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Environmental and economic benefits of variable rate nitrogen fertilization in a nitrate vulnerable zone

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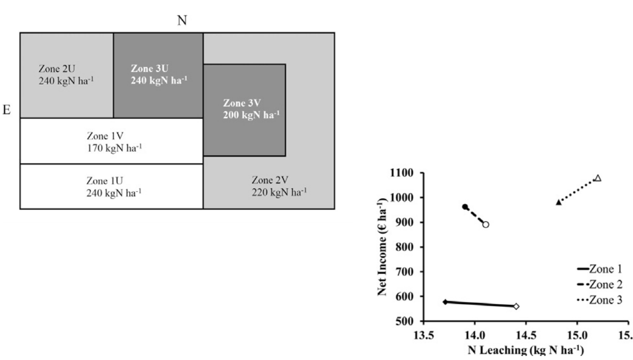
HIGHLIGHTS

- The economic and environmental impact of Nitrogen fertilization was evaluated;
- Management zones were defined using spatio-temporal analysis of field characteristic and previous yields maps;
- Optimal N rates were defined through a modeling system approach (SALUS);
- Optimal N rates were applied within the field and validated through measurements over two successive years.
- Variable rate nitrogen reduced nitrate leaching and increased profit

GRAPHICAL ABSTRACT



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ABSTRACT

Agronomic input and management practices have traditionally been applied uniformly on agricultural fields despite the presence of spatial variability of soil properties and landscape position. When spatial variability is ignored, uniform agronomic management can be both economically and environmentally inefficient. The objectives of this study were to: i) identify optimal N fertilizer rates using an integrated spatio-temporal analysis of yield and site-specific N rate response; ii) test the sensitivity of site specific N management to nitrate leaching in response to different N rates; and iii) demonstrate the environmental benefits of variable rate N fertilizer in a Nitrate Vulnerable Zone. This study was carried out on a 13.6 ha field near the Venice Lagoon, northeast Italy over four years (2005–2008). We utilized a validated crop simulation model to evaluate crop response to different N rates at specific zones in the field based on localized soil and landscape properties under rainfed conditions. The simulated rates were: 50 kg N ha^{-1} applied at sowing for the entire study area and increasing fractions, ranging from 150 to 350 kg N ha^{-1} applied at V6 stage. Based on the analysis of yield maps from previous harvests and soil electrical resistivity data, three management zones were defined. Two N rates were applied in each of these zones, one suggested by our simulation analysis and the other with uniform N fertilization as normally applied by the producer. N leaching was lower and net revenue was higher in the zones where variable rates of N were applied when compared to uniform N fertilization. This demonstrates the efficacy of using crop models to determine variable rates of N fertilization within a field and the application of variable rate N fertilizer to achieve higher profit and reduce nitrate leaching.

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1. Introduction

Agronomic input and management practices have traditionally been applied uniformly on agricultural fields despite the spatial heterogeneity of soil properties and landscape position. When spatial variability is not taken into account, uniform agronomic management can be both economically and environmentally inefficient (Pierce and Nowak, 1999). Site-specific management (SSM) practices, proposed within the Precision Agriculture (PA) framework, gives farmers the possibility to increase yield, reduce inputs, and minimize environmental impact (Robert, 2002, Robertson et al., 2012; Basso et al., 2013). The potential benefits of SSM strategies are greatly dependent on the how accurately such variability can be assessed. Many authors have proposed guidelines for the delineation of management zones which can be defined as areas within a field that are homogeneous with regard to yield limiting factors (Mulla, 1991, Ferguson et al., 2004, Schepers et al., 2004, Chang et al., 2004; Basso et al., 2007; Basso et al., 2015). Pierce and Nowak (1999) highlighted how temporal and spatial variability of soil N has to be taken into account for successful SSM of N fertilization.

One of the most studied components of SSM is nitrogen (N) management. In areas where N fertilizer is cheap or subsidized, farmers tend to apply it in large quantities which can result in environmental problems including nitrate leaching, ammonia volatilization, nitrous oxide emissions or soil acidification (Grace et al., 2011). The pressure that over-fertilization exerts on the environment is getting more awareness as climate change and deterioration of fresh water become more critical. The European Union (EU), through the Nitrates Directive, aimed to preserve the quality of groundwater through a reduction of N fertilizer by promoting good farming practices (91/676/EEC).

