# SPATIAL VARIABILITY OF MEASURED SOIL PROPERTIES ACROSS SITE- SPECIFIC MANAGEMENT ZONES

**M. Mzuku**

*Department of Agricultural Engineering and Land Planning*
*Botswana College of Agriculture*
*Gaborone, Botswana*

**R. Khosla, and D. Inman**

*Department of Soil and Crop Sciences*
*Colorado State University*
*Fort Collins, Colorado*

**R. Reich, F. Smith, and L. MacDonald**

*Department of Forest, Range, and Watershed Stewardship*
*Colorado State University*
*Fort Collins, Colorado*

## ABSTRACT

The spatial variation of productivity across farm fields can be classified by delineating site-specific management zones. Since productivity is influenced by soil characteristics, the spatial pattern of productivity could be caused by a corresponding variation in certain soil properties. Determining the source of variation in productivity can help achieve more effective site-specific management. The objectives of this study were (i) to characterize the spatial variability of soil physical properties across irrigated corn (*Zea Mays L.*) production fields and (ii) to determine if soil physical properties could explain the variability in productivity between site-specific management zones. The study was conducted over three study sites in northeastern Colorado. The soil properties measured were bulk density, cone index, organic carbon, texture, sorptivity, and surface water content. A multi-response permutation procedure was used to test for significant differences among soil properties between management zones. Overall, this study showed that soil physical properties exhibited significant spatial variability across production fields. The trends observed for the measured soil physical properties corresponded to the productivity potential of the management zones. Utilizing site specific management zones could help manage the in-field variability of yield-limiting soil physical properties.

**Keywords:** Site-specific management, spatial variability, precision farming

# INTRODUCTION

Several studies have documented that soil properties vary across farm fields, causing spatial variability in crop yields (Rockström et al., 1999; Gaston et al., 2001). Precision farming or site-specific management is aimed at managing soil spatial variability by applying inputs in accordance with the site-specific requirements of a specific soil and crop (Fraisse et al., 1999). Such management practices require quantification of soil spatial variability across the field. One of the recent approaches to quantify soil spatial variability for site-specific management is to divide fields into productivity level management zones (Khosla et al., 2002; Fleming et al., 2000). A management zone is a sub-region of a field with homogeneous yield-limiting factors, for which a single rate of a specific crop input is appropriate (Doerge, 1999).

Various techniques of delineating management zones are currently being investigated in different parts of the USA (Fraisse et al., 1999; Fleming et al., 2000; Khosla et al., 2002; Fleming et al., 2004). Site-specific management zones as described by Fleming et al. (2000) and Khosla et al. (2002) were delineated from the variability in color observed in bare soil imagery of conventionally tilled field, farmer's perception of field topography, and farmer's knowledge of past production practices. The variability in bare soil reflectance, and that observed by the farmer, is due, in part, to non-uniform distribution of certain soil properties that influence crop productivity. Variability in soil properties is a direct result of the five soil forming factors; climate, organisms, relief, parent material, and time (Jenny, 1941).

Of the five soil forming factors, relief (topography) can be most readily assessed. Changes in field topography influence the distribution of soil properties and crop productivity across a field. Multi-fold variations in crop yields within a field have been reported in several studies. Crop yields ranged from 1.0 to 6.7 Mg $ha^{-1}$ in a field in east-central Alberta, Canada (Goddard and Grant, 2001). Low, medium, and high organic matter zones were found to correspond with top, middle, and bottom slope landscape positions (Mulla and Bhatti, 1997). They also reported increasing grain yields with increasing soil organic matter content.

Spatial variability in soil physical properties, nutrient levels and water content has been well documented (Fulton et al., 1996; Chung et al., 2000; Gaston et al., 2001). Chung et al. (2000) found that grain yield, electrical conductivity, Ca, K, Mg, Na, and $SiO_2$ can exhibit significant and large-scale variability within a relatively small area of relatively low topographic relief (i.e., 3 ha). Soil compaction and bulk density have also been documented as varying significantly within single fields (Fulton et al., 1996; Wells et al., 2000). Spatial variability in certain soil parameters can have influence on the spatial distribution of crop productivity potential. Variability in clay and soil organic carbon was shown to exert influence on the location and density of weeds (Gaston et al., 2001). Inman et al. (2005) reported that fields that have a high degree of spatial variability in soil properties could be better managed using site-specific management zones.

