THESIS

THE RELATIONSHIP BETWEEN MEASURED SOIL PROPERTIES, SITE-SPECIFIC MANAGEMENT ZONES, AND BARE SOIL REFLECTANCE: COLORADO, USA

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY MONGA MZUKU ENTITLED THE RELATIONSHIP BETWEEN MEASURED SOIL PROPERTIES, SITE-SPECIFIC MANAGEMENT ZONES, AND BARE SOIL REFLECTANCE BE ACCEPTED AS FULFILLING, IN PART, REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT

THE RELATIONSHIP BETWEEN MEASURED SOIL PROPERTIES, PRECISION FARMING MANAGEMENT ZONES, AND BARE SOIL REFLECTANCE

Soil productivity varies across farm fields and it is influenced by soil physical and chemical properties. Bare soil imagery can be used to delineate areas of homogeneous soil characteristics, based on variations in reflectance. The objectives of this study were to: (i) evaluate site-specific management zones on the basis of spatial variability in measured soil properties, and (ii) determine the measured soil properties whose variability could be best explained by remotely sensed bare soil reflectance data. The study was conducted on three irrigated fields near Greeley, Wiggins and Yuma in northeastern Colorado, U.S.A. Each field had previously been sub-divided into three management zones corresponding to areas of high, medium and low levels of productivity. Each field was divided into grid cells of 0.4 ha each, with one sample point per cell. The soil properties measured were bulk density, cone index, surface color, organic carbon, texture, total pore space, sorptivity; and surface water content. Surface bulk density and sand content were inversely related to the productivity level of the management zones at study sites I (Greeley) and II (Wiggins). At these study sites, organic carbon and silt content were directly related to the productivity level of the zones. At study site II, clay content and cone index at the 20 cm depth had a direct and indirect relationship, respectively, with the productivity level of the zones. The amount of variability of soil properties that was explained by the appropriate spectral bands ranged from 35 to 55% at site I (Greeley), 13 to 73% at site II (Wiggins), and 10 to 52% at site III (Yuma). In the test involving both zones and wavelength bands, some soil properties were related to either zones or bands only, while others were related to both bands and zones. The amount of variability of soil properties explained by either zones or bands, or a combination of both, ranged from 11 to 77% in Wiggins and 17 to 56% in Yuma. The variation in some of the measured soil properties explained the variable productivity of the management zones. The variation of some soil properties across a field can be explained by the variability in reflectance observed on bare soil imagery.

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CHAPTER 1

INTRODUCTION

Precision farming overview

Precision or site-specific farming is about managing farm-field variability by applying inputs in accordance with the specific requirements of a location (Fraisse et al., 1999). It has the potential to improve crop production and protect the environment by matching inputs with crop requirements at the sub-field level (Goddard and Grant, 2001). Morgan and Ess (1997) stated that farmers adopt precision farming in response to the variability in soil and crop characteristics that within their fields. According to Fulton et al. (1996), there are variations of soil physical properties, nutrient levels, and water content between and within fields. Therefore, effective site-specific management can be achieved by first understanding the spatial distribution of the limiting soil properties in a crop field. One of the goals of site-specific farming is to determine the factors that contribute to the variation in productivity within a soil landscape (Goddard and Grant, 2001). The main sources of the variation were summarized as (Steven and Miller, 1997):

(1) Soil related factors such as structure and type, nutrient availability and compaction;

(2) Agronomic variables, such as crop disease, plant emergence and seed rates; and

(3) Others, for example, drainage.

This research was part of a study on precision farming on three irrigated fields in the Western Great Plains region of Colorado, USA. The farms are near Greeley, Wiggins, and Yuma. The main purpose of the study was to develop environmentally safe and economically viable methods of managing the inherent spatial variability that exists in farm fields (Khosla et al., 2000). The emphasis was on site-specific management of crop production inputs such as fertilizer, so that they could be applied in varying amounts across a field to match soil productivity and crop requirements.

Management zones

Doerge (1999) defined a precision-farming management zone as a sub-region of a field that expresses a functionally homogeneous combination of yield-limiting factors for which a single rate of a specific crop input is appropriate. Therefore, management zones are delineated in order to classify the spatial variability within a field. The task of determining these homogeneous sub-field areas is difficult because of the complex combination of potential yield-limiting factors (Fraisse et al., 1999; Fridgen et al., 2000). Doerge (1999) suggested that when management zones are delineated, the inclusion of factors that have direct effects on crop yield could result in relatively accurate variable rate application maps. He also stated that surrogate data, such as soil color, need to be correlated with factors that directly affect crop yield in order to make more accurate management zone delineations. Some site-specific characteristics, such as soil color and other soil physical properties, which are directly measurable and stable over time, would be reliable ways to define management zones if these properties are related to crop yields (Doerge, 1999). Typical spatial data that can be used to initially develop a management zone strategy include grower knowledge, bare soil photographs, first order soil survey maps, field topography and electrical conductivity (Doerge, 1999). The management zones can later be modified over time by adding information that further describes the pattern of yield variation within a field (Doerge, 1999).

Several strategies based on site characteristics have been suggested for the delineation of management zones. According to Bell et al. (1995) cited in Fraisse et al. (1999), three basic approaches have been used. They are

1. The use of county (order 2) soil surveys prepared by the National Cooperative Soil Survey program at scales ranging from 1:12,000 to 1:24,000. Order 1 surveys at the scale of approximately 1:5,000 have also been used. However, they stated that these traditional soil surveys are normally too coarse for the delineation of zones for site-specific management.
2. The use of geostatistical interpolation techniques to estimate the spatial distribution of soil properties from a network of point measurements.
3. The use of temporally-stable land and soil properties such as soil electrical conductivity and landscape position.

Fridgen et al. (2000) applied unsupervised continuous classification of soil electrical conductivity (E.C.), elevation and slope data for delineating management zones in two fields. They stated that fuzzy or continuous classification procedures were more appropriate than crisp classification, because the continuous nature of soils data does not provide for sharply defined boundaries. Continuous classification allows individual data points to have partial class membership instead of assigning one observation to exactly one class. Table 1.1 shows the different categories of characteristics that can be used to develop variable-rate input strategies.

In this study, each field was sub-divided into three management zones, corresponding to areas of high, medium and low productivity. Each management zone defined a homogeneous area that required the same amount of fertilizer input, but it differed from the other zones. According to Khosla et al. (2000), one objective of the study was to develop and compare four approaches of defining management zones within a field. These approaches were listed as:

1. Management zones developed using soil color from bare soil imagery, topography, and farmer's knowledge of the variability in production within a field. Management zones delineated in this way would be evaluated in order to develop variable rate fertilizer maps for nitrogen application.
2. Management zones developed using soil organic matter, cation exchange capacity, soil texture, yield monitor map of the previous year, soil color from bare soil imagery, and topography. Therefore, this approach is aimed at adding more layers to those listed in the first approach. Khosla et al. (2000) suggested that this would help to delineate more precise management zones for long-term use and crop management.
3. Management zones developed from soil electrical conductivity (EC). Khosla et al. (2000) reported that soil EC data collected over two years might be a good surrogate measure of soil texture, organic matter and cation exchange capacity. They also stated that electrical conductivity could serve as the best data layer in explaining spatial variability in crop yield.
4. Development of management zones using multivariate statistics and spatial statistics with a non-grid based soil sampling design.

Table 1.1 Crop inputs that are commonly applied using variable rates and the site characteristics often used to define management zone strategies for these inputs.

Crop inputs	*Management zone factors to use*
Immobile nutrients (P and K)	Topography/landscape, grid or targeted soil test data, bare soil photo, soil survey maps, soil E.C. map
N and manure	Soil texture, organic matter, yield zones, bare soil photo, soil nitrate-N (NO_3-N), crop canopy reflectance
Lime	Soil pH, buffer pH, soil texture
Gypsum	Grower knowledge, yield patterns, E.C. map, soil tests for pH and sodium (Na)
Seeding rate	Historical yield levels, top soil depth
Hybrid or variety	Topography, yield patterns, grower knowledge, aerial photos for chlorosis, bare soil photo, geo-referenced pest samples (e.g. soybean cyst nematode, Phytophthora root rot, corn rootworm)
Herbicides	Weed maps or visualization, soil organic matter, soil texture
Pesticides	Soil properties, geo-referenced soil samples and scouting reports
Water	Soil texture, topography, soil organic matter, yield zones

Source: Doerge (1999)

At the beginning of this thesis research project, management zones had been delineated in each of the three fields using the first approach (i.e. bare soil imagery, topography, and farmer's input). The variability in bare soil reflectance, and that observed by the farmer, may be a reflection of the non-uniform distribution of certain soil properties that influence land productivity. Changes in topography may also result in variation in the distribution of a given soil property across the field. Therefore, in order for the variability to be managed effectively, the soil properties that cause it should be understood. For example, if the soil in a low productivity level management zone is found to be relatively prone to compaction, farming practices that increase compaction may be reduced or eliminated from that management zone.

Scope and objectives

The purpose of this thesis project was to determine whether the variability defined by management zones could be explained by, or associated with, any variable distribution of certain soil properties across each field. If a soil property is found to influence the variability in land productivity, appropriate management practices can be recommended to reduce the impact of that property in lower productivity areas. In addition, it could be possible to determine the soil properties that are mainly expressed by the variability of reflectance that was observed on bare soil imagery. This would make it possible for farmers and scientists to select those soil properties that can be measured and used to delineate management zones. An investigation of possible yield-limiting soil properties in precision farming environments where management zones were delineated from bare soil imagery, could also focus on the soil properties selected in this thesis project. The soil properties examined were

1. Bulk density
2. Cone penetration resistance
3. Surface color
4. Organic carbon
5. Texture
6. Total porosity
7. Sorptivity
8. Water content

The objectives of this thesis project were

1. To evaluate site-specific management zones on the basis of spatial variability in measured soil properties.
2. To determine the measured soil properties whose variability could be best explained by remotely sensed bare soil reflectance data.

CHAPTER 2

LITERATURE REVIEW

Spatial variability of soil properties and productivity

The overall productivity of agricultural soils is related to both the physical and chemical properties of a soil (Hillel, 1980). Therefore, it would be expected that soil productivity would vary in space and in correspondence with the spatial variation of certain soil properties.

Wallace et al. (1994), cited by Rockström et al. (1999), reported a range of 0 to 2,885 kg/ha for millet grain yield in a 1 ha field in Niger. Rockström (1999) stated that some of the factors suspected to be responsible for this yield variability were water and nutrient availability. Goddard and Grant (2001) carried out research in a field that had rolling topography, in the black soil zone of east-central Alberta, Canada. The purpose of their project was to investigate how landscape variability influenced soil properties and processes that affect the soil's release of nitrogen (N), phosphorus (P), potassium (K), and sulfur (S), as well as crop responses to these nutrients. Crop yields in kg/ha across the field ranged from 1,000 to 6,700 for wheat (1997); 1,000 to 6,700 for barley (1998); 1,000 to 4,030 for canola (1999) and 670 to 8,060 for wheat (2000). In all these years, they found that the highest yields were from the lower slope positions, and the lowest yields from the upper slope positions. The wetter footslope positions yielded high crop biomass, and the crop nutrient uptake levels were high, compared to the shoulder and backslope positions.

