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Raí Augusto Schwalbert

FERTILIZAÇÃO A TAXA VARIÁVEL DE NITROGÊNIO EM TRIGO INTEGRANDO SENSORIAMENTO DE CULTURA E ZONAS DE MANEJO NA REGIÃO SUL DO BRASIL

Santa Maria, RS
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Dissertação apresentada ao Curso de Mestrado do Programa de Pós-Graduação em Engenharia Agrícola da Universidade Federal de Santa Maria (UFSM), como requisito parcial para obtenção do grau de **Mestre em Engenharia Agrícola**

Orientador: Prof. Dr. Telmo Jorge Carneiro Amado

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RESUMO

FERTILIZAÇÃO A TAXA VARIÁVEL DE NITROGÊNIO EM TRIGO INTEGRANDO SENSORIAMENTO DE CULTURA E ZONAS DE MANEJO NA REGIÃO SUL DO BRASIL

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Existem basicamente duas abordagens para a prescrição da taxa variável de nitrogênio, a primeira baseada em zonas de manejo (preditivas) e a segunda baseada em sensoriamento remoto (reativas). Essas abordagens possuem características complementares e quando integradas podem resultar em uma prescrição de N mais eficiente. O objetivo desse estudo foi a delimitação de zonas de manejo com diferentes respostas a fertilização nitrogenada e a comparação diferentes estratégias para prescrição de nitrogênio, incluindo abordagens baseadas em sensores de cultura, zonas de manejo e integração de ambas. As zonas de manejo foram delimitadas usando mapas de produtividade, atributos topográficos e condutividade elétrica aparente do solo e foram classificadas em zonas de alto, médio e baixo potencial produtivo. Houve interação significativa entre doses de N e zonas de manejo para a absorção de N ($p<0.05$) e para a produtividade de grãos ($p<0.05$), sendo que a zona de baixo potencial produtivo apresentou as maiores limitações quanto a resposta ao fertilizante nitrogenado. A estratégia integrando zonas de manejo e sensoriamento remoto foi a que apresentou as maiores produtividades e maiores retornos econômicos para as duas áreas experimentais. O ajuste fino da taxa variável de nitrogênio em trigo baseada em uma abordagem combinando sensoriamento remoto e zonas de manejo é uma ferramenta promissora para agricultura de precisão na região sul do Brasil.

Palavras-chave: sensoriamento remoto, agricultura de precisão, manejo a sítio-específico.

ABSTRACT

VARIABLE RATE NITROGEN FERTILIZATION IN WHEAT INTEGRATING REMOTE SENSING AND MANAGEMENT ZONES IN SOUTHERN BRAZIL

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There are basically two approaches for variable rate of nitrogen prescription, the first one based on management zones (predictive) and the second one based on remote sensing (reactive). These approaches have complementary characteristics and when they are integrated can result in a more efficient N prescription. The main of this study was to delimitate management zones with different nitrogen responses in relation to the nitrogen fertilization and then to compare the different strategies for N prescription, including approaches based on management zones, remote sensing and the integration of both. Management zones were delineated using yield maps, topographic features and soil apparent electric conductivity and were classified as low, medium and high yield potential zone. There was significant interaction between nitrogen rates and management zones for N uptake ($p<0.05$) and for grain yield ($p<0.05$). The low yield potential zone showed the highest limitation in relation to nitrogen response. The strategy integrating management zones and remote crop sensing was the one that showed the highest grain yield and economic return for both investigated areas. Fine-tuning of variable rate of nitrogen in wheat by combining crop remote sensing and management zones approaches is a promising tool for precision agriculture in southern Brazil.

Keywords: remote sensing, precision agriculture, site-specific management.

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1 INTRODUÇÃO GERAL

O nitrogênio (N) é o elemento que mais frequentemente influencia a produtividade das gramíneas devido a características peculiares dessas espécies, como a limitada capacidade de fixação biológica do N atmosférico (BRAGAGNOLO et al., 2013). A mineralização da matéria orgânica (MO), a decomposição dos resíduos culturais e o teor de N mineral presente na camada de enraizamento são as principais fontes desse nutriente em solos agrícolas. Estas fontes raramente são suficientes para atender plenamente a demanda das culturas, de modo que a fertilização suplementar se faz necessária para alcançar produtividades competitivas requeridas pela agricultura contemporânea (AMADO et al. 2002).

De maneira geral, é difícil prever a quantidade disponível de N para as plantas, isso se deve ao fato da maior parte do N no solo se encontrar na forma orgânica, sendo sua disponibilidade influenciada pela cinética da mineralização que é extremamente complexa, e dependente de diversos fatores como tipo de solo, textura, estrutura, temperatura, umidade e pH (ZECH et al., 1997), conduzindo a uma expressiva variabilidade na disponibilidade desse elemento nos solos. Nestas situações, a dose de N estabelecida e aplicada de forma homogênea para toda a área pode levar a limitações ou excessos no suprimento de N, tornando útil e necessária a distribuição à dose variada de N para o aumento da eficiência da fertilização nitrogenada e diminuição dos impactos ambientais pelas perdas desse elemento.

Segundo Jaynes et al. (2011) há essencialmente duas abordagens para a aplicação de N a taxa variada : a) dividir a área em zonas menores e mais uniformes (zonas de manejo) e aplicar o fertilizante por zonas, sendo essa abordagem classificada como uma abordagem preditiva, onde informação de histórico de produtividade, mapas temáticos de solo, atributos topográficos e outros dados espaciais são usados para predizer a performance da cultura e as necessidades de fertilizantes (GEBBERS; ADAMCHUK 2010); e b) o uso de sensores para determinar o requerimento de N durante ou antes da aplicação de fertilizante; classificada como uma abordagem reativa requerendo o uso de sensores proximais, sensoriamento através de sistemas aéreos remotamente pilotados (SARP) ou imagens de satélite.

Normalmente abordagens reativas são preferíveis as abordagens preditivas, uma vez que a prescrição da taxa variada de N nessas últimas são fundamentadas principalmente em uma estimativa do potencial produtivo baseado em mapas de produtividade de anos anteriores. Considerando que existe relativo consenso que a variabilidade espacial da produtividade normalmente é fracamente relacionada com a taxa ótima de N a ser aplicada, uma vez que a variabilidade temporal tem grande efeito nos padrões espaciais da produtividade dentro de campos de produção, os padrões estáticos das zonas de manejo seriam pouco adequados para a prescrição da taxa variada de N devido imprevisibilidade das condições ambientais (SCHEPERS et al. 2004). Scharf et al. (2006) em um estudo demonstraram que em média a variabilidade na produtividade explicou menos de 15% na variabilidade na taxa ótima de N, e Malzer et al., (1999) encontraram que os padrões de resposta a N dentro de um campo de produção não foram semelhantes aos padrões de produtividade, em um estudo de longo prazo (10 anos).

No caso das abordagens reativas baseadas em sensores de cultura, diversos algoritmos têm sido desenvolvidos (HOLLAND; SCHEPERS 2010; RAUN et al. 2005; SOLIE et al. 2012; STONE et al. 1996). De maneira geral esses algoritmos transferem N de áreas de alto e baixo vigor para áreas de vigor intermediário (BERNTSEN et al. 2006), procurando uma maior uniformização da área produtiva, através do incremento da eficiência do uso do N. O objetivo de se evitar a aplicação de altas taxas de N em locais com muito baixo vigor está relacionado ao fato dessas áreas normalmente estarem limitadas por outros fatores além do N, de maneira que incrementos na taxa de N nesses locais não seriam adequados. Berntsen et al., (2006) demonstraram em um estudo que áreas com baixa condutividade elétrica do solo normalmente correspondiam a áreas de menor vigor de plantas e baixa resposta ao fertilizante nitrogenado, dessa maneira os autores incorporaram a variável condutividade elétrica do solo ao algoritmo de prescrição da fertilização nitrogenada, mostrando que a integração dos sensores de cultura com outras variáveis pode aprimorar a prescrição da taxa variada de N.

Assim, percebe-se que as duas abordagens mais comumente usadas para prescrição da taxa variada de N (sensores de cultura e zonas de manejo) possuem características complementares e que quando combinadas podem resultar em uma estratégia mais eficiente para a prescrição da dose variada de N. Essa integração foi sugerida em diversos trabalhos (HOLLAND; SCHEPERS 2010; ROBERTS et al. 2012; SCHEPERS et al. 2004; SHANAHAN et al. 2008; SOLARI et al. 2010), porém ainda existe pouca pesquisa apontando os reais benefícios desta prática.

2 HIPÓTESES

Variáveis de solo (elevação, declividade e condutividade elétrica) e de planta (produtividade de anos anteriores e índices de vegetação) podem delimitar zonas de manejo com distinta resposta produtiva para a fertilização nitrogenada na cultura do trigo.

A eficiência no uso do N difere entre as zonas de manejo delimitadas usando atributos de solo e planta.

A taxa variada de N prescrita através de uma abordagem integrando sensores de cultura e zonas de manejo é capaz de aumentar a eficiência no uso do N e gerar incrementos em produtividade na cultura do trigo em relação ao uso dessas abordagens isoladamente.

3 OBJETIVOS DO TRABALHO

3.1 OBJETIVO GERAL

Aumentar a eficiência da fertilização nitrogenada e a produtividade na cultura do trigo, usando técnicas de sensoriamento remoto adaptadas para condição de cada zona de manejo na cultura do trigo.

3.2 OBJETIVOS ESPECÍFICOS

Delimitar zonas de manejo dentro das áreas de estudo usando técnicas estáticas multivariadas (análise de componentes principais e análise de cluster)

Avaliar a curva de resposta à N dentro de cada uma das zonas de manejo delimitadas.

Determinar a eficiência do uso do nitrogênio em cada uma das zonas de manejo delimitadas.

Criar cenários de distribuição de N baseados em diferentes abordagens para prescrição do fertilizante nitrogenado.

4 REFERÊNCIAS BIBLIOGRÁFICAS

AMADO, T. J. C.; MIELNICZUK, J.; AITA, C. Recomendação De Adubação Nitrogenada para o milho no RS E SC adaptada ao uso de culturas de cobertura do solo, sob sistema plantio direto. **Revista Brasileira de Ciência do Solo**. n. 3, p. 241–248, 2002.

BERNTSEN, J. et al. Algorithms for sensor-based redistribution of nitrogen fertilizer in winter wheat. **Precision Agriculture**, v. 7, n. 2, p. 65–83, 2006.

BRAGAGNOLO, J. et al. Optical crop sensor for variable-rate nitrogen fertilization in corn: i - plant nutrition and dry matter production. **Revista Brasileira de Ciência do Solo**, v. 37, n. 5, p. 1288–1298, out. 2013.

GEBBERS, R.; ADAMCHUK, V. I. Precision Agriculture and Food Security. **Science**, v. 327, n. 5967, p. 828–831, 2010.

HOLLAND, K.; SCHEPERS, J. Derivation of a variable rate nitrogen application model for in-season fertilization of corn. **Agronomy Journal**, v. 102, n. 5, p. 1415–1424., 2010.

JAYNES, D. B.; KASPAR, T. C.; COLVIN, T. S. Economically optimal nitrogen rates of corn: Management zones delineated from soil and terrain attributes. **Agronomy Journal**, v. 103, n. 4, p. 1026–1035, 2011.

MALZER, G. L. et al. Economic benefits and risks associated with site-specific nutrient management. **Proceedings of the 5th site-specific farming workshop**. Fargo, North Dakota. Anais...1999

RAUN, W. R. et al. Optical sensor-based algorithm for crop nitrogen fertilization. **Communications in soil science and plant analysis**, v. 36, n. 19-20, p. 2759–2781, 2005.

ROBERTS, D. F. et al. Relationships between soil-based management zones and canopy sensing for corn Nitrogen management. **Agronomy Journal**, v. 104, n. 1, p. 119–129, 2012.

SCHARF, P. C. et al. Spatially Variable Corn Yield is a Weak Predictor of Optimal Nitrogen Rate. **Soil Science Society of America Journal**, v. 70, n. 6, p. 2154, 2006.