Review of the literature indicates that most previous investigations have focused on the study of spatial variability caused by a particular soil property, i.e. compaction, texture, soil organic carbon, etc. (Fulton et al., 1996; Wells, et al., 2000; Gaston et al., 2001). Classifying fields into different levels of productivity management zones is a relatively new concept. Previous studies investigated spatial variability in field properties independent of productivity level management zones. Also, understanding the role of several soil properties together, and their interactions, may help to explain the cause of variation in crop productivity as defined by site-specific management zones. The objectives of this study were (i) to characterize the spatial variability of soil physical properties across irrigated production corn fields and (ii) to determine if the measured soil physical properties could explain the variability between site-specific management zones.

## MATERIALS AND METHODS

This study was conducted in 2001 and 2002 on three fields that were in irrigated continuous corn in northeastern Colorado. Study site I was furrow irrigated, while study sites II and III were irrigated using center-pivot sprinkler irrigation systems. Prior to planting, site-specific management zones were delineated on all fields using the commercially available AgriTrak Professional software (Fleming et al., 1999). This program relies on three Geographic Information System (GIS) data layers: (i) bare soil aerial imagery on conventionally tilled land; (ii) farmer's perception of field topography; and (iii) farmer's past crop and soil management experience. These data layers were incorporated into a MapInfo (GIS) data base to generate mathematical interpolation surfaces to develop three management zones (Khosla et al., 2002). Traits such as regions of dark color, areas of low-lying topography, and areas of historic high yields as reported by the farmer were designated as a zone of potentially high productivity or high zone. Details of this technique are provided in Fleming et al. (1999), Khosla et al. (2002), Koch et al., (2004), and Inman et al. (2005). Fields ranged from 19 to 35 ha in size (Fig. 1). The high zone accounted for 30, 23, and 35 %; while the medium zone was 35, 46, and 41 %; and the low zone was 35, 21, and 24 for sites I, II, and III, respectively (Fig. 1).

Study site I was at an elevation of 1420 m, and had a slope of 0 – 2%. Soils mapped at site 1 were: Ascalon fine sandy loam (fine-loamy, mixed, superactive, mesic, Ardic Argiustoll), Haverson loam (fine-loamy, mixed, superactive, calcareous, mesic Aridic Ustifluvent), Otero sandy loam (coarse loamy, mixed, superactive, calcareous, mesic Aridic Ustorthent), Nunn clay loam (fine smectitic, mesic, Aridic Argiustoll), and Olney loamy sand (fine loamy, mixed, superactive, meisc Ustic Haplargid) soil series (USDA, 1980). Study site II was a nearly level (0 – 2% slope) field at an elvation of 1437m. Soil mapped were Valentine fine sand (mixed, mesic, Typic Ustipsamment) and Dwyer fine sand (mixed, mesic, Ustic Torripsamment) series (USDA, 1968). Both Valentine soils and Dwyer soils are eolian derived, occur on upland positions, and are excessively well-drained. The Dwyer soil series tends to occur on dune-like features on or near high alluvial terraces. Study site III was located on a nearly level (0 – 2% slope) field at an elevation of 1286 m. Site III was mapped as having Albinas loam (fine-loamy, mixed, superactive, mesic Pachic Argiustoll), Ascalon fine sandy loam (fine-loamy, mixed, superactive, mesic, Aridic Argiustoll), and Haxton loamy sand (fine-loamy, mixed, superactive, mesic Pachic Argiustoll) soil series (USDA, 1981). These soils are characterized as being very deep, well drained, and have accumulated carbonates in the soil solum. The Ascalon series occurs on upland positions and is formed from calcareous parent material. The Haxtun series consist of eolian deposits that overlay buried soil, occuring in drainages and depressions. The Albinas series is alluvial and occurs on fans and terraces.