Chung et al. (n.d.) conducted research with one objective being to determine the within-field variability of rice yield, chlorophyll content, and soil properties in a 100 x 30 m typical Korean rice paddy field. The soil properties were pH, electrical conductivity (EC), organic matter (OM), K, N, calcium (Ca), magnesium (Mg), sodium (Na), P_2O_5, and SiO_2. Descriptive statistics showed that the maximum values for rice yield, EC, Ca, K, Mg, Na, and SiO_2, were more than double the minimum value. This spatial variability was observed despite the flat nature and relatively small size of the rice paddy field. Chung et al. (n.d.) also cited Iida et al. (1999) as having found rice yield variations of almost 2:1 in a 0.5 ha paddy field in Japan. In addition, Chung et al. (n.d.) reported that the mean values in the study field were lower than the optimal range for all soil properties, except EC and N,. Some proportions of the field were also found to have lower than optimal values for all soil properties except N. The researchers concluded that variability in soil properties was potentially of agronomic importance.

According to Kitchen et al. (n.d.), spatial crop productivity by yield monitoring and mapping is one way of determining soil variability. However, they argued that the yield map is confounded by various potential causes of yield variability. Therefore, it would be better to use these maps together with spatial measurements of other potential yield-limiting factors, to identify the influence of soil and landscape properties on crop production. They gave examples of yield-limiting factors as pest incidence and nutrients.

Other possible factors may include fertile soils that are relatively prone to compaction and waterlogging. For example, Colvin et al. (1997) and Sudduth et al. (1977) cited in Kitchen et al. (n.d.) pointed out that high producing areas of a field during “dry” years can be low producing areas of the same field in “wet” years. Therefore, various land and soil properties need to be examined and understood as potential yield-limiting factors.

Kitchen et al. (n.d.) carried out research to evaluate order 1 (1:5 000 scale) and order 2 (1:25 000 scale) soil surveys that were conducted by the USDA Natural Resources Conservation Service, together with a quantitative method using topsoil depth and elevation (TD/ELE). The purpose was to determine the method that best identified sub-field areas that behaved similarly from year to year. They found that variation in grain yield was poorly explained ($R^2 \leq 0.11$) by all management zone methods during years of adequate or excessive rainfall. In years of low precipitation and crop water stress (1994 and 1997), they found that more variation was attributed to management zones ($R^2 \leq 0.30$). They also found that soil mapping units identified with the order 1 soil surveys were the best at delineating potential management zones The quantitative method performed approximately equal to the order 2 soil survey. However, Kitchen et al. (n.d.) also concluded that the TD/ELE method has the advantage of being repeatable, because unlike traditional soil surveys, it involves quantified and geo-referenced data. According to Mount (2001), order 2 soil surveys (1:12 000 to 1:31 680 scale) were not developed for site-specific management. Mount (2001) also stated that earlier research to evaluate the use of soil surveys to identify nutrient management zones produced mixed results because:

(a) Soil surveys do not predict the temporal variability of nutrient concentrations, and

(b) Soil surveys do not measure prior management, such as old building sites, manure applications, and the way the field was cropped, which influences nutrient concentrations. It can, therefore, be suggested that when soil surveys are used to identify productivity level management zones, the incorporation of information concerning prior management can help to improve the accuracy of the exercise.

Wells et al. (2000) took penetrometer measurements at 15 sample points at different depths within each 0.4 ha grid cell in an experimental field. They found that the maximum average cone index values in each grid cell ranged from 1.07 to 1.97 megapascals (MPa) across the field, with the field average being 1.51 MPa. The occurrence of these maxima at depths ranging from 7 to 45 cm showed that deep tillage might need to be applied at variable depths, as well as at different places across a field. According to Fulton et al. (1996), there is a need for farmers to measure soil physical properties, such as bulk density and soil strength, in order to determine the spatial variation of compaction. Site-specific tillage would offer a potential means of increasing crop yield and maximizing tillage costs. Fulton et al. (1996) found that soil bulk density and cone index, which are both indicators of compaction, varied over a 7 ha field. However, they also concluded that on the basis of bulk density values, there was no need for deep tillage, but cone index values showed a need for precision deep tillage. Their conclusions were based on the critical values of 1.6 Mg/m^3 and 2 MPa for bulk density and cone index, respectively.

Stochastic factors, such as weather, often have a greater impact on yield variability than variations in soil productivity (National Research Council (NRC), 1997). They cited a study by Cook et al. (1996) that compared variable rate and uniform application of superphosphate on narrow leaf lupine. The results showed that variable rate application based on nutrient response curves estimated using data from a single year performed poorly. This was because the estimated nutrient response function did not adequately consider the variability in weather conditions (Cook et al., 1996 cited in NRC, 1997). Other studies have also shown low correlation between yield and applied fertilizer when weather conditions and other important factors were not included in nutrient response modeling (Huggins and Alderfer, 1995 cited in NRC, 1997). Therefore, the success of sub-field management can be improved by using techniques that encompass the simultaneous effects of the most important factors influencing yield, rather than individual factors taken in isolation (NRC, 1997). They gave an example of variable-rate application strategies based on nutrient response curves that incorporate soil characteristics, weather conditions, and other factors, in addition to applied fertilizer. Steven and Miller (1997) stated that while weather is important in determining the growth and development of plants, it is not in itself variable to any appreciable extent within a field. They also noted that it is important, however, in modulating the responses to other factors that do vary within fields. These arguments imply that data on different factors that influence crop production need to be collected and used together, to improve sub-field management.

Mulla and Bhatti (1997) investigated the use of surrogate soil properties that could be estimated from remotely sensed images or measured crop and soil properties, to develop management zones for precision agriculture. They used data on soil test nutrient levels and yield goals at 172 locations, in a wheat farm to estimate N and P fertilizer requirements for each sampled location. The estimates for fertilizer requirements were compared with requirements estimated from mean properties in zones delineated by patterns in crop yield and soil surface OM content. The criteria of crop yield and organic matter were both acceptable indicators of spatial patterns in nutrient requirements and soil fertility (Mulla and Bhatti, 1997). The variability in crop yield was a particularly sensitive indicator of spatial patterns in N fertilizer requirements, but was insensitive to variations in P requirements (Mulla and Bhatti, 1997). In contrast, the variability in surface OM content was moderately sensitive to variations in N fertilizer requirements, and highly sensitive to variations in P fertilizer requirements. Low, medium, and high yielding zones generally corresponded to top, middle, and bottom slope landscape positions, respectively. Yields in the low, medium, and high zones averaged 3,166, 4,018, and 4,904 kg/ha, respectively. Measured profile available water content, OM content, and soil pH were significantly different among zones. They used patterns in measured surface soil OM to delineate zones having low (<1.5 %), medium (1.5 – 2.4 %), and high (> 2.4 %) OM content. The low, medium and high OM zones corresponded to top, middle, and bottom slope landscape positions, respectively. Measured grain yields in the low, medium, and high OM zones averaged 3,443, 3,993, and 4,742 kg/ha, respectively. Profile available water content and available P increased significantly from the low to the medium, and from the medium to the high OM management zones (Mulla and Bhatti,1977).

The spatial distribution of certain soil properties can influence the variation in intensity of occurrence of other yield-limiting factors across a field. The spatial distribution of weeds depends, among others, on spatially variable safe sites, which are related to heterogeneity in soil chemical and physical properties (Gaston et al., 2001). In a field in Mississippi, they found that the density of total weeds where clay was greater than 30% was significantly greater than where clay was less than 30%. They also reported significantly higher density of weeds where soil organic carbon (OC) content was greater than 1.6% than where OC content was lower. Gatson et al. (2001) suggested that the basis for the relationship between weeds and clay content was that more available water content and higher fertility are associated with finer, rather than coarser, textured soils. Therefore, soil chemical and physical properties can directly or indirectly influence the spatial variability in soil productivity and yields.

Soil compaction

Rooney et al. (2001) defined soil compaction as an increase of the natural density of soil at a particular depth. It reduces macroporosity, resulting in decreased water intake by plants and restricted gas movement in the soil (Flocker et al., 1959 cited by Nelson et al., 1975). Moreover, according to Nelson et al. (1975), roots cannot grow into openings smaller than the root diameter. Morris (1975), cited by Fulton et al. (1996), reported corn yield reductions of 10 to 22 % due to compaction. Plaster (1997) stated that compaction occurs when pressure is applied to the soil surface, and this, according to Fulton et al. (1996) and Wells et al. (2001), can be caused by machinery traffic and may result in reduced crop productivity and yield. Deep compaction can be caused by harvest and transport equipment that exert loads up to 40 tons per axle (Plaster, 1997). He also stated that a compacted zone referred to as a plow pan can develop just below the plow layer, and restrict root growth and drainage of water deep into the soil. Nelson et al. (1975) pointed out that most agricultural tractors in the United States are heavy enough to reduce the infiltration of loose soil in one trip. Weaver and Jamison (1950), cited by Nelson et al. (1975), observed that with a draft of 533 kg per wheel of a tractor, a Davidson loam soil was compacted to a bulk density of 1,800 kg/m^3 by four passes when the soil was at a moisture content of 11.4 %. Marshall et al. (1996) suggested that pressures of about 100 kPa by machinery can cause compaction in surface soil horizons under intensive agriculture. They stated that this is because surface horizons usually have a relatively small bulk density because of disturbances such as those caused by tillage. Gray and Pope (1986) used a 5,363 kg tractor with 47.5 cm wide rear tires to compact a Drummer silty clay loam in Illinois. They were investigating the effect of soil compaction on soybean [*Glycine max* (L.) Merr.] stand establishment and Phytophthora root rot incidence. They found that soil bulk density was increased significantly by tractor compaction, at the depth of 2.5 to 12.7 cm. They also used a light tandem disk-harrow to disk the plots to a depth of 6.5 cm, so that the seeds were planted in seedbeds underlain by compacted soil. Results showed reduced stands of soybean in the compacted plots due to Phytophthora root rot. This shows that compaction can reduce yields by influencing other yield-related factors.

According to Fulton et al. (1996), compaction varies within fields, and therefore, farmers need to assess this variability through measurements of appropriate soil physical properties. They contended that if compaction is measured and mapped, farmers can be able to specify tillage only in areas of the fields where crop yields could be adversely affected. Soil strength, as determined from cone index measurements, and bulk density are two physical properties that are used to quantify soil compaction (Fulton et al. 1996). According to Plaster (1997), bulk density is a more precise indicator of compaction than cone indices measured with a cone penetrometer.

