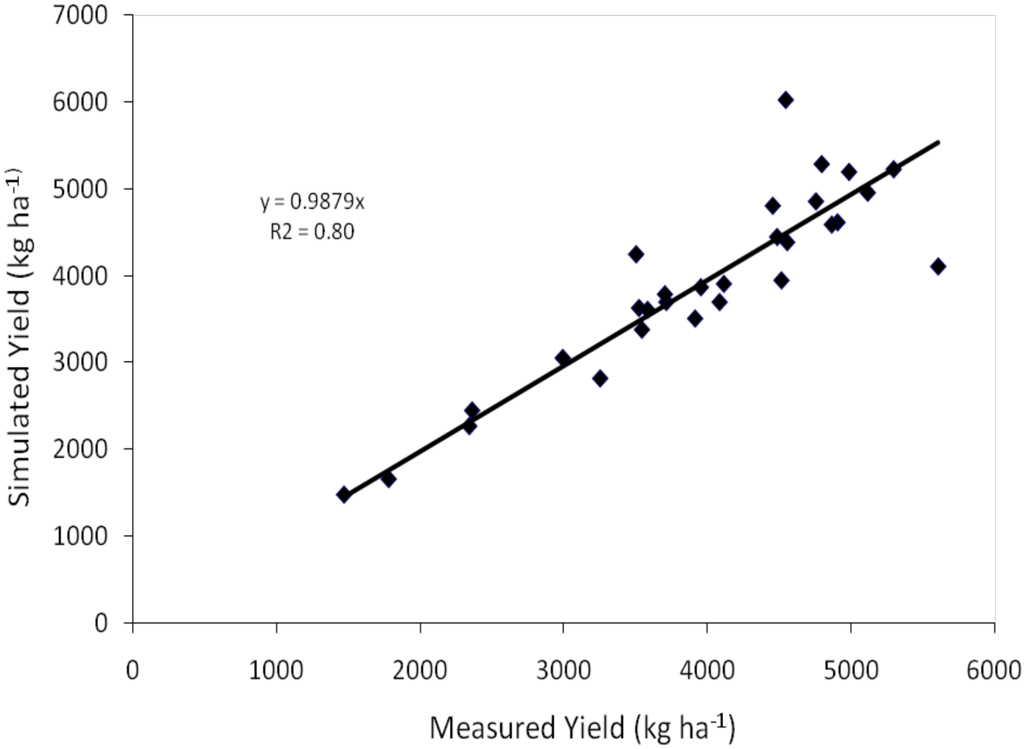

Figure 3. Model validation for the study area. (Basso et al., 2007).