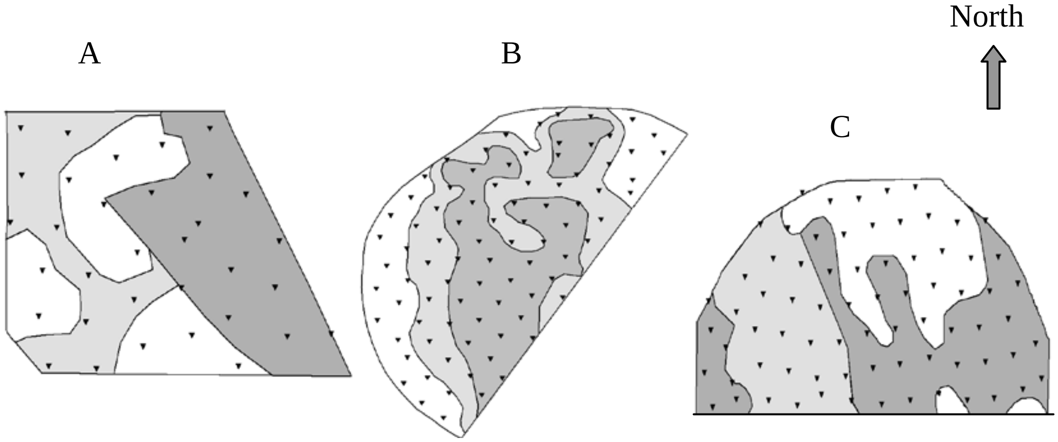

**Fig. 1. A, B, and C represents 19 ha study site I, 35 ha study site II, and 28 ha study site III respectively, showing regions of site-specific management zones and geo-referenced soil sample locations. [Low soil productivity = white; Medium soil productivity = light gray; High soil productivity = dark gray]. Fields are not to scale**

## Measurements and Soil Analyses

Selected soil physical and chemical properties that have been documented in the literature to be directly and indirectly related to productivity potential were measured in this study. Soil samples were collected prior to planting using a non-aligned systematic grid sampling strategy with a sampling density of 2.5 samples per hectare (Fig. 1). Sample positions were logged using a Trimble Ag 114 differentially corrected global positioning system unit. Soil samples were collected with a Giddings hydraulic soil sampling probe. Surface samples were taken from the top 10 cm of each soil core. Subsurface samples were taken at 30, 60, and 90 cm. Soil samples were oven dried to a constant weight. Bulk density of each sample was determined using the method of Donahue et al. (1983). Soil color was determined for both moist and dry surface samples using a Munsell color chart (Schoeneberger et al., 1998). Organic matter and organic carbon content was determined using methods described by Nelson and Sommers (1996). Soil texture was determined using the hydrometer method (Gee and Bauder, 1986). Cone indices were measured with an electronic cone penetrometer at the following soil depths: 0, 5, 10, 15, and 20-cm. Sorptivity measurements were made *in-situ* at each sample location using the method explained in Smith (1999).

Average sorptivity values were adjusted for the initial moisture content to allow comparison among the points (Shaver et al., 2001).

### Statistical Analysis

Statistical analysis was performed using SPLUS 6.1 (Insightful corp., 2001) and SAS 8.0 (SAS Institute, 2001). Moran's I and semi-variogram plots were used to test for spatial auto-correlation in the measured soil properties. Since range of the Moran's I statistic depends on the spatial weight matrix, Moran's I statistics were rescaled. When Moran's I is rescaled by its bounds the statistic is restricted to the range +/- 1 (Upton and Fingleton, 1985).

Multi-response permutation procedure (MRPP) was used to test for significant differences in soil properties between management zones (Mielke, 1991). The MRPP is a median based, distribution free procedure that relies on Euclidean distance functions and it makes use of small samples sizes (Mielke, 1991). MRPP is distribution free in the sense that probabilities of obtaining extreme test statistic values given the validity of the null hypothesis (Type I errors) are based on permutations of the data from randomization theory and are not based on an assumed population distribution (Edgington. 1987; Good, 2000; Mielke and Iyer, 1982).