Bulk density

Soil bulk density is the mass of a volume of undisturbed oven-dry soil (Plaster, 1997), and can be used to estimate differences in compaction of a soil as a result of farm operations (Donahue et al., 1983). Soane (1975) cited by Hillel (1980) pointed out that some 90% of the soil surface may be traversed by tractor wheels during traditional seedbed preparation, followed by a further trampling of at least 25% during harvest with a combine. He indicated that the resultant compaction can increase bulk density to a depth of at least 30 cm.

According to Donahue et al. (1983), the average bulk density of a cultivated loam soil is approximately 1.1 to 1.4 Mg/m^3. They suggested that bulk densities of below about 1.4 Mg/m^3 for clays and 1.6 Mg/m^3 for sands are suitable for good plant growth. As a general rule, it has been suggested that bulk densities of 1.55, 1.65, 1.80, and 1.85 Mg/m^3 can impede root growth and reduce crop yields on clay loams, silt loams, fine sandy loams, and loamy fine sands, respectively (Bowen, 1981 cited by Fulton et al., 1996). A bulk density less than or equal to 1.3 Mg/m^3 has been proposed as non-limiting to crop growth in any soil (Singh et al., 1976, cited by Fulton et al., 1996).

Cone index

Cone index is the applied force required to press the cone penetrometer into a soil, and it is an index of the shear resistance of the soil (Black et al., 1965). It has been referred to as a measure of soil strength as measured with a penetrometer, with soil strength being an indicator of how easily roots can penetrate soil (Fulton et al., 1996). The limiting penetrometer resistance depends upon the soil conditions and characteristics, and the crop of interest (Fulton et al., 1996). Although precise cone index levels which limit plant growth for specific soil types have been rarely documented, a penetrometer measurement of 2 MPa is generally regarded as sufficient to hinder the growth and development of crops (Fulton et al., 1996). From cone penetrometer measurements at different depths on a Maury silt-loam soil, Fulton et al. (1996) observed that site-specific tillage could be feasible and economically viable. Based on a critical cone index value of 2 MPa, they concluded that precision deep tillage could reduce fuel consumption by 50%, compared to sub-soiling the entire 7.1 ha field.

Soil color

Although soil colors have little effect on the behavior and use of soils, they provide clues to the nature of other soil properties and conditions (Brady and Weil, 2002). A change in soil color from the adjacent soils may indicate a difference in the soil's parent material or in soil development (Donahue et al., 1983). Robinson and McCaughey (1911) stated that soil color may indicate the presence of a component that has benefit to the plant, for example, potash in light-colored clayey soils. The three factors that have the greatest influence on the color of a soil are organic matter content, soil water content, and the presence and oxidation states of iron and manganese oxides (Brady and Weil, 2002) An increase in soil organic matter usually results in a darker soil color (Plaster, 1997; Donahue et al., 1983; Brady and Weil, 2002). Moist soils are generally darker in color than dry ones, and red or brown colors of well-drained uplands suggest the presence of oxidized iron oxides (Brady and Weil, 2002). It can be argued that soils that retain more moisture and remain darker for a longer period of time could be more productive than those that lose water and become lighter sooner. This would be partly because the former soils can retain and release water to plants for a relatively long time after the supply of water stops. However, this comparison would be appropriate if both soils come from the same parent material and are located relatively close to each other. The ability for a soil to store moisture for a longer time could be important in rainfed agriculture or when there is a uniform irrigation schedule for the whole field. A uniform irrigation schedule would be designed without due consideration for the within-field spatial variability of the water-holding capacity of the soil. According to Robinson and McCaughey (1911), soil color can be of direct agricultural value through the effect that different colors have in radiating and absorbing heat, and possibly in regulating light intensity, since many chemical and bacterial reactions are influenced by that soil temperature. Differences in soil color due to soil properties and condition could, therefore, be an indication of spatial variability of soil productivity across a field.

Torrent and Barrón (1993) pointed out that substantial errors are involved when soil color is determined using the Munsell Soil Color Charts, because of several psychophysical and physical factors. Therefore, soil scientists have preferred field and laboratory instruments that make more objective, precise, and accurate soil color determinations possible (Torrent and Barrón, 1993). They mentioned tristimulus colorimeters and diffuse reflectance spectrophotometers as instruments that can be used to measure the color of soil materials. Post et al. (1993) reported that sets of soil from 41 different soil samples were given to soil scientists to determine the dry and moist Munsell color of each soil. Results showed that soil scientists agreed on the same color chip for a single color component (hue, value, or chroma) 71% of the time, and there was an average of 52% agreement for all three color components (Post et al., 1993).

Torrent and Barrón (1993) contended that since laboratory measurements of soil color are usually made on small amounts of disturbed soil, the color data reflect the soil composition. This is in contrast to the use of remote sensors, which provide information about properties at the soil surface (Torrent and Barrón, 1993). Properties at the surface are partly a function of the soil composition, but also reflect the microrelief, structure, and other properties of the surface state (Escadafal, 1989 cited by Torrent and Barrón, 1993).

Soil organic carbon

According to Kimble et al. (2001), both soil organic and inorganic carbon contribute to the soil's capacity to supply nutrients, improve the soil's water holding capacity, and increase aggregation. Soil organic carbon and other cations interact with clay to form aggregates, and the degree of aggregation and stability of aggregates influence soil bulk density (Lal and Kimble, 2001). It can be argued therefore, that significantly higher amounts of organic carbon in certain sub-field areas can improve other soil properties, and result in higher productivity of those sub-areas compared to areas with less organic carbon.

Soil texture

When soils on a site are examined, texture is the most important property to determine because it can help with the formulation of many conclusions (Brady and Weil, 2002). Soil texture, which is the relative proportion of sands, silts and clays in a soil, partly determines water intake rates, water storage in soil, soil aeration, and influences soil fertility (Donahue et al., 1983). Clay particles have a large specific area and are capable of adsorbing large amounts of water and other substances as compared to sand particles (Brady and Weil, 2002). However, coarse sandy soil is easy to till and has more aeration for good plant growth compared to soils with over 30 % clay, although sand loses nutrients more easily through more rapid drainage (Donahue et al., 1983). Loam soil contains a fairly balanced mixture of coarse and fine particles, and as a result, its properties are intermediate among those of sand, silt, and clay (Hillel, 1980). Therefore, generally, loam is considered to be the optimal soil for crop production, because it can retain water and nutrients better than sand, and its drainage, aeration, and tillage properties are more favorable than those of clay (Hillel, 1980).

If the texture of a soil changes across a field, the soil properties that texture influences will also change. Since these properties, such as the retention of moisture and nutrients, are related to plant growth, soil productivity may vary across the field in response to the changing texture. Variations in crop yield have been correlated to surface soil texture (Khakural et al., 1996 and McBratney and Pringle, 1997 cited by Kitchen et al., 2000). When determining the relationship between measured soil properties and yield data, Sudduth and Fridgen (2001) concluded that soil clay content was one of the variables that best explained yield variability. Pettygrove et al. (1997) observed the highest yield in the portion of the field where the soil was relatively low in silt content and high in sand. Their findings also showed lowest grain yields in the portion where the surface soil was higher in silt and clay, with a restricting layer (> 50 % clay) at a depth of three to five feet.

Total pore space

Pore spaces in a soil consists of a portion of soil volume not occupied by solids, and are therefore, always occupied by air and water, under field conditions (Donahue et al., 1983). According to Hillel (1980), the value of porosity generally lies in the range 30 to 60 %. Brady and Weil (2002) suggested a value of approximately 50 % porosity for an "ideal" medium-textured, well-granulated surface soil in good condition for plant growth. Total porosity varies among soils for the same reason as bulk density, which is useful in predicting total porosity (Brady and Weil, 2002). In addition, they stated that compaction decreases the total pore space, which generally means that less water is retained at field capacity. It would therefore, be expected that spatial variability of total porosity would correspond to that of bulk density, especially throughout a uniform soil type.

Sorptivity

The spatial variation of soil hydraulic properties can be characterized for applications such as site-specific agriculture (Smith, 1999). Sorptivity values can range from about 0.074 cm/s$^{1/2}$ for clay to 0.228 cm/s$^{1/2}$ for sand (Carsel and Parrish, 1988 cited by Smith, 1999). Loam, which is generally considered to be the optimal soil for crop production (Hillel, 1980) has a sorptivity value of about 0.085 cm/s$^{1/2}$ (Carsel and Parrish, 1988 cited by Smith, 1999). From the literature reviewed, there was no mention of any research to relate spatial variation in sorptivity to productivity.

Soil water content

As soils dry, it becomes more difficult for plants to absorb moisture, and as a result, plants experience moisture stress (Plaster, 1997). However, in farming situations with an appropriate irrigation schedule, moisture stress could be minimized to avoid its effects on crop production. In these situations, water content determined from fields during the non-cropping period may help researchers to make deductions about other soil properties. For example, variations in water content across the field may be a reflection of corresponding variations in soil texture or organic matter content.

CHAPTER 3

MATERIALS AND METHODS

The study sites

The research was conducted on three irrigated fields near the towns of Greeley, Wiggins, and Yuma, Colorado. Precision farming experiments are being conducted at these locations, and this research formed part of these experiments. Each field had previously been divided into high, medium, and low productivity level management zones, as part of the precision farming experiments. The delineation of the zones was based on color variations on bare soil imagery, topography, and the farmers' management experiences (Khosla et al., 2000). Each field is disked at the beginning of the growing season, around April. Furrow irrigation is practiced at the Greeley field. Both the Yuma and Wiggins fields are sprinkler irrigated.

Greeley field (Study site I)

The 33 sample points, together with the productivity level management zones, are shown in Figure 1. The experimental site has an area of about 19 ha.

The soils found in this field are the Ascalon and Haverson loams, Otero sandy loam, Nunn clay loam, and Olney fine sandy loam (USDA, 1980). They are described as well drained, with a generally moderate to rapid permeability. The available water capacity of the soils is moderate to high, and their erosion hazard is low (USDA, 1980).