Despite technological advances in monitoring plant N status, determining the optimum N amount necessary within each uniform management zone in a field remains a daunting task due to the large spatial and temporal variation that these variables exert at the field scale. Plant response to variable management levels is highly dependent upon the weather that occurs during a given growing season (Basso et al., 2007; Basso et al., 2013; Dumont et al., 2014, 2015a). For example, crop response to N in rainfed environments may be high when water is available, or low when the soil water content is limited (Basso et al., 2011a). However farmers must make decisions about N application based on developmental stages of crop growth without foreknowledge of the kind of weather that will occur after fertilizer application. Since future weather conditions are unknown, a risk management strategy needs to be adopted to verify the impact of N fertilizer over a long enough period of time (i.e., 30 years) in order to represent the diversity of climate and soil interactions that are present. The biggest challenge of such an approach is the development of a yield response function that can represent a crop's response to the N rate management and other interactions (Basso et al., 2011b, Dumont et al., 2013, 2015b).

Process oriented crop simulation models integrate the effects on crop growth of multiple stress interactions over time and under different environmental and management conditions (Batchelor et al., 2002; Basso et al., 2013). However their application in PA can be limited because simulations cannot be performed everywhere in a field given that the availability of detailed (soil and crop data) inputs is limited and the costs are prohibitive. Basso et al. (2007) used a more balanced approach to study spatial and temporal variability of crop behavior in a field when they applied a crop simulation model for SSM. They considered temporal stability and spatial variability of measured yield maps to delineate stable or unstable spatial patterns and identify zones of similar crop performance. Then they performed model evaluations at selected sites within each of the management zones. In another study Basso et al. (2011a) presented a tactical and strategic procedure for selection of optimal N fertilizer rates to be applied on management zones identified as homogenous based on the outputs of a crop simulation model and the simulated levels of plant available soil water at the time of the second N application. In this study we simply hypothesized that variable rate nitrogen fertilizer when properly identified in terms of quantity and spatial distributions leads to higher profit and lower environmental impact.

The objectives of this study was to demonstrate the advantages of variable rate management with a field study where variable and *business-as-usual* nitrogen rate were compared with field measured data of yield and farmers' revenues. To achieve the objective of the study, (*i*) uniform management zone were identified using an integrated spatio-temporal analysis; (*ii*) optimal N fertilizer rates were determined on the basis of simulated yield and N-leaching responses to the site-specific N rates; (*iii*) the so-defined optimum N rates were physically applied within each zone of the field; and (*iv*) the economic and environmental benefits of variable rate N fertilizer in a Nitrate Vulnerable Zone was finally demonstrated through a comparison to the *business-as-usual* practice and the subsequent validation measurements.

2. Materials and methods

2.1. Site description

This study was carried out on a 13.6 ha field near the Venice Lagoon, NE Italy (45°22′23.02″N, 12°08′24.27″E, −2 m a.s.l) for the 2005, 2006, 2007, and 2008 growing seasons. The area was identified as a Nitrate Vulnerable Zone (NVZ) according to Nitrate Directive 91/676 (EEC, 1991) because high potential nitrate leaching in ground and surface waters. Soil texture varies greatly in the study area, ranging from sandy to silty-loam (Soil Survey Staff, 1999). Daily weather data were collected by an automatic meteorological station located near the experimental field (ARPAV, Bureau of Meteorology of Veneto Region).

2.2. Agronomic management

The agronomic practices applied to the crops included in this study are representative for the growing area. Crop rotation adopted was sugar beet in 2005 and continuous maize for the remaining three years. A detailed explanation of the agronomic practices applied for the 2007 and 2008 growing seasons are shown in Table 1.

2.3. Soil sampling

An extensive characterization of soil in the study area was made in 2005. A mixed-sampling scheme of the top soil layer (0–30 cm) was followed based on a regular grid: 40 samples were collected at the nodes of a 60-m grid and 80 additional points were collected at the nodes of 10 transects, resulting in a total of 120 samples. Transects were set in the north and east axis at 1, 5, 15, 30 m from 10 randomly chosen nodes of the grid. Soil texture was determined using the hydrometer method (Klute and Dirkens, 1986), soil bulk density was measured with the core method (Grossman and Reinsch, 2002) and soil pH and electric conductivity were measured with a pH/EC tester on a soil water extract. Organic carbon was measured using the Walkley–Black method (Walkley and Black, 1934) and the results converted to organic matter by multiplying the carbon percentage by 1.72. Total N was determined using Kjedahl method and labile phosphorus was determined with the Olsen method. In addition, spatial soil electric conductivity (EC_a) was measured with an EMI sensor (Geonics EM38DD) which determined conductivity in both horizontal and vertical orientations. This instrument provided a weighted depth reading to approximately 0.5 m in the horizontal orientation and 1.5 m in the vertical orientation. EC_a measurements were collected in November 2005, carried out in the field with associated DGPS antenna.