## RESULTS AND DISCUSSION

### Overall Spatial Variability

Mean and coefficient of variation for selected soil properties from all study sites are presented in Table 1. Overall, the sites used in this study were high in sand content, with mean sand ranging from 550 to 860 g $kg^{-1}$. Silt was the most variable soil separate ranging from 50 to 280 g $kg^{-1}$. Mean organic carbon ranged from 5.6 to 9.5 g $kg^{-1}$, with study site I having the highest mean organic carbon content. Average bulk density was highest in study site III. In general, soil separates exhibited the highest degree of variability as compared to the other measured soil properties. Variability in soil texture is likely one of the major factors in the observed variability in productivity potential at the sites used in this study. This is not surprising because the sites used in this study were mapped, at the 1 to 24000 scale, with multiple soil series present. Using the management zone technique described herein, we can potentially detect changes in soil properties at a much finer scale than the commonly used 1:24000 scale employed by the USDA-NRCS. Hence, there is potential for more precise management of farm inputs using site-specific management.

Spatial analysis of the soils data using Moran's I, showed that the three fields had significant spatial variability in soil physical properties ($p < 0.05$). Results from Moran's I (Table 2) along with semi-variogram results (Table 3) indicate that all study sites have soil physical properties that exhibit some degree of positive spatial auto-correlation. Positive spatial auto-correlation indicates that similar attributes (i.e., areas that possess like soil properties) are grouped together spatially. It should be noted, however, that the degree to which spatial correlation

Table 1. Sample mean and coefficient of variation (CV) for selected soil properties from study sites I, II, and III.

| | | ---------------------- Soil Property | | | | | ------------------------- |
|---|---|---|---|---|---|---|---|
| Study Site | Statistic | Sand g $kg^{-1}$ | Silt g $kg^{-1}$ | Clay g $kg^{-1}$ | O.C.[‡] g $kg^{-1}$ | $\rho_b$[§] (0 cm) kg $m^{-3}$ | $\rho_b$ (30 cm) kg $m^{-3}$ |
| I | Mean | 550 | 210 | 240 | 9.5 | 1433 | 1240 |
| | CV[†] % | 16 | 24 | 18 | 15 | 13 | 11 |
| II | Mean | 860 | 50 | 90 | 5.6 | 1703 | 1431 |
| | CV % | 5 | 40 | 37 | 23 | 6 | 13 |
| III | Mean | 590 | 260 | 150 | 8.7 | 1845 | 1520 |
| | CV % | 15 | 24 | 25 | 17 | 5 | 14 |

[†] CV = Coefficient of variation

[‡] O.C. = Organic carbon

[§] $\rho_b$ = Bulk density: measurements were taken at the soil surface (0 cm) and at the 30-cm depth (30 cm).

is characterized is dependant on the sampling grid size. In this study, the spatial structure of the data was not fully realized because of the relatively coarse grid size (i.e., 2.5 samples per hectare) used while collecting soil samples. Soil properties that were found to exhibit significant spatial dependency were modeled using median polish kriging. Coefficients of determination associated with the trend suface and the krigged surface are also presented in Table 3. Spatially auto-correlated ($p < 0.05$) soil properties that were common at all study sites include: organic carbon, sand, and silt (Table 2). These soil properties have a direct impact on water holding capacity and nutrient uptake and therefore affect productivity potential.

## Variability between Management Zones

### Soil Compaction

At study sites I and III, surface bulk density was significantly different between low and high management zones, but surface bulk density was not significantly different between the low and medium, and the medium and high productivity zones. These results are consistent with those reported for site-specific management zones by Inman et al. (2005). Westfall et al. (2003) reported that such a finding is not unexpected, because the management zones are intentionally smoothed during the process of delineation in order to accommodate commercial-scale equipment. Trends observed for surface bulk density indicate that there is an inverse relationship between the high and low management zones. This is not surprising because the low zone has higher sand content and therefore higher bulk density. Al-Ghazal (2002) found surface bulk density could be increased by as much as 0.31 g $cm^{-2}$ with eight passes of a standard tractor. Sites

