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Spatial and Temporal Variability of Soil Fertility in Relation to Crop Yield Zones on Hummocky Terrain

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ABSTRACT

A field study was conducted on hummocky terrain at the Manitoba Zero Tillage Association Research Farm to determine the variability of crop yield as related to landscape position, soil properties, weed populations and plant disease. This information was also used to evaluate technology required for delineation of management units related to precision farming. Variable-rate fertiliser management systems can improve efficiency of fertilizer use and environmental sustainability. Adoption of this technology has been hampered due to the difficulty of classifying fields into management units, the high cost of sampling soils on a grid basis, and the variability of soil and plant properties in the landscape. Technology for variable rate fertilizer systems is available, but there is little information available related to yield response in clay soils on hummocky terrain, and the relationship of plant tissue test levels in relation to soil fertility as measured by soil test nitrate nitrogen. Current soil test recommendations for nitrogen are based on soil test nitrate nitrogen from samples bulked from samples in several locations in the field preferably grouped according to topography.

Yield data for 1997-2001 were classified into groups with the fuzzy k means, normal mixtures and self-organizing map variants of cluster analysis. Although fuzzy k means commonly used for classification of crop yield and soil properties, a method based on self-organizing maps provided consistent classes when compared across years. Soil nitrate nitrogen varied considerably across the landscape at the site, but was not significantly different ($P<0.05$) between classes based on crop yield. Yield data can be used to delineate zones for variable management, although fertilizer inputs may be a function of spring soil moisture, runoff and growing season precipitation as they affect seeding, crop emergence and establishment.

INTRODUCTION

Variable-rate fertiliser management systems can improve efficiency of fertilizer use and environmental sustainability. Adoption of this technology has been hampered due to the difficulty of classifying fields into management units, the high cost of sampling soils on a grid basis, and the variability of soil and plant properties in the landscape. Technology for variable rate fertilizer systems is available, but there is little information available related to yield response in clay soils on hummocky terrain, and the relationship of plant tissue test levels in relation to soil fertility as measured by soil test nitrate nitrogen.

Current soil test recommendations for nitrogen are based on soil test nitrate nitrogen from samples bulked from samples in several locations in the field preferably grouped according to topography. Variability of nitrate nitrogen can vary considerably in landscapes, Cahn et al. (1994) determined the spatial pattern of nitrate nitrogen changed with time, and the frequency distribution was skewed due to a few outlying values, which greatly exceeded the mean. Solohub et al. (1999) concluded mineral nitrogen is highly variable both across the landscape and over distances less than one meter. Current research on variable-rate fertilizer management has focussed on potential crop yield in relation to factors such as erosion and soil fertility as it varies from upper to lower slope positions.

Variability of crop production has been related to the thickness of topsoil (Gregorich and Anderson 1985, Pennock and De Jong 1990) and soil moisture (Verity and Anderson 1990). Previous research (Moulin et al 1994) showed crop yield and soil erosion were related to a multivariate factor composed of relative elevation and surface curvature. Variability of crop yield in a glacial-till landscape was attributed to the effect of relative elevation and surface curvature on overland flow of water and related soil properties.

Subsequent research (Beckie et al 1997) evaluated variable rate fertilizer management in a field classified according to slope position, organic matter and residual soil test nitrogen. The highest efficiency of fertilizer use was found when nitrogen fertilizer was variably applied to land classified according to topography.

Given the considerable variability of crop yield and soil nitrogen, and the significant costs of grid sampling and chemical analysis, the potential for precision agriculture in the Prairie region based on these technologies is prohibitive. Results of this research indicate the variability of soil nitrogen and other properties, is high and not necessarily directly related to elevation or topography in glacial till. Solohub et al. (1999) also found significant variability in mineral nitrogen over short distances in glacial till soils, and suggested bulking a number of samples from a small area to improve resolution. The large number of samples in this study provide considerable statistical power to the analysis of the relationships with elevation and other variables, but this level of sampling is uneconomic in a crop production system.