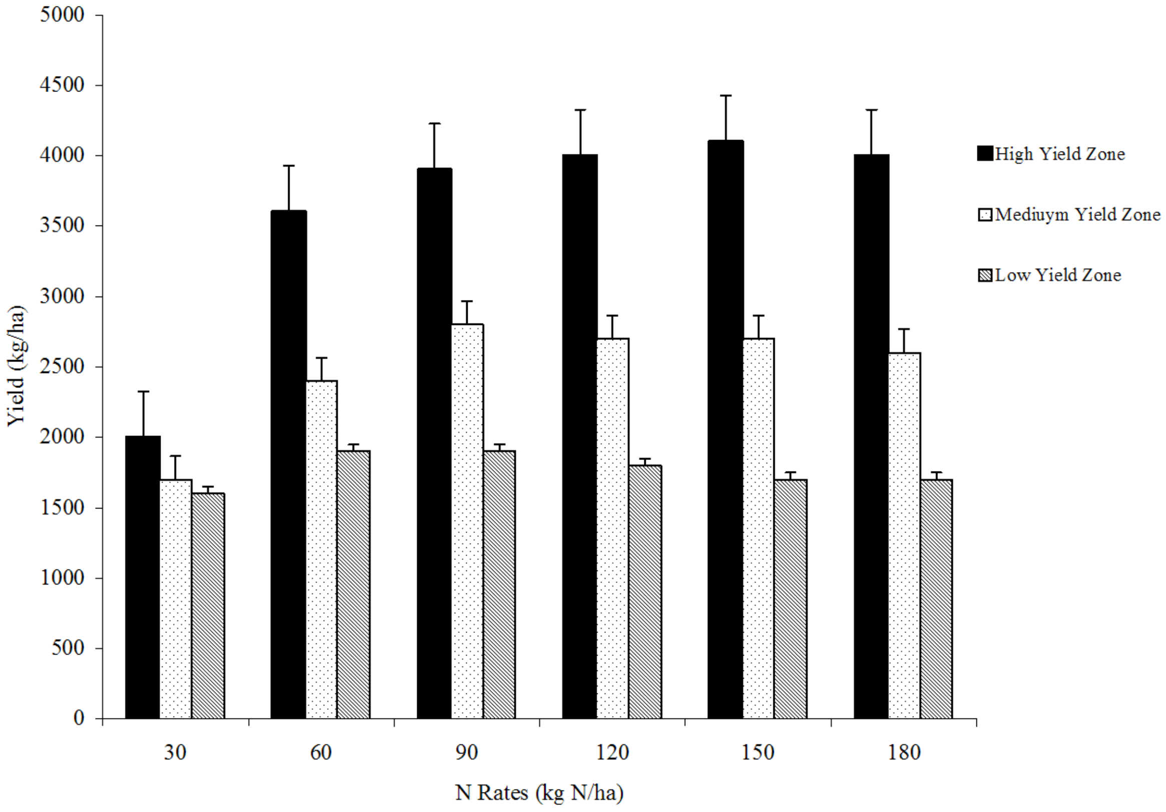

Figure 4. Average yield as function of N rates for the three management zones.

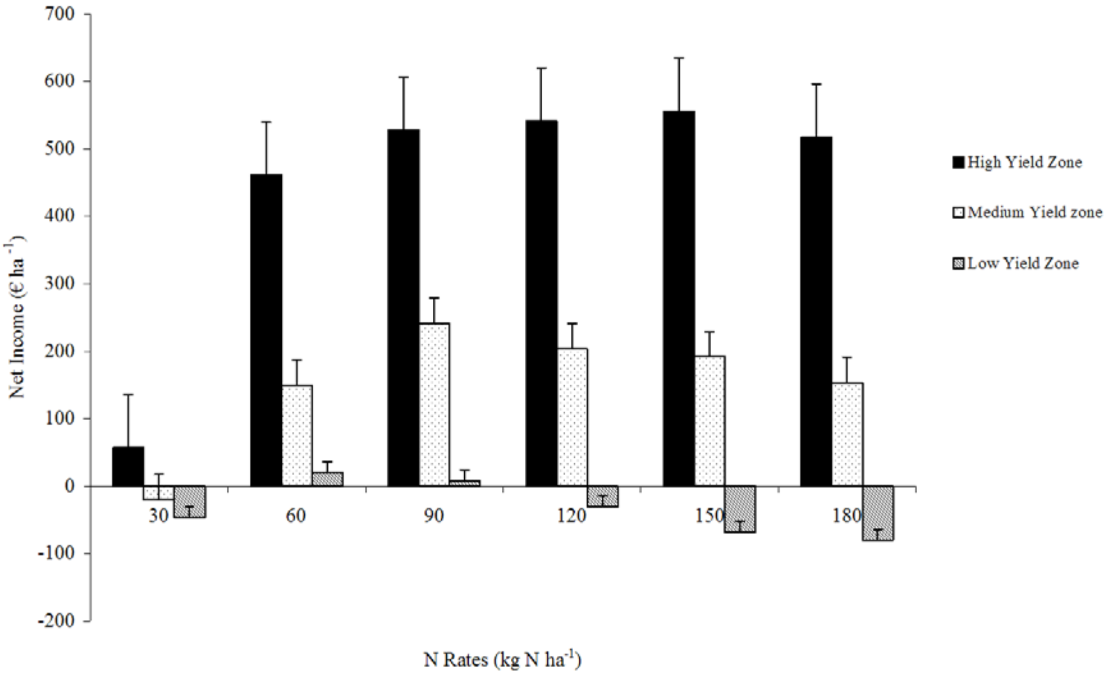

Figure 5. Net income as function of N rates for the three management zones.