Table 2. Soil properties for all study sites that were found to exhibit spatial autocorrelation using Moran's I statistic. All properties listed were significant at $P < 0.05$

| ----------------------Study Site --------------------------- | | | | | |
|---|---|---|---|---|---|
| I | | II | | III | |
| -------------- Soil Property and Moran's I -------------- | | | | | |
| Moisture | 0.07 | Moisture | 0.48 | O.C. | 0.10 |
| O.C. | 0.16 | O.C. | 0.46 | Sand | 0.08 |
| Sand | 0.11 | Sand | 0.59 | Silt | 0.19 |
| Silt | 0.12 | Silt | 0.38 | $\rho_b$ (0 cm) | 0.22 |
| Clay | 0.06 | Clay | 0.62 | $\rho_b$ (30 cm) | 0.06 |
| | | $\rho_b$ (0 cm) | 0.06 | $\Phi$ (0 cm) | 0.22 |
| | | $\rho_b$ (30 cm) | 0.09 | $\Phi$ (30 cm) | 0.06 |
| | | $\Phi$ (0 cm) | 0.22 | | |

O.C. = Organic carbon
$\rho_b$ = Bulk density
$\Phi$ = Soil porosity

used in this study have been intensively managed, and therefore, these results may indicate that the soils in the low zone are more prone to compaction than those in the medium and high zones. Perhaps this could be attributed to the observed increase in organic carbon from the low to the high productivity level zone. Soil organic carbon helps to form stable aggregates that can result in relatively low bulk density (Lal and Kimble, 2001). For study site II, surface bulk density was not significantly different between zones ($p < 0.05$); however, bulk density taken at 30 cm was found to differ significantly between the low and high zones. Contrary to the trends observed for surface bulk density for sites I and III, the highest bulk density measurements taken at 30 cm for site II were found in the high productivity zone. Al-Ghazal (2002) found that in sandy soils, bulk density and infiltration rate have a strong negative relationship ($r = - 0.887$). For site II, the low zone has a lower bulk density at 30 cm and therefore a higher infiltration rate. Because the soils at site II are excessively well-drained (USDA, 1968) any reduction in infiltration rate would likely increase the plant available water in the portion of the soil solum above 30 cm.

Cone indices were also measured to determine soil compaction across management zones and were found to be significantly different between zones for study site III only. Because bulk density was a more reliable measure of soil compaction across sites (i.e., statistically significant across sites and management zones), an in-depth discussion of cone index will be excluded.

Table 3. Variogram parameters (nugget, sill, and range) and the coefficients of determination associated with the trend surface and the final krigged surface for spatially dependant soil properties for each study site ($p < 0.05$).

| Soil Property | Nugget | Sill | Range | $R^2$ (TS)[†] | $R^2$ (KS)[‡] |
|---|---|---|---|---|---|
| ---------------------------------- Study Site I ---------------------------------- | | | | | |
| Moisture | 0.00 | 0.003 | 100 | 0.25 | 0.98 |
| O.C.[§] | 0.00 | 0.024 | 200 | 0.03 | 0.89 |
| Sand | 8.26 | 84.20 | 123 | 0.07 | 0.98 |
| Silt | 1.67 | 26.13 | 112 | 0.11 | 0.99 |
| Clay | 3.11 | 20.17 | 124 | 0.03 | 0.96 |
| ---------------------------------- Study Site II ---------------------------------- | | | | | |
| Moisture | 0.00 | 0.002 | 200 | 0.62 | 0.89 |
| O.C. | 0.00 | 17.38 | 200 | 0.51 | 0.86 |
| Sand | 2.32 | 4.057 | 165 | 0.61 | 0.95 |
| Silt | 0.06 | 9.210 | 131 | 0.48 | 0.99 |
| Clay | 2.11 | 9754 | 161 | 0.59 | 0.92 |
| $P_b$ (0 cm)[¶] | 0.00 | 58194 | 75 | 0.18 | 0.99 |
| $P_b$ (30 cm)[#] | 0.00 | 0.009 | 79 | 0.15 | 0.97 |
| $\Phi$ (30 cm)[††] | 0.00 | | 100 | 0.15 | 0.97 |
| ---------------------------------- Study Site III ---------------------------------- | | | | | |
| O.C. | 0.01 | 0.021 | 100 | 0.09 | 0.99 |
| Sand | 0.51 | 75.59 | 97 | 0.20 | 0.99 |
| Silt | 0.02 | 35.84 | 107 | 0.37 | 0.99 |
| $P_b$ (0 cm) | 0.00 | 11064 | 79 | 0.10 | 0.99 |
| $P_b$ (30 cm) | 74.70 | 94826 | 77 | 0.06 | 0.99 |
| $\Phi$ (0 cm)[‡‡] | 0.00 | 0.005 | 200 | 0.16 | 0.71 |
| $\Phi$ (30 cm) | 0.00 | 0.014 | 77 | 0.06 | 0.99 |