SCHEPERS, A. R. et al. Appropriateness of Management Zones for Characterizing Spatial Variability of Soil Properties and Irrigated Corn Yields across Years. **Agronomy Journal**, v. 96, n. 1, p. 195–203, 2004.

SHANAHAN, J. F. et al. Responsive in-season nitrogen management for cereals. **Computers and Electronics in Agriculture**, v. 61, n. 1, p. 51–62, 2008.

SOLARI, F. et al. An active sensor algorithm for corn nitrogen recommendations based on a chlorophyll meter algorithm. **Agronomy Journal**, v. 102, n. 4, p. 1090–1098, 2010.

SOLIE, J. B. et al. Generalized algorithm for variable-rate nitrogen application in cereal grains. **Agronomy Journal**, v. 104, p. 378–387, 2012.

STONE, M. L. et al. Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. **Transactions of the ASAE**, v. 39, n. 5, p. 1623–1631, 1996.

5 ARTIGO - FINE-TUNNIG OF WHEAT VARIABLE RATE NITROGEN FERTILIZATION BY COMBINING CROP SENSING AND MANAGEMENT ZONES APPROACHES IN SOUTHERN BRAZIL

Abstract

The integration between crop sensors and management zones aiming at prescribing variable rate of nitrogen is an intuitive approach to increase the nitrogen use efficiency. The main of this study was to compare nitrogen fertilization scenarios through simulations for wheat, based on traditional management (flat rate), variable rate of nitrogen based on crop remote sensing, variable rate of nitrogen based on management zones and one approach integrating the use of management zones and crop remote sensing. This research was carried out at 2 commercial fields, located in Carazinho, southern Brazil. Management zones were delineated using yield maps, topographic features and soil apparent electric conductivity. There was significant interaction between nitrogen rates and management zones for N uptake ($p<0.05$) and for grain yield ($p<0.005$). The low yield potential zone showed the highest limitation in relation to nitrogen response. The strategy integrating management zones and remote crop sensing was the one that showed the highest grain yield and economic return for both investigated areas. Fine-tuning of variable rate of nitrogen in wheat by combining crop remote sensing and management zones approaches is a promising tool for precision agriculture in southern Brazil

Introduction

The low nitrogen (N) use efficiency (NUE) in cereals is considered one of the main challenges of modern agriculture. Especially in developing countries, like Brazil, where fertilizer consumption has been increasing, in an attempt to decrease the grain yield gap in relation to developed countries. N is one of the most important factors that influence cereal grain yield but at same time it is one of the most expensive nutrients to supply via mineral fertilizer, due to the high energy consumption during industrial process, representing an important cost in cereal production. In addition, around 50 to 70 % of N fertilizer input in fields is not recovered by the plants (Cassman et al. 2002; Raun and Johnson 1999), representing high economic losses and an important environmental impact. Among the main factors that corroborate to the low NUE in grain crops are: a) N uniform rate fertilization (flat rate) trough out the field without considering spatial variability in soil N supply; b) failure to account for in-season variables that influence crop N demand (Shanahan et al. 2008); c) non accounting to different crop N responses along the field (Peralta et al. 2015; Roberts et al. 2012) and, d) non accounting accurately for N credits, such as, cover crops, crop rotation and organic fertilization (Amado et al. 2002).

Variable rate nitrogen (VRN) has been proposed as one of the main fertilization strategies to increase NUE, enhance the economic return and decrease environmental impact (Bragagnolo et al. 2013; Hurley et al. 2004; Koch et al. 2004; Mamo et al. 2003; Scharf et al. 2005). Generally, VRN prescription is based on crop remote sensing, since the laboratory techniques that involves both plant and soil analysis are costly, demand time and have low spatial resolution. The on-the-go remote sensing technology aiming at prescribing VRN was introduced about two decades ago by Stone et al. (1996), in United States, and Heege and Reusch (1996), in Germany, and currently is commercially available to farmers around the world, but its adoption is still very limited. Recent researches shows that the adoption of VRN based on crop sensors in the United States is around 6% (Erickson and Widmar

2015), being this value much smaller in developing countries. Hence, to change this scenario, intense research and extension work is necessary, to prove the effectiveness of these strategies compared to the traditional management adopted by farmers.

Studies regarding the VRN efficiency based on optical sensors have recently been conducted in Brazil and Argentina, supporting its adoption by innovative farmers (Amaral et al. 2014; Bragagnolo et al. 2013; Bredemeier et al. 2013; Peralta et al. 2015). Increments in NUE by VRN based on crop sensors have frequently been reported in the literature (Fraisse et al. 2001; Link et al. 2004). Otherwise, increases in grain yield either have been very limited (Mayfield and Trengove 2009), or, even non-existent (Bragagnolo et al. 2013; Jørgensen and Jørgensen 2007; Vrindts et al. 2003). This fact justifies that different strategies for VRN prescription, complementary to the crop sensing, be investigated.

Zillmann et al. (2006) reported that crop sensor VRN works efficiently when the N is the main limiting crop yield factor, however when another factor assumes this role, some additional adjustments in the N rate prescription are needed. In part, this fact is due to the spectral signature of the leaves be influenced by other factors than N (Zillmann et al. 2006), like water and thermal stresses (Tilling et al. 2007), diseases (Schnug et al. 1998), and nutritional stress caused by other nutrients (Osborne et al. 2002). In addition, Jørgensen and Jørgensen (2007) reported that the efficiency of optical sensors to detect differences in N uptake by plants was affected by the occurrence of water stress. In the same way, Shiratsuchi et al. (2011) also reported that several vegetation indexes determined by crop sensing were sensitive to water stress. Furthermore, the plant N uptake is also dependent on soil water storage, which has influence in the mass flow mechanism, responsible for supply up to 80% of the plants N demand (Barber et al. 1963). The low N fertilizer recovery by the plants increases the risk of environmental impact of the N fertilization.

In order to enhance the VRN prescription based on crop sensors algorithms have been proposed by Raun et al. (2005), Holland and Schepers (2010), Solari et al. (2010) e Solie et al. (2012). Further, the combined use of different types of crop sensors (Adamchuk et al. 2011), like optical and thermal sensors (Shiratsuchi et al. 2011; Tilling et al. 2007), optical and ultrasonic sensors (Shiratsuchi et al. 2011), optical sensors and soil apparent electric conductivity (ECa) (Berntsen et al. 2006), have been investigated.

Information with high spatial resolution of the topographic features, physical soil attributes and soil water availability may contribute to several site-specific management strategies. The combination of optical sensors and ancillary data (K. Holland and Schepers 2010; Roberts et al. 2012; Schepers et al. 2004; Shanahan et al. 2008) have been proposed as an economic alternative to fine-tuning of VRN. The ancillary data allow the management zones (MZ) delineation (Doerge 1999), making possible set up a target N rate for each MZ (Roberts et al. 2012).

Considering a holistic approach, the fine-tuning of N fertilization can be achieved when the ancillary data were used complementarily to the crop sensors use. In Brazil, there are a lack of studies integrating these strategies to prove its efficiency in prescribe the VRN. Thus, the main objective of this study was to delineate MZ with different N responses for wheat grain yield and compare scenarios of wheat N fertilization: a) traditional farm management (flat rate), b) VRN based on crop sensor, c) VRN based on MZ and d) integrate approach combining MZ and crop sensors.

Material and methods

Description of the experimental sites and investigated soil and plant attributes

This study was developed in two sites, the first one (site 1), located in 28.32° S, 52.73° W, was carried out in 2013, and the second (site 2), located in 28.34° S, 52.71° W, was carried out in 2014. It was necessary the utilization of two different fields because the succession of wheat seeding at the same area is not an agronomic practice recommended in southern Brazil due to high incidence of diseases. The sites were closely located, with 610 m of elevation and have been managed with precision agriculture practices. The soil is classified as Typic Hapludox according to U.S. Soil Taxonomy, deep and well drained, and the climate, according to Köeppen classification, is Cfa—humid, the warmest month is January, with an average temperature of 24.6 °C, and the coldest is June with an average of 12.9 °C. Rainfall is evenly distributed throughout the year ranging from 1500 to 1750 mm.

For delimitation of MZ were made, soil ECa measurements in the depths of 0 to 0.30 m, 30 days before the wheat seeding, using a Veris 3100 (Veris Technologies®, Salina – KS, EUA), and vegetation index (VI) readings using the crop sensor Yara N-Sensor ALS (Yara International ASA, Germany), at the wheat tillering growth stage (Z24, in Zadoks scale). Also, were used corn yield data from previous years: 2011/2012 for site 1 and 2012/2013 for site 2. All data were filtered using Yield Editor software (Sudduth and Drummond 2007). Further, the terrain elevation data were obtained from GPS Novatel® with Ominstar HP correction equipped in the combine, and after this attribute was used to calculated slope.

The ancillary data of terrain elevation, grain yield, ECa and VI were organized and interpolated in raster maps with 10 x 10 m grid size, the interpolator was ordinary kriging using gstat package (Pebesma 2004) in the statistical environment R 3.1.3. In addition, the data were exported in text format using the grid center coordinate so that there was a coincidence to the different layers. All maps were created using the Quantum GIS 2.13 software. To access the influence of the topographic attributes in the water availability along the fields were generated topographic water index (TWI) maps (Fraisse et al. 2001), using the terrain elevation data.

Soil samples were sampled in 0-0.15 m depth with eight subsamples around a georeferenced point with an auger using a 1.0 ha grid in both sites, in order to evaluate the soil organic matter content (SOM), in each MZ. The method used to determinate the SOM was wet combustion (Tedesco et al. 1995).

Management zones delineation

Management zones delineation was performed in two stages, first the data was submitted to a principal component analysis (PCA), this procedure aimed at transforming interdependent variables in independent ones. For this purpose, a linear transformation comprised the original data set inside a substantially smaller data set of non-correlated variables, the principal components (PC), which represent most of information of the original data set (Afifi and Clark 1996), making possible the use of Euclidian distance as dissimilarity measure (Guastaferro et al. 2010). The PCA was performed with R 3.1.3 software using the psych package (Revelle 2015), and GPArotation (Bernaards and Jennrich 2005) to perform varimax rotation. All components with eigenvalues higher than 1 were extracted to be used in the next stage.

The second stage was a cluster analysis of the extracted principal components using the fuzzy c-means algorithm, this technique groups similar individuals into classes, following a dissimilar measure. The cluster analysis was done using the Management Zones Analyst software (MZA 1.0.1) (Fridgen and Kitchen 2004), with the following settings: Fuzziness exponent = 1.3, maximum number of interactions = 300, convergence criteria = 0.0001, minimal number of zones = 2, maximum number of zones = 6. The MZ thematic maps were generated using Quantum GIS 2.12 software.

The best number of MZ was determinate using two indexes, the Normalized Classification Entropy (NCE) that represents the zone homogeneity, and Fuzzi Performance Index (FPI) that represents a measure of the distinction between the groups (Odeh et al. 1992). Both indexes were used with success in previous researches aiming at determining the most adequate number of MZ (Fraisse et al. 2001; Fridgen and Kitchen 2004; Odeh et al. 1992)

Treatments, experimental design and main evaluations

The experimental design was a complete randomized blocks with three repetitions in each MZ, the experimental unit size was 2400 m^2, with 80 m long and 30 m wide. The N rates (0, 40, 80, 120 kg ha^{-1} in site 1 and 0, 40, 80, 120, 160 kg ha^{-1} site 2) were topdress applied in each MZ, at wheat tillering growth stage (Z24), using Urea (45 % N) as N source. The application was done using a commercial spreader model Hercules 5.0 (Stara S/A, Não-Me-Toque), with application width of 30 m. Further, at least 20 m were left as buffer between the start and the end of each experimental unit, in order to improve the accuracy of fertilizer application and yield monitor performance. Every experimental unit received 28 kg ha^{-1} of N, 70 kg ha^{-1} of P_2O_5, and 70 kg ha^{-1} of K_2O during the seeding.

Nitrogen uptake was evaluated through of five randomized manual samples in a known area (1 m^2), in each plot at stem elongation (Z31) and flowering growth stages. Grain yield was evaluated using an optical yield sensor equipped in the combine, and as the head dimensions of the combine was approximately 7 m, just two center passed of the combine in the plot were used to compute the yield. After the grain yield mass was corrected to 13% moisture.