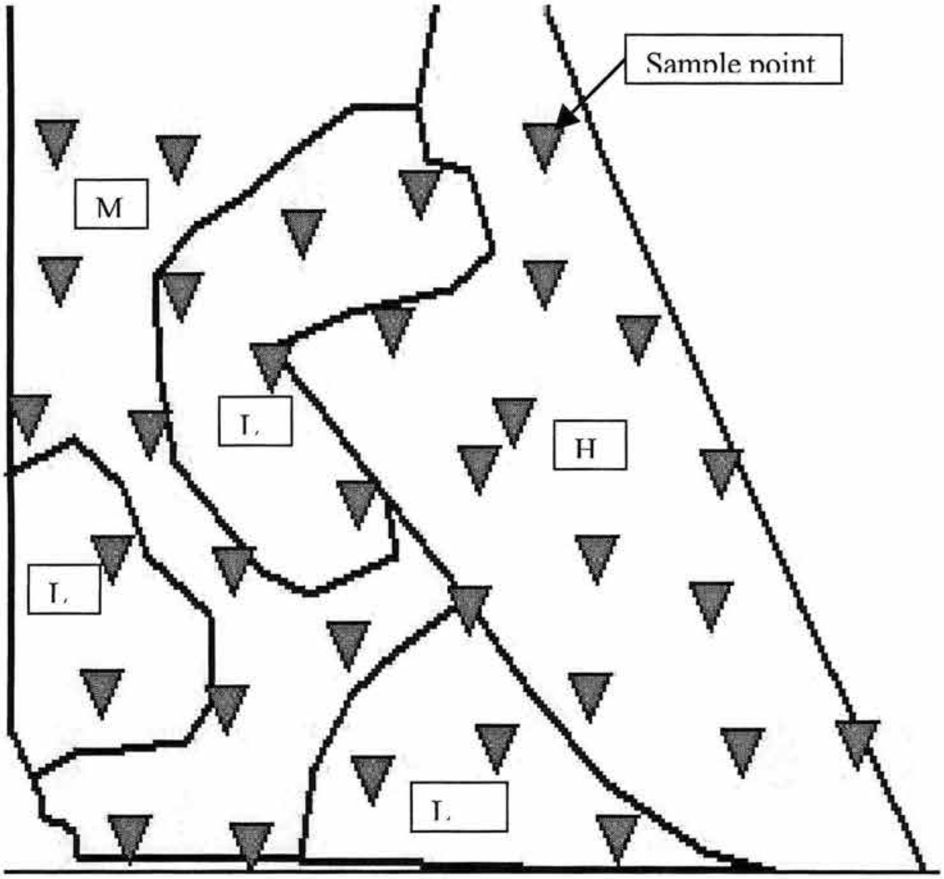

Figure 1.0 Sample points and management zones in the Greeley, Colorado field

Key

H = high productivity zone

M = medium productivity zone

L = low productivity zone

Wiggins field (Study site II)

The 35 ha study area, with management zones and the 86 sample points is shown in figure 2.

The soils are the Valentine-Dwyer sand, Bijou loamy sand, and Valentine sand (USDA, 1968). The Bijou series is well drained to excessively drained, but water erosion may be a hazard on slopes of about 1 to 3%. The Valentine sand occurs on slopes of about 5 to 25% and therefore, has a severe erosion hazard (USDA, 1968).

Yuma field (Study site III)

The study site, with an area of 28 ha is shown in Figure 3, including the management zones and 74 sample points. A boundary map of the field showing the distribution of soil types could not be obtained.

Measurements and soil analyses

Each field was divided into grid cells of 0.4 ha each, with one sample point per cell established by the non-aligned systematic technique. The technique was selected from the computer program Farm GPS, which contained the boundary maps of the fields from previous surveys. Farm GPS was also used to navigate to the sample points in the field.

At study sites I (Greeley) and II (Wiggins), soil samples were collected in March and April 2001 for analysis of soil properties at depth and at the surface, respectively.

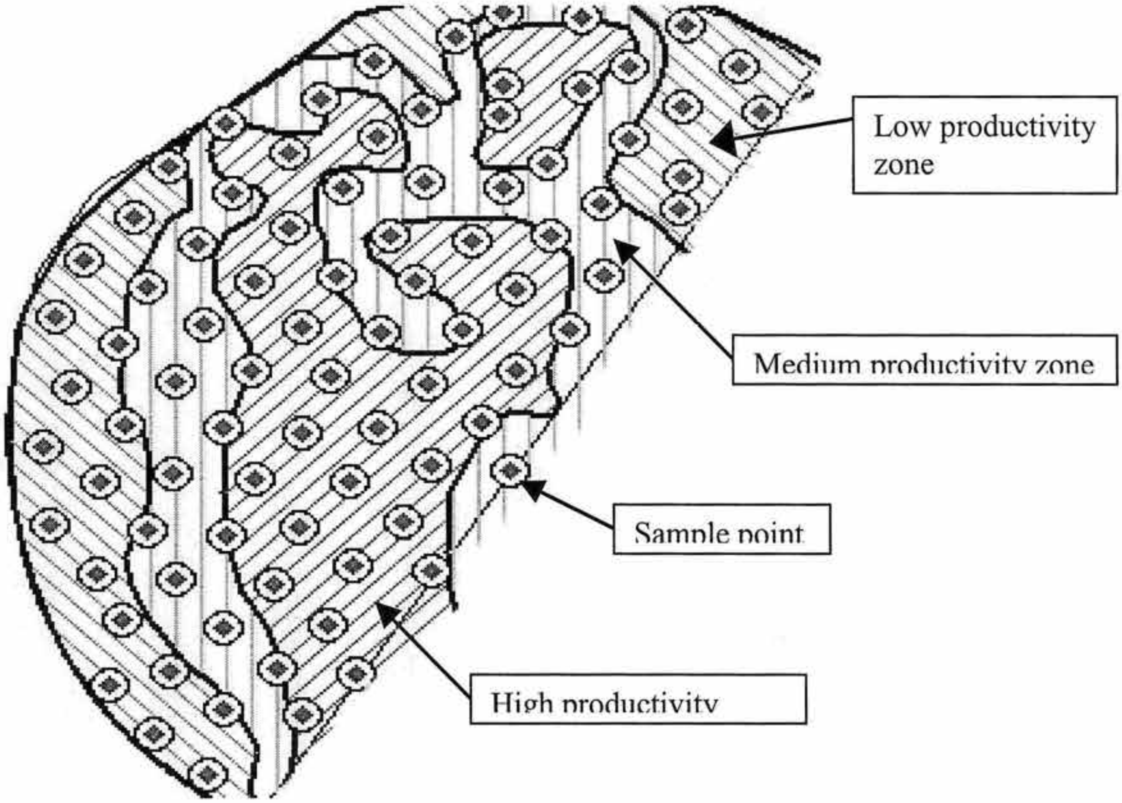

Figure 2.0 Sample points and management zones in the Wiggins, Colorado field

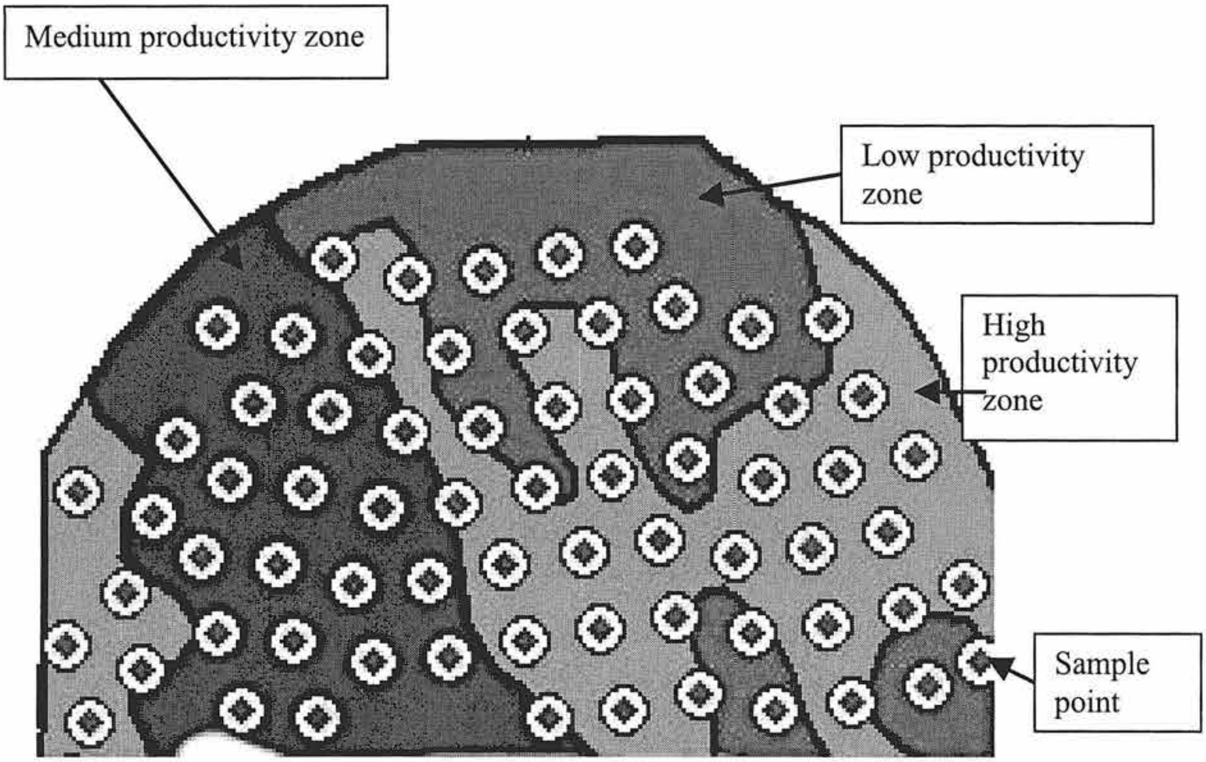

Figure 3.0 Sample points and management zones in the Yuma, Colorado field

At study site III (Yuma), samples were collected in April 2002. Sorptivity and cone index measurements were done in April 2002 at study sites II and III.

Bulk density

Undisturbed surface soil samples were taken with a 4.6 cm diameter core sampler. The 5 to 10 cm soil core was used to determine surface soil bulk density, and the other cores were discarded. Soil samples at 30 cm, 60 cm and 90 cm depths were taken simultaneously by driving a relatively long hydraulic probe into the soil. The 4.6 cm diameter probe was mounted on the back of a truck. A ruler was used to measure cores of length 7.6 cm, at each of the three depths. The probe tube had a slit through which a knife was inserted to slice off segments of the soil as they were measured. Soil cores were stored in moisture cans and transported to the laboratory.

The samples were oven-dried at 105° C for 24 hours, and the bulk density of each sample was determined using the method stated by Donahue et al. (1983) and Miller and Donahue (1990).

Total pore space

The formula stated by Klute (1986) was used to calculate total porosity (ϕ) at the 5 to 10 cm, 30, 60 and 90 cm depths. It is stated as:

$$\phi = 1 - (\rho_b/\rho_p) \qquad (1)$$

where the standard soil particle density, ρ_p, value of 2.65 g/cm^3 (Plaster, 1997) was assumed for all locations.

Cone index

Measurements were made in April 2002 at study sites II and III. At each sampling point, three measurements were made at 0, 5, 10, 15 and 20 cm depths. These were averaged to obtain values for each depth. The soil compaction meter, The Investigator, which is an electronic cone penetrometer, was used to measure cone index data as an indicator of soil compaction. The manual accompanying the penetrometer states that it was designed to ASAE Standard S312.2, and has an accuracy of ± 1.25 cm and ± 103 kPa. It has a range of 0-45 cm depth and 0-7,000 kPa. Compaction values were recorded in kPa/cm. At study site III, measurements were made in April 2001.

Surface soil color

Each surface soil sample (0 to 5 cm depth) was analyzed using the chips in the Munsell Soil Color Charts (USDA, 1954). Both dry and moist soil color were determined. To determine moist soil color, about 40 g of air-dry soil from each sample was mixed with about 10 ml tap water. A sub-sample was taken from the mixture and kneaded between the fingers until it could be squeezed into a ribbon. The soil was then compared with the color chips to select the appropriate color.