[†] $R^2$ (TS) = coefficient of determination associated with the median polish (trend) surface.

[‡] $R^2$ (KS) = coefficient of determination associated with the median polish krigged surface (trend + kriged).

[§] O.C. = organic carbon.

[¶] $P_b$ (0 cm) = bulk density measured at the soil surface.

[#] $P_b$ (30 cm) = bulk density measured at the 30-cm soil depth.

[††] $\Phi$ (30 cm) = soil porosity measured at the 30-cm soil depth.

[‡‡] $\Phi$ (0 cm) = porosity measured at the soil surface.

## Soil Organic Carbon

Soil organic carbon was significantly different between management zones for all study sites. This was expected because the management zone delineation technique used in this study relies on bare-soil imagery, the tone of which is directly affected by organic carbon. At study site I and II, the high and low productivity management zones were significantly different with respect to organic carbon. Organic carbon concentration was significantly different among all three zones at study site III. The differences observed for organic carbon between management zones affects the availability of water to the crop. Since the fields used in this study contain soils that are well to excessively well drained, the availability of water is a key factor in nutrient uptake and therefore productivity potential.

There was an inverse relationship between surface bulk density and organic carbon content for study sites I and III. Higher organic carbon content likely contributed to increased soil aggregation and therefore increased soil aggregate stability in the high productivity zone. Increased organic carbon would also raise the CEC of the soil relative to the other management zones and improve the water holding capacity (Lal and Kimble, 2001).

## Soil Texture

Silt content was found to be significantly different between management zones at all study sites. Again, from Table 1, silt was the most variable soil property measured. Silt content increased from the low to the high zone. Sand content was also found to be significantly different between management zones at study sites I and III. As expected, sand content increased from the high to the low productivity level zone. At sites I and II, silt was not significantly different between the high and medium management zones. However, both the medium and high zones were significantly different from the low zone. At study site III, silt was found to differ significantly between the low and high and between the medium and high zones. Sand was found to differ significantly between the low and high zones, with the low zone having more sand than the high zone. At study site III, the high zone was found to have significantly more clay than the low productivity zone. The spatial variability observed for soil texture reflects the changes in soil map units. At study site I for example, soils ranged from coarse loamy entisols to fine-smectic mollisols. Such changes in soil map units will have pronounced affects on productivity potential.

The increase in silt content from low to high productivity zones, coupled with the increase in organic carbon, could help explain the differences in productivity potential of the management zones. More organic carbon, silt and/or clay and less sand, would increase productivity potential because such zones would have higher CEC and better capability to retain moisture and nutrients. Soil texture is likely one of the major contributors to the differences in productivity potential of the management zones.

## Sorptivity

Sorptivity was significantly different among management zones at study site III. However, the 25th percentile was highest in the medium productivity zone and not in the high productivity zone, as it would be expected because of the textural differences. In addition, sorptivity was significantly different between the low and medium, but not between the low and high productivity management zones. The low and high productivity zones would be expected to be more separable than the low and medium zones if the trend in sorptivity corresponded to that in the productivity of the zones. Overall, sorptivity values were high and therefore were not a factor affecting productivity potential. The observed difference in productivity as delineated by management zones, therefore, could not be attributed to the spatial variation of sorptivity.

### Surface Soil Water Content

Water content increased significantly from the low to the medium, and also from the medium to high productivity management zone at study site III. This trend could be attributed to the corresponding increase in organic carbon, silt, and clay content at this study site. Mulla and Bhatti (1997) also reported a significant increase in profile available water content from the low to the medium, and from the medium to the high organic matter management zones.