In order to compare treatments within each MZ, including the N rate x MZ interaction, one mixed linear model (MLM) of ANOVA (Peralta et al. 2015) was adjust to wheat N uptake and grain yield:

$$y_{ijk} = \mu + T_i + Z_j + B(Z)_{k(t)} + TZ_{(ij)} + \varepsilon_{ijk} \tag{1}$$

where y_{ijk} represents the observed yield or N uptake at the flowering growth stage with the N fertilizer rate i, in *MZj*, block k; μ represents the overall mean; T_i is the fixed effect of N fertilizer rate with i = 1,..,t; Z_j is the fixed effect of the MZ with j =1, .. .,z; $B(Z)_{k(j)}$ is the random effect of blocks within the management zone with k =1, ...,b; $TZ_{(ij)}$ is the effect of interaction between N rate and MZ and ε_{ijk} is the random error which is potentially correlated under two covariance models: a random block (RB) model, and then a random block model plus spatial correlation of plot errors (RB + SP). For the RB + SP models, exponential, gaussian and spherical correlation functions without nugget effect were evaluated using the "nlme" (Pinheiro et al. 2015) package of the R statistical software (R Core Team 2015). These models (RB, RB + SP(Exp), RB + SP(Gau), RB + SP(Sph)) were adjusted with homogenous and heterogeneous variances for the different MZ. Model selection for the correlation structure was done following the Akaike information criteria (AIC). When comparing homoscedastic and heteroscedastic models, Likelihood Ratio Test (LRT) was used. The regression analysis was used to describe the relationship between the investigated fertilizer rates, N uptake and grain yield.

When there was interaction between MZ and N rates a regression analysis was done independently for each MZ. The criteria to choose the model more suitable were the significance by the F test, the highest determination coefficient (R^2) and the smaller residual sum square.

All the economic analysis, as well as calculations of the economic optimum N rate (EONR) was done considering US$ 0.45 kg^{-1} as the price of the N fertilizer, and US$ 155.00 as the price of wheat ton. For the N rates within the each MZ the recovery efficiency of applied N (RE_N) (kg increase in N uptake per kg N applied) was calculated following methodology proposed by Dobermann (2005), using N uptake at the flowering growth stage values from the regression analysis.

Simulation of nitrogen fertilization

Four different strategies were simulated in this study: N flat rate defined as traditional management (T1), VRN based on MZ (T2), VRN based on crop sensor using the algorithm proposed by Holland and Schepers (2010) (T3), and one more complex approach integrating MZ and crop sensor use (T4).

Aiming at simulating the different N fertilizer approaches, a reading in whole area with the Yara N-Sensor was done at Z31 wheat growth stage, so that the variability accessed by the crop sensor at this time was assumed as a function of the soil N supply and of the N fertilization applied during the seeding. The N fertilization scenarios simulated only a single N topdress fertilization at the Z31 growth stage. The average rate of N fertilizer used in this study was 80 kg ha^{-1}, based on wheat grain yield expectative of 3000 kg ha^{-1}.

Thus, for each sensed point within the whole area a N rate was prescribed using four different approaches and a grain yield value was estimated for each situation. This estimation was done through a regression analysis between N uptake at the flowering growth stage and grain yield using the values taken from the experimental plots. To determine the amount of N uptake at the flowering growth stage for the different N fertilization approaches in each point within the whole area the following equation was used:

$$N_f = N_{Z31} + N_{soil} + N_{app} \times RE_{N\,i} \qquad (2)$$

where N_f is the amount of N uptake at the flowering growth stage, N_{Z31} is the amount of N uptake at Z31 growth stage, the N_{soil} are N credits from soil representing the amount of N that the plants would uptake from Z31 to flowering growth stage even they did not receive any N input, N_{app} represents the amount of N applied and the RE_{Ni} is the average N recovery efficiency within the MZ i.

To estimate the N_{Z31} in each sensed point within the area a regression analysis between N uptake and VI at Z31 growth stage was performed, using values taken from the experimental plots. Thus through the sensor reading taken at Z31 growth stage was possible to do this estimative. The N_{soil} was calculated by the difference between the N uptake at Z31 growth stage and N uptake at the flowering growth stage in the plots that not receive N input.

In order to evaluate if one or more fit were necessary to describe the relationship of the dependent variables with the independent one, for the different MZ, liner models of ANCOVA were adjusted. Each model had MZ (*a*) as fixed effects and one covariate (*b*). To capture potential nonlinearities, b^2 was included in the model as an additional covariate when found to be statistically significant. Given that the effect of the covariate was assumed to vary across MZ treatments, the interaction terms between the fixed effects and covariates were included in the model, as well. Thus, the ANCOVA model estimated took the form:

$$y_{jk} = a_j + \beta_j \cdot b + \delta_j \cdot b^2 + \varepsilon_{jk} \qquad (3)$$

where y_{jk} is the dependent variable representing grain yield or N uptake at the Z31, a_j is intercept (fixed effect) for MZ, β_k and δ_k are slope coefficients j^{th} MZ, b is the N uptake at Z31 when grain yield is the dependent variable and VI is the covariate when the N uptake at Z31 is the dependent one, and and ε_{ij} is the independent and identically distributed error term.

When there was interaction between the independent variable and the covariate a regression analysis was done independently for each MZ. The criteria to choose the model more suitable were the significance by the F test the highest determination coefficient (R^2) and the smaller residual sum square. The comparison among the models was based on 95% confidence intervals overlapping. If the confidence intervals overlap, there is 95 % of confidence that they are not significantly different.

For simulated the strategy that considered the MZ as single criteria to prescribe the VRN (T2), the zones were firstly classified in high yield potential zone (HYZ), medium yield potential zone (MYZ) and low yield potential zone (LYZ), according to plant and soil attributes investigated, and then the average N rate (80 kg ha^{-1}) was increased in 10 % in the HYZ and decreased in 10% in the LYZ.

In this experiment was used the virtual-reference concept, as proposed by Holland and Schepers (2013) corresponding to the 95-percentile value from a vegetation-index histogram using values from a reading done at Z31 growth stage. The reference VI was used to calculate the sufficiency index (SI), being mathematically describe as:

$$SI = \frac{VI_{\text{sensed crop}}}{VI_{\text{Reference}}} \qquad (4)$$

where, $VI_{\text{sensed crop}}$ is the vegetation index from the crop, and $VI_{\text{Reference}}$ is the vegetation index from the reference strip.

When the T4 strategy was simulated was used a specific reference value for each MZ, thus the algorithm was applied specifically for each zone. The values used to the parameters in algorithm were: m=0, $SI_{\text{Thereshold}}$ = SI to the dose of 0 kg ha^{-1}, and N_{OPT} = 80 kg ha^{-1}.

Results and discussion

Management zones delineation

The MZ delineation is a requisite to adoption of several site-specific practices in croplands, as variable rate seeding (Fulton et al. 2013; Hörbe et al. 2013; Shanahan et al. 2004), hybrid and cultivars selection (Shanahan et al. 2004), fertilizer prescription (Inman et al. 2005; Jaynes et al. 2011; Khosla et al. 2002), and others. However, the number of MZ is often determined arbitrarily, resulting that the MZ strategies are not always successful in provide an increase in economic return. Thus, the use of statistical parameters, like NCE and FPI, can define accurately the optimum number of MZ, according to spatial variability observed in the field. In this study, four MZ were identify as the optimum number for both sites (Fig. 1), but due to experimental logistic limitation, just 3 MZ were investigated in each site.

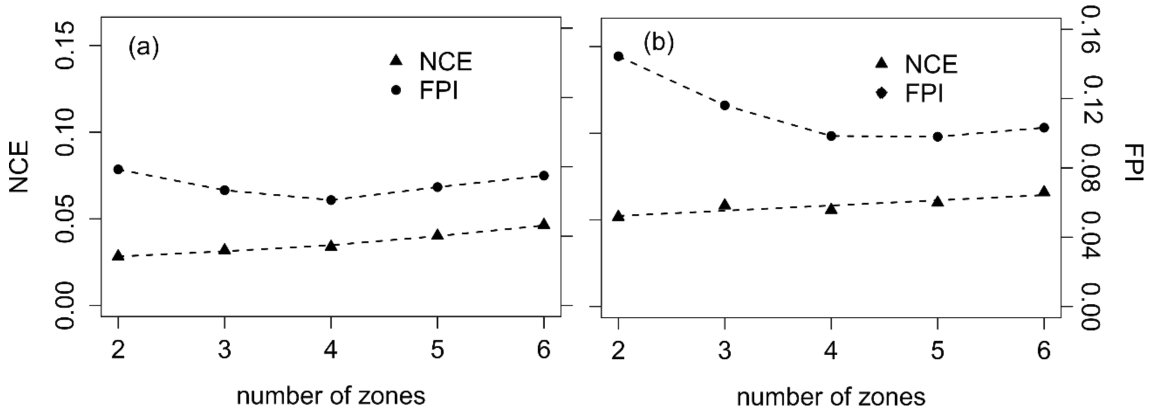

Fig. 1 Normalized Classification Entropy (NCE) that represents the zone homogeneity, and Fuzzi Performance Index (FPI) for experimental sites 1 (a) and 2 (b).

The MZ classification in low, medium and high yield potential was based on soil (ECa), terrain attributes (elevation and slope) and plants attributes (corn grain yield from a previous seasons and wheat VI). The HYZ showed the highest corn grain yield, wheat VI and ECa and intermediated slope among the investigated zones. On the other hand, the LYZ showed the lowest values of corn grain yield, wheat VI and ECa. The MYZ showed as expected an intermediate behavior between the HYZ and LYZ for the investigated plant and soil attributes (Table 1).

Tabela 1 Soil and plant attributes within the management zones for site 1 and site 2.

Site 1						
Attribute	MZ	Average	σ[3]	Max	Min	Range
	HYZ	11.70 a	0.70	13.42	8.56	4.86
Corn grain yield (kg ha^{-1})	MYZ	11.04 b	1.13	14.04	6.54	7.50
	LYZ	8.87 c	1.26	12.6	6.54	6.06
	HYZ	61.47 a	2.32	73.02	50.42	22.60
Wheat VI[1]	MYZ	57.68 b	2.68	64.71	42.86	21.85
	LYZ	56.57 c	3.81	65.28	46.75	18.53
	HYZ	566.21 a	2.71	571.88	550.22	21.66
Elevation (m)	MYZ	569.56 b	2.70	573.79	553.68	20.11
	LYZ	563.72 c	3.89	571.3	552.79	18.51
	HYZ	10.85 a	1.12	14.08	6.13	7.95
ECa[2] (mS m^{-1})	MYZ	8.83 b	1.12	13.2	5.44	7.76
	LYZ	6.87 c	1.20	12.00	4.63	7.37
	HYZ	3.81 a	1.83	9.75	0.54	9.75
Slope (%)	MYZ	3.33 b	1.78	10.79	0.36	10.79
	LYZ	5.99 c	3.64	15.52	0.88	15.52
	HYZ	30.00 a	3.00	32.00	22.00	10.00
SOM[4] (g kg^{-1})	MYZ	26.00 b	3.00	32.00	14.00	18.00
	LYZ	22.00 c	5.00	17.00	27.00	10.00
	HYZ	10.02 a	1.27	16.08	7.44	8.64
TWI[5]	MYZ	9.53 b	1.05	14.15	7.20	6.95
	LYZ	9.21 c	1.03	12.68	6.84	5.84
Site 2						
Attribute	MZ	Average	σ	Max	Min	Range
	HYZ	12.08 a	1.58	15.18	12.16	6.75
Corn grain yield (kg ha^{-1})	MYZ	7.91 b	1.29	12.15	7.71	5.28
	LYZ	7.85 b	1.86	13.11	7.75	4.14
	HYZ	60.27a	1.04	63.12	60.18	56.99
Wheat VI	MYZ	59.34 b	0.9	61.14	58.66	55.76
	LYZ	58.73c	1.26	62.99	59.43	54.31
	HYZ	518.16 a	5.92	528.86	518.43	502.05
Elevation (m)	MYZ	531.07 b	4.46	539.1	530.95	516.74
	LYZ	522.28 c	8.16	539.03	522.05	501.37
	HYZ	9.43 a	0.92	12.15	9.4	6.71
ECa (mS m^{-1})	MYZ	9.93 b	0.92	12.14	9.93	7.66
	LYZ	8.24 c	1.28	11.89	8.11	5.09
	HYZ	4.94 a	1.01	11.03	4.87	2.51
Slope (%)	MYZ	3.47 b	1.07	5.76	3.4	0.91
	LYZ	8.24 c	1.28	11.89	8.11	5.09
	HYZ	35.00 a	3.00	28.00	39.00	11.00
SOM (g kg^{-1})	MYZ	30.00 ab	5.00	20.00	35.00	15.00
	LYZ	30.00 b	8.00	14.00	39.00	25.00
	HYZ	10.02 a	1.27	7.44	16.08	8.64
TWI	MYZ	9.53 b	1.05	7.20	14.15	6.95
	LYZ	9.21 c	1.03	6.84	12.68	5.84

