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Yield response of potato to spatially patterned nitrogen application

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ABSTRACT

Although crop response to nitrogen fertilization has long been studied, classical experimental designs have led to inadequate accounting of spatial variability in field properties and yield response. Analytical methods to explicitly account for spatial variability now exist but the complementary modification of experimental design is still developing. There is a need to combine these analytical methods with non-traditional experimental design. A 2-year study was implemented to assess the response of potato (*Solanum tuberosum* cv. Kennebec) yield to nitrogen fertilizer rate. We used a transect-type plot design where four nitrogen treatments (0, 56, 112, and 280 kg N ha^{-1}) were applied systematically in a continuous sinusoidal pattern along longitudinal transects. Measured field properties included topography, soil texture, pre-application soil nitrate levels, and plant available soil water content. A random field linear model was used to simultaneously account for treatment effects and soil properties. The results showed that treatment effects were significantly different from each other; however, if spatially correlated errors were accounted for, these differences were smaller and significance levels lower. Nitrogen response functions varied widely throughout the field. Of the covariates, only clay content proved important in explaining spatial differences in response to N. The sinusoidal response pattern of N was similar over the 2 years but the amplitudes varied due to differences in weather. Interactions between uncharacteristically high rainfall and a sandy field soil may have minimized discernable effects of the other covariates. The results demonstrated how the statistical analysis of potato response to a patterned application of nitrogen fertilizer can take advantage of spatial correlations to understand the response of potato to nitrogen application over larger areas.

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1. Introduction

It is estimated that nitrogen use efficiency (NUE) for agriculture globally ranges from 10 to 50%, indicating that more than half the applied N is lost to the plant and the immediate crop environment (Mosier et al., 2004). The largest N losses and the lowest NUEs tend to occur in highly industrialized countries where the low cost of N lends itself to excessive fertilization. Not only are costs associated with low efficiency, but the effects of N dispersed in the wider environment can lead to serious environmental and ecologic consequences (Matson et al., 2002). While there has been some increase in NUE in the United States, Cassman et al. (2002) point out that the major impediment to realistic improvement is the lack of understanding "of plant response to spatial and temporal variations in soil conditions." Specifically, Dobermann and Cassman (2004) claim that research results have not been translated properly into farming practice because little use has been made of spatial information in discrete plot-based research; thus, extrapolation to farm-scale operations is compromised. In a review of the current literature, Balasubramanian et al. (2004) show mean NUE of research plot results are consistently higher than mean NUE under current farming practices for several major crops.

Nitrogen as nitrate is primarily found as a solute dissolved in soil water. Since water fluxes in soil can be highly variable from location to location, the transport of N with water is also variable. This can result in spatial variability of N availability in the soil that can result in spatial differences in N response (Scharf, 2001; Bélanger et al., 2000a). The economically optimum N response rate from N response curves varies from field to field and within fields having different optimums and correlation scales (Scharf et al., 2005). These variations in the spatial structure of N response suggest strong linkages to soil properties such as topographic variables, e.g., slope and curvature (Timlin et al., 1998; Pachepsky et al., 2001; Shahandeh et al., 2005.

The majority of agronomic experimentation and inferential statistical techniques used to analyze field experimental data are

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based on the assumption of statistical independence and use blocking and replicates to minimize or remove the (nuisance) effect of spatial variability and maximize the efficiency of sampling number. But, spatial variability in field response variables or covariates are seldom randomly distributed and usually display some patterning. Blocking, too, has come under scrutiny within the context of spatial variability, especially if the assumption of within block heterogeneity is not checked or met (Gusmão, 1986; Mulla et al., 1990; Lin et al., 1993). Hong et al. (2005) showed blocking to be ineffective in some circumstances when spatial variability is otherwise accounted for. Ultimately, the effect of spatial variability when using conventional statistical analyses is that treatment effects and locational effects are often indistinguishable (Heffner et al., 1996), and that the correct probability of Type I and Type II errors is obscured (van Es and van Es, 1993; Legendre et al., 2002), as is the ability to extrapolate from discrete plots to whole-field response. Mulla et al. (1990) using nearest neighbor analysis showed that yield means, thus treatment effectiveness, were sensitive to spatial variability in potato.