Several management systems have been proposed to deal with the need to adequately and economically quantify spatial variability of soil properties and implement variable rate fertilizer. The most common is termed “zone management or patch management” and is based on dividing fields into zones based on crop yield, soil properties, surface reflectance based on air borne or satellite imagery, and digital elevation maps (Viscarra Rossel and McBratney 1998). Soils and plants are then sampled within these zones. This system reduces the number of samples, analyses and costs related to variable management. Zone management would allow producers to avoid sampling soils, which unduly influence the calculation of means and result in an underestimate of fertilizer requirements. The most common method for classification of crop yield and soil properties into management zones is the fuzzy k means, developed by McBratney and de Gruijter,(1992). This method is an iterative procedure, which tests a range of potential zones, and identifies the optimum number based on variability of the fuzziness performance index and the modified partition entropy. The normal mixtures method for classification is similar to k means but is based on probabilities rather than cluster memberships. Normal mixtures are preferred to k-means clustering where clusters overlap and assigning each point to one cluster is problematic. Self-organizing maps (SOM) developed by Kohonen (2001), are another method based on mathematical principles used in neural networks. The goal is to not only form clusters, but to form them in a particular layout on a cluster grid, such that points in clusters that are near each other in the SOM grid are also near each other in multivariate space. The original SOM was cast as a learning process, like the original neural net algorithms, but the version implemented in this study is done in a much more straightforward way as a simple variation on k-means clustering.

Objectives

The objective of this paper is to evaluate and classify spatial and temporal variability of yield zones based on crop yield in hummocky terrain, and to assess the relationship of soil nitrate nitrogen to these zones.

METHODS

Experimental Design and Field Activities

The field site is an area of approximately 2 ha located at the Manitoba Zero Tillage Research Association Research Farm located 17.6 kilometres north of Brandon. Relief at the site is irregular undulating to hummocky with variable drainage. Drainage varies from well to rapid on the upper slopes to very poor in depressed pothole areas. The research farm is situated within the Newdale Plain subsection of the Assiniboine River Plain. The area consists dominantly of undulating to hummocky ground moraine characterised by numerous potholes an sloughs. Surface deposits consists of boulder till of mixed materials derived from shale, limestone and granitic origin. The soils of the Newdale association are moderately to strongly calcareous and belong to the fine loamy particle size class. The dominant soil texture on the farm is clay loam.

The study was initiated in 1997 and continued to 2001. A modified grid of 310 samples sites was established at the site (Figure 1). Baseline soils and data were collected at 310 sites for (0-7.5 cm, 7.5-15 cm, 15-30 cm, 30-60 cm and 60-90cm) in September 1997. Crops seeded at the site were barley in 1997, oats in 1998, canola in 1999 and canola in 2000. Nitrogen solution was added at rates from 60 to 70.0 kg ha^{-1} N, based on soil test levels. Soil phosphorus was sidebanded at a rate of 30 to 40 kg ha^{-1} depending on soil test levels. Spectral radiometer (460 nm, 510 nm, 560 nm, 610 nm, 660 nm, 710 nm, 760 nm, 810 nm), SPAD meter (measures radiation transmitted through the leaf from LEDs at 650 and 940 nm), leaf tissue samples (nitrogen), weeds and data were collected in June and July 1999 and 2000. In July 2000 and August2000, leaf, stem and canola pod disease were surveyed at the site. Weed counts were surveyed in two 0.25 m^{-2} quadrates at each site in 1997, 1999 and 2000. In September and October 1997 through 2000, grain yield and straw samples were collected from the site. Soil samples were analyzed for nitrate-N and sulphate-S ($CaCl_3$ auto-analyzer), phosphorus and potassium (modified Kelowna, P auto analyzer, K flame photometer) (Enviro-Test Laboratories). Canola seed and leaf tissue were analyzed for total nitrogen by combustion with a Carlo-Erba elemental analyzer. Cluster analysis of yield data was conducted with the k-means platform using a fuzzy k-means program by Minasny and McBratney (2000), and the normal mixtures and self-organizing map technique in JMP version 4.04. Yield at each sample site for 1997-2000 was divided by the maximum for the crop year to normalize the data prior to analysis. Classification methods were compared with contrasts of cluster assignments for 1997-2000 and 1997-2001 using analysis of log likelihood.

