Tillage effects on seedbed physical properties

by

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For the Major Program

DEDICATION

To my parents, wife, and family.

Your personal achievements were my greatest inspiration.

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ABSTRACT

Intensive tillage requires high energy input and may be detrimental to the environment. There is a need to develop decision support tools to assist farmers in determining optimum tillage intensity for high yields. Previous studies developed quantitative indices that related tilth conditions to yield. The indices, however, proved to be inadequate and sometimes inconsistent. Thus, a three-part research project was carried out from 1998 to 2000 to quantify seedbed condition following tillage and to explain subsequent variation in corn *(Zea mays L.)* yield. Conventional and spatial statistics were used to study the effects of bulk density, penetration resistance and soil moisture content on and biomass at the V2 growth stage (the corn growth stage when the collar of the second leaf has fully developed), and grain yield. A soil condition index was developed and it combined soil physical properties into a single value that was related to yield using regression methods. The soil condition index gave promising results for prediction of early season plant biomass, but was not helpful in predicting grain yield. Confounding of weather conditions made it difficult to determine the true functional relationship between soil tilth and crop yield. Yield and soil map overlays revealed spatial patterns that would have otherwise been aggregated' if only conventional statistical methods were used. With careful experimental design, the impact of weather and other sources of experimental error in tillage trials could be minimized. The research project provided a framework for future experiments focused on quantifying soil tilth.

CHAPTER 1. GENERAL INTRODUCTION

INTRODUCTION

Conventional tillage remains popular among US farmers despite the increased use of conservation tillage in the 1980's (Cannell and Hawes, 1994). Typical characteristics of conventional tillage are that it has a long tradition, pulverizes the soil for easy root penetration, controls weeds and incorporates agricultural chemicals. Despite the aforementioned benefits, the negative environmental impact of conventional tillage causes is a concern to farmers and society. Conventional tillage loosens the soil surface and destroys the surface vegetation (mostly crop residue) that protects topsoil from the soil erosion that potentially reduces long-term production capabilities of the soil (Cruse and Colvin, 1989). It also exposes soil to higher temperatures, thereby encouraging moisture loss (Guérif et al., 2001). Conventional tillage also requires more draft energy than reduced tillage. That means bigger and more costly implements and tractors, or other power sources are needed for conventional tillage operations compared to conservation tillage which is defined as a tillage operation leaving at least 30% of the soil surface covered by residue after planting.

Given these negative impacts, past and current research has been geared towards limiting tillage to the level that is absolutely necessary for optimizing crop yield. Some studies have shown that crop yield can be increased by plowing the soil, but the amount of tillage needed to obtain optimum yield is not known. The major obstacle to determining this is that soil condition following tillage can not be adequately evaluated (Dexter, 1988). Consequently, it is difficult to judge how much tillage is required to improve the seedbed condition of a particular soil to get optimum yield. A seedbed is defined by Hadas A. (1997), as "the topsoil layer, finely tilled to ensure soil conditions promoting fast seed germination, emergence, and uniform stand establishment."

Attempts have been made to create evaluation tools or methods to quantify seedbed conditions following tillage (Carter, 1990; Hakansson, 1990; Hakansson and Lipiec, 2000; Singh and Colvin, 1992; Tapela and Colvin, 1998). Some of the methods that were proposed used techniques that measured soil physical properties and scaled them by relating them to expected yield (Singh and Colvin, 1992; Tapela and Colvin, 1998). These approaches provided some useful guidelines, but were neither adequate nor consistent.

A useful seedbed evaluation tool would be one that could be used to select the type of tillage implement to use under given soil conditions, to achieve an optimal seedbed condition, with minimum possible energy input (Bertrand, 1967). The use of these evaluation tools, in conjunction with spatial analysis and yield mapping, may provide a better assessment of how tillage management can be improved. The aim should be to balance the benefits of soil conservation against a desired tilth condition.

DISSERTATION ORGANIZATION

This dissertation follows a paper (manuscript) format. It is organized into five chapters. Chapter one (this chapter) consists of the general introduction that gives a brief overview on the relevance of the research topic to agricultural production. This chapter also gives the organizational structure of the dissertation, general literature review, statement of the research problem and the general objectives. References cited in this chapter are listed at the end of the dissertation before the appendix section.

Chapters two, three and four contain separate papers (manuscripts) covering topics that fall within the general theme introduced in the first chapter. Specifically, chapter two describes a method for combining different soil physical properties into an index through regression methods, and make pair-wise comparisons of the seedbed conditions resulting from three different tillage practices (no-tillage, reduced tillage and conventional tillage). Chapter three describes research that uses yield data and maps to compare crop yield variation for different years under different tillage practices (Fall moldboard plow, fall chisel plow, slot plant on ridges, spring disk and till-plant). Soil physical properties are used to explain variability or patterns that occur in the yield maps. Chapter four discusses statistical considerations in designing and carrying out experiments for spatially dependent data. It includes a proposed statistical design that may be suitable for tillage evaluation trials. Chapter five provides the overall conclusions and suggestions for future research work based on these results. Appendices 1 and 2 include the raw data used to prepare tables and figures in Chapters 1 and 2 respectively.

LITERATURE REVIEW

Benefits of tillage to crop production

Tillage is as old as crop production itself. Early humans used primitive tools such as sticks to create a hole in the ground into which to plant seeds. In time, the stick evolved into a more efficient tool that required less human effort until it eventually took the different plow forms as we now know them (moldboard, disk, chisel and tined plows). The basic reason for tillage is to create a soil condition that allows easy placement of the seed and puts the seed in contact with the soil to provide moisture, support and warmth (Dexter, 1988). With modern equipment, other benefits of tillage include burying of weeds, soil compaction control (Cannell and Hawes, 1994), incorporation of agricultural chemicals, and creation of surface structures that control wind erosion.

Concerns about excessive tillage

Despite the benefits of conventional tillage, it has two major disadvantages. These are the amount of energy required to carryout the tillage operations and the environmental impact that tillage has on soil, water and air resources. Of all the farm operations performed in the developed world, tillage ranks among the top two (the other being harvesting) with regard to power consumption. This puts an economic strain on farmers, especially if the tillage operation does not increase crop productivity. As fields get larger, tillage equipment also tends to get bigger and heavier. With regard to environmental impact, conventional tillage with a moldboard or disk plow that completely turns the soil has been blamed for promoting soil erosion (Guérif et al., 2001). As the soil is overturned, crop residue is buried and the subsoil is usually exposed rendering it vulnerable to erosion. Conventional tillage also promotes rapid decomposition of mulch and thus adds to the release of CO_2 to the atmosphere. Carbon dioxide is known to promote global warming that leads to changes in weather patterns. Given these economic and environmental concerns, there has been a move to direct research and farm operations toward methods that minimize tillage intensity to levels that are necessary to optimize crop yield, and yet minimize environmental inputs.

Strategies for limiting tillage intensity

Conservation tillage generally reduces tillage intensity (Cannell and Hawes, 1994), by using tillage and planting tools that work the soil to a more shallow depth. These tools include chisel plow, no-till, ridge-till planters, and slot-planters. Residues or mulch left on the surface limit evaporation, soil erosion and soil crusting (Guèrif et al., 2001). Conservation tillage methods are less aggressive on the soil, and because of that, do not require as much specific draft power as conventional tillage. Guèrif et al. (2001) also reported that conservation tillage methods save time, usually without reducing yields. Their use however normally compels farmers to use herbicides to control weeds, and thus pose another possible problem with environmental contamination.

Another strategy is to be less aggressive on the soil, but still do controlled conventional tillage. To be able to limit the amount of tillage done requires one to be able to adequately evaluate a plowed field and judge whether it has been tilled suitably for the crop to be planted. This need leads to the subject of seedbed evaluation methods. At present "it is not possible to predict the resulting soil condition from any tillage operation" (Dexter, 1988). A valid soil evaluation method would be one that could be used to select the type of implement to use under given soil conditions, to achieve optimal seedbed conditions, with minimum possible energy input and lowest impact on the environment.

Seedbed evaluation methods

The traditional method of seedbed evaluation is to make a visual assessment of the adequacy of the soil to support a planted crop. The method is qualitative and leads to arbitrary and subjective classification (Tapela and Colvin, 1998), such as "good tilth" or "poor tilth". The problem with subjective evaluation methods is that they can not be used reliably to make management decisions regarding tillage. Thus, there is a need to develop quantitative evaluation methods that are more predictable. Karlen et al. (1998) pointed out that soil quality can not be measured directly, but must be inferred or estimated by key indicators.

Quantitative seedbed evaluation methods can generally be classified into two categories. The first is to directly measure soil physical or mechanical properties and rate them according to how much yield is produced. The second includes methods that combine several soil physical properties into mathematical expressions, pseudo-transfer functions or process models (Acock and Pachepsky, 1997), to give a more global evaluation of the soil.

In the first category, soil physical properties that are often measured include bulk density, penetration resistance, mean weight diameter, clod size and porosity (Becher et al., 1997; Carter, 1990; Fragin, 1986; Hakansson, 1990; Luttrell, 1963, Steyn and Tolmay, 1995). Because these methods involve measuring a single property, they provide "a relatively simple methodology for rapid determination of soil structure" (Carter, 1992). But Karlen et al., (1997) warns that measuring and reporting an individual soil parameter is no longer sufficient since some properties such as bulk density may be confounded by several other factors. Confounding factors include soil moisture and organic matter content (Karlen et. al, 1999; Steyn and Tolmay, 1995). As Shein and Makhnovetzkaya, (1996) recommend, "an ideal index of (soil) physical condition must reflect numerically not a single property, but an entire agrophysical status of a soil."

Methods that are classified in the second category include the soil tilth index (Singh et. al., 1992; Tapela and Colvin, 1998), the index of physical condition (Shein and Makhnovetzkaya, 1996), scoring functions (Karlen and Stott, 1994), and the least limiting water range index (da Silva et. al., 1994). They are developed from empirical data measuring soil physical properties and crop yield. The yield is predicted from the soil properties to develop a quantitative relationship that can be used to predict future production levels.

Soil is a complex medium, consisting not only of physical but also biological and chemical factors. Environmental factors, such as rainfall and temperature levels, also affect yield. These factors interact to make it difficult to model the effects of physical conditions on yield. "Empirical models are not very useful, because they have none of our understanding of crop behavior built into them" (Acock and Pachepsky, 1997). However, some methods show promising results, even though certain inconsistencies remain.

More recently, geographic information systems and other precision farming technologies have been used to study the effects of seedbed conditions on crop yield. Spatially referenced soil and yields maps are used to understand yield variations (Shatar and McBratney, 1999). The science is new, and therefore still needs perfecting, as seen in the number of data errors (O'Neal et al. 1988).

OBJECTIVES

The general objective of this research is to study how soil physical properties may be used to quantitatively evaluate soil conditions and yield differences following tillage. The specific objectives are to:

1. use soil physical properties to quantify seedbed conditions and compare yield levels resulting from different tillage systems.
2. use soil physical properties to explain yield variability on a field managed under different tillage systems.
3. review statistical design methods for spatial data, and propose a suitable statistical approach for investigating seedbed conditions.

CHAPTER 2. QUANTIFYING SEEDBED CONDITION USING SOIL PHYSICAL PROPERTIES

A paper submitted the Soil and Tillage Research Journal

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ABSTRACT

Soil physical condition following tillage influences crop yield, but the desired condition cannot be adequately evaluated with current techniques. This study was conducted to determine a soil condition index (SCI) that could be used to select the type of implement needed to achieve an optimal seedbed with minimum energy input. Effects of bulk density, moisture content, and penetration resistance resulting from three tillage systems (no-till, chisel plow and moldboard plow), on the growth of corn *(Zea mays L.)* were studied. The experiment was conducted in Boone County, Iowa on soils that are mostly Aquic Hapludolls, Typic Haplaquolls and Typic Hapludolls with slopes ranging from 0 to 5%. The results are from the 2000 season, which had normal weather conditions and yield levels for the state of Iowa. The average corn grain yield at this site was 9.36 Mg/ha. At the V2 corn growth stage (growth stage when the collar of the second

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leaf has just completely opened), the average dry biomass was 1.34 g/plant. The soil physical properties were normalized with respect to reference values and combined via multiple regression analysis against plant biomass into the SCI. Mean SCI values for the no-till, chisel and moldboard plow treatments were 0.86, 0.76, and 0.73, respectively, all with a standard error of 0.013. The lower the SCI, the more optimum the soil physical conditions. An analysis of variance showed significant differences among mean SCI for each treatment (p-value = 0.001). The SCI appears to sufficiently model the effect of proctor density ratio (PDR) and moisture ratio (MR) on corn biomass at the V2 stage. Use of the SCI could improve the tillage decision-making process in environments similar to the one studied.

Keywords: bulk density, penetration resistance, moisture content, soil quality, tilth, soil condition.

INTRODUCTION

Tillage has many purposes, including the creation of a suitable seedbed for germination and plant growth, incorporation of agricultural chemicals and crop residues, burying weeds, or construction of certain land structures for wind erosion control. For seedbeds, tillage often pulverizes the soil allowing for unimpeded root growth and easy flow of air and water. Many of the benefits of tillage are well known, but the amount of tillage necessary to achieve optimum soil conditions is not.

The tilth or soil condition resulting from the use of different tillage tools depends on both the type of implement used and the soil condition when tillage occurs. At present, it is not possible to consistently predict the resulting soil conditions from any tillage operation. According to Dexter (1988), too much emphasis has been placed on primary failure of soil surfaces and not enough on the crumbling produced by tillage. Although some tillage is generally needed, excessive tillage can cause the soil to be vulnerable to wind and water erosion. It can also increase the operational costs incurred by farmers.

Previous attempts to quantify the seedbed conditions following tillage have been made, but it has been difficult to determine which soil physical properties should be used to measure tilth. Researchers often use porosity, bulk density, structure, compaction, particle size distribution, and clod size distribution (Luttrell, 1963; Fragin, 1986; Hakansson, 1990; Steyn and Tolmay, 1995; ESCAP, 1995). Among these properties, bulk density remains the most popular and widely measured. Bulk density changes are most evident following tillage, when compared to other physical soil condition indicators. Burov et al, (1973) however, warned that the field method for determining bulk density is not very accurate and gives only an approximate idea of soil make up. Karlen et al. (1999) further state that since several factors (such as moisture and organic matter content) can confound bulk density measurements, it should not be the only soil physical factor used as a soil quality indicator.

Recently, some soil properties have been mathematically adapted to both describe the tilth and the capacity of a soil to support a particular crop for maximum yield. Measurements such as the K coefficient (Fragin, 1986), roughness index (Gupta et al, 1991), resistance to penetration (Becher et al, 1997), relative compaction (Carter, 1990) and degree of compactness (Hakansson, 1990; da Silva et. al, 1997; Hakansson and

Lipiec, 2000) were proposed by the researchers as possible ways to quantify soil condition.

The degree of compactness, relative compaction and resistance to penetration indices, use a single soil property to model a complex environment. Therefore, they risk oversimplifying the tilth status and also may result in a mathematically correct relationship that has no physical or biological relationship to crop growth and development.