Organic carbon

The organic carbon content at each sample position was determined by dividing the organic matter content by a factor of 1.724 . The organic matter content determinations were made at MDS Harris Laboratory in Lincoln, Nebraska, from the soil samples collected in 2001. The organic matter was determined by Loss-on-Ignition, and the conversion factor was based on the assumption that organic matter contained 58 % organic carbon (Byron Vaughan 2002, pers. comm.).

Soil texture

Soil texture was determined at MDS Harris Laboratory using soil samples that were collected in the year 2001. The particle size analysis was done by the hydrometer method (Byron Vaughan 2002, pers. comm.).

Sorptivity

Two measurements were made around each sample point. Cylindrical metal rings with a height of 10.5 cm and a diameter of 9.8 cm were used. If there was any loose plant material where the measurement was to be made, it was removed without disturbing the soil surface. The ring was gently pushed into the soil to a depth of about 2 cm. An amount of 75 ml water, equivalent to a depth of 1 cm, was poured into the ring. The water was applied against the inside wall of the ring so that the soil surface inside the ring was not disturbed. The time it took for the water to infiltrate was recorded to 0.1 s using a stop watch.

Considering that 1 ml of water is approximately equal to 1 cm^3, it can be shown that

$$\begin{aligned} \text{equivalent depth} &= (\text{volume})/(\text{surface area}) \qquad (2) \\ &= (75\ cm^3)/\pi(9.8\ cm/2)^2 \\ &\approx 1\ cm \end{aligned}$$

Sorptivity (S_j) was calculated from the equation stated by Smith (1999), as follows:

$$\text{Sorptivity, } S_j = D / \sqrt{t} \qquad (3)$$

for sample position j =1, 2, …., n

where D is the depth of water in cm corresponding to the water volume of 75 cm^3, and

t is the time in seconds it took for the water to infiltrate.

Whereas Smith (1999) used t as the time from the application of water until half the soil surface was exposed, in this project t was measured until the last free water disappeared.

A soil sample was taken near each measurement position to determine the initial soil water content and adjust the sorptivity values for the variations in initial moisture content deficit. The procedure to adjust the values is as follows (L. R. Ahuja 2002, pers. comm.):

1. Calculation of the initial volumetric soil water content, θ_i, for each sample position:

$$\theta_i = w * G_a \qquad (4)$$

where gravimetric initial water content, w = (mass of water)/(mass of dry soil), and

$$\text{specific gravity, } G_a = (\rho_{bs})/(\rho_w) \quad (5)$$

where ρ_{bs} is the surface soil bulk density, and ρ_w is the density of water = 1 g/cm^3

2. Calculation of the field saturated volumetric water content, θ_s for each sample position:

$$\theta_s = \phi * f \quad (6)$$

where f = 0.85 to account for the air entrapped at field saturation

3. Calculation of the initial soil water deficit, $\Delta\theta$, for each sample position:

$$\Delta\theta_j = \theta_{sj} - \theta_{ij} \quad (7)$$

for sample position j = 1, 2, …., n.

4. Calculation of the average soil water content deficit, $\overline{\Delta\theta}$, for the whole field:

$$\overline{\Delta\theta} = \frac{1}{N}\sum_{j=1}^{N}\Delta\theta j \quad (8)$$

where N is the number of sample points in a field.

5. Calculation of adjusted sorptivity, S*, for each sample position:

$$S^*_j = S_j * \sqrt{(\overline{\Delta\theta})/(\theta sj - \theta ij)} \quad (9)$$

Surface volumetric water content

Volumetric water (θ_v) content was determined from the 5 – 10 cm soil core samples that were used to determine surface soil bulk density. The formula used to calculate θ_v is:

$$\theta_v = \frac{M_w / \rho_w}{V} \quad (10)$$

where M_w = (mass of moist soil) – (mass of dry soil), and V is the volume of the sample.

Statistical analysis

Regression analysis was used to test for significant relationships between the bare soil reflectance and measured soil properties. The bare soil reflectance imagery had a spectral range of 0.51 to 0.59 μm for the green wavelength band, 0.62 to 0.70 μm for red, and 0.735 to 0.865 μm for infrared. An analysis of variance was used to test for significant differences in soil properties among management zones. To account for the presence of spatial autocorrelation among soil properties, the analysis included a spatial component in the models.

CHAPTER 4

SPATIAL VARIABILITY OF CERTAIN SOIL PROPERTIES ACROSS SITE-SPECIFIC MANAGEMENT ZONES

Abstract

Soil productivity is influenced by soil physical and chemical properties. If soil productivity varies across a field, a corresponding variation in certain soil properties would be expected. In order for growers to effectively manage within-field variability, it is necessary to first determine the source of the variation in productivity. This study was conducted to determine whether measured soil properties were significantly different among productivity level management zones developed from bare soil imagery, topography and farmer's knowledge of within-field variability. The study was conducted on three irrigated fields near Greeley, Wiggins, and Yuma in northeastern Colorado. The soil properties investigated were bulk density, cone index, surface soil color, organic carbon, texture, total pore space, sorptivity, and surface water content. An analysis of variance was used to test for significant differences in soil properties among zones. The analysis included a spatial component in the models, to account for the spatial autocorrelation in soil properties. Surface bulk density and sand content were inversely related to the productivity level of the management zones at study sites I (Greeley) and II (Wiggins). At these study sites, organic carbon and silt content were directly related to the productivity level of the zones. At study site II, clay content and cone index at the 20 cm depth had a direct and indirect relationship, respectively, with the productivity level

of the zones. Investigation of soil properties in precision farming productivity level management zones would help farmers to implement appropriate site-specific soil management practices in order to improve the productivity of sub-field areas.

Introduction

Soil physical factors are among the most widespread causes of yield variation (Clarke et al., 1996 and Stafford et al., 1996 cited by Dampney and Moore, 1998). Precision farming is aimed at managing soil spatial variability by applying inputs in accordance with the site-specific requirements of a crop (Fraisse et al., 1996). One way to achieve site-specific management is to divide fields into productivity level management zones. A management zone is a sub-region of a field that with a functionally homogeneous combination of yield-limiting factors, for which a single rate of a specific crop input is appropriate (Doerge, 1999). In order for the farmer to be able to manage within-field variability, it is necessary to determine the source of the variation (Steven and Miller, 1997; Taylor et al., 1997).

The fields used in this investigation had previously been divided into site-specific management zones. The zones were delineated from the variability of color observed on bare soil imagery, topography, and the farmer's knowledge of within-field variability (Khosla et al., 2000). The variability in bare soil reflectance, and that observed by the farmer, stem from the non-uniform distribution of certain soil properties that influence productivity. Changes in topography can influence the distribution of soil properties and productivity across a field. For example, crop yields ranged from 1,000 to 6,700 kg/ha across the variable topography of 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 organic matter content.

A literature review indicates that most previous investigations have focused on the spatial variability of plant nutrients for the purpose of site-specific fertilizer application (Goddard and Grant, 2001; Chung et al., n.d; Mulla and Bhatti 1997). Even though some researchers have studied the spatial variability of soil physical properties (Fulton et al., 1996; Wells et al., 2000) the results may not be generalized to other fields or locations because of the spatial variability of fields. Soil properties need to be investigated further to understand possible sources of variability in any precision farming environment. This would help individual farmers to take remedial action appropriate to their respective situations.

Variations of soil physical properties, nutrient levels and water content have been shown to exist within fields (Fulton et al., 1996). In a relatively flat, 100 x 30 m rice paddy field in Korea, maximum values were more than twice the minimum values for yield, electrical conductivity, calcium, potassium, magnesium, sodium, and S_iO_2 (Chung et al.,n.d.). Wells et al. (2000) took penetrometer measurements at 15 sample points at different depths within each 0.4 ha grid cell in an experimental field. They found that the maximum average cone index values in each grid cell ranged from 1.07 to 1.97 MPa across the field, with the field average of 1.51 MPa. The occurrence of these maxima at depths ranging from 7 to 45 cm led them to conclude that deep tillage might need to be applied at variable depths and different places across a field. There was spatial variability of bulk density and cone index, which are both indicators of compaction, across a 7 ha field (Fulton et al., 1996). They concluded that on the basis of bulk density, there was no need for deep tillage. However, cone index values showed a need for precision deep tillage. Their conclusions were based on the critical values of 1.6 Mg/m^3 and 2 MPa for bulk density and cone index, respectively.

The spatial distribution of some soil properties can influence the pattern of other yield-limiting factors, which in turn can produce the variability in crop characteristics observed by the farmer. For example, in a field in Mississippi, the density of weeds was significantly greater where the clay content was more than 30 % (Gatson et al., 2001). They also reported a significantly higher density of weeds where soil organic carbon (SOC) content was greater than 1.6 %. Soil color has little effect on the behavior and use of soils (Brady and Weil, 2002), but may indicate the presence of a component that is beneficial to the plant (Robinson and Mc Caughey, 1911). Therefore, soil color variability within a field may be related to variation in productivity, which may be reflected in crop characteristics.

The observed variation in productivity was defined by the delineation of management zones, but the causes of the variation were not known. The objective of this study was to evaluate site-specific management zones on the basis of spatial variability in measured soil properties.

Materials and methods

At study sites I (Greeley) and II (Wiggins), soil samples were collected in March and April of 2001. At study site III (Yuma), they were collected in April 2002. Sorptivity and cone index measurements were done in April of 2002 at sites II and III.

Experimental field sites

This investigation was part of an on-going large field study on precision farming on three different irrigated fields in the northeastern plains Region of Colorado, USA. The fields were located near Greeley, Wiggins, and Yuma, in Colorado. Each field had previously been divided into site-specific management zones (SSMZ) corresponding to areas of high, medium, and low productivity, using three GIS data layers, i.e. (i) bare soil reflectance, (ii) topography, and (iii) farmer's experience (Khosla et al., 2000). The sizes of the fields are site I (19 ha), site II (35 ha), and site III (28 ha).

Measurements and soil analyses

Each field was divided into grid cells of 0.4 ha each, with one sample point per cell established by the non-aligned systematic technique. Altogether, there were 33 sample points at site I (Greeley), 86 at site II (Wiggins), and 74 at site III (Yuma).

A hydraulic core sampler (Giddings) mounted on the back of a truck was used to take one core at each sample point. Core sections of length 7.6 cm were then cut at positions corresponding to 30, 60 and 90 cm depths. Bulk densities were determined using the method described by Donahue (1983). Cone indices were measured with an electronic cone penetrometer. At each sample point in the field, three measurements were made at

0, 5, 10, 15, and 20 cm depths. Readings were averaged to obtain a cone index value for each depth at each sample point.