## CONCLUSIONS

In this study, soil physical properties were shown to exhibit significant positive spatial auto-correlation across continuous corn irrigated production fields. Surface plots revealed that the spatial variability for the soil properties exhibited salient patterns within the fields. Site-specific management zones were shown to differ significantly with regard to some of the measured soil physical properties. Overall, the low management zone was consistently separable from the high management zone based on bulk density, organic carbon, sand, silt, porosity, and soil moisture. Soil properties that were significantly different between management zones ultimately affected the available water and therefore the nutrient uptake within each zone. In general, the trends observed for the soil properties followed the productivity potential of the management zones. An overall goal of precision farming is to manage inherent in-field variability in the most cost-effective and efficient manner. Using site-specific management zones, low productivity potential areas can be reliably separated from the high productivity potential areas thus allowing for differential management of highly variable crop production fields.

## REFERENCES

Al-Ghazal, A.A. 2002. Effect of tractor wheel compaction on bulk density and infiltration rate of a loamy sand soil in Saudi Arabia. Emir. J. Agric. Sci. 14: 24- 33.

Chung, S.O., J.H. Sung, K.A. Sudduth, S.T. Drummond and B.K. Hyun. 2000. Spatial variability of yield, chlorophyll content, and soil properties in a Korean rice paddy field. In: Proc. 5th International Conf. On Precision Agriculture. Robert, Rust and Larson (Eds.), ASA, CSSA, Madison, WI, (CD-rom).

Doerge, T.A. 1999. Management Zone Concepts [Online]. Available at http://www.ppi-far.org/ssmg (verified 1 Feb. 2004).

Donahue, R.L., R.W. Miller, and J.C. Shickluna. 1983. Soils: An introduction to soils and plant growth. 5th ed. Prentice-Hall Inc. New Jersey.

Edgington, E.S. 1987. Randomization tests.Marcel Dekker, Inc., New York. 341pp.

Fleming, K.L., D.G. Westfall, D.W. Wiens, L.E. Rothe, J.E. Cipra, and D.F. Heermann. 1999. Evaluating farmer developed management zone maps for precision farming. p.335-343. *In*: P.C. Robert, R.H. Rust, and W.E. Larson (eds) Precision Agriculture. Proceedings of the 4th Intl. Conf., ASA, CSSA, and SSSA, Madison, W.I.

Fleming, K.L., D. F. Heermann, and D. G. Westfall. 2004. Evaluating soil color with farmer input and apparent soil electrical conductivity for management zone delineation. Agron. J. 2004 96: 1581-1587.

Fleming, K.L., D.G. Westfall, D.W. Weins, and M. Brodhall. 2000. Evaluating farmer defined management zone maps for variable rate fertilizer application. Precision Agriculture 2:201-215.

Fraisse, C.W., K.A. Sudduth, N.R. Kitchen, and J.J. Fridgen. 1999. Use of unsupervised clustering algorithms for delineating within-field management zones. ASAE Paper No. 993043. International Meeting, Toronto, Ontario, Canada. July 18-21.

Fulton, J.P., L.G. Wells, S.A. Shearer, and R.I. Barnhisel. 1996. Spatial variation of soil physical properties: A precursor to precision tillage. ASAE Paper No. 961002. International Meeting, Phoenix, Arizona. July 14-18.

Gaston, L.A., M.A. Locke, R.M. Zablotowicz, and K.N. Reddy. 2001. Spatial variability of soil properties and weed populations in the Mississippi delta. Soil Sci. Soc. Am. J. 65:449-459.

Gee, G.W. and J.W. Bauder. 1986. Particle size analysis. p. 404-408. *In* Arnold Klute (ed.) Methods of soil analysis. Part I. ASA, Madison, WI.

Goddard, T. and R. Grant. 2001. Landscape management of agronomic processes for site-specific farming [Online]. Available at http://www.ppi far.org/far/farguide.nsf (verified 20 February 2002).

Good, P. 2000. Permutation tests: A practical guide to resampling methods for testing hypotheses. 2nd edition.Springer. 270pp.

Inman, D.J., R.Khosla, and D.G. Westfall. 2005. Nitrogen uptake across site specific management zones in irrigated corn production systems. Agron. J. 97. 169 – 176.