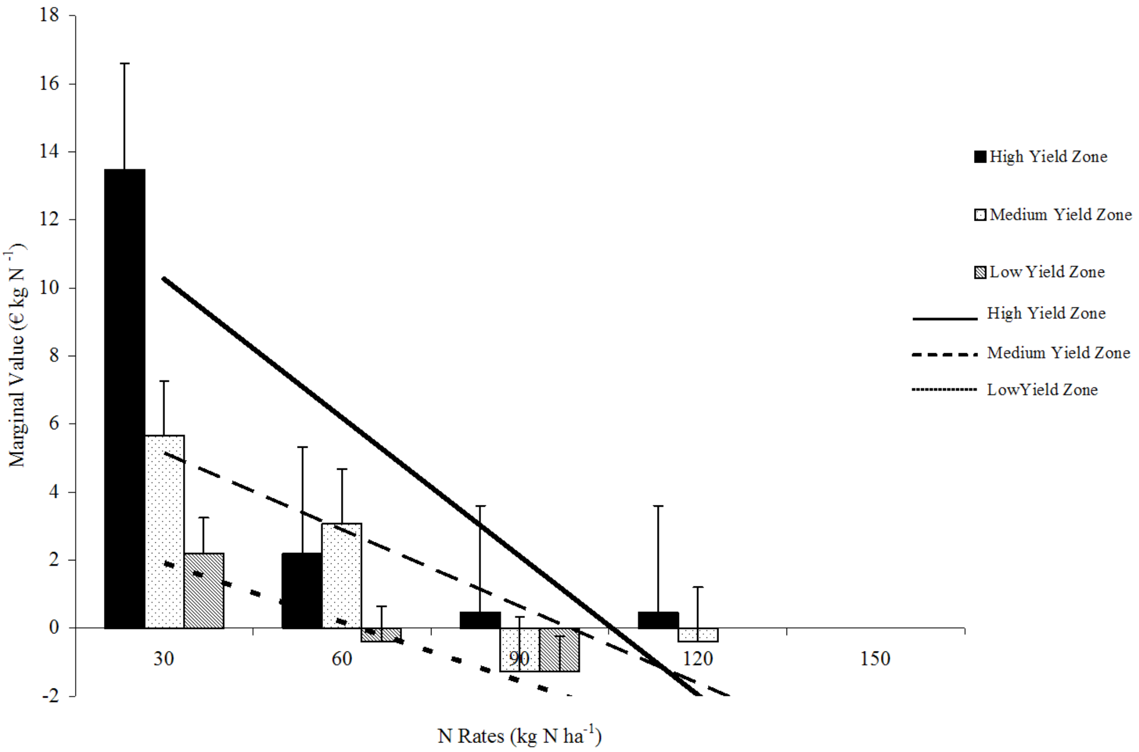

Figure 6. N Marginal value as function of N rates for the three management zones.

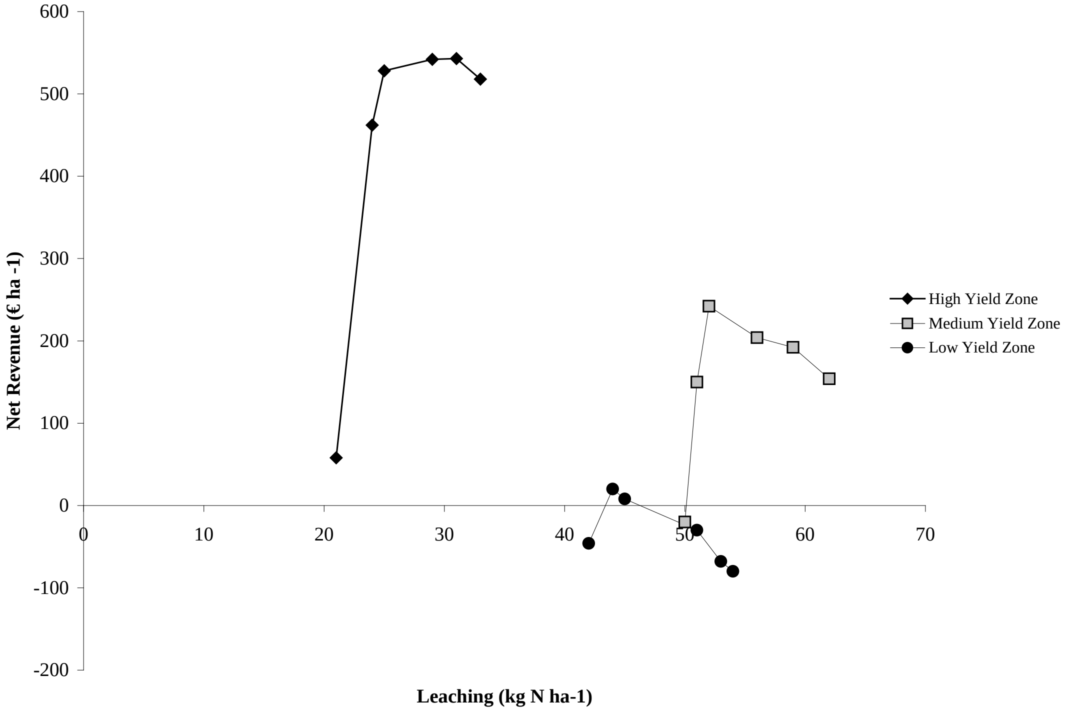

Figure 7. Net revenue and leaching as function of N rates for the three management zones. Each symbol represent the N rates starting from 30 Kg N ha-1 till 180 Kg N ha-1 with a 30 Kg N increment.