Both dry and moist surface (0-5 cm) soil color were determined from the soil samples using the Munsell Soil Color Charts (USDA, 1954). Organic matter content was determined at MDS Harris Laboratory, 621 in Lincoln, Nebraska, for the 0 to 15 cm depth at site I, and 0 to 20 cm depth at sites II and III. The soil organic carbon for each sample point was determined by dividing the organic matter content by a factor of 1.724. Soil texture was also determined at MDS Harris Laboratory using the hydrometer method. The values for percent sand, silt, and clay were used in this project. Total porosity (ϕ) was determined for the 30, 60 and 90 cm depths by substituting the measured bulk density (ρ_b) and the standard particle density (ρ_p) value of 2.65 g/cm^3 (Plaster, 1997) into the equation:

$$\phi = 1 - (\rho_b/\rho_p)$$

Two sorptivity measurements were made at each sample point using the method suggested by Smith (1999). The cylindrical rings used had a height of 10.5 cm and a diameter of 9.8 cm.

The sorptivity (S_j) at sample point j = 1, 2, …., n was calculated by

$$S_j = D / \sqrt{t}$$

where D = 1 cm depth of water corresponding to a 75 ml volume of water, and t is the time in seconds from application of water until the time when the last free water disappeared. The average of the two sorptivity values at each sample point was adjusted for the initial moisture content to allow comparison among the points. The adjusted sorptivities (S*) were obtained from (L. R. Ahuja 2002, pers. comm.):

$$S^*_j = S_j * \sqrt{(\overline{\Delta\theta})/(\theta sj - \theta ij)}$$

$$\text{where } \overline{\Delta\theta} = \frac{1}{N}\sum_{j=1}^{N}\Delta\theta j$$

where $\overline{\Delta\theta}$ is the average soil water content deficit for the whole field,

N is the number of sample points in a field, and

$$\Delta\theta_j = \theta_{sj} - \theta_{ij}$$

θ_s (the saturated volumetric soil water content) = $\phi * f$

where f = 0.85 to account for the air entrapped at field saturation

θ_i (the initial volumetric soil water content) = w * G_a

where w (gravimetric initial water content) = (mass of water)/(mass of dry soil)

and G_a (the specific gravity) = $(\rho_{bs})/(\rho_w)$

where ρ_{bs} is the surface soil bulk density, and ρ_w is the density of water = 1 g/cm^3. Volumetric water content was determined from the 5 – 10 cm soil core samples that were used to determine surface soil bulk density. The formula used states:

$$\theta_v = \frac{M_w / \rho_w}{V}$$

where M_w = the mass of moist soil – mass of dry soil, and V is the volume of the sample.

Statistical analysis

Analysis of variance was used to test for significant differences in soil properties among management zones at the 5 % level, using the spatial autocorrelation model. For any soil property that was significant, the spatial model was compared to the ordinary least squares (OLS) model. When the two models were not significantly different at the 10% level of significance, the OLS model was used.

Results and Discussion

The results of the test of significance among management zones are summarized in Tables 4.1 to 4.3, together with the mean values to show any trend of soil property values across the zones.

Compaction

At study sites I and II, surface bulk density (5-10 cm) was significantly different among management zones. The mean surface bulk densities in the respective zones at these sites increased from the high to the low productivity level zone (Tables 4.1 and 4.2). This suggests that surface bulk density could be contributing to the observed productivity variations among the different zones. An increase in soil bulk density shows compaction which can adversely affect yield-related soil properties (Flocker et al., 1959 cited by Nelson et al., 1975). Although the mean surface bulk density in each zone at site I was less than the critical value of 1,600 kg/m^3 mentioned by Fulton et al. (1996), compaction could significantly reduce yields in the lower productivity zones. This is because the field contains clay loam (USDA, 1980), and a bulk density greater than 1,550 kg/m^3 can reduce yields on clay loams (Donahue et al., 1983). The mean bulk density of the low productivity level zone in this field was greater than the approximate maximum value of 1,400 kg/m^3 suggested by Donahue et al. (1983) for a cultivated loam soil.

Table 4.1. Mean values of soil properties that were significantly different among management zones, with standard deviations in parenthesis, at study site I (Greeley), Colorado.

Soil Property	P-value	Mean Value in Zone			Statistical
		High	Medium	Low	Model
Surface bulk density (kg/m^3)	0.0387	1,373 (±115)	1,414 (± 134)	1,515 (± 197)	Spatial
Organic carbon (%)	0.0136	1.04 (± 0.16)	0.96 (± 0.13)	0.86 (± 0.13)	OLS[#]
Sand (%)	0.0107	50 (± 9)	55 (± 8)	61 (± 9)	OLS
Silt (%)	0.0020	24 (± 5)	22 (± 5)	17 (± 4)	OLS
Cone index at 5 cm depth (kPa)	0.0203	628 (± 176)	814 (± 376)	538 (± 203)	Spatial

[#] OLS refers to the ordinary least squares model

Table 4.2. Mean values of soil properties that were significantly different among management zones, with standard deviations in parenthesis, at study site II (Wiggins), Colorado.

	P-value	Mean Value in Zone			Statistical model
Soil Property		High	Medium	Low	
Surface Bulk Density (kg/m^3)	< 0.01	1,669 (± 100)	1,701 (± 94)	1,751 (± 87)	OLS[7]
Volumetric Water Content	< 0.01	0.20 (± 0.04)	0.15 (± 0.03)	0.13 (± 0.02)	Spatial
Dry Surface Soil Color	< 0.01	3.7[1]	5.0[2]	5.3[3]	Spatial
Wet Surface Soil Color	< 0.01	2.2[4]	2.8[5]	3.0[6]	Spatial
Organic Carbon (%)	< 0.01	0.64 (± 0.12)	0.51 (± 0.10)	0.45 (± 0.07)	Spatial
Sand (%)	< 0.01	85 (± 5)	88 (± 4)	90 (± 2)	Spatial
Silt (%)	< 0.01	7 (± 2)	5 (± 2)	4 (± 1)	Spatial
Clay (%)	< 0.01	8 (± 4)	7 (± 3)	6 (± 3)	Spatial
Cone Index at 20 cm (kPa/cm)	0.01	2,131 (± 403)	2,429 (± 545)	2,507 (± 536)	Spatial
Sorptivity	0.01	0.14 (± 0.03)	0.15 (± 0.03)	0.13 (± 0.02)	Spatial

[1] 3.7 ≈ 4 (10YR 4/3); [2] 5 (10 YR 5/3); [3] 5.3 ≈ 5 (10YR 5/3)
[4] 2.2 ≈ 2 (10YR 3/2); [5] 2.8 ≈ 3 (10YR 4/2); [6] 3 (10YR 4/2)
[7] OLS refers to ordinary least squares

Table 4.3. Mean values of soil properties that were significantly different among management zones, with standard deviations in parenthesis, at study site III (Yuma), Colorado.

Soil Property	P-value	Mean Value in Zone			Statistical
		High	Medium	Low	Model
Bulk density at 30 cm depth (kg/m^3)	0.0181	1,578 (± 102)	1,547 (± 211)	1,421 (± 211)	OLS[7]
Dry surface soil color	< 0.01	3.0[1]	3.4[2]	4.0[3]	OLS
Wet surface soil color	< 0.01	1.0[4]	1.3[5]	1.6[6]	OLS
Silt (%)	0.0187	27 (± 7)	27 (± 6)	22 (± 4)	OLS
Cone index at 5 cm (kPa/cm)	0.0471	929 (± 299)	758 (± 280)	901 (± 257)	OLS

[1] 3 (10YR 5/2); [2] 3.4 ≈ 3 (10YR 5/2); [3] 4 (10YR 5/3)
[4] 1 (10YR 4/1); [5] 1.3 ≈ 1 (10YR 4/1); [6] 1.6 ≈ 2 (10YR 4/2)
[7] OLS refers to the ordinary least squares

In cultivated fields, surface bulk densities are expected to be relatively low throughout the whole field. The various sub-areas of a field are probably compacted at different rates by raindrops, irrigation and other farm operations. If this compaction starts to occur before or during plant emergence from the soil, emergence rates may be different across the field. The soils in the lower productivity level zones may, therefore, be more prone to compaction than those in zones of higher productivity, at sites I and II. This could be attributed to the increase in organic carbon from the low to the high productivity level zone, as shown by the mean organic carbon values. Soil organic carbon helps to form stable aggregates that can result in relatively low bulk density (Lal and Kimble, 2001).

Soil bulk density at 30 cm depth differed significantly among zones at site III, but the mean values increased with productivity. This is contrary to what would be expected. The mean bulk density in each zone was not greater than the critical value, and so compaction at 30 cm depth is not sufficiently large to reduce productivity.

Cone index at the 5 cm depth was significantly different among zones at sites I and III. However, the highest mean zone values in both fields were less than half the critical value of 2,000 kPa mentioned by Fulton et al. (1996). This indicates that there was insufficient compaction in all zones at 5 cm depth to reduce productivity.

Mean cone index values by zone at the 20 cm depth at site II showed that compaction increased from the high to the low productivity level zone. The cone index values also showed that compaction was significantly different among zones, although bulk density at the same depth did not show this difference. In all three zones in this field, mean cone index values at the 20 cm depth were greater than the critical value. Based on cone index results, compaction at this depth may help explain the variations in productivity among management zones.

Soil organic carbon

Organic carbon was significantly different among zones at study sites I and II, and its mean content increased from the low to the high productivity level zone. In both fields, mean values show that surface bulk density increased as organic carbon content decreased. It could be suggested, therefore, that an increase in organic carbon content contributed to a higher degree of formation and stability of soil aggregates, resulting in a relatively high resistance of the soil against compaction agents. Organic carbon and other cations interact with clay to form aggregates, and the degree of aggregation and stability of aggregates influence soil bulk density (Lal and Kimble, 2001). Through its influence on soil properties such as bulk density, the variable carbon content among zones could contribute to the variable productivity among zones.

Soil texture

The proportion of silt was significantly different among management zones in all three fields. It generally increased from the low to the high productivity level zone, as shown by the mean silt percentage in each zone. The proportion of sand was also significantly different among zones at sites I and II, but it increased from the high to the low productivity level zone. With more silt and/or clay and less sand, soil productivity would be expected to increase because soils with more silt or clay tend to have more organic matter content, higher cation exchange, and better capability to retain moisture and nutrients (Brown, 1998). At site II clay content increased from the low to the high productivity level zone. Soil texture was, therefore, related to the variation in productivity among the management zones in this investigation.

Sorptivity

Sorptivity was significantly different among zones at site II. However, the medium and low productivity level zones had the highest and lowest sorptivities respectively, based on the mean values. The difference in productivity could not, therefore, be attributed to the observed difference in sorptivity.

Surface soil water content

Water content differed significantly among zones at site II, and also increased from the low to the high productivity level zone. Mulla and Bhatti (1997) 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. Mean organic carbon values also increased from the low to the high productivity level zone at site II. The variation in soil water content may be related to the variation in organic matter content, which is directly proportional to organic carbon. Both fresh organic matter and humus absorb water and help to increase the water-holding capacity of soils (Plaster, 1997).