[1]Vigor index, [2] Soil apparent electric conductivity, [3]Standart deviation. [4]Soil organic matter, Topographic Wetness Index. Same letters are not significantly different (Tukey with significance level of 5 %)

For MZ delimitation the use of auto-correlated variables or variables that have low spatial variability are not adequate, but the new variables from PCA do not have this limitation once they are uncorrelated and have a high degree of data variability explanation. Thus, in the site 1, ECa, corn yield and wheat VI show the higher loadings for PC1, while for PC2 the variation was caused, mainly, for topographical components (elevation and slope) (Table 2). The ECa variable showed a significant correlation with corn grain yield (r =0.41), and with wheat VI (r = 0.32) (Table 3), indicating the high potential of these variables to delineate MZ. The ECa has been also correlated with water holding soil capacity and soil physical properties (Kaffka et al. 2005; Kitchen and Drummond 2003), besides the SOM content and solution salt concentration.

Tabela 2 Principal component analysis for site 1 and site 2.

	Site 1	
Variance components	Principal components	
	1	2
Eigenvalue	1.63	1.62
Proportion (%)	32.70	32.40
Accumulated proportion (%)	32.70	65.10
Attributes	Factor Loadings	
Corn grain yield	0.61	0.07
Wheat vegetation index	0.74	-0.02
ECa[1]	0.81	0.07
Elevation	-0.10	0.92
Slope	-0.22	-0.88
	Site 2	
Variance components	Principal components	
	1	2
Eigenvalue	1.98	1.20
Proportion (%)	39.60	24.00
Accumulated proportion (%)	39.60	63.60
Attributes	Factor Loadings	
Corn grain yield	0.82	0.28
Wheat vegetation index	0.13	0.75
ECa	-0.24	0.71
Elevation	-0.92	0.22
Slope	0.62	-0.12

[1] Soil apparent electric conductivity

In site 2, the original variables were summarized into 2 PC, being PC1 most influenced by corn grain yield, elevation and slope, while for PC2 wheat VI and ECa showed the highest contributions (Table 2). In this site there was inverse relationship between corn yield and elevation (r = -0.69) (Table 3), similar results were previously reported by Peralta and Costa (2013) where the highest crop yields were associated to the lowest areas due to occurrence of deeper soils, higher SOM and clay deposition from erosion process, and higher water holding soil capacity (Kaspar et al. 2003; Kravchenko and Bullock 2000). The relevance of topographic components to MZ delineation was also reported by Jaynes et al. (2011) and Roberts et al. (2012), once they are related to SOM content, soil physical attributes and mainly with soil water dynamic, influencing processes like water infiltration, runoff and erosion.

Tabela 3 Pearson correlation between attributes utilized in the management zones delineation for the first and second experimental areas.

Site 1					
	Corn grain yield	Wheat VI	Elevation	ECa	Slope
Corn grain yield	1.00*	0.14*	-0.01	0.32*	-0.16*
Wheat VI[1]		1.00*	-0.10*	0.41*	-0.20*
Elevation			1.00*	0.06*	-0.62*
ECa[2]				1.00*	-0.14*
Slope					1.00*
Site 2					
	Corn grain yield	Wheat VI	Elevation	ECa	Slope
Corn grain yield	1.00*	0.15*	-0.69*	0.02	0.20*
Wheat VI		1.00*	0.08*	0.11*	0.02
Elevation			1.00*	0.32*	-0.47*
ECa				1.00*	-0.09
Slope					1.00*

[1]Vigor index, [2] Soil apparent electric soil conductivity *$p<0.001$

Surface water flow in management zones

The combination of soil attributes, like aggregation, SOM content, texture and topographic components, can significantly affect the soil water availability. Elevation, slope and surface curvature has direct effect in infiltration and runoff (Kaspar et al. 2003). For explain better the influence of the terrain attributes in the crop performance and water dynamics at the MZ the TWI was calculated (Fig. 2), this index is a spatial representation of the water accumulation along the landscape (Fraisse et al. 2001) and generally have a high relationship with crop yield (Iqbal and Read 2005; Marques da Silva and Silva 2008).

It was observed, for both sites, a higher frequency of areas with low soil water accumulation in LYZ, on the other hand, in HYZ it was observed higher TWI values, indicating that in this zone there was a higher plant water availability (Table 1). The Oxisoils investigated in this study were deep, well drained and with good physical conditions of aeration, moreover they had a low-relief swell so that soil water accumulation is a preponderant factor to crop performance. Relationships between topographic features and grain yield variability along the cropland are common in literature, Santi et al. (2012) for example reported that water infiltration was the main factor, which explains corn and soybean grain yield variability in an Oxisoil in southern Brazil; also Marques da Silva and Silva (2008) reported that soil water availability for the plants, was one of the principal factors affecting grain yield, even in irrigated fields.

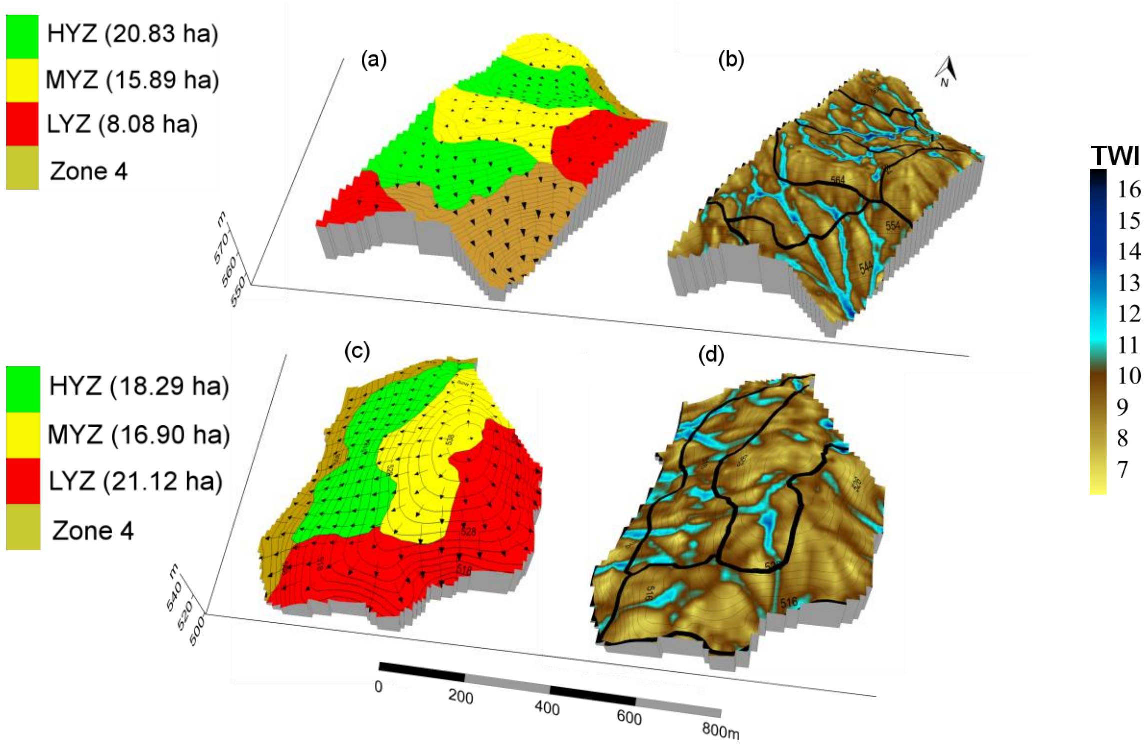

Fig. 2 Management zones for site 1 (a) and site 2 (c), vectors show the water flow direction; and topographic wetness index (TWI) for site 1 (b) and site 2 (d). HYZ = high yield potential zone, MYZ = medium yield potential zone, and LYZ= low yield potential zone.

Wheat N uptake as function of the interaction between N fertilization and management zones

In the experiment with N responses curves the relation between N uptake at the flowering growth stage and MZ was investigated. The randomized blocks were sufficient to account for spatial correlation indicating that the blocks were relatively homogenous, and the residual variance was considered homogenous in each MZ. In this study, the interaction between N rates and MZ was significant ($p<0.05$) for wheat N uptake, regardless the site investigated. In the site 1, the wheat N uptake ranged from 59 to 148 kg ha^{-1} to N rates ranging from 0 to 120 kg ha^{-1}, whereas, in the site 2 the N uptake range was from 52 to 104 kg ha^{-1} with N rates ranging from 0 to 160 kg ha^{-1} (Fig. 4). The larger range in wheat N uptake in the site 1 was due to better weather conditions during the season (2013), mainly related to daily average temperatures, which were more favorable to wheat development (Fig. 3).

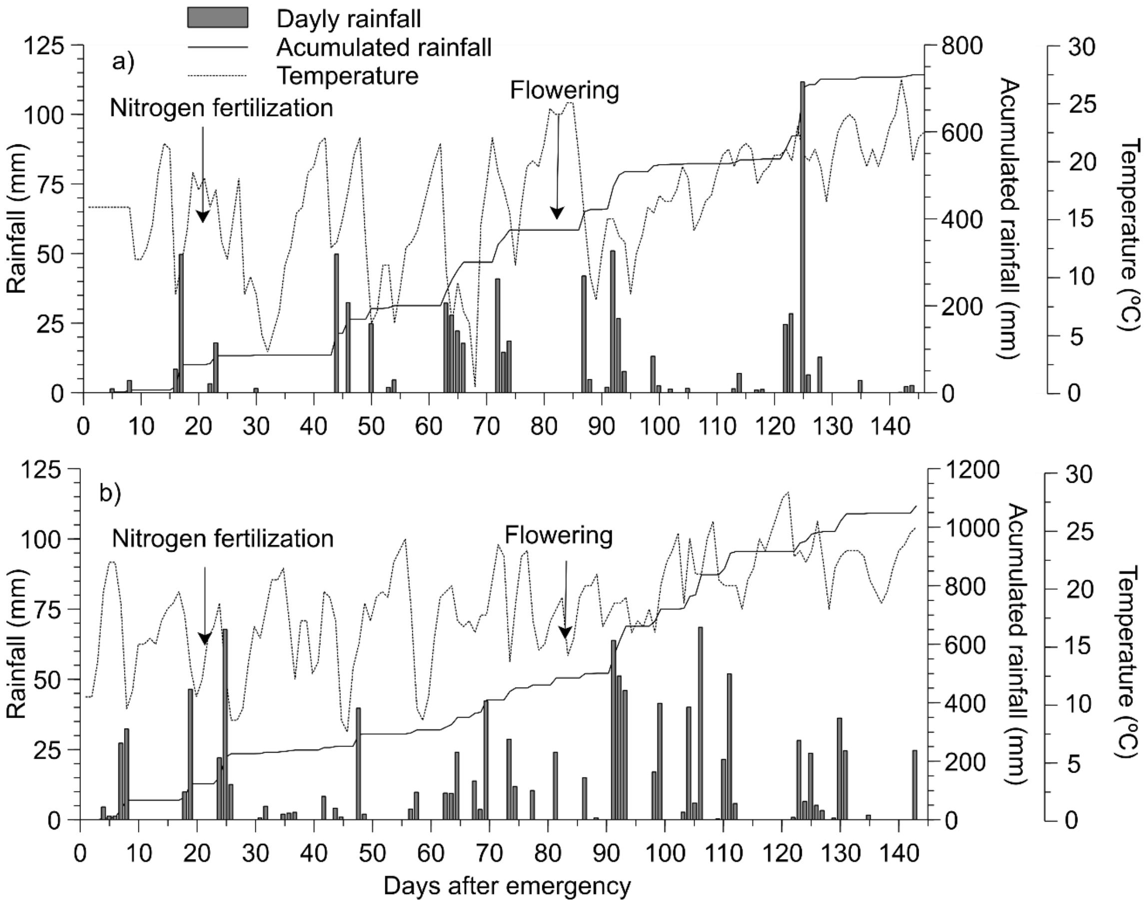

Fig. 3 Daily distribution of rainfall, total rainfall and daily temperature for; a) site 1 in 2013 and b) site 2 in 2014, Carazinho, RS

In the site 1, at the HYZ, the wheat N uptake ranged from 69 to 148 kg ha^{-1}, and in the site 2 it ranged from 62 to 104 kg ha^{-1} to the lowest and highest N rates, respectively. On the other hand, at the LYZ, the wheat N uptake ranged from 59 to 95 kg ha^{-1} in the site 1 and from 52 to 75 kg ha^{-1} in the site 2 (Fig. 4). Specially, in the site 2, where the weather conditions were somewhat less favorable, at the LYZ, there was a limited N uptake, so that for the highest N rate tested the wheat N uptake was just 37% higher than the check plot.