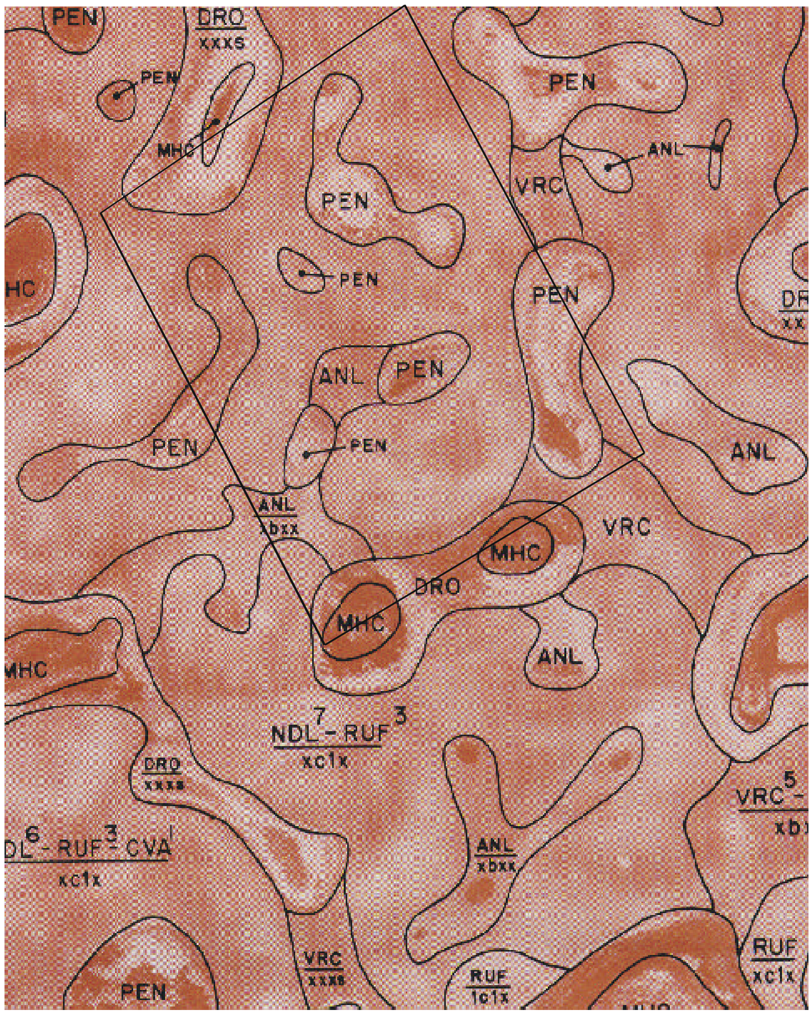

Figure 1. Soils map of study area. Study area outlined in black, Manitoba Zero Tillage Research Farm. Soil Series: NDL - Newdale, RU Rufford ANL Angusville, PEN Penrith , CVA Cordova

RESULTS

Topography

Elevation varies considerably at the site (Figure 2) but is typical of hummocky glacial soils of the Newdale association. Soils at the site are predominantly Newdale clay loam (Orthic Black), with imperfectly drained Angusville loam-clay loam (Gleyed Eluviated Black) in depressions. Penrith loam-clay loam (Humic Luvic Gleysol), Rufford clay loam (Rego Black), and Cordova clay loam (Calcareous Black) soils are also present in the area adjacent to the site (Podolsky and Schindler 1994). Several depressions fill with water due to runoff in the spring, but can normally be seeded in years with average precipitation. In 1999 the area received in excess of 200% normal precipitation. Several depressions were not seeded due to excess moisture.