Combining several soil physical factors to account for the complexity of the soil environment was a common goal among researchers in the 1990s (Singh and Colvin, 1992; Williams et al., 1992; da Silva et al, 1994; da Silva and Kay, 1997; da Silva et al, 1997). Regression procedures were used by Williams et al. (1992) to model tilth. They selected only those soil variables that made a significant contribution toward yield. da Silva et al. (1994) characterized the structural quality of the soil using the least limiting water range index (LLWR). The LLWR was a range in soil water content after rapid drainage had ceased and where water potential, aeration, and mechanical resistance to root penetration had minimal effect on plant growth (da Silva and Kay, 1997). They found that using the degree of compaction (relative density) instead of bulk density improved the applicability of the model by diminishing differences in values of LLWR between different soil types. Similar results were obtained by da Silva et al. (1997). However, calculation of LLWR is time consuming, therefore limiting its adoption for use on a routine basis (da Silva and Kay, 1997). Thus, pedo-transfer functions to model the influence of tillage and soil properties on LLWR have been developed in order to reduce the amount of required data collection. Singh and Colvin (1992) and Singh et al. (1992)

used tilth coefficients to model the relationship between soil variables and yield. The "Tilth Index" was a quantitative value ranging from 0.0 for worst to 1.0 for best conditions used to describe soil conditions relating to plant growth. Tapela and Colvin (1998) found that determining the tilth coefficients was iterative and arbitrary. They modified Singh et. al. (1992)'s linear correlation model to a new quadratic relationship. However, neither model could consistently distinguish which tillage method produced better tilth. This confirmed that their methods needed further refinement and investigation.

Soil condition can be examined holistically by considering the chemical, biological, and physical factors affected by tillage. This approach is consistent with the concept of soil quality that has been extensively researched by Karlen et al. (1999). Simply defined, soil quality is the capacity of the soil to function. Each soil indicator supporting a given function is related quantitatively to the function it supports (Harris et al., 1996). Using scoring functions requires no simulation modeling to estimate the functional relationships between soil properties and soil quality, and the method is easy to use.

Despite the attempts made over the years, seedbed evaluation remains subjective. Being able to quantify such a condition would allow farmers to target the intensity of their tillage operation. This would eliminate unnecessary costs incurred by farmers using aggressive tools to achieve what could be done using lower disturbance tools. It would also help to interpret data from various soil measurements and show whether management is having the desired results on productivity (Granatistein and Bezdicek, 1992). Research is therefore needed to identify appropriate parameters and protocols for combining various soil measurements into meaningful index values at various scales.

The objective for this research is to combine soil physical properties through regression methods, and use them to make pair-wise comparisons of seedbed conditions resulting from three different long-term tillage practices (no-till, reduced tillage and conventional tillage).

MATERIALS AND METHODS

A field experiment was conducted at the Kelly experimental farm operated by Iowa State University in Boone County, Iowa. The experiment was a randomized complete block design comparing no-till, fall moldboard and fall chisel plowing. No further cultivation was done following primary tillage. Roundup®[1] (glyphosate) herbicide was applied in spring one week before planting to control weeds. The test crop was corn (*Zea mays L.*), Pioneer variety 34B23, and was planted at a seeding rate of 74500 plants per hectare. Liquid urea-ammonium nitrate fertilizer (32% N) was applied at a rate 0.21 tons $ha^{-1}$of on all plots. Previously the site had been managed using a soybean (*Glycine max. L*), corn (*Zea mays L.*) and oats (*Avena sativa*) rotation for three years. The primary tillage tool used in previous seasons was fall moldboard followed by spring cultivation. The soils at the experimental site are Aquic Hapludolls, Typic Haplaquolls and Typic Hapludolls with slopes ranging from 0 to 5 % (USDA,1981). The

[1] Trade names are provided for the benefit of the reader and do not imply endorsement or preferential treatment of the products by Iowa State University or the USDA/ARS National Soil Tilth Laboratory.

average monthly temperature during the growing season (May 5 – October 13) was 16^{0}C and with average mean monthly precipitation of 60 mm.

The experiment was set-up by establishing 12 plots (7.6 m wide and 53.3 m long) that lay side by side lengthwise. Four blocks of three plots each were created across the direction of the field slope. Measurements were made on each plot in the inter-row spaces not affected by wheel traffic in order to identify differences in bulk density (D_b), penetration resistance or cone index (CI), and moisture content (MC) due to tillage. The inter-row spacing was 0.76 m, making a total of 10 rows per plot.

Before tillage in fall 1999, D_b was measured within the surface layer using undisturbed cores that were 76 mm diameter by 51 mm high. The sampling depth was from the soil surface. Each plot was sampled 6 times in a staggered design spanning the length of the field, thus providing a total of 72 D_b measurements. The same cores collected for D_b were also used to determine the soil moisture content by the oven drying method (Blake and Hartge, 1986). For measurement of penetration resistance, a standard digital cone penetrometer (13 mm^2, 12 mm diameter and 30°-cone slope) was used. CI measurements were also taken 6 times in each plot from locations beside D_b measurements. Readings were taken at 5, 10, and 15 cm depths (plowing zone) at each location following the procedure described in the ASAE standard S313.2 (ASAE, 1993). A second sampling for D_b, CI, and MC was made in spring 2000 before planting.

From the D_b measurements, proctor density ratio (PDR) was computed as D_b/D_{bp}. The value of D_{bp} in the ratio is the proctor density of the soil at the same moisture content when D_b was measured. It was important to have the ratio at the same moisture content so that comparison can be made across similar soils at different moisture levels. PDR ranges between 0 and 1 for cultivated fields. A low PDR value will indicate a loose soil while a dense soil will approach 1.

Penetration ratio (PR) was calculated from penetration resistance values. It was computed as (MCI – CI) MCI^{-1}. The value of CI is the average penetration resistance measured at the three depths for each point location, and MCI (3.5 MPa) is the maximum cone index found in most fields (Tapela and Colvin, 1998; Vepraskas and Wagger, 1989). The 3.5 MPa was used as the limiting value instead of the common crop growth limit of 2 MPa (da Silva et al, 1994; Singh et al, 1992), so that the CI can be related to the maximum compaction in the cultivated field. The value is an approximation, as it is strongly dependent on moisture content, a factor accounted for in the moisture ratio (MR).

Moisture ratio was derived from the measured moisture content values and is computed as $1 - \{[(\Sigma (MC-FC)^2)/6]^{1/2}\}FC^{-1}$. It describes the variation of the field moisture content from field capacity (FC) based on an average of six moisture samples collected per plot. Field capacity was assumed to be the moisture of a soil held between 0.01 and 0.03 kPa matric suction (Klenin et al, 1970, da Silva et al, 1994). The pressure cell procedure for determining soil moisture at field capacity is outlined in Klute (1986). For this study, five undisturbed core surface soil samples (76 mm diameter x 76 mm height) were collected prior to tillage in fall 1999 and were used for the low range pressure systems (0.03kPa). Moisture levels were measured after subjecting the samples to 0.03 kPa suction for 72 hours. The average moisture content at 0.03 kPa was assumed to be equivalent to the field capacity.

Soil sampling for the Proctor compaction test was done by randomly collecting four samples of approximately 20 kg each from throughout the whole field in the fall 1999 and allowing the samples to air-dry. After drying, clods were broken down using a soil grinder and each sample was sieved through a 4.75 mm sieve to obtain about 12 kg of soil. The sieved samples were mixed together and again divided into five sub-samples of about 2.3 kg each. The sub-samples were then wetted to varying moisture contents by adding increasing amounts of water and thoroughly mixing in sealed plastic bags. The sub-samples were allowed to remain in the bags for five days at room conditions (22°C). Each day they were stirred to obtain a thorough mix and uniform moisture distribution. After that the standard proctor density test was performed as outlined in ASTM D 698 standard (ASTM, 1998, Liu and Evett, 2000). The D_{bp} was plotted against soil moisture and the maximum D_{bp} was determined graphically.

With values for PDR, PR and MR, the soil condition index (SCI) for each plot, following tillage, was calculated as (p_1 x PDR + p_2 x PR + p_3 x MR). The p_i –values (i =1, 2, 3) were the proportion of improvement to the coefficient of determination as each factor was included in the model that predict yield. Crop growth measurements were average biomass per plant at V2 growth stage (Ritchie et al, 1993) and grain yield. Six locations were randomly identified within each plot for plant biomass sampling. Sampling was done by uprooting single plants on three rows for each location, and determining the average dry mass of the above-ground material. An assumption was made that proctor values at the same moisture content and water retention at similar tensions were uniform across the whole field.

The Statistical Analysis System (SAS®, 1990) package was used to randomly assign treatments to the plots on the different blocks. An analysis of variance (ANOVA) was performed to assess the influence of tillage method on yield and plant dry biomass at the V2 corn growth stage. Multiple regression analysis was also done to determine the influence of PDR, PR and MR on yield and plant dry biomass at the V2 corn growth stage. The anova and multiple regression used mean values for the six PDR, PR and MR measurements from each treatment. Mallows' Cp model selection procedure (SAS, 1990; Ramsey and Schafer, 1997) was used to determine the best regression model (among all possible independent variable combinations) that could be used to predict yield and plant dry biomass at V2 growth stage. An analysis of variance was also done to determine if there was any difference in mean SCI for each tillage treatment within the blocks.

RESULTS AND DISCUSSION

Measured values of D_b, MC and CI ranged from 1.16 to 1.69 Mg m^{-3}, 16 to 30 % and 0.6 to 3.8 Mpa, respectively, across the whole field before tillage in fall 1999. At planting in spring 2000, the values ranged from 0.94 to 1.66 Mg m^{-3}, 9 to 27 % and 0.1 to 3.2 MPa for D_b, MC and CI, respectively. The lower D_b and CI values in spring sampling are a result of tillage operations that loosened the soil after fall sampling. Moisture content was also lower in spring because sampling was done after 8 weeks of low rainfall. However, all the three parameters were within levels that would not impede plant growth. Table 1 shows average values for PDR, MR, PR and response values from each plot based on spring sampling data. Analysis of variance for biomass differences among tillage treatments within was significant (p-value=0.02), but was not significant for mean tillage yield within blocks (p-value=0.16). Mean biomass for moldboard tillage was significantly different from either chisel or no-till systems when tested with the Tukey multiple comparison test. The non-significant yield differences may be due to compensatory growth after V2 stage as found on soybeans by Yusuf et al. (1999).

Multiple regression of PDR, MR and PR against biomass at V2 stage based on fall sampling data had a coefficient of determination of 0.71. However, the only significant regression coefficient was that for MR (p=0.05). Letey (1985) also noted similar result that; water was a dominant controlling factor related to plant growth and soil penetration resistance tends to increase with increasing moisture tension (Bilanski and Varma, 1976), affecting subsequent crop growth. Including blocking factor in the same regression model did not provide much improvement (R^2=0.72). Similar results were obtained when the same data was used in a regression model of PDR, MR and PR against yield values. The model had a coefficient of determination of 0.47, and again only MR had a significant coefficient (p=0.03).

The results based on spring data show that a decrease in MR leads to an increase in PDR and a corresponding decrease in PR (Figure 1). Essentially, it means low moisture content is associated with an increase with both bulk density and penetration resistance, resulting in a decrease in both plant and root growth (Letey, 1985). The association occurs because greater reduction in water content lead to a greater increase in soil cohesion and internal friction, leading to higher bulk density and penetration resistance (Bilanski and Varmin, 1976). Multiple regression of PDR, MR and PR on biomass based on spring sampling data had a coefficient of determination of 0.85 (p-value=0.001). The coefficient for PR was not significant (p=0.92). The reason may be that PR is closely related to PDR (r= -0.76), which was already included in the model. Other correlations between soil variables were not as high as between PDR and PR (PDR vs. MR = -0.43; PR vs. MR = 0.05).

The multiple regression coefficient of determination of yield against PDR, MR and PR was 0.49 (p-value=0.127). It showed there was no significant difference in yield due to the independent variables. Unlike biomass, yield was measured at the end of the season after other environmental factors, such as precipitation and temperature, had affected the crop. Thus it is not possible to isolate differences due to these factors from the ones being tested. The lack of linear correlation between yield and biomass at V2 stage is confirmed by a low correlation coefficient of –0.23. Because of low correlation with yield, no further interpretation was done on the yield model. A regression equation (Equation 1) for biomass against the independent variables was written using the estimated regression parameters (Table 2) as;

$$\text{Biomass} = 4.389 - 1.69\text{PDR} - 2.03\text{MR} - 0.03\text{PR} \qquad (1)$$

A t-test, to determine if any of the parameter estimates were equal to zero, showed that the parameter for PR was not significant (Table 2). Therefore, it was safe to exclude PR from the full model, as it contributed very little to individual plant biomass level. The t-test was confirmed when the Mallows' C_p model selection criterion was used (Table 3). Accordingly, the model with only PDR and MR as independent variables was selected ($C_p = 2.01$).

The exclusion of the PR from the model does not mean that penetration resistance was not important in soil physical conditions. The reason may be that it was so closely related to the PDR, (r = -0.76) that it was in fact a linear transformation of this variable. Alternatively, it may be that the form in which PR was presented in the model needs some modification, such as log transformation, so that it relates better to individual plant biomass.

After performing the regression procedure using PDR, PR, and MR, the proportion of each coefficient towards the sum of the regression slopes was used to define the SCI shown in equation (2). Since the contribution due to PR was negligible, only two variables remained in the model.

$$\text{SCI} = 0.73\, PDR + 0.27\, MR \qquad (2)$$

Coefficients in equation (2) are the proportions of variation in equation 1 explained by each of PDR and MR. Equation (2) is specific for the soil environmental conditions during the studied season at the Kelly field. However, it can be easily adapted to fields of similar soil types by determining the field capacity and the proctor density levels for those soils and substituting the values in the regression model.

From the way the SCI is designed, it will range from zero to unity. A low value will reflect desirable conditions and a value of 1 will mean the worst conditions. For example, if a farmer goes to the field and takes some soil measurements in spring before tillage and calculates the SCI to be 0.9, he or she will know the conditions are not suitable for corn early growth, and that some tillage will be necessary unless done for other purposes; such as fertilizer incorporation and weed eradication. Analysis of variance showed a significant difference between SCI for each treatment within each block (P-value = 0.001). Mean SCI values for no-till, chisel and moldboard plow were 0.858, 0.763, and 0.735 respectively, with a standard error of 0.0127. The no-till SCI value was significantly different from both moldboard SCI (p-value=0.001) and chisel SCI (p-value=0.001). That means SCI can be used to distinguish the soil physical conditions created by the different tillage methods. The critical SCI level has not yet been determined, but will depend on what the farmer assumes as a reasonable individual plant biomass level to assure a good yield. The coefficients of determination of SCI against biomass and SCI against yield were 0.30 and 0.07 respectively. The results confirmed that corn biomass at V2 growth stage quantified the seedbed conditions better than yield. When blocking was included in the regression models, it had a significant effect on biomass (p-value=0.027). This suggests that there may be other confounding factors (biological, climatological or chemical) that are difficult to represent because the research modeled only the physical properties of the soil. Confounding factors include organic matter content, soil temperature and soil aeration. Tilled soil is warmer than untilled soil during warming periods, and the reverse is observed during cooling (Hadas, 1997). Similarly, oxygen distribution in the soil depends on the continuous air-filled pores that are characteristic in tilled soil. These factors need further investigation.