The quantity of wheat N uptake with no topdress N fertilizer input, in the site 1, at the HYZ, was 16% higher than the observed at the LYZ. In site 2, this difference was 18 %. The higher wheat N uptake at the HYZ in relation to LYZ is probably associated to the higher SOM content at the HYZ (Table 1) resulting in a higher N availability by the mineralization process. The SOM variability, in special the labile fractions (Changere and Lal 1997; Kravchenko and Bullock 2000), is associated to topographic attributes, once they affect the intensity of the transport and deposition process (Ebeid et al. 1995). In general, for both sites, the HYZ is located at regions with larger water accumulation being a region of sedimentation (Fig. 2). The higher water accumulation and consequently availability for the plants is another factor that can explain the higher N uptake at the HYZ because it can result in a higher soil N mineralization and a higher efficiency of plant N supply mechanism.

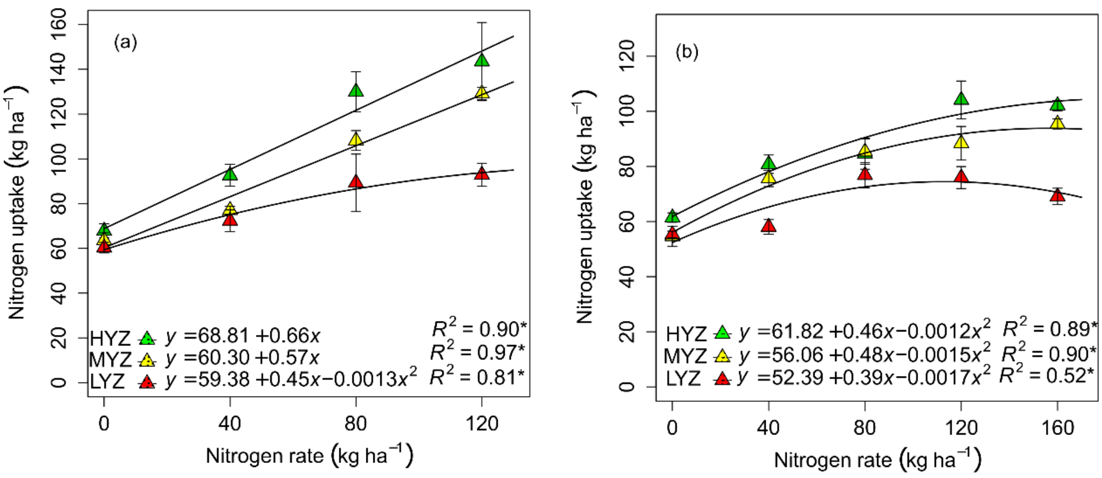

Fig. 4 Wheat N uptake influenced by N doses at the management zones, for site 1 (a) and site 2 (b) *p<0.001. HYZ = high yield zone, MYZ = medium yield zone, LYZ= low yield zone.

In rolling relief conditions, as verified in the studied sites, the topographic factor has a strong relationship with soil water dynamic, nutrient uptake and crop yield potential (Khosla et al. 2008; Marques da Silva and Silva 2008). The studied sites showed average slope of 4 and 6 % for the site 1 and site 2 respectively, and for both ones, the LYZ showed the highest slope, 6 and 8 % respectively. Peralta et al. (2015) reported previously similar results to the showed in this study, where the soil water availability to plants was the preponderant factor to justify the highest wheat N uptake at the HYZ. Thus, the highest slope and the smallest ECa at the LYZ (Table 1) suggest that mainly under water stress conditions the N response of this zone would be smaller than the others.

The MZ effect in the amount of wheat N uptake was higher in the highest N rates investigated (120 and 160 kg ha^{-1} for site 1 and site 2, respectively) it is because in lower N rates the N plant nutrition was dependent, mainly, of the N soil mineralization, whereas, in the higher N rate the NUE and the crop yield potential become important factors. Inman et al. (2005) and Khosla et al. (2008) reported that at the LYZ the corn plants, independent of the N rate investigated, always showed the lowest N uptake between the evaluated zones.

The first aim of N fertilization is enhancing the N uptake, improving the plant nutritional status. The LYZ, regardless the site, showed the lowest N uptake and the mathematical adjustment between N uptake and N rates was quadratic suggesting that after a given N rate the increases in wheat N uptake was no longer observed, therefore, the use of high N rates at the LYZ could increase the risk of environmental impact, because a high percentage of N input would not be recovered by plants, staying in a mineral form, being subject to losses by volatilization, leaching and denitrification according to prevailing weather conditions (Nielsen 2006).

Wheat grain yield affected by the interaction between N rates and management zones

In the same way as for N uptake, for grain yield the randomized blocks were sufficient to account for spatial correlation, and the residual variance was considered homogenous in each MZ. In the site 1 the wheat grain yield ranged from 1984 to 5167 kg ha^{-1} with a difference of 2.6 times between the highest and the lowest grain yield, whereas in the site 2 it ranged from 2507 to 4424 kg ha^{-1}, with a difference of 1.8 times. These results evidence, as expected, an elevated grain yield response to the N fertilization for both sites, despite the site 1 has been more responsive than the site 2, which is in accordance with the N uptake that was also higher in this site (Fig. 4). In both sites the grain yield was influenced by N rates x MZ interaction ($p<0.05$) (Fig. 5), therefore there was an optimal N rate for each MZ, and the increment of the N rate did not annul the yield limiting factors present at the LYZ. Similar results were previously reported by Khosla et al. (2008) and Roberts et al. (2012) with corn, and by Peralta et al. (2015) with wheat. Otherwise, Bachmaier and Gandorfer (2009) also reported MZ effects in wheat grain yield, but the difference between the MZ were so small that would not justify the VRN adoption.

The wheat grain yield response to N rates followed a quadratic adjustment for all zones, regardless the site, and the occurrence of a plateau was more evident for the site 2, this is probably related to the maximum N rate tested, which was 160 kg ha^{-1}, 33 % higher than the maximum N rate tested in the site 1. By any means, in the site 2, the effect of high N rates allowed the MYZ to achieve a grain yield similar to the HYZ, but this fact was not observed in site 1. Further, at the LYZ, the wheat grain yield was always lower than the other zones, regardless the site. At the LYZ, the occurrence of yield limiting factors with a high severity degree resulted that even the input of high N rate was not sufficient to minimize the effect of those plant limiting factors. Thus, in the site 1 the wheat grain yield at the HYZ with no topdress N fertilization was 8% higher than at the LYZ with N fertilization equivalent to the rate that promoted the highest yield (Agronomic Optimum Nitrogen Rate - AONR) (97 kg^{-1}). However, at the MYZ under the occurrence of less severe yield limiting factors, the N fertilization results in reduction (site 1) or annulation (site 2) of the grain yield gap of that zone in relation to the HYZ.

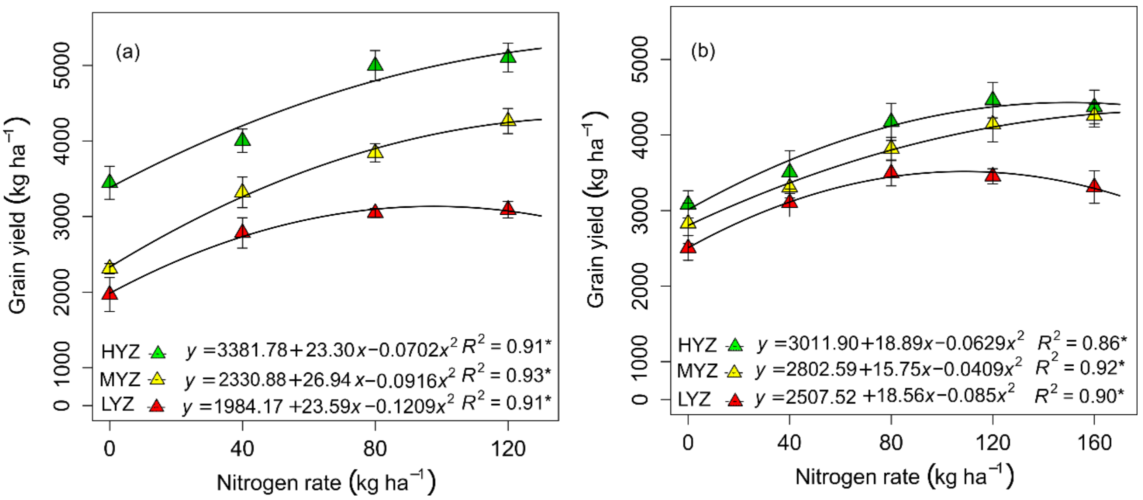

Fig. 5 Wheat grain yield influenced by N doses at the management zones, for site 1 (a) and site 2 (b) *$p<0.001$. HYZ = high yield zone, MYZ = medium yield zone, LYZ= low yield zone.

For the site 1, in the absence of N fertilization, the HYZ showed a wheat grain yield 45 % higher than the MYZ and 70 % higher than the LYZ (Fig.5). Further, for the N rate of 120 kg ha^{-1} the wheat grain yield at the HYZ was 21 % higher than the MYZ and 68% higher than the LYZ. For the last one, the AONR was 98 kg ha^{-1} and the Economic Optimum Nitrogen Rate (EONR) was 86 kg ha^{-1}. These values were 20 and 29% lower than the EONR (120 kg ha^{-1}) of the HYZ and MYZ. Also, it can be highlighted that at the LYZ the EONR rate promoted an increment of 57% (1134 kg ha^{-1}) in wheat grain yield in relation to the treatment that did not receive N fertilizer, while at the MYZ this increment was of 82% (1922 kg ha^{-1}), and at the HYZ it was 52% (1758 kg ha^{-1}). Peralta et al. (2015) in a study with wheat carried out in Argentina also found a relevant MZ effect in 3 of the 5 investigated areas, the authors reported a smaller N response at the LYZ, where the grain yield average increment was of 10 % in relation to plot that did not receive N fertilization, whereas at the HYZ this increment was of 18%.

For the site 2, the HYZ only with the base fertilization (28 kg ha^{-1}) showed a grain yield 7 and 20% higher than the MYZ and LYZ, respectively (Fig. 5). Moreover, at the HYZ the EONR was 128 kg ha^{-1} showing a grain yield similar to the MYZ with the EONR (158 kg ha^{-1}), but with 19 % less N input. Further, at the LYZ the EONR was 92 kg ha^{-1} being 28 and 42% lower than the HYZ and the MYZ, respectively. For this site, at the LYZ, the EONR promoted a grain yield increment of 39% (988 kg ha^{-1}) in relation to the treatment with no N fertilizer, whereas at the MYZ this yield increment was of 52% (1467kg ha^{-1}), and at the HYZ it was of 46% (1387 kg ha^{-1}). The lowest N response for wheat grain yield at the LYZ in part can be explained by higher slope (Table 1), lower water accumulation (TWI) (Fig. 2) and smaller ECa in relation to other MZ. Berntsen et al. (2006) investigating a VRN prescription based on crop-sensor (Yara N-Sensor) reported that the regions with a smaller ECa had a lower N response; the authors linked this fact to lower soil water availability to plants at these regions. Otherwise, the MYZ showed the highest N response for grain yield even though the HYZ had the highest wheat N uptake, it can be explained by the highest SOM contents at the HYZ in relation to the MYZ providing a higher soil N availability and wheat N uptake, as observed in the treatment that did not receive N fertilization (Fig. 4).