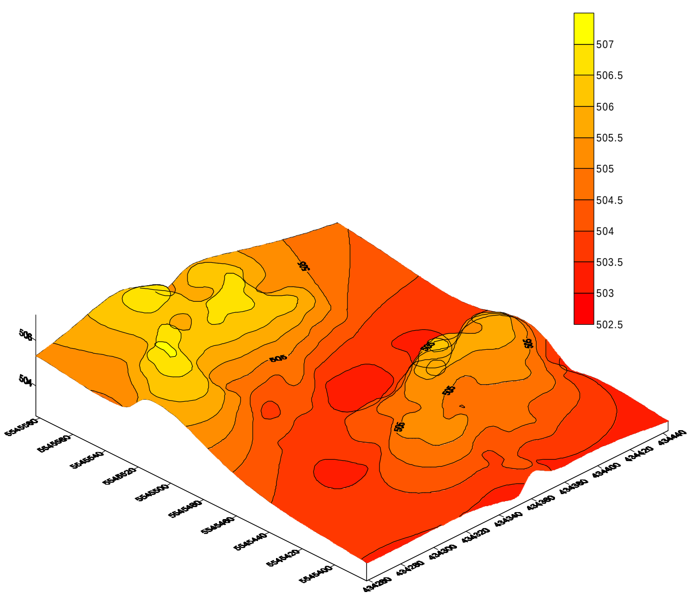

Figure 2. Topography and elevation (m ASL) at site

Surface curvature

Soil curvature varies considerably at the site. Concave curvature occurs at upper and lower slope positions, with channels oriented from upper to lower slopes (Figure 3).

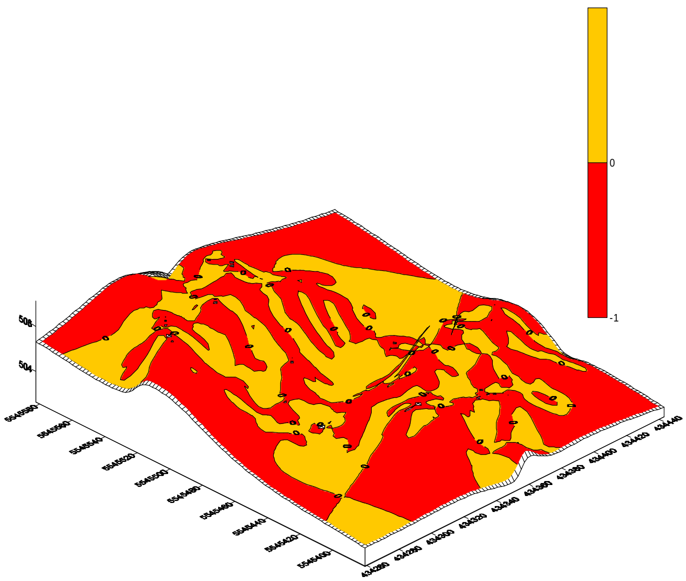

Figure 3. Horizontal surface curvature. Dark areas represent divergent flow.

Soil Properties

Spatial distribution of soil carbon (Figure 4) and nitrate nitrogen was related to elevation. The frequency distributions of soil-nitrate nitrogen for 1999 are skewed due to the presence of values greater than 200 kg ha^{-1}. Soil test nitrogen in fall 1999 was relatively high due to poor production in 1999.

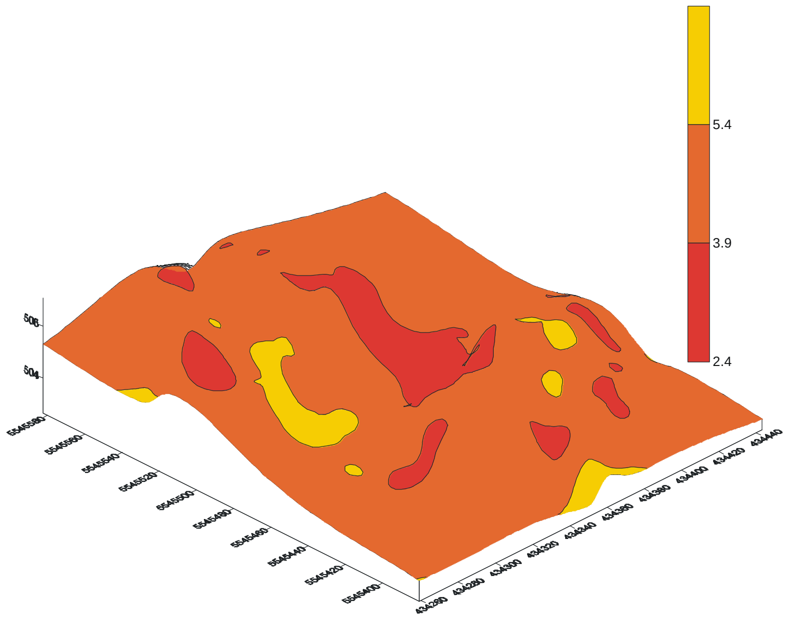

Figure 4. Soil organic carbon 0-7.5 cm (%)