FINAL COMMENTS

Regression procedures were used to develop a soil condition index that related soil physical properties to different tillage systems. The SCI was used to make quantitative comparison of the seedbed conditions of the tillage systems. Thus, the objectives of this study were met. However, the results were preliminary, since they represent data from a single season at one location and crop. A fully developed SCI would represent a quantitative method that can be used by farmers and researchers to evaluate soil following tillage, and make management decisions regarding tillage intensity required. Such evaluations would eliminate the unnecessary costs incurred by farmers using aggressive tools to achieve what low disturbance tools can do. Further research is required to validate the model. Long-term field results are also necessary to make sure the model does not capture only one-time response of the crop to a given set of soil conditions.

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Table 1. Summary results for spring 2000 data analyzed from Kelly fields

Block	Tillage	PDR	MR	PR	SCI	Biomass (g/plant)	Yield (Mg/ha)
1	N	0.89	0.78	0.37	0.86	0.98	10.06
1	C	0.76	0.92	0.66	0.81	1.16	10.40
1	M	0.70	0.79	0.85	0.73	1.22	9.58
2	M	0.70	0.84	0.88	0.74	1.24	9.80
2	C	0.71	0.81	0.66	0.73	1.33	10.00
2	N	0.93	0.76	0.41	0.89	1.01	8.13
3	M	0.74	0.76	0.90	0.74	1.25	9.19
3	N	0.94	0.64	0.62	0.86	1.27	9.05
3	C	0.85	0.60	0.67	0.78	1.69	9.43
4	M	0.80	0.56	0.83	0.73	1.83	8.77
4	C	0.81	0.53	0.67	0.73	1.74	9.11
4	N	0.89	0.65	0.36	0.83	1.38	8.81

N = No-till; C = Reduced till; M = Conventional till PDR = Proctor density ratio
MR = Moisture ratio, PR = Penetration ratio, SCI = Soil condition index

Table 2. Parameter estimates for the Biomass regression model

Variable	DF	Parameter	Std error	t-value	P-value
Intercept	1	4.39	1.02	4.31	0.0026
PDR	1	-1.69	0.79	-2.13	0.0663
MR	1	-2.03	0.38	-6.09	0.003
PR	1	-0.03	0.34	-0.10	0.9211

Table 3. Models ranked according to C_p selection method

Rank	C(p) - value	Variables in Model
1	2.01	PDR, MR
2	4.00	PDR, MR, PR
3	6.52	MR, PR
4	12.67	MR
5	39.03	PDR, PR
6	40.58	PR
7	46.39	PDR

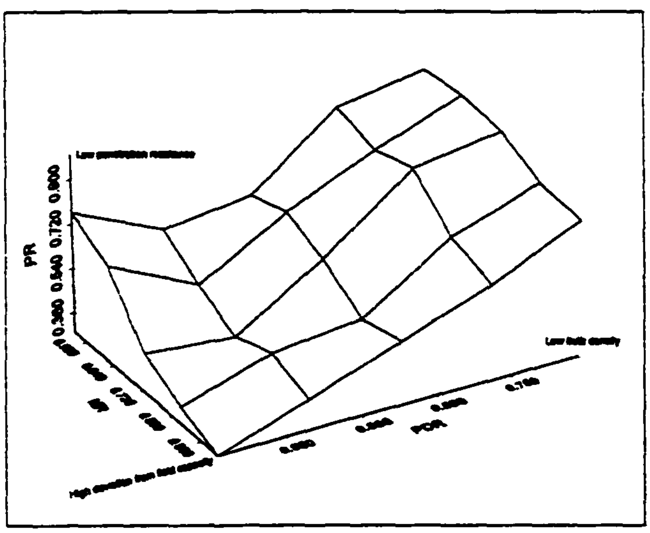

Figure 1. Relationship between soil physical properties for spring 2000 data

CHAPTER 3. SPATIAL AND TEMPORAL VARIABILITY IN CORN YIELD GROWN WITH DIFFERENT TILLAGE SYSTEMS.

A paper to be submitted to the Precision Agriculture Journal

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ABSTRACT

Multiple years of yield data from the same field usually exhibits both spatial and temporal variability. Often it is difficult to explain this variability because yield is affected by many factors including soil conditions, weather and management practices. This study was conducted to determine if yield maps, in combination with soil information, would explain the annual variation in corn (*Zea mays L.*) yield. The data were from a field study conducted on Typic Hapludolls and Typic Haplaquolls soils between 1998 and 2000. Five tillage treatments (moldboard, chisel, till-plant, slot-plant, spring disk) were compared using randomized complete block design with four replications. Analysis of variance showed no significant yield differences between tillage treatments in either 1998 (p=0.275) or 2000 (p=0.150). Significant differences were

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observed in 1999 ($p<0.0001$). Moldboard tillage was highest at 9.96 Mg ha^{-1} and slot-planting lowest with 7.75 Mg ha^{-1}. A paired t-test showed no significant yield differences among soil types in 1998 ($p=0.106$) and 1999 ($p=0.257$). There were significant differences in 2000 ($p=0.0001$). Visual interpretation of yield maps with soil map unit overlays supported both statistical analyses. A significant season, and season by tillage interaction was identified. Significant differences in bulk density and penetration resistance influenced the mean yield for each treatment. Soil moisture levels in all treatments for 1998 and 1999 were not significantly different, but in 2000 there were significant differences ($p=0.0185$), with disk and moldboard treatments being significantly drier than the other tillage treatments. This study shows that soils and yield maps can be used to better understand results obtained by classical statistical methods.

Keywords: spatial variability, yield variability, yield monitor, soil properties, tillage, geographic information systems

INTRODUCTION

Detailed maps created using a yield monitor and a global positioning system (GPS) data are increasingly being used to quantify spatial and temporal variation within fields. Being able to visualize differences for specific areas within a field can guide studies to determine causes for low or inconsistent yields. If patterns are observed, investigations can be done to determine if soil type, pH, organic matter content, nutrient levels, drainage, water retention or other factors are responsible. Bakhsh et al. (2000a) overlaid yield and topographic maps to explain the variability in corn grain yield and determine the cause and effect relationships. They concluded that the approach could delineate sub-areas within a field for site specific management. Shatar and McBratney (1999) used a similar approach to model soil properties and sorghum *(Sorghum bicolor L.)* yield. They were able to define soil properties that were limiting production.

These studies have shown that yield maps can be reliably used to investigate spatial and temporal variability within a field, but before doing so it is important to understand how yield data for these maps are collected and where errors can occur. Comparisons between yield monitor data and that collected simultaneously with a weighing scale (Perez-Munoz and Colvin, 1996; Al-Mahasneh and Colvin, 2000) showed good agreement. However, despite the accuracy of the yield monitor and GPS in collecting data, there are some systematic errors associated with mapping the two together.

O'Neal et al. (2000) have extensively reviewed methods of correcting GPS and yield monitor errors. Typically, the correction requires transformation of yield values before creating the maps. The corrections include adjusting plot yield to standard moisture content, eliminating extreme values, adjusting for lag time between cutting/gathering and sensing with the combine, correcting for GPS errors, and interpolating or aggregating the data into a smooth yield map. In the review, O'Neal et al. (2000) found that some researchers do not correct all known errors because some have minimal effect on the final yield maps. Errors that are consistently corrected include moisture content, extreme yield values, GPS errors (flyers) and interpolation errors.

To correct for extreme values, O'Neal et al. (2000) eliminated all values greater than 31384 kg ha^{-1} (500 bu ac^{-1}). They concluded that those values were unreasonable and most likely were caused by instrument error. Willis (1999) set the limit at 21969 kg ha^{-1} (350 bu ac^{-1}). Both limits were based on yield values that experience showed to be reasonable. Peterson (1996) and Beck et al. (1999) on the other hand used a statistical approach to eliminate values greater than three standard deviations from the mean yield. In a normally distributed sample, three standard deviations will include all reasonable values and any value outside the limit will be extreme.

'Flyers' from GPS error may be easily removed by visual inspection (Willis, 1999). These data points, lying clearly outside field boundaries, may also be removed by expert filters such as the one described by Blackmore and Moore (1999). Yield monitors such as the Ag Leader yield Monitor 2000[2] automatically correct for grain moisture content, lag time and speed changes (Ag Leader Technology Inc., 2000).

Yield maps for different seasons can be compared to show temporal variability. Sudduth et al. (1997) used two yield maps from the same field for different seasons to identify relationships between crop yield and topography. Maps produced from measured data compared well with those produced using projection pursuit regression with topographic parameters. Drummond et al. (1995) reported similar results for a different study.

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[2] Trade names are provided for the benefit of the reader and do not imply endorsement or preferential treatment of the products by Iowa State University or the USDA/ARS National Soil Tilth Laboratory.

Blackmore and Larscheid (1997) used spatial trend and temporal stability maps to categorize a field into stable, average and unstable regions. The maps were then combined to identify high, low and stable, or unstable yield locations.

The objective of this paper is to compare yield variation in corn grown with different tillage systems for three years on the same field using statistical methods. Soil and yield maps were used to identify possible causes for variability or patterns in yield.

MATERIALS AND METHODS

Experimental design and sampling

The experiment was conducted at the Agricultural Engineering Research Center (AERC) in Boone County, Iowa. The design was a randomized complete block with four replications and five tillage treatments being, conventional fall moldboard plow; fall chisel plow; slot plant on ridges, spring disk and a till-plant system (Figure A2-1). Both moldboard and chisel plow were followed by spring cultivation with a tined field cultivator. Roundup® (glyphosate) herbicide was applied in spring to control weeds. Liquid urea-ammonium-nitrate (UAN) fertilizer (32% N) was applied uniformly across all plots at a rate of 0.21 tons ha^{-1}. The experiment had been running for almost twenty years under continuous corn (*Zea mays L.*) and was initially set up as described by Erbach (1982).

The site was established by creating four blocks, each with 5 plots of dimensions 91 m by 23 m. Blocks were arranged in an east-west direction with a spacing of about 12 m between them. The planting scheme resulted in 30 crop rows per plot with 76 cm between the rows and 15cm between plants within a row. Tillage treatments (plots) were separated by 4 m wide (5 rows) practice strips. The practice strips were used for test runs during plowing, planting and harvesting. The Boone county soil survey report (Andrews and Diderickson, 1981) indicated that the area was characterized by Typic Haplaquolls (Webster) and Typic Hapludolls (Clarion) soils (Figure A2-1). The soils had gentle slopes of up to 5%. The grain yield results and soil data considered were from the 1998-2000 harvest seasons. During that time, the cropping season (March to September) mean temperatures were 16.8 ^{0}C, 16.4 ^{0}C and 17.3 ^{0}C for the years 1998, 1999 and 2000 respectively. The respective total mean precipitations in the same time period were 704 mm, 940 mm and 387 mm. The weather data were obtained from the research weather station at the experiment site. The long term averages for temperature and rainfall are 16.0 ^{0}C and 665 mm respectively.

Bulk density was measured by collecting undisturbed core samples from the ground surface to a depth of 5 cm using a cylinder with 76 mm diameter and 51 mm height. The samples were collected in April immediately before planting from a spot randomly chosen around the mid-point of each plot. This provided a 5 by 4 array of sampling points representing the entire field. Exact geographic locations of the sampling points were recorded using a Trimble® Pathfinder global positioning system. The same soil cores were used to measure moisture content by drying them at 105 ^{0}C for 72 h. Penetration resistance was measured adjacent to the bulk density sampling sites using a hand held digital penetrometer. For each location, readings were taken at the 5 cm, 10 cm, and 15 cm depth and then averaged to give a single value for each location.

Corn grain yield data were obtained using a John Deere® 4420 five-row combine harvester equipped with an Ag Leader® 2000 yield monitor and a Trimble® AgGPS 22 global positioning system. The yield monitor also recorded other attributes such as grain moisture content, swath width and travel speed (Table A2-1).

Data correction and analysis

Data were analyzed using the SAS® System for Windows statistical software (SAS Institute, 2000). Yield data were corrected for mapping using Arc View® 3.2 geographic information systems software (ESRI, 1999).

Yield correction was manually done to remove extreme yield values and unusual speed changes (Figures A2-2 and A2-3). To correct for extreme yields, all values outside two standard deviations were removed. Further, a cut-off of two standard deviations was used for speed values so that they could be made less variable. The Ag-Leader® software used for downloading yield data (Precision Map® 2000, Version 2.0 and later SMS Basic®, Version 1.0) allowed for automatic correction for grain moisture to a standard content of 15% (wet basis) (Table A2-1). The software also corrected yield values for 'lag time' by shifting all points 12 seconds backwards. Other errors known to occur during the use of yield monitors were regarded as insignificant and therefore not corrected.

Analysis of variance (ANOVA) was performed on yield data and soil property data for each year. Treatment means were compared using the least significant difference (LSD) multiple comparison method. The yield data were also analyzed as a repeated measure, with tillage plots being experimental units. Yield means from each plot were compared among years to evaluate temporal variability.

Using the corrected yield data, thematic yield maps were created for each year and visual interpretations were made. Yield maps were created using the Kriging interpolation method provided by an Arc View extension, (Kriging Interpolator 3.2). Yield interpolation for each year was done for the entire field. Several semi-variogram fitting models (spherical, exponential, Gaussian, linear and circular) were explored before deciding on an appropriate interpolation technique. The best fitting model was chosen based on the Akaike Information Criterion (Ramsey and Schafer, 1997). Each yield map was characterized based on the number of standard deviations from the mean. The categories ranged from –3 to +3 standard deviations with an increment of 1 standard deviation within each category range.

A soils map was obtained from the USDA Soil Conservation Service (Andrews and Diderickson, 1981). The yield and soils maps were overlaid and visual evaluations were made to explain the observed patterns. Yield differences between the two soil types were statistically compared using a paired t-test procedure. Two adjacent blocks of about 20 square meters each were selected to determine the average yield per block. Where both soil types occurred, one block per soil type was selected. The two blocks provided pairs of yield estimates that were used in the t-test for each of the years.

RESULTS AND DISCUSSION

There were no significant differences among mean yield for tillage treatments in 1998 or 2000 (Table 1). In 1999, there were significant yield differences between the moldboard plow (9.96 Mg ha^{-1}) treatment and the other tillage treatments. The chisel plow (9.12 Mg ha^{-1}) treatment was also significantly different from both spring disk (8.35

Mg ha^{-1}) and slot-plant (7.75 Mg ha^{-1}) treatments while till-planting (8.52 Mg ha^{-1}) was different only from slot-planting. Over the three seasons, moldboard plowing always gave the highest yield (8.36-9.96 Mg ha^{-1}) followed by chisel plow (7.99-8.52 Mg ha^{-1}) and till-plant (7.21-8.35 Mg ha^{-1}) respectively. The ranking of spring disk and slot-plant treatments was not as apparent. Our results are consistent with those of Tapela and Colvin (1998) on continuous corn yield from the same field. The problem with moldboard tillage is the potential for soil erosion and increased rate of organic matter breakdown (Colvin et al., 2001). Thus, conventional tillage may only be suitable where environmental or long term soil quality concerns are not a factor.

The different tillage methods created a range of soil bulk densities following their application. Till-plant and slot-plant treatments had relatively more dense seedbed conditions than moldboard, spring disk plow or chisel plow treatments (Table 2). In the three years, both till-plant and slot-plant were significantly different from the other tillage treatments. The high bulk density reflected high soil penetration resistance, which could have impeded root growth (Bilanski and Varma, 1976) and hence lead to lower yields. Soil moisture level in all treatments for 1998 and 1999 were not significantly different. In the year 2000, soil moisture was significantly different ($p=0.0185$) with the disk (16.27 %) and moldboard (14.63 %) treatments being significantly lower than the other tillage methods. Slot-plant (22.22 %) and till-plant (20.74 %) treatments had the highest moisture levels, while chisel plow was in the middle with 17.23 %.