Recovery efficiency of nitrogen at the management zones

The $RE_{N,}$ it is an indicator of environmental risk because while the N fertilizer recovery by plants decreases the risks of the N losses and environmental impact increases (Cassman et al. 2002). Dobermann (2005) suggests that an RE_N between 0.3 and 0.5 kg kg^{-1} is generally common for cereals. For the site 1, most values were within of that range, and they were very similar to the values found by Ladha et al. (2005) for wheat, while for the site 2, the treatments with high N rates showed values lower than that range.

In the site 1 the RE_N was in general higher than the site 2. This result was due to higher amount of rainfall after the N fertilization in the site 2 in relation to the site 1 (Fig. 3), what can have induced greater N losses by leaching. The highest RE_N values for the site 1 are in according to the highest wheat N uptake (Fig. 4) and with the highest grain yield (Fig. 5). For Dobermann (2005) RE_N values between 0.5 and 0.8 kg kg^{-1} corresponding to areas where the N fertilizer was well managed. Thus, in the first experimental area the HYZ and the MYZ showed high efficiency regardless to the N rate tested. On the other hand, in the second experimental area all MZ showed a low RE_N.

With exception of the HYZ and MYZ in the site 1, where the RE_N did not change with the N fertilizer rate increments, the others showed, like expected, a decrease in that index in response to the increase in the N rates (Fig. 6). Previously, Peralta et al. (2015) reported that RE_N decreases as the N rates increase; this behavior, in part, can be explained by the fact that under conditions of N deficiency, as verified under low N rates, the ER_N is generally elevated (Bragagnolo et al. 2013; Dobermann 2005). Further, different from the site 1, where the HYZ always showed a RE_N higher than the MYZ, in site 2 the HYZ and the MYZ showed an ER_N very similar, regardless of the nitrogen rate.

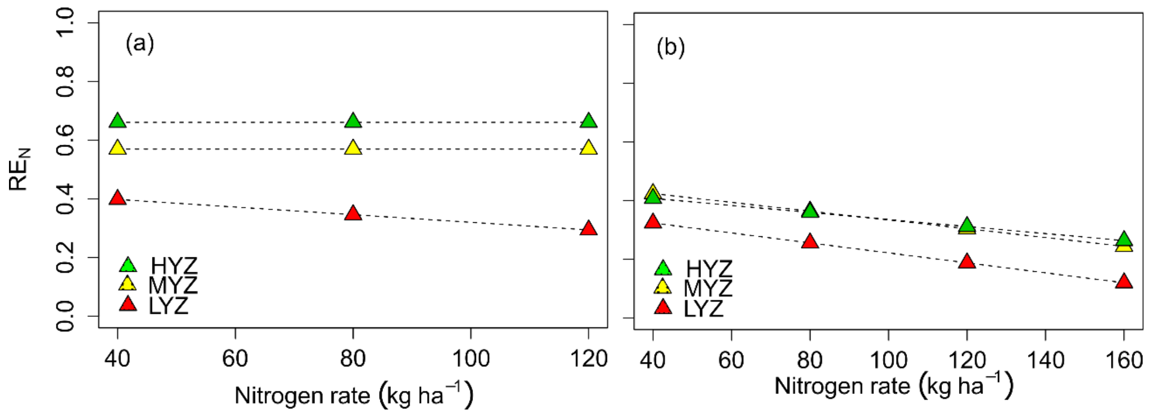

Fig. 6 Wheat nitrogen recovery efficiency (RE_N) influenced by N rates at the management zones, for site 1 (a) and site 2 (b). *p<0.001. HYZ = high yield zone, MYZ = medium yield zone, LYZ= low yield zone.

It can also be noted that regardless the MZ, the LYZ always showed the lowest RE_N and, for the highest N rate, this zone showed a decrease of 56 and 55 % in the RE_N in relation to the HYZ, for sites 1 and 2 respectively. This results indicated that the use of high N rates at the LYZ increases the environmental risk of the N fertilization.

Economic return of different strategies for VRN prescription

The 95% confidence intervals of the coefficients for the regression involving N uptake and VI among the MZ overlapped, thus just one linear adjustment was sufficient to describe the relationship between these variables. The VI was a good predictor for N uptake at Z31 growth stage (Fig. 7) for both sites, and could be used to estimate the amount of N uptake in each sensed point within the area. In addition, for both sites, the relation grain yield and between N uptake at the flowering growth stage was also significant (p<0.001), and did not differ for HYZ and MYZ, where the fit was linear, suggesting that they respond of the same way for the N uptake at the flowering growth stage. Otherwise for the LYZ the fit was quadratic showing a plateau beyond which the grain yield does not increase anymore, confirming a smaller N physiological efficiency (kg of grain increase per kg of N uptake) for this zone.

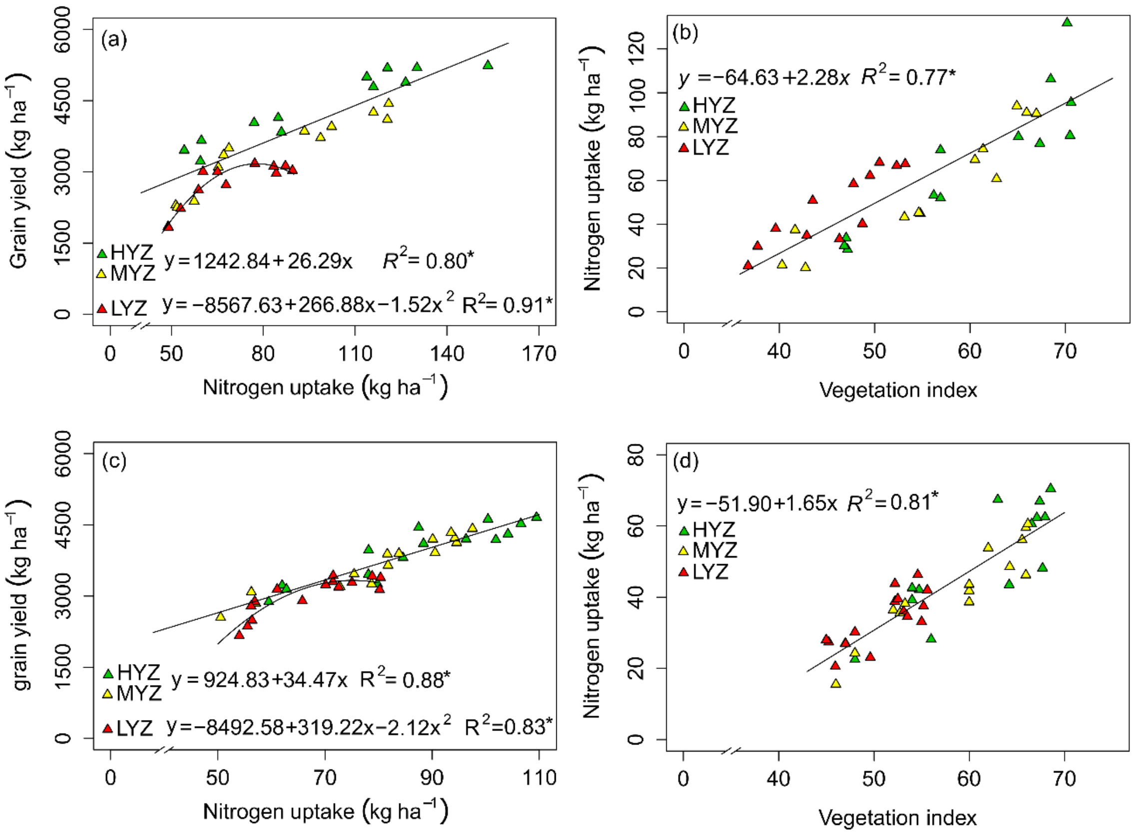

Fig. 7 Regression analysis between vegetation index and N uptake (Z31) (a and c) and N uptake and wheat grain yield (b and d) for two site-years (2013-2014), *p<0.001.

The different approaches simulated resulted in different wheat grain yield and economic returns (Table 4). As the prescribed average N fertilization rate was similar among the different VRN strategies, it was possible a comparison between them. For T2 strategy the results were quite different between the sites, while in the site 1 the increments in grain yield by use of this strategy was 105 kg ha^{-1} in relation to the traditional management (FR – T1), in the site 2 this increment was just 19 kg ha^{-1}. In previous studies Lambert (2006) and Schepers et al. (2004) reported that the VRN based only on MZ was not an efficient strategy, once it was not able to consider in-season variability in plant N demands related to the temporal inconsistences in the yield pattern along the years. The MZ effect was extremely explicit through the simulated scenarios once that regardless the fertilizer approached used the LYZ always showed the lowest grain yield. Further, it can be realized that important spatial variability remains even within the MZ (Fig. 8) justifying the use of in-season remote sensing in attempt to accounting for this.

Tabela 4 N rates, grain yield and economic return by MZ of different VRN strategies for two sites.

Strategy	N Rate (kg ha^{-1})				Grain Yield (Mg ha^{-1})				Economic return (US$ ha^{-1})			
S_1	Average	HYZ	MYZ	LYZ	Average	HYZ	MYZ	LYZ	Average	HYZ	MYZ	LYZ
Flat rate	80	80	80	80	4558	4994	4836	3145	670	738	714	451
MZ	82	88	80	72	4663	5195	4899	3133	686	766	723	453
CS	81	79	79	90	4595	5032	4892	3146	676	744	723	447
CS + MZ	85	112	80	41	4838	5604	4907	3146	712	818	725	469
S_2												
Flat rate	80	80	80	80	3984	4348	4317	3475	582	638	633	503
MZ	79	88	80	72	4003	4439	4317	3453	585	648	633	503
CS	79	81	82	89	4017	4364	4344	3523	587	640	636	506
CS + MZ	86	111	109	52	4209	4699	4654	3524	614	678	672	523

MZ = management zone; CS = crop sensor; CS + MZ = integration between crop sensor and MZ; S1 = site 1; S2 = site 2.

The crop sensors based on optical spectrometry are considered an efficient tool to prescribe VRN, however in this study its performance, for both sites, was compromise by the limited N response at the LYZ (Fig. 7). As this zone showed the lowest values for VI, there was the prescription of the highest N rates; but it reached a grain yield just slightly higher than FR in traditional management for both sites (1 and 48 kg ha^{-1} for the site 1 and 2, respectively). The other zones also showed small increases in grain yield in relation to the FR. Therefore, the approach based on crop sensors, for the whole area, showed only a small increment in relation to the FR, which was 37 and 33 kg ha^{-1} higher than that traditional management, for the sites 1 and 2, respectively. These results corroborate with the ones found by Mayfield and Trengove (2009) where the wheat grain yield increment was of 40 kg ha^{-1}. Jørgensen and Jørgensen (2007) and Vrindts et al. (2003) did not observe wheat grain yield increases by the crop sensors use.

Moreover, the strategy that combined MZ with crop sensor had the highest grain yield for both sites, with increases in grain yield of 280 (6%) and 225 (6%) kg ha^{-1} in relation to the FR, for the sites 1 and, respectively (Table 4). Similar results were reported by Longchamps and Khosla (2015) in a very similar study with corn, where the approach integrating MZ and crop sensor use showed a better performance in relation to the others. In addition, these grain yield values were 243 (5%) and 192 (5%) kg ha^{-1} higher than those reported with the use of crop sensors alone. Considering the grain yield improvement by MZ, the HYZ showed increments of 610 kg ha^{-1} (12%), and 351 kg ha^{-1} (5%), and the MYZ showed increments of 71 kg ha^{-1} (2 %) and 337 kg ha^{-1} (8 %) in relation to FR for the site 1 and 2, respectively. The LYZ practically does not showed increments for site 1 (1 kg ha^{-1}) and shows increments of 49 kg ha^{-1} (10%) for site 2 in relation to FR (Table 4).