Crop Yield

Crop yield varied considerably during the period from 1997 to 2001. Average yield in 1999 was 386 kg ha^{-1} in 1999 due to a combination of late seeding date and excess soil moisture. Canola yield was ranged from 0- in flooded areas (Figure 3), furthermore yield was highly variable across the landscape. In 2000, average yield was 1860 kg ha^{-1}.

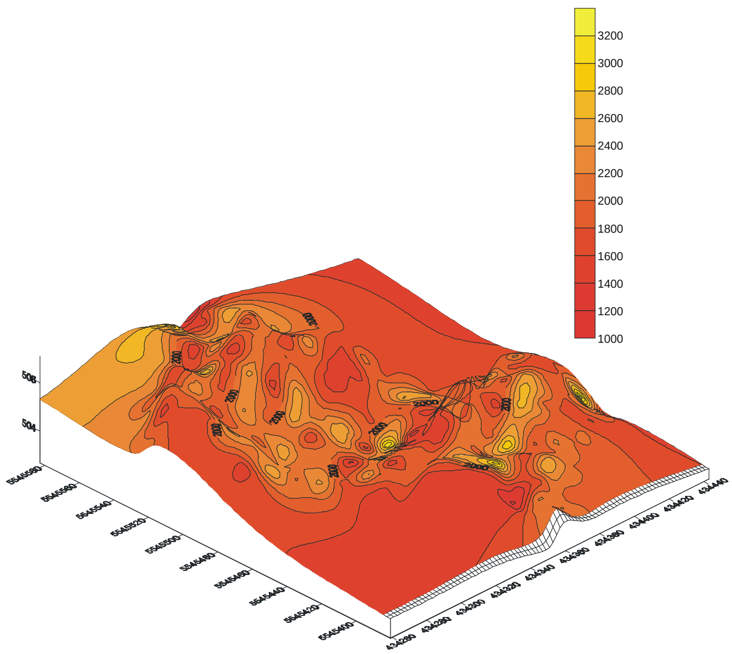

Figure 5. Relationship of canola yield (kg ha^{-1}) to elevation (m ASL), 2000.

Cluster analyses

Cluster analysis of crop yield for 1997 to 2001 with the k-means method shows an optimum number of 6 based on the analysis of the fuzziness performance index and modified partition entropy (Figure 6). Although the optimum number is well defined in the k-means analysis, the distribution of clusters appears to be affected by the presence of outliers for the fourth cluster (Figure 7). Analysis with the self-organizing map method shows 6 distinct clusters (Figure 8). Comparisons of classifications with data from 1997-2000 in relation to 2001 showed better prediction using the self-organizing map method compared to k means.