The temporal (year) effect on yield in the repeated measures analysis (Pillai's Trace) was highly significant ($p < 0.0001$). There was also a highly significant year by tillage interaction, but the interaction between year and block was not significant. These results are shown in Table 3. Seasonal yield is affected by weather conditions as well as the treatments imposed on them (Jaynes and Colvin, 1997). For example, the March to September 2000 precipitation (387 mm) was well below the long-term (1951-2000) average of 665 mm. On the other hand, 1999 had a relatively high precipitation level (940 mm) while 1998 was almost average with 704 mm. High soil moisture can limit nitrate availability to crops while in a dry year the soil water holding capacity may control yield (Jaynes and Colvin, 1997). Bulk density and soil moisture content showed similar time effects, while penetration resistance did not seem to be affected by time.

Figures 1 to 3 show the spatial relationship between yield and soil type. Yield is represented in categories of standard deviations from the mean. The figures show that two soil types, Typic Hapludolls (Clarion) and Typic Haplaquolls (Webster) dominate the field. Since Kriging of yield data was done across the four blocks, interpolation was also done in the spaces between the blocks where there were no data points. However, tillage plots were shown so that interpretation of the maps can be limited to field boundaries. Previous studies used a single tillage method across the whole field (Sadler et al., 2000; Bakhsh et al., 2000b; Sudduth et al., 1997). That arrangement made it easier to interpret the Kriged map, because a single factor affected the field conditions uniformly. However, imposing tillage treatments on the field introduced soil variability that followed a pattern where points that are closer together within a tillage treatment are more similar than two points on different tillage treatments. The pattern resulted in a semi-variogram that had a low nugget effect, high sill and a short range. Maps generated for the field therefore could not be used for predicting yield levels at a particular spot, but could only assess patterns.

In 1998 and 1999 (Figures 1 and 2), yield variations follow tillage treatment orientation. In the two blocks on the left of figures 1 and 2, the high yield levels for the moldboard plow treatment are evident. The high yield shade is equally distributed in both soil types within the same tillage treatment. This suggests that differences in soil type did not have an effect on yield. This observation was confirmed by the paired t-test results. The results show that the p-values for equal yield means between soil types were 0.107 and 0.257 for 1998 and 1999 respectively. Extrinsic soil properties that have been modified by tillage treatment, such as bulk density and penetration resistance, are the cause of yield variability as shown by analysis of variance.

Map overlay of soil type and yield in the year 2000 (Figure 3) is different. There are bands of low yield that cut across tillage treatments in a north-south direction. This is evident in the block on the west side and the block on the extreme east. The low yield bands may be a result of access strips created before harvesting. The t-test shows that there are differences in mean yield between the two soil types, but the result is not apparent by visual inspection. If yield patterns resembled the shape of soil type polygons, then the interpretation may be that soil type influenced yield (Bakhsh et. al, 2000a). The cause for yield differences between soil types in 2000 may be interpolation across the access strips.

CONCLUSIONS

The following conclusions may be made from the results of this study:

1. Using conventional tillage with moldboard plow under continuous corn gave superior yield than other forms of reduced tillage.

2. The yield responses of different tillage methods are time (season) dependent. This is due to the differences in environmental factors such as precipitation and temperature that affect the availability of soil water and nutrients to plants.
3. Yield maps overlaid with soil maps provide a visual perspective of the relationship between the two variables. Spatial correlation is assessed by inspecting any trends in patterns on the map overlays. Visual interpretation may be validated by statistical methods. There seemed to be no evidence of soil type influencing yield variation. Yield tended to be more influenced by tillage method used.

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Table 1. Comparisons between mean corn yield of the tillage treatments using LSD test.

	Mean corn yield, $Mg\ ha^{-1}$		
Treatment	**1998**	**1999**	**2000**
Moldboard plow	8.48^{a}	9.96^{a}	8.36^{a}
Chisel plow	8.14^{a}	9.12^{b}	8.24^{a}
Spring disk	7.27^{a}	8.35^{cd}	7.81^{a}
Till-plant	7.99^{a}	8.52^{bc}	8.20^{a}
Slot-plant	6.95^{a}	7.75^{d}	7.87^{a}
Standard error	0.525	0.199	0.169
Block p-value	0.820	0.027	0.17
Tillage p-value	0.275	< 0.0001	0.15

Note: Treatments with the same letter in the same year indicate that there is no evidence of yield differences between them at 5% significance level.

Table 2. Comparisons between mean soil physical properties of the tillage treatments using LSD test.

	1998		1999		2000	
Tillage Treatment	Bulk density (kg m^{-3})	Penetration resistance (Mpa)	Bulk density (kg m^{-3})	Penetration resistance (Mpa)	Bulk density (kg m^{-3})	Penetration resistance (Mpa)
Moldboard plow	1.01^{b}	0.31^{b}	1.19^{ab}	0.55^{a}	1.01^{b}	0.42^{b}
Chisel plow	0.77^{c}	0.39^{b}	1.08^{bc}	0.47^{a}	0.86^{b}	0.70^{ab}
Spring disk	0.78^{c}	0.97^{a}	0.97^{c}	0.66^{a}	0.85^{b}	0.99^{a}
Till-plant	1.35^{a}	1.02^{a}	1.28^{a}	0.93^{a}	1.24^{a}	1.91^{a}
Slot-plant	1.34^{a}	0.89^{a}	1.31^{a}	0.78^{a}	1.22^{a}	0.94^{a}
Standard error	0.050	0.083	0.042	0.120	0.056	0.166
Block P-value	0.410	0.980	0.599	0.115	.916	0.581
Tillage P-value	<0.0001	<0.0001	0.0005	0.117	0.0005	0.080

Note: Treatments with the same letter in the same year indicate that there is no evidence of yield differences between them at 5% significance level.

Table 3. Results of the repeated measures test on yield and soil properties

P-values for Pillai's Trace			
Factor	**Time effect**	**Time*Block effect**	**Time*Tillage effect**
Yield	<0.0001	0.5431	0.0276
Bulk density	0.0004	0.9985	0.1208
Penetration resistance	0.2125	0.1271	0.4055
Soil moisture	0.0199	0.3715	0.4369

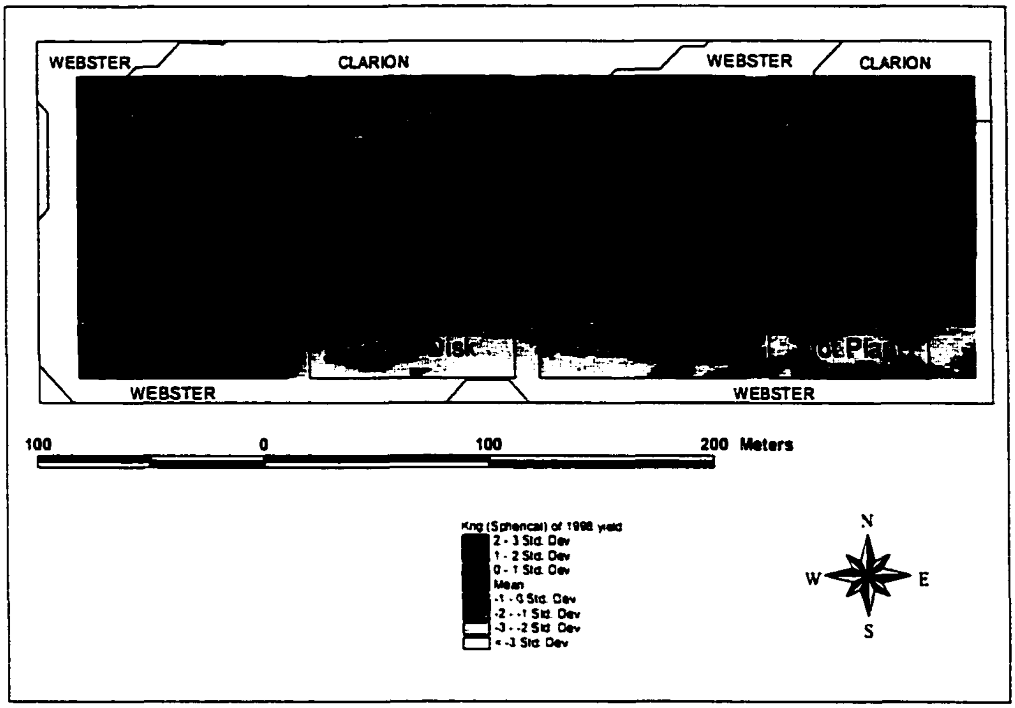

Figure 1. Yield categories and soils map overlay for the year 1998 cropping season.

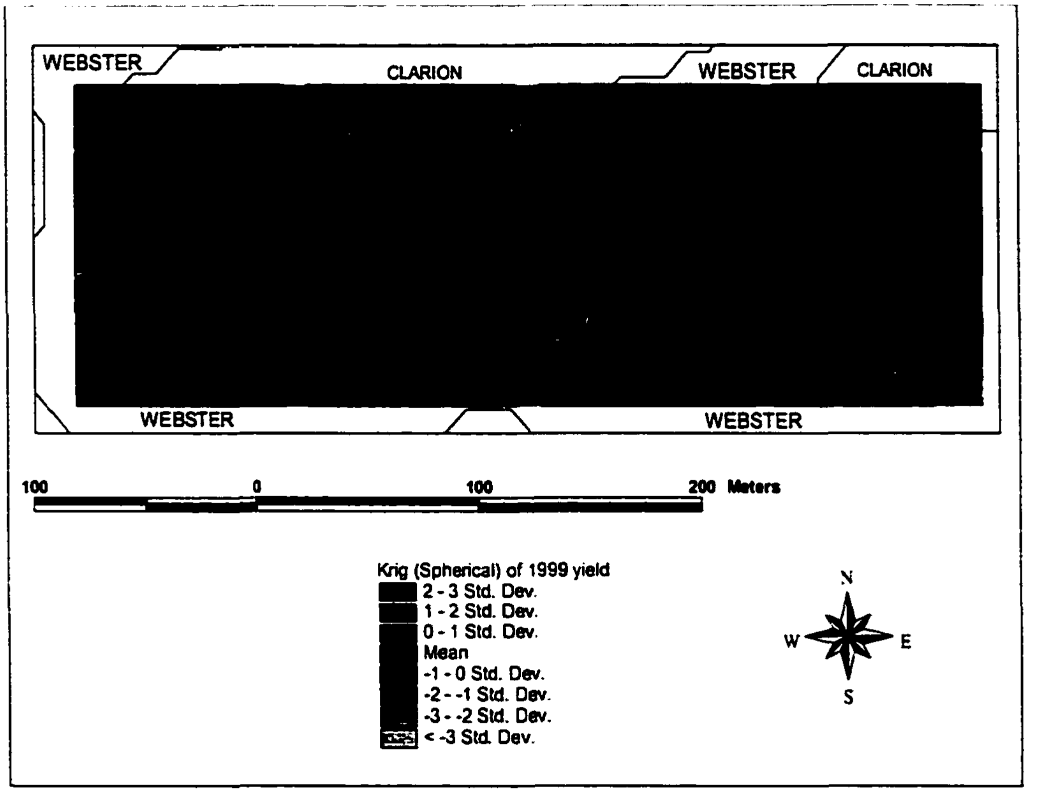

Figure 2. Yield categories and soils map overlay for the year 1999 cropping season.

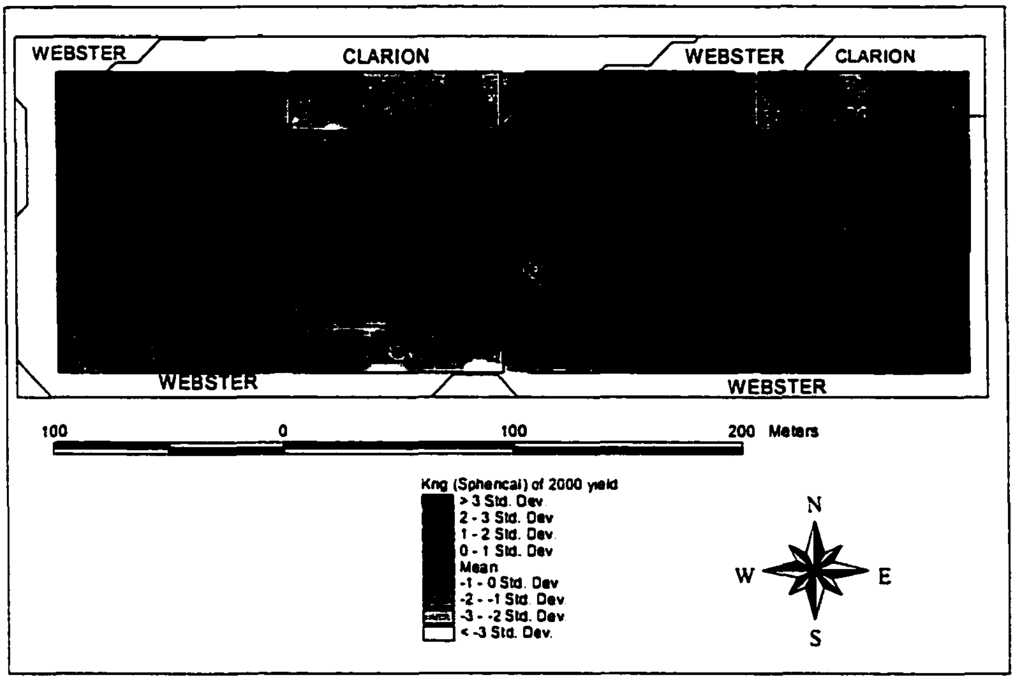

Figure 3. Yield categories and soils map overlay for the year 2000 cropping season.

CHAPTER 4. STATISTICAL CONSIDERATIONS IN THE DESIGN AND ANALYSIS OF EXPERIMENTS THAT QUANTIFY SEEDBED CONDITIONS.

A paper to be submitted to the Precision Agriculture Journal

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ABSTRACT

Validation of methods that quantify seedbed conditions and mapping of the results is primarily influenced by the statistical design used in the experiment. A review was carried out to illustrate how experimental design, soil sampling methods, and choice of indicator variables could influence the validation of the tilth index. Physical variation of the soil condition following tillage was discussed. Four methods previously used to quantify soil physical conditions were described and the statistical designs used to validate them were critiqued. The methods were the Tilth Index, Prognostic Air-Water Regime, Least Limiting Water Range and the Degree of Compactness. Thereafter, a step-by-step procedure for validating soil tilth was proposed. General recommendations were that; (i) conventional statistical methods were appropriate where there was no spatial

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dependency, and if the research question was concerned with differences in mean values; (ii) If a soil physical property showed spatial correlation, then spatial statistics should be used to determine the seedbed condition index values at unsampled locations; (iii) Crop biomass at the early stages of growth should be used as an indicator of the tilth status rather than yield; (iv) Classification for mapping of the tilth variation should be based on methods that are less subjective such as the standard deviation.