It can be observed that despite the economic return has been positive for all strategies in relation to FR, the highest one was verified for the T4 approach. Hence, the approach based on MZ resulted in the average of the MZ an increment of US$ 16 and US$ 3 ha^{-1} in relation to FR, for the sites 1 and 2, respectively. Further, the T3 approach showed an economic return of US$ 6 and US$ 5 ha^{-1} in relation to FR. Finally, the T4 approach showed an economic return of US$ 42 and US$ 32 ha^{-1} for sites 1 and 2 respectively. Considering the economic return by MZ this strategy provided increments of US$ 80 and US$ 40 ha^{-1} for HYZ, US$ 11 and US$ 19 ha^{-1} for MYZ and US$ 18 and US$ 20 ha^{-1} for LYZ in relation to FR, for the sites 1 and 2, respectively. In addition, the T4 approach showed an increase in the economic return of US$ 36 and US$ 27 ha^{-1}, in relation to the crop sensor use alone for the sites 1 and 2, respectively. At the HYZ the main factor responsible for improving the economic return was the increases in grain yield, while at the LYZ there was a combined effect between increases in grain yield (site 1) and reduces in fertilizer costs (Table 4).

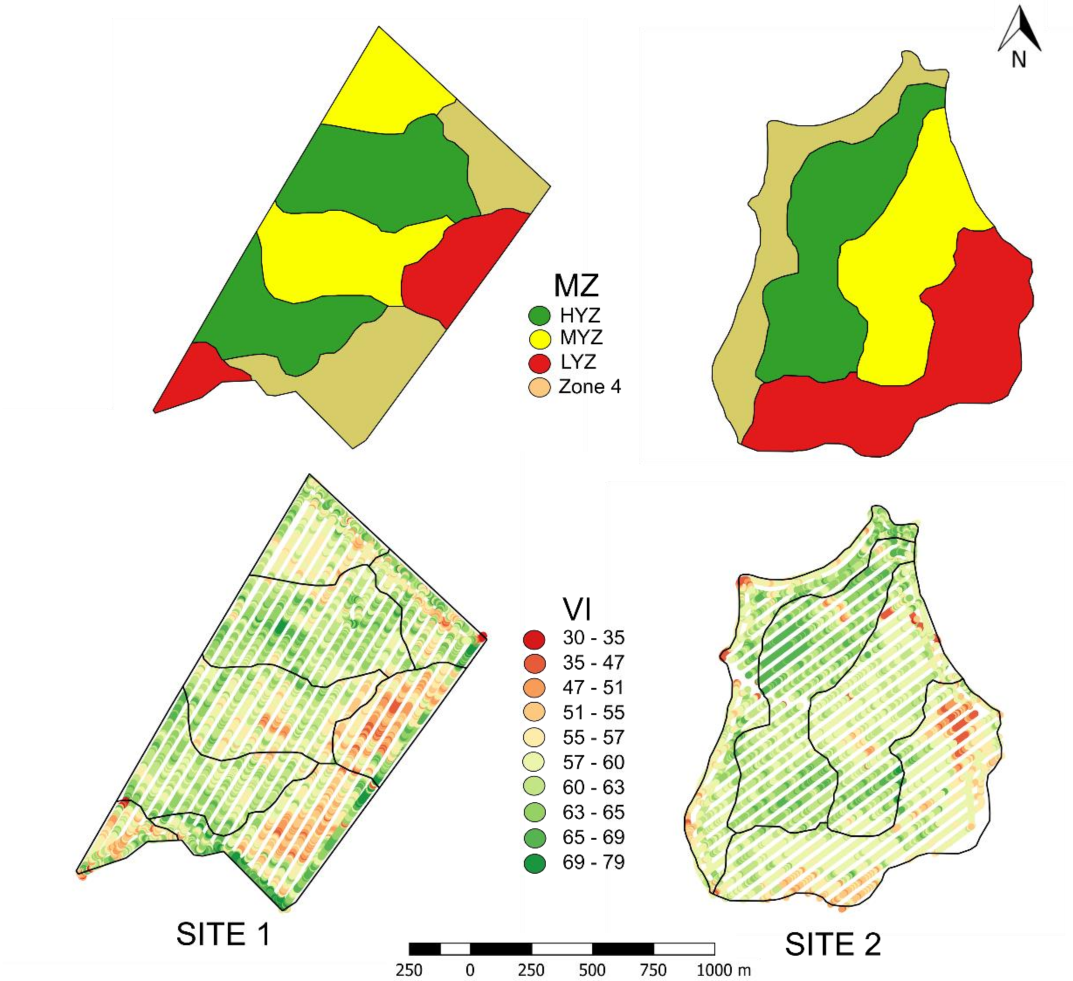

Fig. 8 Vegetation index variability within the MZ for site 1 and site2.

The combination of different strategies aiming at prescribing VRN enhanced the crop sensor performance; it avoided that high N rates were prescribed at the LYZ, and made possible that more elevated N rates were prescribed for the MYZ and HYZ, which showed the highest N responses for wheat grain yield (Table 4). Roberts et al. (2012) highlighted that the VRN based on crop sensors could be still improved if the prescription was also adjusted to the N response potential of each MZ and not only by the crop nutritional status. Thus the N rates ranged from 35 to 137 kg ha^{-1} and 60 to 148 kg ha^{-1} for HYZ, from 20 to 124 kg ha^{-1} and from 38 to 144 kg ha^{-1} for MYZ, and from 6 to 113 kg ha^{-1} and from 10 to 123 kg ha^{-1} for LYZ for site 1 and 2, respectively.

The results found in this study highlight that a N FR for the whole area was not the most efficient management both from the economic and environmental points. Hence, since the MZ showed distinct grain yield potentials and N use efficiency, these results support that, in future studies, the MZ component should be included in the N prescription based on crop sensors.

Conclusions

The multivariate techniques involving PCA and cluster analysis using soil (ECa), topographic (elevation and slope) and plants attributes (VI and corn grain yield) were efficient to delineate MZ with different N response. Once the relationship between N uptake and grain yield followed the same trend for HYZ and MYZ the main factor that explain the different grain yield behaviors between them was the RE_N. Otherwise the LYZ respond differently for grain yield in relation to the other zones for N uptake suggesting that other factors are limiting the grain yield than N.

The differences in RE_N among the MZ can be explained by the differences in water availability, once the HYZ showed the higher water accumulation indicated by TWI, and the highest RE_N justifying the highest N response in relation to the LYZ. Further, the use of high N rates at the last one resulted in decrease of RE_N, increasing the environmental risk and decreasing the economic return.

The N fertilization adjustment in the wheat crop based on the combination of crop sensor and MZ was the most efficient strategy to VRN prescription, once the MZ component avoid that high amounts of N fertilizer were applied at LYZ and the remote sensing component accounting for important variability within the MZ. Thus this study demonstrates that the two approach most common for VRN (crop sensor and MZ) are complementary and can be coupled in one strategy.

References

Adamchuk, V. I., Rossel, R. a V., Sudduth, K. a, & Lammers, P. S. (2011). Sensor Fusion for Precision Agriculture. In *Sensor Fusion - Foundation and Applications* (pp. 27–40).

Afifi, A., & Clark, V. (1996). Discriminant analysis. In *Computer-aided multivariate analysis* (pp. 243–280). Springer.

Amado, T. J. C., Mielniczuk, J., & Aita, C. (2002). Recomendação De Adubação Nitrogenada Para O Milho No Rs E Sc Adaptada Ao Uso De Culturas De Cobertura Do Solo, Sob Sistema Plantio Direto (1), (3), 241–248.

Amaral, L. R., Molin, J. P., Portz, G., Finazzi, F. B., & Cortinove, L. (2014). Comparison of crop canopy reflectance sensors used to identify sugarcane biomass and nitrogen status. *Precision Agriculture*, *16*(1), 15–28. doi:10.1007/s11119-014-9377-2

Bachmaier, M., & Gandorfer, M. (2009). A conceptual framework for judging the precision agriculture hypothesis with regard to site-specific nitrogen application. *Precision Agriculture*, *10*(2), 95–110. doi:10.1007/s11119-008-9069-x

Barber, S. A., Walker, J. M., & Vasey, E. H. (1963). Mechanisms for Movement of Plant Nutrients from Soil and Fertilizer to Plant Root. *Journal of Agricultural and Food Chemistry*, *11*(3), 204–207. doi:10.1021/jf60127a017

Bernaards, C. A., & Jennrich, I. R. (2005). Gradient Projection Algorithms and Software for Arbitrary Rotation Criteria in Factor Analysis. *Educational and Psychological Measurement*. article.

Berntsen, J., Thomsen, A., Schelde, K., Hansen, O. M., Knudsen, L., Broge, N., et al. (2006). Algorithms for sensor-based redistribution of nitrogen fertilizer in winter wheat. *Precision Agriculture*, *7*(2), 65–83.

doi:10.1007/s11119-006-9000-2

Biggs, G. L., Blackmer, T. M., Demetriades-Shah, T. H., Holland, K. H., Schepers, J. S., & Wurm, J. H. (2002). Method and apparatus for real-time determination and application of nitrogen fertilizer using rapid, non-destructive crop canopy measurements. U.S. Patent 6,393,927.

Bragagnolo, J., Amado, T. J. C., Nicoloso, R. da S., Santi, A. L., Fiorin, J. E., & Tabaldi, F. (2013). Optical crop sensor for variable-rate nitrogen fertilization in corn: II - indices of fertilizer efficiency and corn yield. *Revista Brasileira de Ciência do Solo*, *37*(5), 1299–1309. doi:10.1590/S0100-06832013000500019

Bredemeier, C., Variani, C., Almeida, D., & Rosa, A. T. (2013). Estimativa do potencial produtivo em trigo utilizando sensor óptico ativo para adubação nitrogenada em taxa variável. *Ciência Rural*, *43*(7), 1147–1154. doi:10.1590/S0103-84782013005000080

Cassman, K., Dobermann, A., & Walters, D. (2002). Agroecosystems, nitrogen-use efficiency, and nitrogen management. *AMBIO: A Journal of the Human Environment*, *31*(2).

Changere, A., & Lal, R. (1997). Slope position and erosional effects on soil properties and corn production on a Miamian soil in central Ohio. *Journal of Sustainable Agriculture*.

Dobermann, A. (2005). Nitrogen use efficiency–state of the art.

Doerge, T. (1999). Defining management zones for precision farming. *Crop Insights*, *8*(21), 1–5.

Ebeid, M. M., Lal, R., Hall, G. F., & Miller, E. (1995). Erosion effects on soil properties and soybean yield of a Miamian soil in Western Ohio in a season with below normal rainfall. *Soil technology*, *85*(2), 97–108.

Erickson, B., & Widmar, D. (2015). Precision Agricultural Services Dealership Survey Results. *SPONSORED BY CROPLIFE MAGAZINE AND THE CENTER FOR FOOD AND AGRICULTURAL BUSINESS*.

Fraisse, C., Sudduth, K., & Kitchen, N. (2001). Delineation of site-specific management zones by unsupervised classification of topographic attributes and soil electrical conductivity. *Transactions of the ASAE*, *44*(1), 155.

Fridgen, J., & Kitchen, N. (2004). Management zone analyst (MZA). *Agronomy Journal*, *96*(1), 101–108.

Fulton, J. P., Winstead, A., Shaw, J. N., Rodekhor, D., & Brodbeck, C. J. (2013). A case study for variable-rate seeding of corn and cotton in the Tennessee valley of Alabama. *Journal of Chemical Information and Modeling*, *53*(9), 1689–1699. doi:10.1017/CBO9781107415324.004

Guastaferro, F., Castrignanò, A., de Benedetto, D., Sollitto, D., Troccoli, A., & Cafarelli, B. (2010). A comparison of different algorithms for the delineation of management zones. *Precision Agriculture*, *11*(6), 600–620. doi:10.1007/s11119-010-9183-4

Heege, H., & Reusch, S. (1996). Sensor for on the go control of site specific nitrogen top dressing. *ASAE Paper*, *961018*.