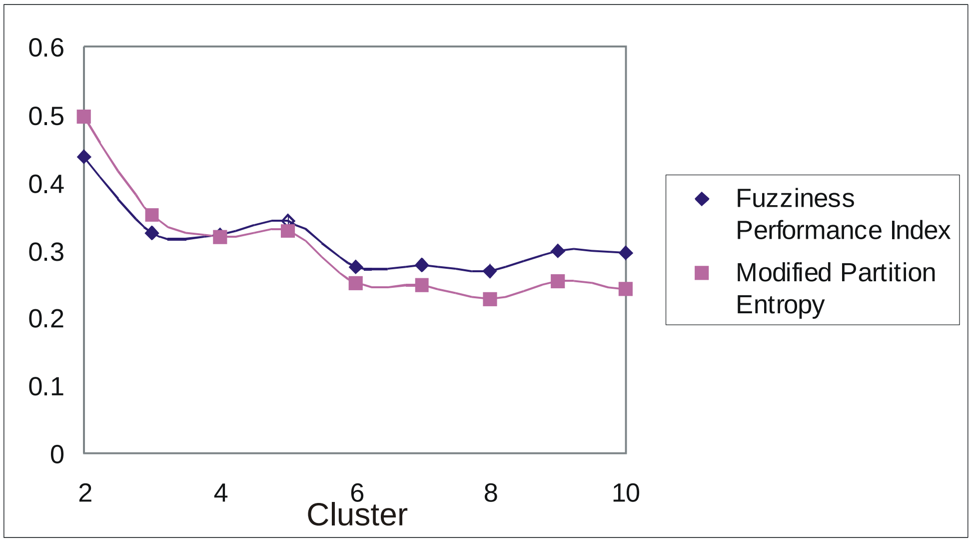

Figure 6. K-means analysis of cluster number for crop yield 1997-2001.

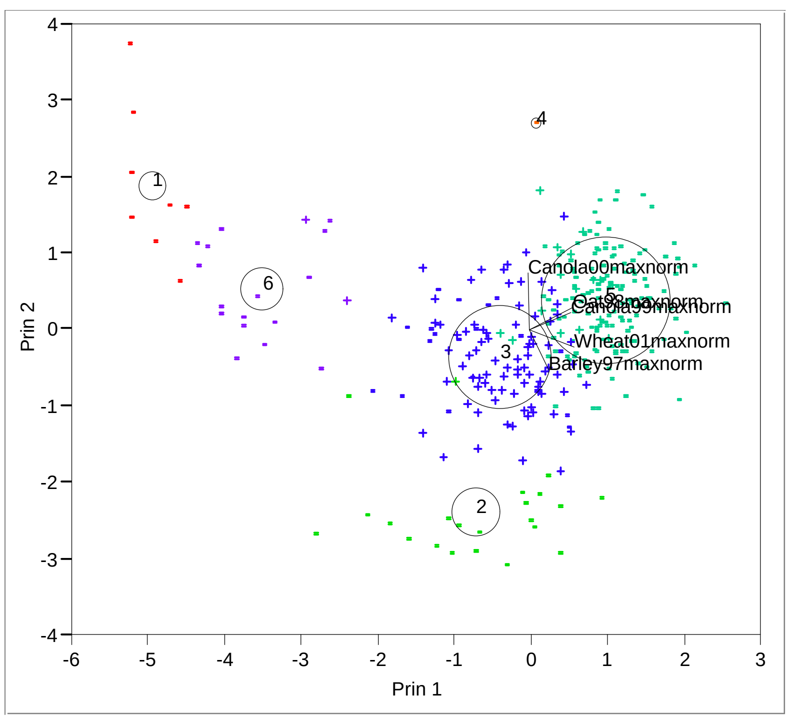

Figure 7. K-means analysis in principle component space of cluster number for crop yield 1997-2001.