Insightful Corporation. 2001. S-Plus 6.1. Insightful Corporation, Seattle, WA.

Jenny, H. 1941. Factors of soil formation. McGraw-Hill. New York, New York.

Khosla, R., K. Fleming, J.A. Delgado, T. Shaver, and D.G. Westfall. 2002. Use of site-specific management zones to improve nitrogen management for precision agriculture. J.Soil and Water Conserv. 57(6):513-518.

Koch. B., R. Khosla, M. Frasier, D.G. Westfall, and D. Inman. 2004. Economic feasibility of variable rate nitrogen application utilizing site-specific management zones. Agron. J. 96: 1572 - 1580.

Lal, R. and J.M. Kimble. 2001. Importance of soil bulk density and methods of its measurement. p. 31-44. *In* R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart (ed.) Assessment methods for soil carbon. Lewis Publishers, Boca Raton, London, New York, Washington, D.C.

Mielke, P.W. and H.K. Iyer. 1982. Permutation techniques for analyzing multi response data from randomized block experiments. Commun. Statist. –Theory Meth. 11:1427- 1437.

Mielke, P.W., Jr. 1991. The application of multivariate permutation methods based on distance functions in the earth sciences. Earth-Science Reviews 31:55-71.

Mulla, D.J. and A.U. Bhatti. 1997. An evaluation of indicator properties affecting spatial patterns in N and P requirements for winter wheat yield. p. 145-153. *In* J.V. Stafford (ed.) Precision Agriculture. Vol. 1: Spatial Variability in Soil and Crop. BIOS Scientific Publishers Limited.

Nelson, D.W., and L.E. Sommers.1996. Total carbon, organic carbon, and organic matter. Chapter 34. Pp 961-1010. In Methods of soil analysis. Part 3. Chemical methods. D.L. Sparks, Ed. SSSA Book Series No. 5. Soil Science Society of America , Inc., American Society of Agronomy, Inc.

Rockström, J., J. Barron, J. Brouwer, S. Galle, and A de Rouw. 1999. On-farm spatial and temporal variability of soil and water in pearl millet cultivation. Soil Sci. Soc. Am. J. 63:1308-1319.

SAS Institute. 2001. Statistical Analysis Software Version 8. SAS Institute, Cary, NC. USA.

Schoeneberger, P.J., D.A. Wysocki, E.C. Benham, and W.D. Broderson. 1998. Field book for describing and sampling soils. Natural Resources Conservation Service, USDA, National Soil Survey Center, Lincoln, NE.

Shaver, T.M., G.A. Peterson, L.R. Ahuja, D.G. Westfall, L.A. Sherrod, and G. Dunn. 2001. Surface soil physical properties after 12 years of dryland no-till management. Soil Sci Soc Am J. 66:1296-1306.

Smith, R.E. 1999. Technical Note: Rapid measurement of soil sorptivity. Soil Sci. Soc. Am. J. 63:55-57.

Upton, G.J.G. and B. Fingleton. 1985. Spatial data analysis by example: Vol. 1, Point pattern and quantification data. John Wiley and Sons, New York, New York, USA. 409p.

USDA. 1968. Soil Survey of Morgan County, Colorado. USDA Soil Conservation Service.

USDA. 1980. Soil Survey of Weld County, Colorado, Southern Part. USDA Soil Conservation Service.

USDA. 1981. Soil Survey of Yuma County, Colorado. USDA Soil Conservation Service.

Wells, L.G., S.A. Shearer, J.P. Fulton, and L.W. Murdock. 2000. Assessment of remote sensing for implementation of precision tillage. ASAE Paper No. 001084. International Meeting, Milwaukee, Wisconsin. July 9-12.

Westfall, D.G., W.J. Gangloff, R. Khosla, R.M. Reich, A. Hornung, D.F. Heermann, H.J. Farahani, and K. Fleming. 2003. Development of production level management zones for nitrogen fertilization. p 141-142. *In*: Werner, A. and A. Jarfe (eds) Program book of the joint conference of ECPA-ECPLF. Wageningen Academic Publishers, The Netherlands.