Keywords: spatial variability, soil properties, experiment design, variogram soil tilth

INTRODUCTION

Studies on quantification of seedbed condition (tilth) following tillage operations have been going on for some time now. The quantification indices proposed by different researchers range from simple measures of soil physical properties such as bulk density, penetration resistance and soil porosity (Luttrell, 1963; Fragin, 1986; Carter, 1990; Becher et al., 1997; Hakansson and Lipiec, 2000) to relatively complicated methods that mathematically or statistically combine several soil properties (Singh et al., 1992; Williams et al., 1992; da Silva et al., 1994; Tapela and Colvin, 2001). Since the soil dynamics of tillage operations can not be predicted, it is impossible to directly measure tilth conditions. The above indicators quantify seedbed conditions by relating soil physical properties to crop yield. However, yield is a result of several factors besides soil tilth. Yield is affected by both chemical and biological makeup of the soil as well as the climatic conditions during the growing season. Thus it becomes difficult to judge how well these indices are able to quantify tilth.

To validate the tilth condition indices, a common statistical design approach is to apply different tillage systems on a field, and make observational measurements of the soil properties, and use conventional statistics such as analysis of variance to analyze the data (Tapela and Colvin, 2001; Singh et al., 1992). Regression analysis is used for single tillage systems to determine the correlation between tilth condition index and yield. Conventional statistics limits the validation of soil condition indices to field scale levels since mean values are used. A single soil condition value is calculated to represent the whole-field physical condition. Conventional statistical methods are also based on assumptions for normally distributed random variables which when violated, as is often the case with spatial data, will cause statistical biases in mean estimates (Mulla et al., 1990; Zhang and Selinus, 1998). Cressie (1993 p19) warns that assumptions should be based on prior knowledge of the soil physical property distribution and soil-plant relations, and not on mathematical convenience. Careful formulation of statistical assumptions is as important as the science behind any soil condition index.

Soil physical variation within the field is ignored by conventional statistics. However, spatial variation becomes important in site specific farming where different management systems are applied to different sections on one field. Spatial statistics can provide a more targeted validation of the tilth condition indices.

A combined understanding of the physical process of soil tillage and statistical methods may be used to design research experiments that adequately evaluate the physical condition of the soil. For example appropriate statistical procedures may be used to account for the influence of environmental factors if yield is used as a response to tilth condition.

OBJECTIVES

The objectives of this research were to:

1. Review the current methods for quantifying soil tilth and discuss the science behind each method.
2. Discuss the appropriateness of the statistical design used in assessing tilth.
3. Discuss spatial variability of soil physical properties and how it may be measured.
4. Propose a general statistical approach for experiments that quantify soil tilth.

METHODS USED FOR QUANTIFYING SEEDBED CONDITIONS

Scientific knowledge provides the basis for choosing soil physical properties to be used in quantifying soil tilth. The physical properties that have some relationship to crop growth are used to develop the soil tilth indices. The indices are then validated experimentally to determine if they can be reliably used to determine what type of tilth condition will produce optimal yield. Four of these methods are described in this section.

1. The Tilth Index

This method was first proposed by Singh and Colvin (1990) in an experiment on Bangkok soils. Singh et al. (1992) later used a similar approach on Iowa soils. The index used soil bulk density, cone index (penetration resistance), aggregate uniformity coefficient, organic matter content and the plasticity index to predict crop yield. The index was scaled to range from zero for unsuitable soil condition to one (unity) for a soil that did not physically limit plant growth. Scaling was accomplished by setting critical limits for each of the soil properties and fitting a regression curve between the critical points. In Iowa, the index was validated using a randomized complete block design experiment with four replications and five tillage treatment levels. The tilth index had a positive a correlation to yield with coefficient of determination, r^2 ranging from 0.15 to 0.86. Tapela and Colvin (1998) modified the tilth index from a linear to a quadratic relationship and used different plant limiting levels for bulk density and penetration resistance. The modified tilth index did not result in any significant improvement of the tilth index as suggested by Singh et al. (1992).

2. Prognostic Air-Water Regime

The prognostic air-water regime was based on water retention properties and the hydraulic conductivity function of the soil (Shein and Makhnovetzkaya, 1996). It was a quantitative agro-physical measure that gave a statistical rating of the soil based on the probability of occurrence of critical levels of moisture deficit. Soil parameters measured were the bulk density, soil texture and micro-aggregate composition of the soil. The soil parameters were not used directly to quantify tilth but were incorporated in calculations that determined the soil water retention curve and hydraulic conductivity. The method assumed that yield was primarily formed by favorable moisture and aeration regimes. The statistical design to validate this criterion used four separate field plots with similar soil-genetic and agricultural conditions. Each plot was given a different watering (irrigation) level from others. Alfalfa (*Medicago sativa L. subsp. Sativa*) plant biomass at one month after germination was used as the indicator variable. The experiment was repeated on a different soil type using carrot (*Daucus carota L.*) biomass as the indicator variable.

3. Least Limiting Water Range

The Least Limiting Water Range, LLWR was another index that evaluated seedbed condition through soil water properties. It was defined as the soil water content that minimized plant growth limitations associated with matric pressure, aeration and mechanical resistance (da Silva et al., 1994). For each of these properties, the water content at the limiting levels was determined. The smallest range between the limiting water contents was termed the LLWR. To use LLWR as an index, it was correlated to bulk density that had a known effect on crop growth (Bilanski and Varma, 1976). A randomized complete block design with four replicates and two treatments (two crop types) was used to validate the index. Conventional tillage was used in all fields. Regression procedures were used to develop relational functions between soil and plant properties. That was followed by stepwise multiple linear regression to select significant soil and crop indicator variables. The LLWR was more sensitive to changes in soil structure than soil available water. In a different experiment by da Silva and Kay (1997), it was concluded that the magnitude of the LLWR could be used as an indicator of the soil structure that may contribute to moisture conditions that limit plant growth. But optimizing the LLWR by changing the soil structure should include inherent soil properties such as soil clay content and organic matter (da Silva and Kay, 1997).

4. Degree of Compactness

The degree of compactness was defined as the percent of dry bulk density of a soil with reference to standardized bulk density obtained by standard uniaxial compression test at a stress of 200 kPa (Hakansson, 1990). The index was similar to the one proposed by Carter (1990) who instead used the Proctor compaction density to standardize measured bulk density values. It was meant to be simple and to characterize the state of soil compaction with regard to machinery traffic and crop yield response. Since the degree of compactness was a standardized ratio, it was independent of the soil texture. More than 100 experiments were conducted to validate the index. The experiments had a randomized design with four compaction treatment levels and three replications. Bulk density was measured using the frame sampling technique to reduce the number of replications required by the core sampling technique. It was found that the optimum degree of compactness was 87 percent for mineral soils in Sweden. Further studies on the degree of compactness were carried out by Lipiec and Hakansson (2000) and Hakansson and Lipiec (2000) to determine its influence on penetration resistance and air-filled porosity, both of which are important crop growth factors. da Silva et al. (1997) used regression methods to determine the relationship between the degree of compactness and bulk density.

CRITIQUE OF THE METHODS QUANTIFYING SEEDBED CONDITIONS

The methods described in the previous section used conventional statistics to validate the indices without further analysis of spatial relation of the sampling points. Conventional statistics assumed additive effects of variables and independent errors that are normally distributed with a common variance (Gomez and Gomez, 1984 p294). It is common for soil data to violate these assumptions and so relations among different variables could be performed using methods such as correlation analysis and regression analysis (Zhang and Selinus, 1998). Cressie (1993) recommends that "analysis based on spatial dependencies should give a more complete understanding of the phenomenon influencing crop growth and yield."

From the regression of tilth index against yield proposed by Singh et al. (1992), the method had some potential even though it had a wide variation in r^2 values. The main concern, though, was that some of the soil parameters included such as the aggregate uniformity coefficient, plasticity index and to some extent organic matter content were inherent properties not normally altered by soil tillage. So, including them in the index may not help in making management decisions but instead add to the variability in estimating the tilth index. Model selection procedures like the Mallow's C_p criterion and stepwise regression method could help to assess if the extra properties were needed since r^2 could always be improved by adding enough regression parameters (Ramsey and Schafer, 1997 p276).

Even though the LLWR experiment was a completely randomized design, the statistical analysis was based on comparing regression functions of soil resistance against soil water on two different soil types (silt loam and loamy sand). Differences in soil types made the comparison more complex than when the soils were similar. An analysis of variance was not possible because the treatment levels did not match (different crops). That resulted in not being able to incorporate crop response data. Therefore it could have been possible to develop a mathematically functional relationship that did not have any physical or biological significance (Guérif et al., 2001). The treatment and blocking effects were not analyzed. A similar weakness in design was observed in the validation of the prognostic air-water regime. The experiments were carried out with two different crops under different soils. The differences in crop type were confounding and there was no way of knowing if yield differences were due to crop effect or tilth condition.

Tilth condition was a term used to reflect the overall condition of a seedbed, and so to use a sampling frame that aggregates a wider area (as in Hakansson, 1990) than the core method would be a better representation of the spatial extent influencing plant growth. Small areas generally had more plot to plot variability than large plots (Mulla et al., 1990). However, the question then was when to sample for bulk density. Malicki et al. (1997) argues that immediately following tillage, soil density significantly differed from the optimum because it had not stabilized. It may be recommended that soil aggregates should be allowed to form and attain stability before taking measurements.

Since soil tillage intensity can not be measured directly by current methods it had to be inferred from soil physical properties and made agronomically meaningful by relating it to yield. Grain yield was used as an indicator of soil conditions by Singh et al. (1992), and Tapela and Colvin (1998). Yield was measured at the end of the growing season when several other factors had influenced it. Influences could be from weather, pests, weeds, and intermediate management operations (Jaynes and Colvin, 1997). So, to use yield as an indicator, an assumption would be made that these factors had no significant influence on yield and that yield was largely due to the tilth conditions. It is debatable whether that is a reasonable assumption or not, especially when trying to formulate an index that will be widely applicable. The results reported by da Silva and

Kay (1997) show that weather effects (represented as year factor) were highly significant. So, an effort must be made to remove or at least account for the influence of factors other than soil physical conditions. The steps taken could be through statistical design or selection of indictors less influenced by those factors.

Shein and Makhnovetzkaya (1996) and Tapela and Colvin (2001) used plant biomass in the early growth stages as one way of reducing the influence of climatic conditions on the indicator variable. Plant requirements with respect to tillage are especially important during germination and sprouting, and during initial development of the root system (Malicki et al., 1997). That was evident in the results obtained by Tapela and Colvin (2001) where crop biomass response to tillage was significant. The recommendation was to use crop biomass at an early growth stage even though it did not guarantee superior yield. On the other hand, quantification of the moisture-aeration regime instead of the physical properties of soil particles raises a question of whether it is the tilth status of the soil that is important to plants or the processes that result because of the tilth condition. Tillage may only be a primer for processes like rapid decomposition of organic matter, increased soil aeration and increased uptake of nutrients. Quantifying these processes is much easier and better understood. They affect plant growth more directly than soil physical conditions. Optimizing these processes instead of yield may be a better indicator of tilth condition

SOIL VARIABILITY AND SAMPLING

Classical statistical methods are used by researchers to study crop response to tillage treatment on a whole plot basis. This approach assumes uniform soil tilth conditions throughout the experimental unit, which is the plot. The predicted value at any point within the plot is the mean value for the plot in which it lies (Burgess et al., 1981). The assumption ignores localized variations that may be important in precision farming. The soil variability is brought about by different factors that include soil type, biological activity and composition, and soil reaction to physical manipulation. The dynamics of the soil during tillage are not completely understood but seem to be influenced to varying degrees by both the implement used and intrinsic soil properties. Sometimes it is possible to map localized variation using techniques such as inverse square distance, local moving averages, Kriging, Akima's interpolators, Hardy's multiquadric method and the tension finite difference method (Caruso and Quarta, 1998; Zhang and Selinus, 1998; Whelan et. al., 1996). However, the mapping can only be as good as the sampling technique used.

Several sampling strategies have been proposed by van Groenigen et al. (2000). They suggested partitioning the field according to known soil characteristics such as topography and soil type to decrease the number of samples needed when compared to a regular grid. The approach is especially relevant in a tillage trial where a single tillage treatment would form a soil partition. Webster (1985) found that a good sampling scheme would be a regular equilateral triangular grid but for convenience in entering data on the computer and managing the field, a square grid is usually preferred. Typically, "sample sizes of less than 10 will not allow any kind of localized spatial prediction and estimates of the mean for the field would be rather poor" (Whelan, et al., 1996). Using the standard error and t-tables (Gomez and Gomez, 1981 p535) is inappropriate because the method only concerns experiments that estimate the mean. Besides, Royle (1980 p11) warned that the standard error method usually leads to unacceptably high number of samples.

Burgess et al. (1981) based the sampling interval on the maximum estimation variance of the soil property being measured.

SPATIAL PATTERNS AND PREDICTION

Soil sampling will result in soil property values only at sampling locations. The values between sampling locations can be predicted through interpolation techniques. Spatial patterns are better evaluated using variograms (Webster, 1985; Jaynes and Colvin, 1997; Cressie, 1993). The variogram expresses the variation between data points as a function of distance separating them and typically, variance increases as the distance between data points does (Jaynes and Colvin, 1997). The variogram shows the degree of spatial dependency. Variograms depend on the sample size, shape and orientation. Measurements made on core samples encompass less variation than those on larger samples (Webster, 1985). Smaller sized samples will have a high nugget effect when sampling interval is large. Variograms may be fitted using either linear, spherical, exponential, quadratic, hyperbola or circular models (Royle, 1980;Webster, 1985; Cressie, 1993 pp61). The model of choice is the one that provides a better fit than other models. Figure 1 show variograms fitted using the models on soil bulk density values from experimental data. Comparison between the variogram models is made using model evaluation criteria indicated on the table below the graphs in Figure 1.

The data used to construct the variograms were obtained from soil samples collected in the experiment described by Tapela and Colvin (2001). Soil sampling for bulk density was done from the soil surface (0-5 cm depth) in spring 1999 just before planting. The experiment was a complete randomized block design with four blocks and three tillage treatments. Six soil bulk density samples were collected from each plot. Plot sizes were 53.3 m by 7.6 m.

In all the graphs shown on Figure 1, the nugget effect is equal to the maximum variability. In that case, there is no spatial dependency and variability is wholly due to random factors (Royle, 1980). There is either no spatial correlation or the sampling interval was too large for estimating point values between sampling points. Figure 1 suggests that the plot mean is a good estimate of the structural state of the soil. It may be better to fit a characterization model instead of a prediction model for this soil property. Characterization creates management units that group together areas with similar soil property values. Characterization may be achieved using, for example, Thiessen polygons (van Groenigen et al., 2000). The management units may highlight differences that need different tillage intensities on experimental as well as commercial fields. If the variograms indicate a significant spatial correlation, then one of the several interpolation methods is to be used. Among the common interpolation methods used are Kriging, inverse square distance and local moving averages. Interpolation creates a trend surface allowing prediction between sampling points. However, the approach is only reasonable in soil properties that are known to vary in a smooth gradient through space. Examples of these properties are soil texture, soil pH, and chemical elements.