Surface soil color

Both dry and wet surface soil color were significantly different among zones for the Wiggins (site II) and Yuma (site III) fields. At site II, the average moist and dry soil Munsell value was darker in the high productivity level zone, but the same for both medium and low productivity level zones. The darker color may be due to more organic matter content in the high productivity level zone as shown by the organic carbon content. Value extends from pure black (0/) to pure white (10/) (Soil color: http://www.irim.com/ssm/ssm00085.htm, 4 October, 2002).

Conclusions

At two of the three study sites, surface bulk density, organic carbon, silt and sand content were significantly different among management zones. The spatial variability of these soil properties was consistent with the observed variation in productivity of the management zones.

At one study site, compaction at the 20 cm depth as indicated by cone index, could explain the observed increase in productivity from one management zone to the other.

The darker soil color in zones of higher productivity may be related to soil properties such as higher organic carbon content which can affect soil color and productivity.

CHAPTER 5

RELATIONSHIP BETWEEN SOIL PROPERTIES AND REFLECTANCE

Abstract

Spatial variation of soil and crop characteristics within fields has led to the adoption of precision farming by growers. To improve the efficiency of management, fields are divided into homogeneous productivity level management zones. One of the approaches to the delineation of zones is the use of color variations as seen on remotely sensed bare soil images. The determination of soil characteristics that can explain these color variations can help in the selection and investigation of possible yield-limiting soil properties in precision farming situations where management zones were developed from color variation on bare soil imagery. This study was conducted to determine the measured soil properties whose variability could be best explained by remotely sensed bare soil reflectance data. The study was conducted on three irrigated fields near Greeley, Wiggins and Yuma in northeastern Colorado, U.S.A. Each field had previously been divided into three management zones corresponding to areas of high, medium and low levels of productivity. Each field was divided into grid cells of 0.4 ha each, with one sample point per cell established by the non-aligned systematic technique. Measured soil properties were bulk density, cone index, surface color, organic carbon, texture, total pore space, sorptivity, and surface water content. The amount of variability of soil properties that was explained by the appropriate spectral bands ranged from 35 to 55% at study site I (Greeley), 13 to 73% at site II (Wiggins), and 10 to 52% at site III (Yuma). In the test

involving both zones and wavelength bands, some soil properties were related to either zones or bands only, while others were related to both bands and zones. The amount of variability in soil properties that was explained by zones, bands, or a combination of both, ranged from 11 to 77% in Wiggins and 17 to 56% in Yuma. Reflectance data can be used to explain the variability of certain soil properties across a field.

Introduction

Remotely sensed bare soil images are a record of the electromagnetic energy reflected by the bare soil. When electromagnetic energy strikes matter, the amount of energy reflected depends in part on the composition and physical properties of the medium (Avery and Berlin, 1992). Color variations on a bare soil image may indicate variations in soil characteristics. If these characteristics are related to crop production, then regions or zones of different levels of productivity can be identified by grouping areas with similar color or reflectance.

Coleman and Tadesse (1995) investigated the use of color infrared-digital orthophoto quadrangle (CIR-DOQ) in differentiating among surface soils. In addition, they wanted to identify the CIR-DOQ spectral band that might be most useful in estimating selected soil properties. They concluded that all three of the CIR-DOQ bands helped explain the variation in soil properties. They also found that red was the key band for predicting sand content, whereas silt and clay content was best predicted by the blue band. The R^2 values were quite low at 0.035 and 0.149, respectively (Coleman and Tadesse, 1995). Clay type and silt were found to influence the intensity of energy reflected by soils in the 0.5 to

2.6 μm range (Matthews et al., 1973 cited by Coleman and Tadesse, 1995). Reflectance measurements in the near infrared (0.72 to 1.3 μm) and middle infrared (1.3 to 3.0 μm) spectral regions often reveal textural, structural, and/or other detectable significant differences (Stoner et al., 1980 cited by Coleman and Tadesse, 1995).

Page (1974) compared the reflectance of surface horizons of 96 Coastal Plain soils to percent organic matter. Reflectance explained 79% of the variation in soil organic matter in the 0 to 5% (Page, 1974). The visible wavelength region provided better information than the infrared region for determining organic matter content (Krishnan et al., 1980). However, it was also reported that a near infrared band 0.76 to 0.90 μm was the key band in explaining the variability attributable to organic matter content (Montgomery, 1987 cited by Coleman and Tadesse, 1995). In the investigation by Coleman and Tadesse (1995) involving the use of CIR-DOQ data, 21% the variability in organic matter content could be explained by using all three bands.

From the literature, it appears that most of the previous investigations were aimed at determining the relationship between soil reflectance and organic matter content. This investigation was part of a large study on precision agriculture in three different irrigated fields in the Western Great Plains Region of Colorado, USA. The three fields were located near Greeley (study site I), Wiggins (site II), and Yuma (site III). Each field had previously been divided into productivity level management zones corresponding to areas of high, medium and low productivity. The zones were delineated from the variability of reflectance observed on bare soil imagery, topography, and the farmer's knowledge of within-field variability (Khosla et al., 2000). In the absence of any data on soil properties, it was not known which soil characteristics might explain the variability observed on the remotely sensed images. If this knowledge is documented, it may help future investigations to focus on certain soil properties, to understand the spatial variability that exists on farm fields and further help in delineating more precise management zones. The objective of this investigation was to determine the measured soil properties whose variability could be best explained by remotely sensed bare soil reflectance data.

Materials and methods

At study sites I (Greeley field) and II (Wiggins field), soils samples were collected in March and April of 2001. At study site III (Yuma field), they were collected in April of 2002. Sorptivity and cone index measurements were done in April of 2002 at sites II and III.

Experimental field sites

Investigations were conducted on three arable fields located near the towns of Greeley (study site I), Wiggins (site II), and Yuma (site III), in Colorado, USA. The sizes of the fields were site I (19 ha), site II (35 ha), and site III (28 ha).

Measurements and soil analyses

Each field was divided into grid cells of 0.4 ha each, with one sample point per cell established by the non-aligned systematic technique. There were 33 sample points at site I (Greeley), 86 at site II (Wiggins), and 74 at site III (Yuma).

A hydraulic core sampler (Giddings) mounted on the back of a truck was used to take one core at each sample point. Core sections of length 7.6 cm were then cut at positions corresponding to 30, 60 and 90 cm depths. Bulk densities were determined using the method described by Donahue (1983). Cone index was measured with an electronic cone penetrometer. At each sample point in the field, three measurements were made at 0, 5, 10, 15, and 20 cm depths. Readings were averaged to obtain a cone index value for each depth at each sample point.

Both dry and moist surface (0-5 cm) soil color of soil samples were determined using the Munsell Soil Color Charts (USDA, 1954). Organic matter content was determined were made at MDS Harris Laboratory in Lincoln, Nebraska, for the 0 to 15 cm depth (site I), and 0 to 20 cm (sites II and III). The soil organic carbon for each sample point was determined by dividing the organic matter content by a factor of 1.724. Soil texture was also at MDS Harris Laboratory using the hydrometer method. The values for percent sand, silt and clay were used in this project. Total porosity (ϕ) was determined for the 30, 60 and 90 cm depths by substituting the measured bulk density (ρ_b) and the standard particle density (ρ_p) value of 2.65 g/cm^3 (Plaster, 1997) into the equation:

$$\phi = 1 - (\rho_b/\rho_p)$$

Two sorptivity measurements were made at each sample point, using the method suggested by Smith (1999). The cylindrical rings used had a height of 10.5 cm and a diameter of 9.8 cm. S_j, the sorptivity at sample point $j = 1, 2, \ldots, n$ was calculated by:

$$S_j = D / \sqrt{t}$$

where D = 1 cm depth of water corresponding to a 75 ml volume of water, and t is the time in seconds from the application of water until the time when the last free water disappeared. The average of the two sorptivities at each sample point was adjusted for the initial moisture content to allow comparison among the points. The adjusted sorptivities (S*) were obtained from (L. R. Ahuja 2002, pers. comm.):

$$S^*_j = S_j * \sqrt{(\overline{\Delta\theta})/(\theta sj - \theta ij)}$$

$$\text{where } \overline{\Delta\theta} = {}^1\!/_N \sum_{j=1}^{N} \Delta\theta j$$

where $\overline{\Delta\theta}$ is the average soil water content deficit for the whole field,

N is the number of sample points in a field, and

$$\Delta\theta_j = \theta_{sj} - \theta_{ij}$$

θ_s (the saturated volumetric soil water content) = $\phi * f$

where f = 0.85 to account for the air entrapped at field saturation

θ_i (the initial volumetric soil water content) = $w * G_a$

where w (gravimetric initial water content) = (mass of water)/(mass of dry soil)

and G_a (the specific gravity) = $(\rho_{bs})/(\rho_w)$

where ρ_{bs} is the surface bulk density, and ρ_w is the density of water = 1 g/cm^3. Volumetric water content was determined from the 5 – 10 cm soil core samples used to determine surface soil bulk density. The formula used states:

$$\theta_v = \frac{M_w / \rho_w}{V}$$

where M_w = the mass of moist soil – mass of dry soil, and V is the volume of the sample.

Bare soil imagery

Digital color infrared aerial imagery was acquired for the study sites in April 2001. It was obtained by Agro Engineering Incorporated. The imagery had a spectral range of 0.51 to 0.59 μm for the green band, 0.62 to 0.70 μm for the red, and 0.735 to 0.865 μm for the infrared infrared band.

Statistical analysis

Regression analysis was used to test for significant relationships between bare soil reflectance and management zones on the one hand, and measured soil properties on the other. To select the spectral bands that best explained the variability of soil properties, the lowest Corrected Akiake's Information Criteria (AICC) was used. For any soil property that was significantly related to reflectance data the spatial model was compared to the ordinary least squares (OLS) model. If the two models were not significantly different at the 10% level, the OLS model was used. A regression of each soil property on both zones and bands was done to select bands and/or zones that were best related to each soil property. A regression of each wavelength band was done on all measured soil properties, to select those that were best related to a particular band.

Results and Discussion

For the soil properties that were significantly different among management zones, the wavelength bands that best explained the variability of each soil property were determined, and the results are presented in Tables 5.1 through 5.3.

Table 5.1. The best spectral bands for explaining the variability of soil properties that were significantly different among management zones, and the amount of variability (R^2) explained, at study site I (Greeley), Colorado.

Soil Property	Spectral band	Model Type[b]	R^2
Organic carbon	NIR	Spatial	0.35
Sand fraction	NIR	OLS	0.45
Silt fraction	NIR	OLS	0.55
Cone index at 5 cm depth	NIR; R[a]	Spatial	0.49

[a] NIR and R refer to the near infrared and red wavelength bands, respectively.

[b] If the two models were not significantly different at the 10 % level, then the spatial model was preferred over the ordinary least squares (OLS) model.

Table 5.2. The best spectral bands for explaining the variability of soil properties that were significantly different among management zones, and the amount of variability (R^2) explained, at study site II (Wiggins), Colorado.