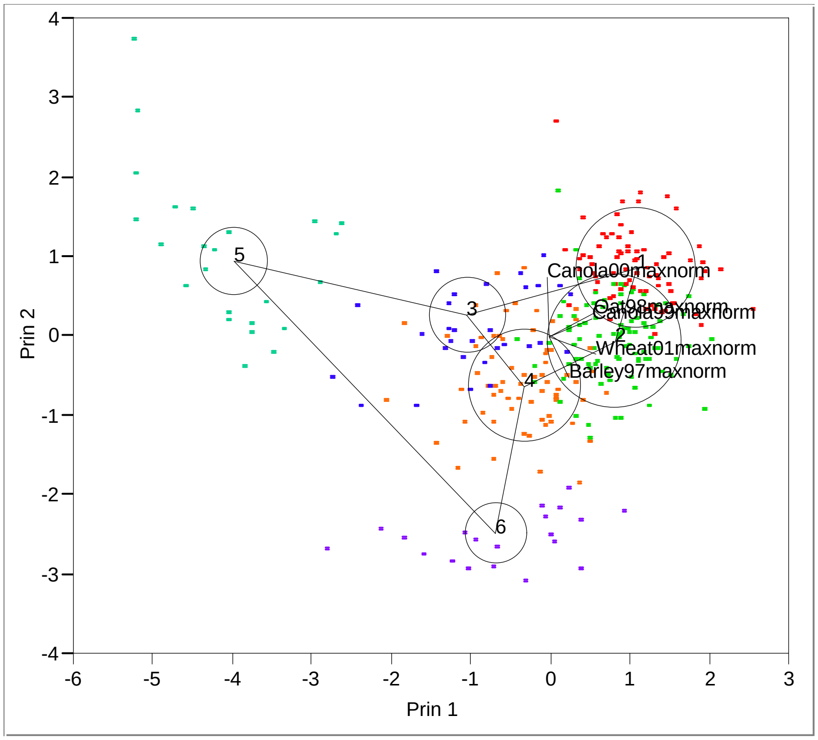

Figure 8. Self-organized map clusters in principle component space for crop yield 1997-2001.

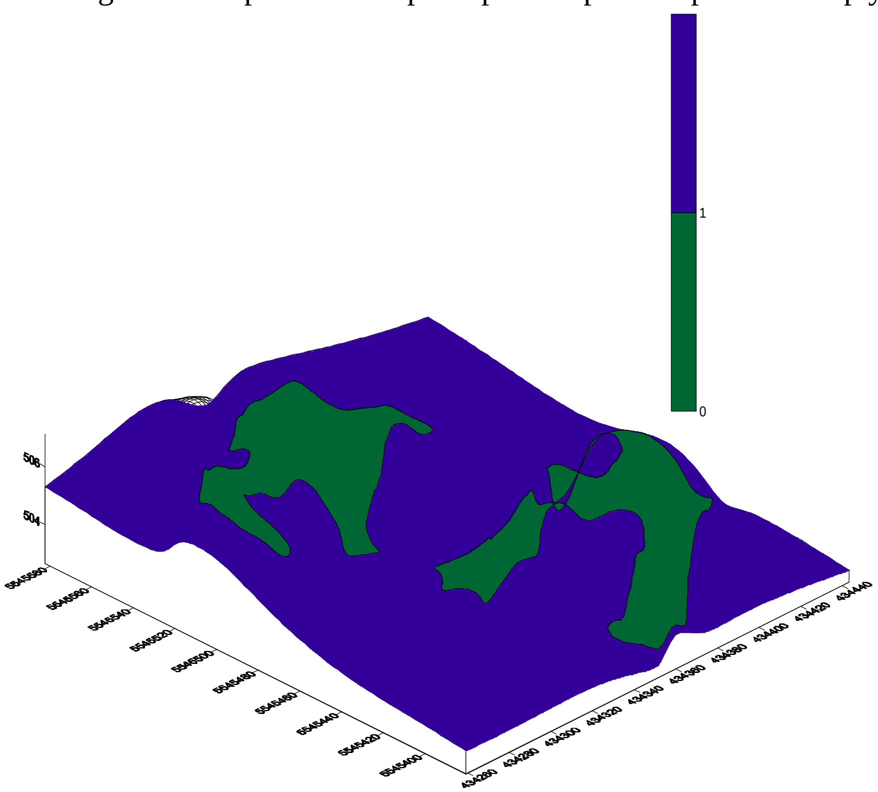

Figure 9. Yield zones based on self-organized map cluster analysis of normalized yield for 1997-2000.