Peterson et al. (1993) stated that there is a need to move away from small-plot research toward more field-scale experimentation across soil and climatic gradients. The incorporation of a landscape approach will not only help to better understand crop response, but also to increase applicability of results. In a recent review of the design and analysis of agronomic experimentation during the past 100 years, Edmondson (2005) stated that future emphasis will be on the design of spatially efficient experiments since computational intensity is no longer an impediment. Nielsen and Wendroth (2003) question the need for discrete treatment experimentation when techniques exist to analyze more realistic continuously varying treatments across a gradually changing landscape. Gotway and Cressie (1990) showed that analysis of variance methods could be used to test treatment effects by correcting the variance–covariance structure of a linear model for spatial dependence through the use of geostatistical semivariogram functions. Zimmerman and Harville (1991) advocated the direct modeling of spatial correlation and provided a rigorous development of the above analysis they called the random field linear model (RFLM). The general form of the RFLM included a fixed (mean) component, a random (e.g., blocking) component (optional), and a correlated error structure. They used restricted maximum likelihood methods for parameter estimation, and showed that RFLM methods to assess treatment effects within the context of spatial variability provided more appropriate variance estimates than nearest neighbor analysis. Brownie and Gumpertz (1997) confirmed the development of Zimmerman and Harville (1991) and concluded that gains in statistical efficiency in spatially correlated error analysis over classical statistical approaches did not sacrifice statistical validity. The work by Zimmerman and Harville (1991) provided the basis for the development of spatial analysis in the SAS PROC MIXED statistical package (Littell et al., 1996).

The use of RFLM in agricultural experimentation is recent and increasing. To assess the effects of soil and fertilizer on corn yield, Hoosbeek et al. (1998) concluded the RFLM approach supplied better predictors than kriging alone as explanatory variables could be explicitly assessed. The usefulness of the RFLM to extrapolate from plot to field scale was highlighted. In a study of sugar-cane yield variability, Anderson et al. (1999) commented on the usefulness of the RFLM to account for spatial variability and still allow for inference testing. Singh et al. (2003) tested several classical models (e.g., complete/incomplete block design) with and without spatially correlated errors on three crops (chickpea, lentil and barley) and found that accounting for spatially correlated errors was more critical than model structure in assessing total variability in field trials. Eghball et al. (2003) used RFLM to adjust corn yield means for spatial variability in a multifractal analysis of variable rate nitrate management. RFLM studies have proven particularly amenable to precision agriculture. Griffin et al. (2005) used RFLM to assess yield-monitor data for whole-field applications and concluded the RFLM provided efficient and unbiased estimates regardless of replication. Recently, Hong et al. (2005) provided a thorough methodological development and application procedure.

Few studies have utilized patterned application of treatment variables specifically to quantify the effects of spatial variability on response functions. Fox (1972) was one of the first to carry out a field study where fertilizer application rates were imposed in a gradually increasing rate along a transect as an alternative to using small randomized plots. Citing this study as an example, Nielsen and Wendroth (2003) recommended alternative approaches to impose treatments such that variation in response functions can be understood and quantified with respect to the entire field. The objectives of the research presented here were to: (a) quantify the spatial response of potato yield to four levels of a nitrogen fertilizer applied in a sinusoidal spatial pattern on a (134 m $\times$ 14 m) field as suggested by Nielsen and Wendroth (2003), and (b) to quantify the effects of continuously variable soil properties (soil texture, initial nitrate content and water holding capacity) on the resultant yield pattern. This will allow for the presentation of a yield response function over a large heterogeneous area (Cassel et al., 1988; Hoosbeek et al., 1998; Sadler et al., 2002) and induce a known spatial yield pattern over presumably unknown distributions of field properties. Ultimately, we will show that it is possible to exploit the spatial relationships inherent in yield data and in correlated soil properties to extrapolate whole-field responses to nitrogen application.

2. Materials and methods

2.1. Experimental design and site characteristics

The field experiment was conducted in 2003 and 2004 at the Henry A. Wallace Agricultural Research Center, Beltsville, Maryland (BARC). The research center is located at 39.03472 latitude, −76.90778 longitude. Average monthly temperature for April to August (inclusive) is 20.4 °C, where July is typically the warmest month. Average monthly precipitation for the same period is 91 mm, or a total of 455 mm for the period, which accounts for approximately 40% of the average annual precipitation.

The experimental field measured approximately 134 m $\times$ 14 m (0.18 ha) (Fig. 1). The majority of the field was classified as Downer-Ingleside loamy sands (coarse-loamy, siliceous, mesic Typic Hapludults [Haplic Acrisols, FAO]). The soils at the north and south ends of the field were classified as Matawan and Keyport series (fine-loamy, siliceous or mixed, mesic Aquic Hapludults [Gleyic Acrisols, FAO]). Each year, the Farm Management Unit at the research center collects a composite of 10–12 soil samples from the surface 10 to 15 cm for nutrient analysis (nitrogen (N), phosphorous (P), potassium (K), OM and pH). Based on soil tests for the past 8 years, the organic matter content of the surface soil varied from 0.9 to 1.3 g kg^{-1} and the pH from about 5.7 to 6.1. The phosphorus content was generally high and potassium moderate. The field was fertilized accordingly at pre-plant. A rye (*Secale cereale*) winter cover crop was planted in the field prior to both the 2003 and 2004 experiments. The rye was mechanically plowed under while chiseled and disked during field preparation prior to planting. The field had been planted with vegetables followed by a winter rye cover crop for the 3 years preceding the 2003 experiment. Field topography was sampled via a real-time kinematic GPS survey at an approximate spacing of 1 point per 2.7 m.