Soil Property	Spectral band	Model Type[b]	R^2
Volumetric water content	NIR; R; G[a]	Spatial	0.73
Dry soil color	NIR; R	OLS	0.65
Wet soil color	NIR; R	Spatial	0.60
Organic carbon	NIR; G	Spatial	0.65
Sand fraction	G	Spatial	0.42
Silt fraction	G	Spatial	0.41
Clay fraction	G	Spatial	0.33
Sorptivity	G	Spatial	0.13

[a] NIR, R and G refer to the near infrared, red, and green wavelength bands, respectively.
[b] If the two models were not significantly different at the 10 % level, then the spatial model was preferred over the ordinary least squares (OLS) model.

Table 5.3. The best spectral bands for explaining the variability of soil properties that were significantly different among management zones, and the amount of variability (R^2) explained, at study site III (Yuma), Colorado.

Soil Property	Spectral bands	Model Type[b]	R^2
Dry soil color	NIR; G	Spatial	0.37
Wet soil color	NIR; R; G[a]	OLS	0.52
Silt fraction	R; G	Spatial	0.32
Cone index at 5 cm depth	NIR; G	Spatial	0.10

[a] NIR, R and G refer to the near infrared, red, and green wavelength bands, respectively.

[b] If the two models were not significantly different at the 10 % level, then the spatial model was preferred over the ordinary least squares (OLS) model.

Although the variability of surface bulk density among management zones was significant in all fields, it had no significant relationship with reflectance in any of the three wavelength bands. When compaction occurs, soil particles are rearranged and the size of macropores is reduced. Variations in surface compaction would, therefore, be expected to have different effects on the amount of radiation reflected by the particles, and that entrapped in the soil pores. The amount of variability (10%) of cone index at the 5 cm depth explained by the green and near infrared (NIR) bands at site III was relatively small (Table 5.3). However, cone index at the same depth at site I showed a relatively high relationship ($R^2 = 49\%$) between compaction and reflectance in the NIR and red bands (Table 5.1). This could show that reflectance may be better correlated with compaction measured with cone index than that measured with bulk density. This is probably because both cone index and reflectance are related to soil moisture conditions, whereas bulk density is measured on a dry soil basis. Wells et al. (2001) found a relationship between cone index in the upper 400 mm of the soil and NIR. Wells et al (2000) found the correlation between reflectance data and cone index to be disappointing. They suggested that the appropriate time to acquire remote imagery for identifying areas of potential compaction would be a short time after a substantial rainfall event. Areas of compaction would be waterlogged and appear darker than other areas on an image. It appears that the NIR band can help explain the variability of compaction measured with cone index.

All the three bands could be used to explain the variability of dry and moist soil color, with any combination of bands found to differ from one field to another. The variability of soil color explained by the bands was 60 to 65% at site II (Table 5.2) and 37 to 52% at site III (Table 5.3). This could be due to the significant difference in organic carbon among zones at site II. The amount of variability of organic carbon explained by reflectance data was 65% at site II, which is similar to the variability of color explained by reflectance data at the same site. The amount of variability of dry soil color explained by the red and green bands at site I (Table 5.4) was 36%. This was similar to the amount of variability (35%) of organic carbon explained by the NIR band at the same site (Table 5.4). Page (1974) found that 80% of the total variation in organic matter could be accounted for by reflectance. Other studies showed that the variability in organic matter could be explained by the NIR band (Page, 1974), and by all three of the CIR-DOQ bands (Coleman and Tadesse, 1995). It appears that the variability in organic carbon can be classified using a combination of any of the green, red and NIR bands. The variability of organic carbon also appears to be related to the variability of soil color.

When both the zones and bands were used together to explain the variability of color, the amount of variability ranged from 65 to 69% at site II (Table 5.5) and 40 to 56% at site III (Table 5.6). This suggests that the variability of soil color explained by the management zones was relatively related to the variability of color explained by reflectance data.

Although Coleman and Tadesse (1995) found that red was the key band for predicting sand content, Table 5.2 shows that green was the key band for predicting the variability of all three soil separates at site II. The amount of variability explained by the green band at this site was 33%, 41%, and 42% for clay, silt, and sand, respectively . A combination

Table 5.4. The amount of variability explained by the model whose parameters were selected from a combination of management zones and wavelength bands, for study site I (Greeley), Colorado.

Soil Property	Model[a]	R^2
Surface Bulk Density	Zones	0.26
Dry Soil Color	R; G	0.36
Organic Carbon	NIR	0.35
Sand Fraction	NIR	0.46
Silt Fraction	NIR	0.56
Clay Fraction	R; G	0.34
Cone Index at 5 cm Depth	NIR; R	0.49

[a] NIR, R, and G refer to the near infrared, red, and green wavelength bands, respectively

Table 5.5. The amount of variability explained by the model whose parameters were selected from a combination of management zones and wavelength bands, for study site II (Wiggins), Colorado.

Soil Property	Model	R^2
Surface Bulk Density	Zones	0.11
Bulk Density at 60 cm Depth	Zones; R; G	0.15
Bulk Density at 90 cm Depth	NIR; R; G[a]	0.20
Total Pore Space at 60 cm Depth	Zones; R; G	0.15
Total Pore Space at 90 cm Depth	R; G	0.17
Volumetric Water Content	Zones; NIR; G	0.77
Dry Soil Color	Zones; NIR; R	0.69
Wet Soil Color	Zones; R	0.65
Organic Carbon	Zones; NIR; G	0.69
Sand Fraction	Zones; G	0.46
Silt Fraction	Zones; G	0.50
Clay Fraction	G	0.33
Cone Index at 20 cm Depth	Zones	0.25
Sorptivity	Zones; NIR; G	0.30

[a] NIR, R, and G refer to the near infrared, red, and green wavelength bands, respectively

Table 5.6. The amount of variability explained by the model whose parameters were selected from a combination of management zones and wavelength bands, for study site III (Yuma), Colorado.

Soil Property	Model[a]	R^2
Surface Bulk Density	Zones	0.17
Bulk Density at 30 cm Depth	Zones; R; G	0.25
Total Pore Space at 30 cm Depth	Zones; R; G	0.25
Volumetric Water Content	Zones; R; G	0.29
Dry Soil Color	Zones; NIR; G	0.40
Wet Soil Color	Zones; NIR; G	0.56
Organic Carbon	R; G	0.47
Sand Fraction	R; G	0.29
Silt Fraction	R; G	0.32
Clay Fraction	NIR; G	0.18
Sorptivity	NIR; R	0.20

[a] NIR, R, and G refer to the near infrared, red, and green wavelength bands, respectively

of the green band and zones explained 46% and 50% of the variability in sand and silt content, respectively, at site II (Table 5.5). At site I, 45% and 55 % of the amount of variability of sand and silt, respectively was explained by the NIR band (Tables 5.1 and 5.4). The amount of variability of silt explained by the green and red bands was 32% at site III (Table 5.6). Stoner et al (1980) cited by Coleman and Tadesse (1995) reported that reflectance in the NIR often reveals textural differences. Montgomery (1976) cited by Hoffer (1978) found that the amount of silt present was the major factor in explaining the level of reflectance in both the visible and reflective infrared portions of the spectrum. The results of this study, and those reported in the literature, suggest that any one band or a combination of the visible and NIR bands could explain textural differences, depending on the site properties. The inclusion of zones, in addition to reflectance data, resulted in a less than 10% increase in the amount of variability of soil separates explained.

It is suggested that soil texture may provide misleading information if color as seen on bare soil images is used to delineate zones. For example, if the sand fraction is significantly different across a field, the amount of reflected energy would be reduced in those areas with a relatively high sand fraction. Hoffer (1978) stated that if other factors are constant, as particle size decreases, more incoming energy is reflected. Reflectance also decreases with an increase in organic matter content (Hoffer, 1978). If color as seen on a remotely sensed image is used to delineate management zones, areas that appear darker may be thought to indicate higher fertility due to relatively high organic matter content. The dark color may be due to a relatively high sand fraction, resulting in these areas being less productive than the finer textured soils which would appear lighter on the same field.

The surface soil properties that were, in combination, best related to each band were selected from all the measured soil properties, and the results are shown in Tables 5.7 to 5.9. At sites I (Greeley) and II (Wiggins), silt was related to all three bands (Tables 5.7 and 5.8), but it was related to the NIR band only in Tables 5.1 and 5.4. This could show that although NIR is the most important, the green and red bands can also be used to assess the variability of silt. This result from sites I and II supports the observation from a previous investigation. The amount of silt was more important than that of sand and clay in explaining the level of reflectance in both the visible and reflective infrared portions of the spectrum (Montgomery, 1976 cited by Hoffer, 1978).

All three bands were also important in explaining the variability of both dry and wet color, surface water content, and organic carbon at either site II or III (Tables 5.8 and 5.9). Reflectance was best related to surface water content and dry soil color at site II (Table 5.8), and it was best related to organic carbon and moist soil color at site III (Table 5.9). The results in Table 5.9 could indicate that the variability of color may best be assessed by remote sensing when the soil is relatively moist. The variability of carbon, which could be closely related to that of moist color, would also be best assessed by remote sensing when the soil is relatively moist. Dry soil color was more related to reflectance than moist soil color was related to reflectance at site II (Table 5.8).

Table 5.7. The models that comprise a combination of surface soil properties that had the best relationship with individual wavelength bands, at site I (Greeley), Colorado.

Band	Best Model Parameters	R^2
NIR	Silt fraction	0.55
Red	Silt fraction; Cone index at 0 cm (surface) Cone index at 5 cm	0.59
Green	Silt fraction; Cone index at 0 cm (surface) Cone index at 5 cm	0.61

Table 5.8. The models that comprise a combination of surface soil properties that had the best relationship with individual wavelength bands, at site II (Wiggins), Colorado.

Band	Best Model Parameters	R^2
NIR	Surface water content; Dry surface soil color; Silt fraction;	0.64
Red	Surface water content; Dry surface soil color; Silt fraction	0.73
Green	Surface water content; Dry surface soil color; Silt fraction	0.74

Table 5.9. The models that comprise a combination of surface soil properties that had the best relationship with individual wavelength bands, at site III (Yuma), Colorado.

Band	Best Model Parameters	R^2
NIR	Moist surface soil color; Organic carbon	0.59
Red	Moist surface soil color; Organic carbon	0.65
Green	Moist surface soil color; Organic carbon	0.62

Therefore, the desirable state of the soil when remote sensing is used to assess the variability of soil properties could depend on both the site characteristics and soil properties to be assessed.

Conclusions

The variability of certain soil properties can be explained by bare soil reflectance. These soil properties include compaction, soil color, organic carbon and soil texture. Bare soil reflectance can, therefore, be used to delineate fields into zones of similar productivity on the basis of soil properties.

The most important wavelength bands that could explain the variability of a given soil property differed from one field to another. However, even though some bands were more important than others in a given field, it was found that the NIR, red and green bands could be all useful in assessing the variability of most soil properties.

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