MAPPING OF SOIL AND YIELD VARIABILITY

The common ways of mapping soil and yield variability are through the use of contour maps (2-Dimensional) and map surfaces (3-Dimensional). Map surfaces emphasize the high points and low points within the field but make it difficult to recognize localized variations and patterns. For that reason, contour maps are more common. Contour maps allow for map overlays that make visual correlation and interpretation easier. The limitation though is that the same data can generate totally different maps depending on how data are aggregated or categorized. Thus instead of mapping actual values, standard deviations are used to define category boundaries. Standard deviation based categories provide a statistical basis that always has the same number of classes (Sudduth et. al., 1997; Tapela et al., 2001; Taylor et. al., 2000). Tapela et al. (2001) used the approach to compare maps of the same field from different years to determine if certain areas were consistently below or above the mean value. The trade off is that the ability to compare how one field performed relative to another field is lost.

PROPOSED APPROACH TO STATISTICAL DESIGN

The approach to experimental design is fairly universal as noted in the discussions by Gomez and Gomez, (1984 p562), Cressie (1993 p324), Petersen (1994 p365), and Ramsey and Schafer, (1997 p659). Randomization, replication and blocking are some of the most emphasized design factors. Differences between experimental designs become apparent only when the objectives are defined. To carryout research on seedbed evaluation, the following statistical approach is proposed. The approach is structured into a five-step procedure for ease of illustration.

1. Define the question of interest

The main factor that should dictate the design and ultimately the data analysis of an experiment is the question that needs to be answered. If the experiment question can not be explicitly stated, often what follows is an inadequately designed experiment, and data analysis that answers the trivial. For example, two questions that may be of interest are: (i) Is there a significant difference in the average physical index (e.g. tilth index) values between plots under different tillage systems; (ii) Is there a difference in soil index values at any two locations with similar tillage treatment? Both questions deal with quantification of tilth conditions but require different sampling schemes and statistical analysis procedures. The first may be adequately addressed by spreading the soil sample points as widely as possible throughout the tillage plots and using analysis of variance to test mean differences. On the other hand the second question requires one to sample as closely as possible around the location of interest and use t-tests for significance of difference. Ramsey and Schafer (1997 p672) prepared a checklist of eight tasks involved in the design of any study. Likewise, the first step is to define the objective or the question of interest.

2. Decide on the correct response value

As noted in the proceeding sections, seedbed conditions may be evaluated using a variety of methods. The method of choice relies on the science that associates the response factor with tilth conditions. As tilth can not be measured directly, it must be inferred from measurable factors. Crop yield is often a factor of choice because it is what ultimately matters to farmers. But other indictors such as biomass at early growth stages, and germination percentages should be considered. Previous studies may help in the choice of a reliable indicator.

3. List design factors and confounding factors

It is very difficult if not impossible to pre-set tilth conditions in field trials. That is why tillage trials are mostly observational. The best that can be done is to have tillage methods as treatment factors and assume each produce uniform conditions throughout the field. To accommodate the assumption, the chosen tillage treatments must be as distinct as possible. We recommend experimental designs that utilize a combination of conventional plowing and conservation tillage. Other factors that may be confounding such as soil pH, nutrient levels, residue cover, and moisture availability must be measured and included in the model so that true differences in tillage effects can be measured.

4. Decide on the experimental design

Having identified experimental factors, the next step is to consider the scope of applicability of the results. Since the experiment is at the research level, it may be necessary to limit the scope to fields at the research site. That means sampling from areas within the research site. Otherwise sampling may be done from a wider area to include different soil conditions. Depending on whether the question of interest is about characterization or prediction, the optimum soil sampling scheme may be determined as suggested by Burgess et al., 1981. Whatever experiment design is decided upon, it must include some form of blocking to control covariates, and improve prediction. Randomization will also eliminate bias and ensure independence. Some common designs are randomized complete block or Latin square.

5. Outline the statistical analysis

Two approaches may be used depending on the question of interest. Conventional statistics such as analysis of variance, analysis of covariance and regression is appropriate for characterization, while spatial analysis is for prediction. Depending on whether the objective is to determine differences in mean tilth conditions or estimate tilth at a specific location, either conventional methods or spatial methods may be chosen respectively.

CONCLUDING REMARKS

Quantification of soil tilth conditions is a complex science that will probably take a long time to unravel. Presently, soil tilth can not be measured directly and so must be inferred from other factors. The functional relationship of these factors to soil tilth are not well understood either. Some factors such as weather conditions are not even predictable. The soil tilth indices that have been proposed thus far are not useful for predicting the influence of tilth status on future yield. In that sense, they are not helpful for management decisions. The conventional statistics used in verifying these methods suggests only probable cause of yield levels. Spatial statistics has similar drawbacks, and in addition is difficult to apply since tilth condition appears to be a random process. Future research needs to be more directed towards identifying valid measures of tilth and also ways of removing the influence of other confounding factors, especially weather.

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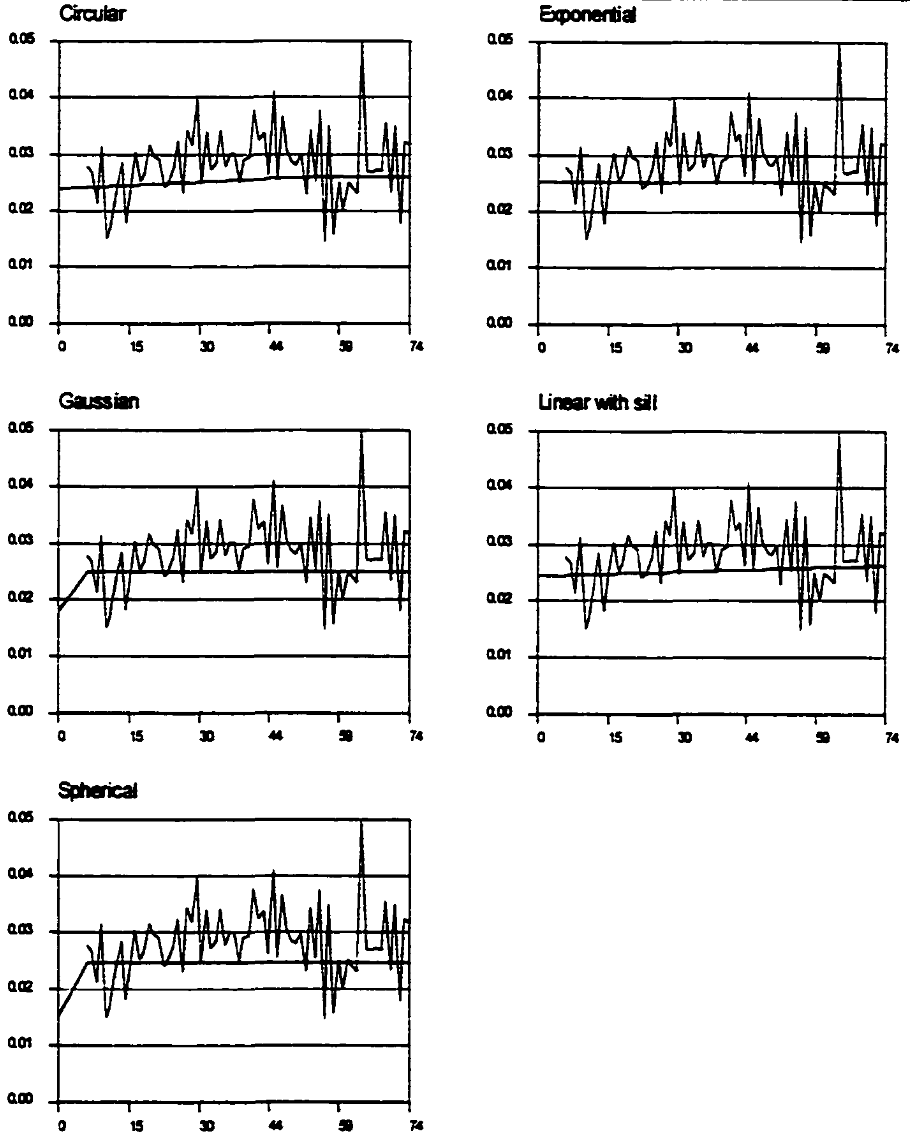

Model	AIC	BIC	SSE	RMSE	n
Circular	-383.95	-377.25	0	0.01	69
Exponential	-382.13	-375.43	0	0.01	69
Gaussian	-378.53	-371.82	0	0.01	69
Linear with sill	-383.38	-376.68	0	0.01	69
Spherical	-375.23	-368.53	0	0.01	69

LAG INTERVAL = 1

Figure 1. Variograms fitted on bulk density data using different models

CHAPTER 5. SUMMARY AND GENERAL CONCLUSIONS

Intensive use of tillage operations requires high energy input and may be detrimental to the environment. Thus there is a need to develop decision support tools to assist farmers in determining how much tillage is optimal for highest economic returns. Previous studies have developed quantitative indices that related tilth conditions to yield. The indices, however, proved inadequate and sometimes inconsistent. A three-part research project was carried out from 1998 to 2000 to further explore strategies for quantifying the seedbed condition following tillage. The three parts focused on the development of a soil condition index, spatial representation of yield variation and soil properties, and experimental design for tilth quantification. The research used soil physical properties (bulk density, penetration resistance, and soil moisture) to determine corn yield grown under different tillage systems. Conventional statistical methods and map overlays of soil and yield were used to understand yield variability. The results were largely consistent with previous studies regarding yield relation to both bulk density and penetration resistance. The general conclusions that were drawn from the study were as follows;

1. Crop response to tillage systems is significant for biomass during early growth and is not significant for grain yield. This suggests early plant growth to be a better indicator of tilth conditions even though a crop with superior biomass does not guarantee highest yield.
2. Moisture content was dominant among factors that related physical conditions to crop growth. The soil penetration resistance tended to increase as soil

moisture decreased. Penetration resistance was highly correlated to bulk density and hence was not included in a soil condition index model already containing bulk density.

3. Conventional statistics when used with spatial representation of yield and soil properties provided a visual relationship that assisted in explaining yield variability. Areas that are consistently low performing were revealed and thus could be further investigated.
4. Soil physical properties are a result of a random process that was difficult to quantify and predict. Conventional statistics are limited in explaining the effect of soil properties on yield and had no capacity to reliably predict future yield. Spatial statistics was appropriate only for characterization of soil properties. The effect of confounding factors, especially weather conditions, made it difficult to determine the true functional relationship of tilth to yield. With careful experimental design, the impact of weather could be accounted for in tillage trials.

RECOMMENDATION FOR FUTURE RESEARCH

This research explored methods for quantifying tilth, representing soil and yield variability as well as statistical design conditions. The study revealed that more work is still needed and thus the following recommendations for future research are made:

1. The results obtained in the soil condition index experiment can be considered preliminary since they were limited to one season. The research provided a framework for an extended study that should last for at least three years in order to

avoid time specific conclusions. It is also desirable to conduct the research on different locations and soil types so that when soil condition index is finally developed, it will have wide applicability.

2. It is still difficult to quantify the effects of weather conditions on crop yield. Further research is necessary to partition the effects of different factors on yield. Otherwise weather conditions will always be confounding and hence reduce the usefulness of tilth quantification.
3. Soil properties are interrelated, and no single factor is totally responsible for yield. Thus future research should focus on determining the most appropriate measure of tilth condition since a direct measurement is not currently possible.