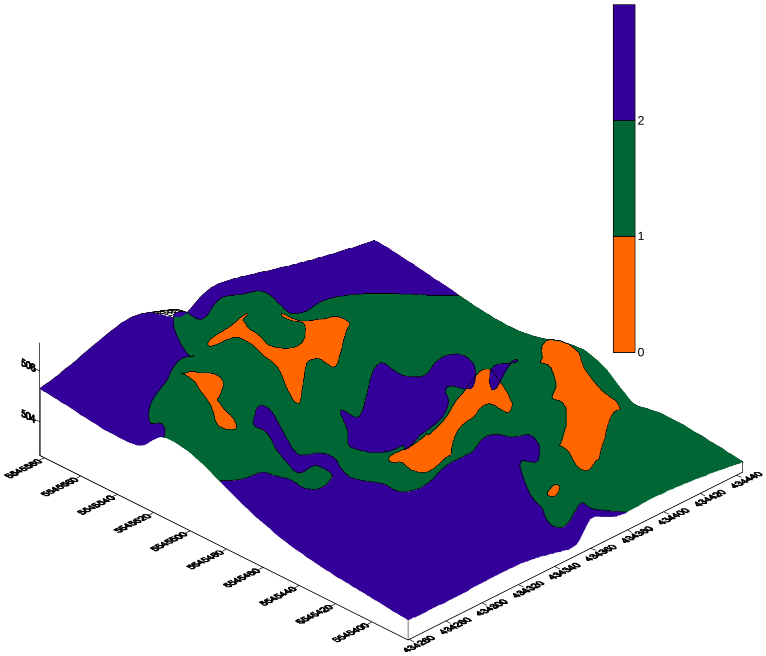

Figure 10. Yield zones based on self organized map cluster analysis of normalized yield for 1997-2001.

Soil Nitrate Nitrogen

Nitrate nitrogen varied considerably across the landscape and between years. Although there was considerable variability, there were no significant ($p<0.05$) differences in nitrate nitrogen within years between 2 3 or 6 (Figure 11) yield zones. Variable rate management of nitrate nitrogen may not be dictated by the soil test analysis from preceding years, but from the potential for yield as defined by spring soil moisture, runoff and precipitation during the growing season.

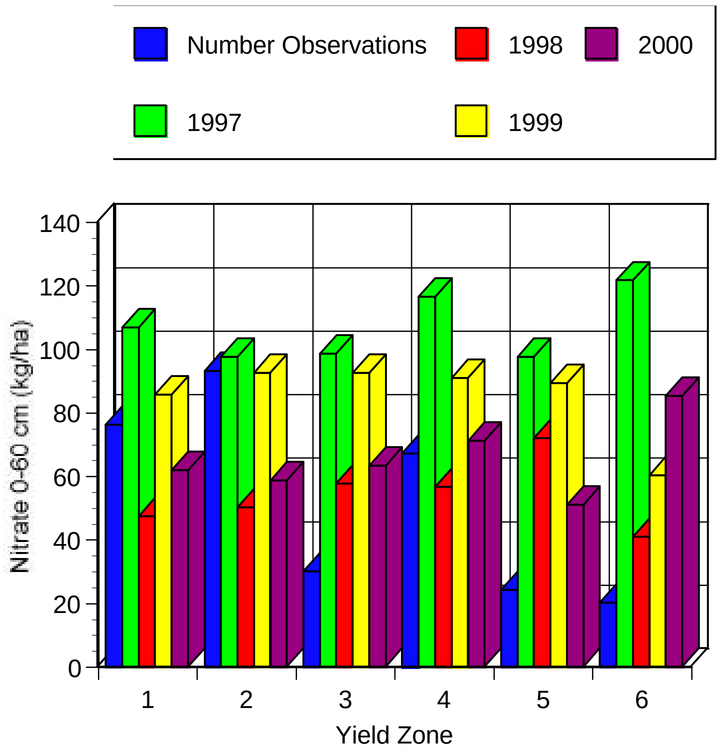

Figure 11. Soil nitrate nitrogen in 6 yield zones based on self organized map cluster analysis of normalized yield for 1997-2001.

CONCLUSIONS

Variable management of crop inputs has the potential to improve economic return and maintain environmental quality. Although fuzzy k means clustering methods are commonly used for classification of crop yield and soil properties, a method based on self-organizing maps provided consistent classes when compared across years. Soil nitrate nitrogen varied considerably across the landscape at the site, but was not significantly different ($P<0.05$) between classes based on crop yield.

Yield data can be used to delineate zones for variable management, although fertilizer management should be based on soil test analyses for each zone. Fertilizer inputs may be a function of spring soil moisture, runoff and growing season precipitation which affect seeding, crop emergence and establishment.

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