Holland, K. H., & Schepers, J. S. (2013). Use of a virtual-reference concept to interpret active crop canopy sensor data. *Precision Agriculture*, *14*(1), 71–85. doi:10.1007/s11119-012-9301-6

Holland, K., & Schepers, J. (2010). Derivation of a variable rate nitrogen application model for in-season fertilization of corn. *Agronomy Journal*, *102*(5), 1415–1424.

Hörbe, T. A. N., Amado, T. J. C., Ferreira, A. O., & Alba, P. J. (2013). Optimization of corn plant population according to management zones in Southern Brazil. *Precision Agriculture*, *14*(4), 450–465. doi:10.1007/s11119-013-9308-7

Hurley, T. M., Malzer, G. L., & Kilian, B. (2004). Estimating Site-Specific Nitrogen Crop Response Functions.

Agronomy Journal, *96*(5), 1331. doi:10.2134/agronj2004.1331

Inman, D., Khosla, R., Westfall, D. G., & Reich, R. (2005). Nitrogen uptake across site specific management zones in irrigated corn production systems. *Agronomy Journal*, *97*(1), 169–176. doi:10.2134/agronj2005.0169

Iqbal, J., & Read, J. (2005). Relationships between soil–landscape and dryland cotton lint yield. *Soil Science Society of America Journal*, *69*. doi:10.2136/sssaj2004.0178

Jaynes, D. B., Kaspar, T. C., & Colvin, T. S. (2011). Economically optimal nitrogen rates of corn: Management zones delineated from soil and terrain attributes. *Agronomy Journal*, *103*(4), 1026–1035. doi:10.2134/agronj2010.0472

Jørgensen, J., & Jørgensen, R. (2007). Uniformity of wheat yield and quality using sensor assisted application of nitrogen. *Precision Agriculture*, *8*(1), 63–73. doi:10.1007/s11119-006-9029-2

Kaffka, S. R., Lesch, S. M., Bali, K. M., & Corwin, D. L. (2005). Site-specific management in salt-affected sugar beet fields using electromagnetic induction. *Computers and Electronics in Agriculture*, *46*(1–3 SPEC. ISS.), 329–350. doi:10.1016/j.compag.2004.11.013

Kaspar, T. C., Colvin, T. S., Jaynes, D. B., Karlen, D. L., James, D. E., Meek, D. W., et al. (2003). Relationship Between Six Years of Corn Yields and Terrain Attributes. *Precision Agriculture*, *4*(1), 87–101. doi:10.1023/A:1021867123125

Khosla, R., Fleming, K., Delgado, J. a, Shaver, T. M., & Westfall, D. G. (2002). Use of site-specific management zones to improve nitrogen management for precision agriculture. *Journal of Soil and Water Conservation*, *57*(6), 513–518.

Khosla, R., Inman, D., Westfall, D. G., Reich, R. M., Frasier, M., Mzuku, M., et al. (2008). A synthesis of multi-disciplinary research in precision agriculture: Site-specific management zones in the semi-arid western Great Plains of the USA. *Precision Agriculture*, *9*, 85–100. doi:10.1007/s11119-008-9057-1

Kitchen, N., & Drummond, S. (2003). Soil electrical conductivity and topography related to yield for three contrasting soil–crop systems. *Agronomy Journal*, *95*(3). doi:10.2134/agronj2003.4830

Koch, B., Khosla, R., & Frasier, W. (2004). Economic feasibility of variable-rate nitrogen application utilizing site-specific management zones. *Agronomy Journal*, *95*(6). doi:10.2134/agronj2004.1572

Kravchenko, A. N., & Bullock, D. G. (2000). Correlation of Corn and Soybean Grain Yield with Topography and Soil Properties. *Agronomy Journal*, *92*(1), 75. doi:10.2134/agronj2000.92175x

Ladha, J., Pathak, H., & Krupnik, T. (2005). Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. *Advances in agronomy*, *87*. doi:10.1016/S0065-2113(05)87003-8

Lambert, D. (2006). Economic analysis of spatial-temporal patterns in corn and soybean response to nitrogen and phosphorus. *Agronomy Journal*, *95*(1). doi:10.2134/agronj2005.0005

Link, A., Jasper, J., & Olfs, H. W. (2004). Variable nitrogen fertilisation by tractor-mounted remote sensing. *Controlling Nitrogen Flows and Losses*, 188. Journal Article.

Longchamps, L., & Khosla, R. (2015). Improving N use efficiency by integrating soil and crop properties for variable rate N management. In *Precision agriculture '15* (pp. 249–256). inbook. doi:10.3920/978-90-8686-814-8_30

Mamo, M., Malzer, G. L., Mulla, D. J., Huggins, D. R., & Strock, J. (2003). Spatial and Temporal Variation in Economically Optimum Nitrogen Rate for Corn. *Agron. J.*, *95*(4), 958–964. doi:10.2134/agronj2003.9580

Marques da Silva, J. R., & Silva, L. L. (2008). Evaluation of the relationship between maize yield spatial and temporal variability and different topographic attributes. *Biosystems Engineering*, *101*(2), 183–190. doi:10.1016/j.biosystemseng.2008.07.003

Mayfield, A. H., & Trengove, S. P. (2009). Grain yield and protein responses in wheat using the N-Sensor for variable rate N application. *Crop. Pasture Sci.*, *60*(9), 818–823. doi:10.1071/CP08344

Nielsen, R. (2006). Loss Mechanisms and Nitrogen Use Efficiency. In *Purdue nitrogen management workshops* (pp. 1–5).

Odeh, I. O., Chittleborough, D. J., & McBratney, A. B. (1992). Fuzzy-c-means and kriging for mapping soil as a continuous system. *Soil Science Society of America Journal*, *56*(6), 1848–1854.

Osborne, S. L., Schepers, J. S., Francis, D. D., & Schlemmer, M. R. (2002). Use of spectral radiance to estimate in-season biomass and grain yield in nitrogen- and water-stressed corn. *Crop Science*, *42*(1), 165–171. doi:10.2135/cropsci2002.0165

Pebesma, E. J. (2004). Multivariable geostatistics in S: the gstat package. *Computers & Geosciences*. article.

Peralta, N. R., & Costa, J. L. (2013). Delineation of management zones with soil apparent electrical conductivity to improve nutrient management. *Computers and Electronics in Agriculture*, *99*, 218–226. doi:10.1016/j.compag.2013.09.014

Peralta, N. R., Costa, J. L., Balzarini, M., Castro Franco, M., Córdoba, M., & Bullock, D. (2015). Delineation of management zones to improve nitrogen management of wheat. *Computers and Electronics in Agriculture*, *110*(JANUARY), 103–113. doi:10.1016/j.compag.2014.10.017

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., & R Core Team. (2015). nlme: Linear and Nonlinear Mixed Effects Models. manual.

R Core Team. (2015). R: A Language and Environment for Statistical Computing. manual, Vienna, Austria. https://www.r-project.org/

Raun, W. R., & Johnson, G. V. (1999). Improving Nitrogen Use Efficiency for Cereal Production. *Agronomy Journal*, *91*(3). doi:10.2134/agronj1999.00021962009100030001x

Raun, W. R., Solie, J. B., Stone, M. L., Martin, K. L., Freeman, K. W., Mullen, R. W., et al. (2005). Optical Sensor-Based Algorithm for Crop Nitrogen Fertilization. *Communications in Soil Science and Plant Analysis*, *36*(19–20), 2759–2781. doi:10.1080/00103620500303988

Revelle, W. (2015). psych: Procedures for Psychological, Psychometric, and Personality Research. manual, Evanston, Illinois.

Roberts, D. F., Ferguson, R. B., Kitchen, N. R., Adamchuk, V. I., & Shanahan, J. F. (2012). Relationships between soil-based management zones and canopy sensing for corn Nitrogen management. *Agronomy Journal*, *104*(1), 119–129. doi:10.2134/agronj2011.0044

Santi, A. L., Amado, T. J. C., Cherubin, M. R., Martin, T. N., Pires, J. L., Flora, L. P. Della, & Basso, C. J. (2012). Análise de componentes principais de atributos químicos e físicos do solo limitantes á produtividade de graos. *Pesquisa Agropecuaria Brasileira*, *47*(9), 1346–1357. doi:10.1590/S0100-204X2012000900020

Scharf, P. C., Kitchen, N. R., Sudduth, K. A., Davis, J. G., Hubbard, V. C., & Lory, J. A. (2005). Field-Scale Variability in Optimal Nitrogen Fertilizer Rate for Corn. *Precision Agriculture*, 452–461.

Schepers, A. R., Shanahan, J. F., Liebig, M. a., Schepers, J. S., Johnson, S. H., & Luchiari, A. (2004).

Appropriateness of Management Zones for Characterizing Spatial Variability of Soil Properties and Irrigated Corn Yields across Years. *Agronomy Journal*, *96*(1), 195–203. doi:10.2134/agronj2004.0195

Schnug, E., Panten, K., & Haneklaus, S. (1998). Sampling and nutrient recommendations - The future. *Communications in Soil Science and Plant Analysis*, *29*(11–14), 1455–1462. doi:10.1080/00103629809370042

Shanahan, J. F., Doerge, T. A., Johnson, J. J., & Vigil, M. F. (2004). Feasibility of site-specific management of corn hybrids and plant densities in the great plains. *Precision Agriculture*, *5*(3), 207–225. doi:10.1023/B:PRAG.0000032762.72510.10

Shanahan, J. F., Kitchen, N. R., Raun, W. R., & Schepers, J. S. (2008). Responsive in-season nitrogen management for cereals. *Computers and Electronics in Agriculture*, *61*(1), 51–62. doi:10.1016/j.compag.2007.06.006

Shiratsuchi, L., Ferguson, R., Shanahan, J., Adamchuk, V., Rundquist, D., Marx, D., & Slater, G. (2011). Water and Nitrogen Effects on Active Canopy Sensor Vegetation Indices. *Agronomy Journal*, *103*(6), 1815. doi:10.2134/agronj2011.0199

Solari, F., Shanahan, J. F., Ferguson, R. B., & Adamchuk, V. I. (2010). An active sensor algorithm for corn nitrogen recommendations based on a chlorophyll meter algorithm. *Agronomy Journal*, *102*(4), 1090–1098. doi:10.2134/agronj2010.0009

Solie, J. B., Dean Monroe, a., Raun, W. R., & Stone, M. L. (2012). Generalized algorithm for variable-rate nitrogen application in cereal grains. *Agronomy Journal*, *104*, 378–387. doi:10.2134/agronj2011.0249

Stone, M. L., Solie, J. B., Raun, W. R., Whitney, R. W., Taylor, S. L., & Ringer, J. D. (1996). Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. *Transactions of the ASAE*, *39*(5), 1623–1631.

Sudduth, K., & Drummond, S. (2007). Yield Editor. *Agronomy Journal*, *99*(6). doi:10.2134/agronj2006.0326

Tedesco, M., Gianello, C., & Bissani, C. (1995). *Análises de solo, plantas e outros materiais*. Porto Alegre: Universidade Federal do Rio Grande do Sul.

Tilling, A. K., O'Leary, G. J., Ferwerda, J. G., Jones, S. D., Fitzgerald, G. J., Rodriguez, D., & Belford, R. (2007). Remote sensing of nitrogen and water stress in wheat. *Field Crops Research*, *104*, 77–85. doi:10.1016/j.fcr.2007.03.023

Vrindts, E., Reyniers, M., Darius, P., De baerdemaeker, J., Gilot, M., Sadaoui, Y., et al. (2003). Analysis of Soil and Crop Properties for Precision Agriculture for Winter Wheat. *Biosystems Engineering*, *85*(2), 141–152. doi:10.1016/S1537-5110(03)00040-0

Zillmann, E., Graeff, S., Link, J., Batchelor, W. D., & Claupein, W. (2006). Assessment of cereal nitrogen requirements derived by optical on-the-go sensors on heterogeneous soils. *Agronomy Journal*, *98*, 682–690. doi:10.2134/agronj2005.0253