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APPENDIX 1. TABLES AND FIGURES FROM DATA COLLECTED AT KELLY FIELD

Table A1-1 Soil data sampled before planting in spring 2000 at kelly field

Plot #	Sample #	GPS Code	Can #	Can Wt (g)	Wet Soil + Can (g)	Dry Soil + Can (g)	Dry Soil Wt. (g)	Density (g/cm^3)	Moisture Wt. (g)	% Moisture (db)	2" Pen (lb)	4" Pen (lb)	6" Pen (lb)	Ave. Pen (lb)
B1P1	1	B1P11	341	74.28	464.68	401.42	327.14	1.41	63.26	19.34	72.0	49.5	44.1	55.2
B1P1	2	B1P12	362	73.57	515.37	444.57	371.00	1.60	70.80	19.08	80.6	77.8	66.0	74.8
B1P1	3	B1P13	90	73.66	459.38	398.41	324.75	1.40	60.97	18.77	32.6	53.3	58.8	48.2
B4P1	4	B1P14	181	75.07	411.14	353.39	278.32	1.20	57.75	20.75	70.6	61.6	56.6	62.9
B1P1	5	B1P15	63	73.28	444.07	382.79	309.51	1.34	61.28	19.80	94.4	95.3	84.1	91.3
B1P1	6	B1P16	86	73.94	497.46	424.16	351.22	1.52	73.30	20.87	24.0	65.3	60.3	49.9
B1P2	1	B1P21	119	74.12	445.43	380.20	306.08	1.32	65.23	21.31	56.8	70.3	57.4	61.5
B1P2	2	B1P22	129	74.02	424.55	355.39	281.37	1.21	69.16	24.58	24.3	31.2	32.0	29.2
B1P2	3	B1P23	105	72.38	436.46	363.13	290.75	1.28	73.33	25.22	4.3	52.1	42.8	33.1
B1P2	4	B1P24	303	73.61	387.52	326.14	252.53	1.09	61.38	24.30	24.6	34.6	36.6	31.9
B1P2	5	B1P25	390	74.43	354.32	294.07	219.64	0.95	60.25	27.43	18.0	40.5	45.9	34.8
B1P2	6	B1P26	186	73.52	368.78	308.45	234.93	1.01	60.33	25.68	3.0	4.9	34.2	14.0
B1P3	1	B1P31	100	73.63	369.13	318.86	245.23	1.06	50.27	20.52	2.7	18.2	24.0	15.0
B1P3	2	B1P32	153	74.20	377.02	331.08	256.88	1.11	45.94	17.88	9.1	18.6	40.9	22.9
B1P3	3	B1P33	169	73.06	389.14	342.88	269.82	1.16	46.26	17.14	1.8	5.2	47.5	18.2
B1P3	4	B1P34	204	73.28	405.31	348.91	275.63	1.19	56.40	20.46	1.7	2.4	28.3	10.8
B1P3	5	B1P35	114	74.70	398.59	330.17	255.47	1.10	68.42	26.78	6.2	3.1	8.5	5.9
B1P3	6	B1P36	12	74.28	381.21	319.99	245.71	1.08	61.22	24.92	1.5	15.8	32.9	16.7
B2P1	1	B2P11	315	73.41	371.09	325.54	252.13	1.09	45.54	18.06	4.1	3.1	6.7	4.6
B2P1	2	B2P12	358	73.40	384.09	324.95	251.48	1.09	59.14	23.52	3.9	6.3	44.0	18.1
B2P1	3	B2P13	110	73.05	344.43	291.31	218.26	0.94	53.12	24.34	20.1	24.8	17.4	20.8
B2P1	4	B2P14	32	74.84	408.74	351.90	277.06	1.20	56.84	20.52	3.6	5.2	5.6	4.8
B2P1	5	B2P15	82	74.43	433.97	369.75	295.32	1.27	64.22	21.75	10.2	8.8	21.1	13.2
B2P1	6	B2P16	91	73.63	368.67	311.80	238.17	1.03	56.87	23.88	3.9	15.9	16.3	12.0
B2P2	1	B2P21	185	73.66	373.46	321.90	248.24	1.07	51.56	20.77	33.2	45.3	53.0	43.8
B2P2	2	B2P22	165	73.29	365.60	311.17	237.88	1.03	54.43	22.88	5.6	38.7	61.8	35.4
B2P2	3	B2P23	375	74.47	387.55	334.12	259.65	1.12	53.43	20.58	14.6	44.0	59.4	39.3
B2P2	4	B2P24	110	72.48	403.14	350.92	278.44	1.20	52.22	18.75	38.1	41.6	47.7	42.5
B2P2	5	B2P25	218	72.43	413.47	358.00	285.57	1.23	55.47	19.42	9.5	7.2	44.5	20.4
B2P2	6	B2P26	152	74.26	374.86	321.29	247.03	1.07	53.66	21.72	2.4	21.4	55.5	26.4
B2P2	1	B2P31	308	74.97	504.34	433.39	358.82	1.55	70.95	19.77	69.0	85.9	80.9	78.3
B2P3	2	B2P32	67	73.66	479.54	414.97	341.41	1.47	64.57	18.91	97.5	88.6	87.9	91.3
B2P3	3	B2P33	156	73.65	489.66	424.43	350.78	1.51	65.23	18.60	29.4	39.9	32.4	33.9
B2P3	4	B2P34	322	73.81	474.53	408.74	334.93	1.45	65.79	19.64	17.4	30.0	45.8	31.1
B2P3	5	B2P35	175	75.08	463.95	399.59	324.51	1.40	64.36	19.83	74.3	67.5	51.4	64.4
B2P3	6	B2P36	180	74.66	488.46	420.55	345.89	1.53	67.91	19.62	65.4	67.7	60.7	61.3
B3P1	1	B3P11	78	75.40	371.30	314.93	239.53	1.03	56.37	23.53	1.5	3.6	24.3	9.8
B3P1	2	B3P12	218	73.20	431.15	365.57	292.37	1.28	65.58	22.43	9.7	26.4	23.3	19.8
B3P1	3	B3P13	122	73.13	386.64	338.26	265.13	1.14	48.38	18.24	0.3	2.3	9.4	4.0
B3P1	4	B3P14	139	73.98	414.30	369.45	295.47	1.28	44.85	15.18	12.4	10.9	19.2	14.2
B3P1	5	B3P15	317	74.24	399.57	344.32	270.08	1.17	55.25	20.46	6.6	6.6	4.4	5.9
B3P1	6	B3P16	136	74.23	400.06	348.00	273.77	1.18	52.06	19.02	18.3	6.8	0.0	8.4
B3P2	1	B3P21	144	74.24	520.03	458.32	384.08	1.60	61.71	16.07	83.3	0.0	0.0	27.8
B3P2	2	B3P22	104	73.06	461.23	405.36	332.30	1.43	55.87	16.81	56.4	79.7	0.0	45.4
B3P2	3	B3P23	165	73.66	412.23	363.44	289.78	1.25	48.79	16.84	77.1	54.4	77.5	69.7
B3P2	4	B3P24	131	74.18	478.15	424.54	350.36	1.51	53.61	15.30	101.1	0.0	0.0	33.7
B3P3	5	B3P25	98	72.91	453.57	398.89	325.98	1.41	54.68	16.77	78.2	0.0	0.0	26.1
B3P2	6	B3P26	271	73.89	458.30	404.26	330.37	1.43	54.04	16.36	81.7	0.0	0.0	27.2
B3P3	1	B3P31	161	73.55	417.97	370.56	297.01	1.28	47.41	15.96	17.1	88.5	83.7	63.1
B3P3	2	B3P32	162	74.46	453.64	408.15	333.69	1.44	45.49	13.63	12.5	70.2	71.6	51.4
B3P3	3	B3P33	92	74.05	373.47	333.35	259.30	1.12	40.12	15.47	9.4	12.5	36.4	19.4
B3P3	4	B3P34	303	74.46	481.24	423.12	348.66	1.51	58.12	16.67	5.2	8.7	35.0	16.3
B3P3	5	B3P35	120	73.65	379.16	338.07	264.42	1.14	41.09	15.54	23.6	14.2	46.9	28.2
B3P2	6	B3P36	112	73.29	392.02	353.40	280.11	1.21	38.62	13.78	8.8	26.4	40.1	25.1
B4P1	1	B4P11	386	74.46	436.83	370.44	295.98	1.32	66.39	22.42	10.4	9.4	26.3	15.4
B4P1	2	B4P12	333	73.13	350.90	317.83	244.70	1.06	33.07	13.51	11.0	8.7	39.3	20.0
B4P1	3	B4P13	189	74.75	394.57	337.86	263.11	1.14	56.71	21.55	10.3	14.4	33.5	19.4
B3P1	4	B4P14	370	73.94	356.46	327.61	253.67	1.09	28.85	11.37	7.0	5.7	11.4	8.0
B3P1	5	B4P15	189	74.06	431.89	403.07	329.01	1.42	28.82	8.76	5.4	16.5	31.0	17.6
B3P1	6	B4P16	183	74.61	385.69	347.30	272.69	1.18	38.39	14.08	18.1	27.9	31.7	25.9
B4P2	1	B4P21	266	73.95	391.81	343.83	269.88	1.19	47.98	17.78	14.4	13.1	28.6	18.7
B4P2	2	B4P22	25	74.00	404.09	346.87	272.87	1.18	57.22	20.97	28.3	33.5	71.8	44.5
B4P2	3	B4P23	93	74.53	406.09	372.30	297.77	1.29	33.79	11.35	5.5	6.4	75.1	29.0
B4P2	4	B4P24	142	73.96	384.70	347.01	273.05	1.19	37.69	13.80	8.6	10.9	70.4	30.0
B4P2	5	B4P25	189	74.74	366.83	341.94	267.20	1.16	24.89	9.32	7.8	72.4	97.1	59.1
B4P2	6	B4P26	182	73.36	406.60	372.74	299.38	1.29	33.86	11.31	4.5	8.1	38.9	17.2
B4P3	1	B4P31	84	73.77	394.76	344.39	270.62	1.17	50.39	18.62	87.8	90.3	66.7	81.6
B4P3	2	B4P32	133	74.37	496.52	431.45	357.08	1.54	65.07	18.22	68.7	60.3	92.2	73.7
B4P3	3	B4P33	115	74.70	474.64	410.19	335.49	1.45	64.45	19.21	53.3	68.2	61.6	61.0
B4P3	4	B4P34	176	73.65	480.75	422.05	348.40	1.50	58.70	16.85	44.2	78.7	67.4	63.4
B4P3	5	B4P35	217	73.00	427.01	383.51	310.51	1.34	43.50	14.01	20.3	38.9	48.2	35.8
B4P3	6	B4P36	321	73.83	406.09	365.01	291.18	1.26	41.08	14.11	51.3	63.7	77.2	64.1

Table A1-2 Corn biomass data collected at V2 Stage

Sample #	Wmass(g)	Dmass(g)	Wbag(g)	Wwater(g)	Biomass(g)	MC (%)
B1P11	20.22	11.84	10.78	8.38	1.06	88.77
B1P12	17.39	11.47	10.76	5.92	0.71	89.29
B1P13	21.42	11.89	10.68	9.53	1.21	88.73
B1P14	18.48	11.63	10.78	6.85	0.85	88.96
B1P15	19.04	11.47	10.57	7.57	0.90	89.37
B1P16	21.48	11.93	10.76	9.55	1.17	89.09
B1P21	19.45	11.78	10.79	7.67	0.99	88.57
B1P22	24.38	12.30	10.77	12.08	1.53	88.76
B1P23	18.88	11.70	10.78	7.18	0.92	88.64
B1P24	21.74	11.97	10.81	9.77	1.16	89.39
B1P25	19.67	11.78	10.82	7.89	0.96	89.15
B1P26	23.54	12.26	10.85	11.28	1.41	88.89
B1P31	23.73	12.10	10.73	11.63	1.37	89.46
B1P32	18.19	10.42	9.38	7.77	1.04	88.20
B1P33	21.23	10.62	9.28	10.61	1.34	88.79
B1P34	22.18	10.99	9.51	11.19	1.48	88.32
B1P35	19.98	11.80	10.70	8.19	1.10	88.16
B1P36	19.20	11.79	10.83	7.41	0.96	88.53
B2P11	20.96	10.72	9.44	10.24	1.28	88.89
B2P12	21.80	10.76	9.41	11.04	1.35	89.10
B2P13	19.74	10.66	9.47	9.08	1.19	88.41
B2P14	21.13	12.01	10.83	9.12	1.18	88.54
B2P15	19.13	10.44	9.29	8.69	1.15	88.31
B2P16	20.76	10.60	9.30	10.16	1.30	88.66
B2P21	20.82	10.63	9.44	10.19	1.19	89.54
B2P22	22.78	10.84	9.31	11.94	1.53	88.64
B2P23	21.07	10.88	9.53	10.19	1.35	88.30
B2P24	20.24	10.49	9.27	9.75	1.22	88.88
B2P25	21.96	10.61	9.28	11.35	1.33	89.51
B2P26	21.71	10.63	9.27	11.08	1.36	89.07
B2P31	22.46	11.98	10.78	10.48	1.20	89.73
B2P32	18.74	10.54	9.48	8.20	1.06	88.55
B2P33	18.90	10.47	9.39	8.43	1.08	88.64
B2P34	16.06	10.00	9.25	6.06	0.75	88.99
B2P35	17.19	10.14	9.29	7.05	0.85	89.24
B2P36	19.81	11.83	10.74	7.98	1.09	87.98
B3P11	21.64	10.90	9.46	10.74	1.44	88.18
B3P12	22.89	11.89	10.43	11.00	1.46	88.28
B3P13	17.59	11.23	10.35	6.36	0.88	87.85
B3P14	19.10	10.50	9.32	8.60	1.18	87.93
B3P15	21.57	10.72	9.27	10.85	1.45	88.21
B3P16	17.87	10.44	9.32	7.43	1.12	86.90
B3P21	19.04	10.64	9.51	8.40	1.13	88.14
B3P22	21.32	10.76	9.33	10.56	1.43	88.07
B3P23	18.35	10.62	9.53	7.73	1.09	87.64
B3P24	19.87	10.50	9.23	9.37	1.27	88.06
B3P25	20.45	10.63	9.28	9.82	1.35	87.91
B3P26	20.03	10.63	9.28	9.40	1.35	87.44
B3P31	26.18	11.50	9.68	14.68	1.82	88.97
B3P32	27.81	11.37	9.36	16.44	2.01	89.11
B3P33	26.85	11.27	9.24	15.58	2.03	88.47
B3P34	18.78	11.05	9.46	7.73	1.59	82.94
B3P35	23.73	11.02	9.42	12.71	1.60	88.82
B3P36	21.40	10.71	9.63	10.69	1.08	90.82
B4P11	26.74	11.24	9.27	15.50	1.97	88.72
B4P12	26.62	11.22	9.27	15.40	1.95	88.76
B4P13	22.85	11.64	10.32	11.01	1.52	87.87
B4P14	23.35	11.08	9.43	12.27	1.65	88.15
B4P15	19.96	11.44	10.31	8.54	1.13	88.31
B4P16	33.34	13.05	10.32	20.29	2.73	88.14
B4P21	27.44	12.33	10.32	15.11	2.01	88.26
B4P22	29.16	12.61	10.42	16.55	2.19	88.31
B4P23	22.04	11.73	10.40	10.31	1.33	88.57
B4P24	21.85	10.81	9.38	11.04	1.43	88.53
B4P25	25.11	11.23	9.42	13.88	1.81	88.46
B4P26	25.38	11.93	10.27	13.45	1.66	89.01
B4P31	21.02	10.90	9.47	10.12	1.43	87.82
B4P32	21.67	11.01	9.51	10.66	1.50	87.66
B4P33	22.98	10.83	9.30	12.15	1.53	88.82
B4P34	20.55	10.43	9.32	10.12	1.11	90.12
B4P35	23.42	10.81	9.49	12.61	1.32	90.52
B4P36	21.07	10.79	9.41	10.28	1.38	88.16

Table A1-3. Data collected from the Standard Proctor Compaction test

Project: PhD. Research | Location: Kelly fields | Sample depth: 0-30cm

Date sampling: | Date tested: 01-25-00 | Researcher: M. Tapela

Volume of mold: 1 / 30 (ft^3) or 994cm^3

Item	Unit	1	2	3	4	5	6
Weight of mold:	kg	4.256	4.256	4.256	4.256	4.256	4.256
Compacted soil + mold:	kg	5.673	5.715	5.845	6.01	5.973	5.939
Compacted soil + mold:	lb	12.51	12.6	12.89	13.25	13.17	13.09
Can number:	–	321	357	376	98	194	106
Mass of can:	g	73.85	74.95	73.98	72.97	73.83	73.2
Mass of wet soil + can:	g	194.39	213.26	169.66	221.36	236.93	278.23
Mass of dry soil + can:	g	186.47	200.99	157.58	198.67	201.33	229.73
Water content:	%	7.032499	9.735005	14.44976	18.05091	27.92157	30.98448
Dry unit weight:	kg/m^3	1331.888	1337.592	1396.763	1494.768	1350.331	1292.641
Dry unit weight:	lb/ft^3	87.73036	88.03025	92.00543	98.3474	88.88259	84.9719

Comments:

1lb/ft^3 = 16.018 kg/m^3

Table A1-4. Soil sampling results used to calculate the density ratio

Project: PhD Research   Location: Kelly fields   Sample depth: 0-5cm

Sampling date: 04-25-00   Researcher: M. Tapela

Plot #	Ave.Moisture (%)	Ave. Density (kg/m^3)	Max. Proctor Density	Density Ratio
B1P1	19.77	1.4115	1.5929	0.8861
B1P2	24.75	1.1406	1.4965	0.7622
B1P3	21.15	1.1141	1.5829	0.7038
B2P1	22.01	1.1024	1.5681	0.7031
B2P2	20.68	1.1200	1.5884	0.7051
B2P3	19.26	1.4863	1.5912	0.9341
B3P1	19.81	1.1772	1.5929	0.7391
B3P2	16.36	1.4481	1.5326	0.9449
B3P3	15.22	1.2829	1.5071	0.8512
B4P1	15.28	1.2001	1.5084	0.7956
B4P2	14.08	1.2087	1.4835	0.8148
B4P3	16.84	1.3765	1.5438	0.8916

Table A1-5. Data collected to determine the moisture content at soil field capacity

Start date: 01-10-00 | Bar Description: 0.03 MPa | Plate Number:

End Date: 01-13-00 | Recorder: M. Tapela

Ring No. :	C 67	C 68	C69	C 72	C 73	
Can No. :	C 67	C 68	C 69	C 72	C 73	
Can Weight :	159.46	159.50	159.23	159.39	159.26	
Can + wet soil:	712.40	788.20	779.70	811.50	793.90	
Can + Dry soil:	590.49	664.00	652.00	685.00	671.40	Average:
Dry Soil weight:	431.03	504.50	492.77	525.61	512.14	
Moisture (%) :	28.28	24.62	25.91	24.07	23.92	25.36

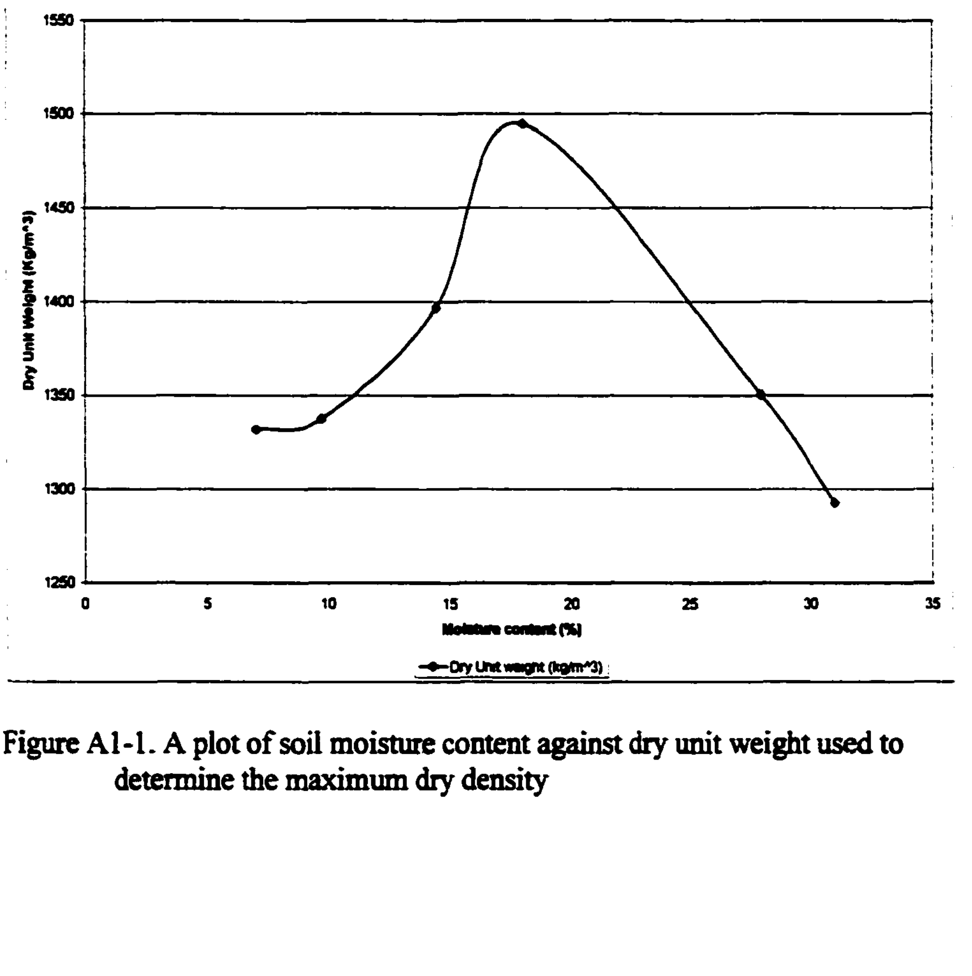

Figure A1-1. A plot of soil moisture content against dry unit weight used to determine the maximum dry density

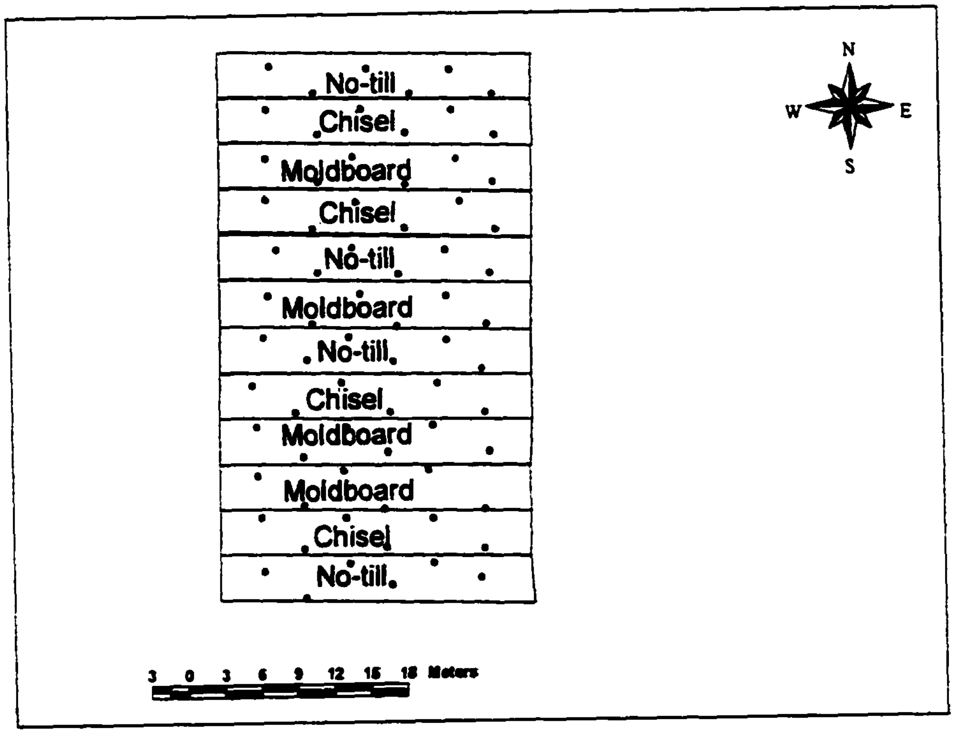

Figure A1-2. A map of Kelly field showing tillage treatments and soil sampling points

APPENDIX 2. TABLES AND FIGURES FROM DATA COLLECTED AT THE AGRICULTURAL ENGINEERING RESEARCH CENTER FIELD

Table A2-1. An Example of data recorded by a yield monitor and GPS unit during harvesting

LON	LAT	FLOW_LBS_S	GPS_SEC	CYCLES	DIST_IN	SWATH_IN	MC	STATUS	PASS	SERIAL	FIELD	LOAD	GRAIN	GPS_STATUS	PDOP	ELEV_FT	DISTANCE	YLD_BU_A	MC
-94	42	6.76	970146014	1	3	149	11	33	0	990210	F15:70	L1:	CORN	7	0	1122.7	0	157.2	11
-94	42	3.66	970146025	1	13	149	12	33	0	990219	F15:70	L1:	CORN	7	0	1123	0	208.1	12
-94	42	5.59	970146026	1	32	149	16	33	0	990210	F15:70	L1:	CORN	7	0	1122.7	0	126.8	16
-94	42	5.59	970146027	1	32	149	16	33	0	990210	F15:70	L1:	CORN	7	0	1122.7	0	126.8	16
-94	42	7.41	970146028	1	32	149	16	33	0	990210	F15:70	L1:	CORN	7	0	1122.7	0	168.7	16
-94	42	7.86	970146029	1	41	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.7	0	143.6	15
-94	42	7.86	970146030	1	45	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	129.2	15
-94	42	6.83	970146031	1	46	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	143.3	15
-94	42	6.83	970146032	1	44	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	150.7	15
-94	42	9.06	970146033	1	44	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	154.4	15
-94	42	6.53	970146034	1	45	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	140.6	15
-94	42	6.53	970146035	1	46	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	132	15
-94	42	6.74	970146036	1	50	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	131.2	15
-94	42	9.9	970146037	1	49	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	150.9	15
-94	42	9.9	970146038	1	49	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	150.9	15
-94	42	9.06	970146039	1	49	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	138.1	15
-94	42	9.06	970146040	1	49	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	138.1	15
-94	42	9.61	970146041	1	49	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	146.4	15
-94	42	9.06	970146042	1	49	149	14	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	139	14
-94	42	9.08	970146043	1	49	149	14	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	133	14
-94	42	7.62	970146044	1	49	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	116.3	15
-94	42	9.2	970146045	1	50	149	15	33	0	990210	F15:70	L1:	CORN	7	0	1122.4	0	138	15

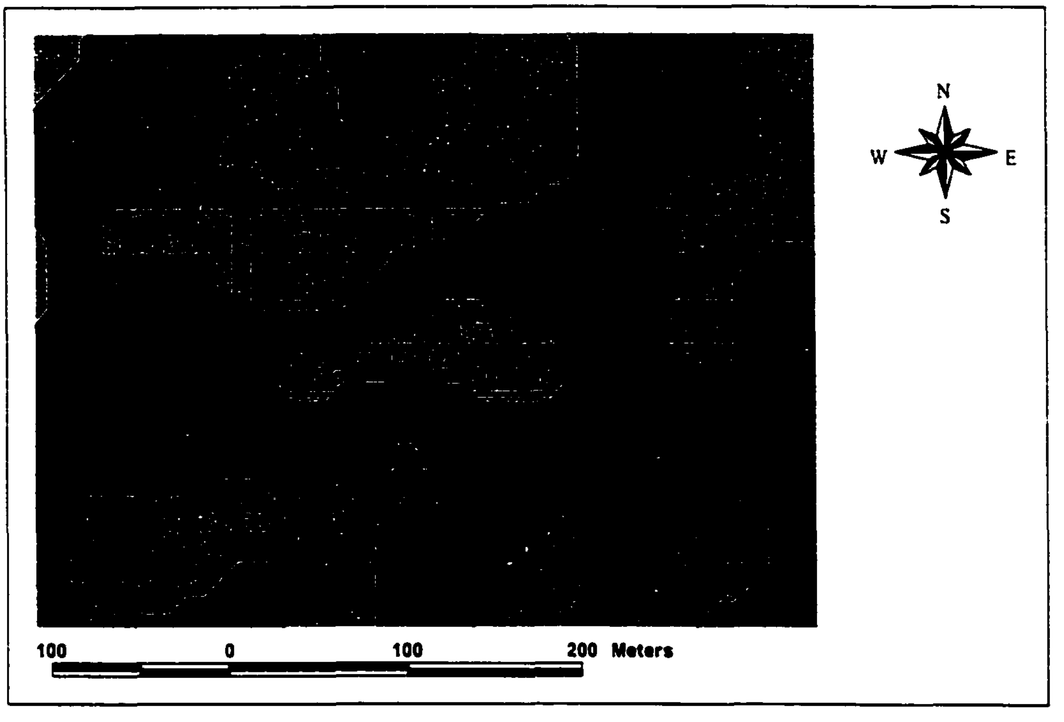

Figure A2-1. A map of AERC field showing experiment design and soil types

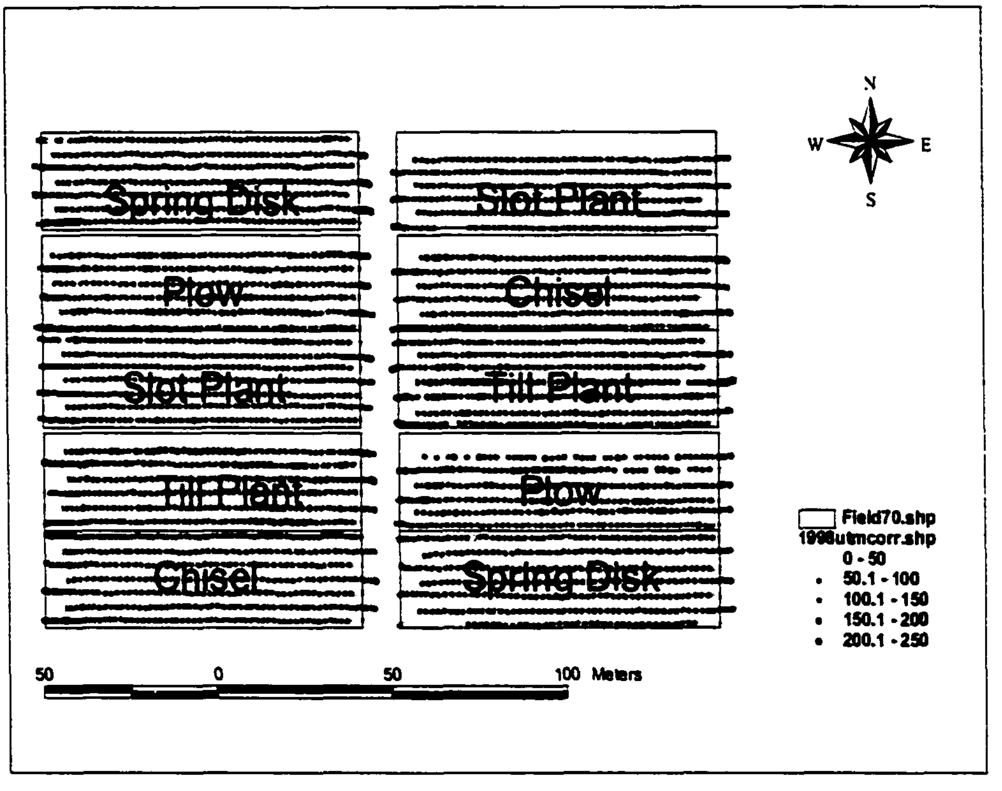

Figure A2-2. Yield monitor data on two blocks before cleaning of extreme values, flyers and inconsistent speed in 1998.

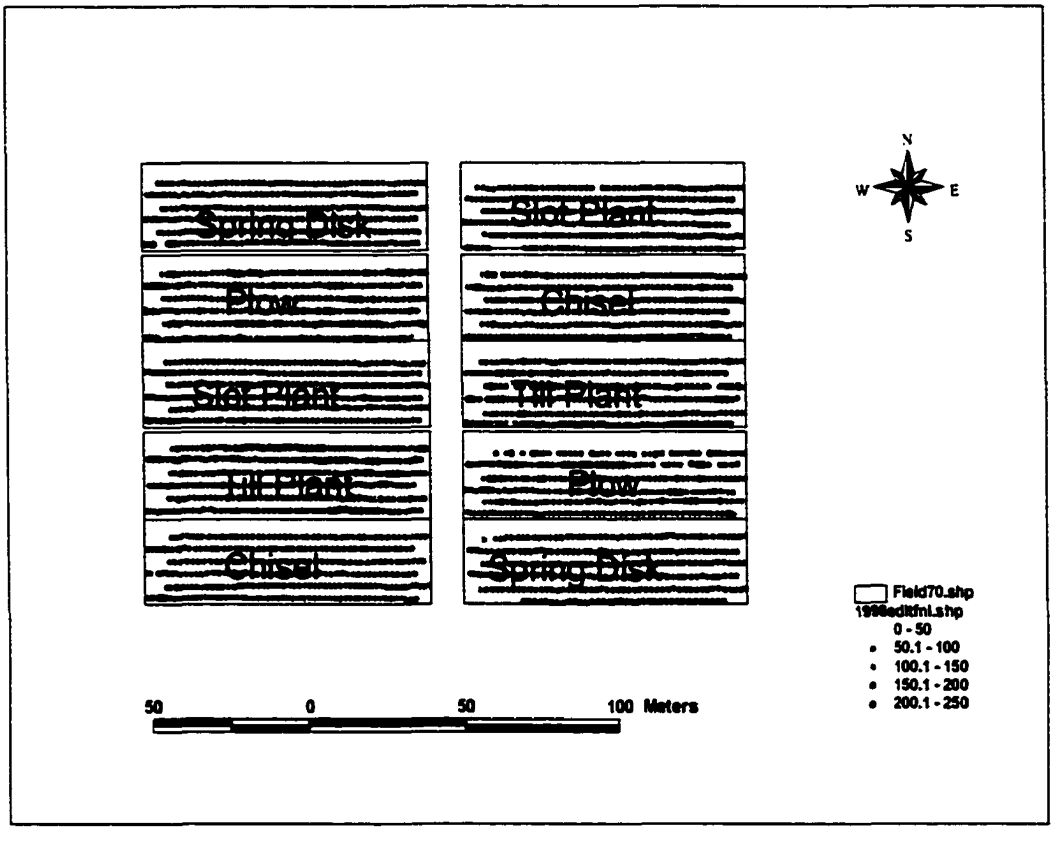

Figure A2-3. Yield monitor data on two blocks after cleaning of extreme values, flyers and inconsistent speed in 1998.

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