MONTANA STATE UNIVERSITY

Soil and terrain attributes for predicting soil fertility and winter wheat yield
by Kirk Lowndes McEachern

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Soils
Montana State University

Abstract:
Large-scale geographic information system (GIS) applications are largely absent in agronomic applications. There is an opportunity to use this and related digital terrain analysis techniques to investigate crop and soil relationships. These merit study to ascertain if these technologies have validity in a farm-scale GIS.

The objective of this work was to investigate relationships of the digital elevation model (DEM) attributes of slope, profile curvature, plan curvature and wetness index to winter wheat yield and the soil fertility variables NO3-N, P, K, pH and organic matter. The analysis included investigating these relationships in context of Soil Conservation Service (SCS) mapping units and fertilizer treatments.

Three fertilizer treatments representing a "Farm Soils, Not Fields" rate, the same rate plus sulfur and a field average rate were applied to a 100 m by 1600 m (16 ha) study site located in Teton County, Montana in August, 1990. Soil fertility samples were collected pre- and post-harvest in 0-15, 15-30 and 30-60 cm increments. Two elevation data sets were collected representing points around the study site and points within the study site. These data were interpolated into a regular grid spacing using a FORTRAN interpolation routine and entered into the DEM TAPES-G.

Results indicate that most of the variation in yield occurred in the SCS mapping units when compared to the fertilizer treatments. Analysis of yield differences by DEM attribute class showed positive trends in the relationships between slope, wetness index and yield and is consistent with the concept of increasing yield with increasing water content. Nitrate-N explained only about 19% of the variation in yield and suggests that some other group of physical or chemical properties are controlling yield. Stepwise regression of the DEM variables with the soil fertility variables resulted in slope being the most consistently predictive variable as it occurred in the regressions for NO3-N, K, pH and organic matter. The relationships between NO3-N, organic matter and slope were the inverse of that expected. The regressions of the soil fertility variables with the DEM variables explained between 17% and 24% of the variation in yield.

It appears that in this study, the most predictive approach for explaining yield variation in the study area was the standard SCS mapping units. Thus, future work should center on elucidating what combination of chemical or physical properties expressed in the SCS mapping units control yield.

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ABSTRACT

Large-scale geographic information system (GIS) applications are largely absent in agronomic applications. There is an opportunity to use this and related digital terrain analysis techniques to investigate crop and soil relationships. These merit study to ascertain if these technologies have validity in a farm-scale GIS.

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INTRODUCTION

Scope and Purpose

Geographic Information Systems (GIS) are routinely used to investigate natural resource issues at watershed, county, state or regional resource scales. Few precise agricultural applications have been attempted to date. GIS may assist in studies of relationships between the environment and crop production.

A field-scale geographic system (FSGIS) can be used to inventory and manage the soil and related environmental factors. The purpose of such a FSGIS would be to capture the economic or environmental benefits of managing soils according to their individual needs. This "Farming Soils, Not Fields" concept (Carr et al., 1991) would match soils with appropriate yield goals and fertilizer rates and increased profit may be achieved. Soil variability is the driving force behind the need for a FSGIS and soil-specific farming. Soil test data must be spatially accurate for this type of application.

Traditional soil sampling for fertilizer recommendations requires taking several samples in a field and mixing them for a composite sample. This would average any differences in soil test levels due to contrasting soil types or other factors. Several different soil sampling methods have been used to generate maps which more accurately reflect the variation in soil fertility in a field. Carr et al. (1991) describes sampling by Soil Conservation Service (SCS) soil mapping units. This method requires an accurate soil map and professionals with the ability to discern soil boundaries. Another method is to sample a field on a grid basis. Fertilizer rates are then formulated for the field based on these sample points. A third method could be based upon a parametric partitioning of the landscape as originally formulated by Speight (1974) in which the shape of the land surface and the movement of water

across the surface are quantified. Maps of these landscape parameters can now be generated by using a digital elevation model (DEM) in a GIS framework. Relationships of soil test results to DEM attributes need to be investigated to determine if a DEM merits inclusion into a FSGIS.

The work presented here originated from a demonstration of variable rate fertilizer applications as navigated by global positioning system technology (McEachern et al., 1990). Pre-plant soil fertility data had been collected for the demonstration and it was decided to extend this pilot study by collecting yield data and post-harvest soil fertility data. The purpose of the work was to investigate relationships between soil test results, DEM attributes and winter wheat yields.

Objectives

The first objective was to investigate effects of variable rate fertilizer treatments and Soil Conservation Service (SCS) mapping units on winter wheat yield. Three treatments were applied representing a "Farm Soils, Not Fields" rate, the same rate plus sulfur and a "field average" rate. The second was to determine the sensitivity of terrain characteristics to the pattern and density of elevation points used as input. Two elevation data sets, one representing points on the perimeter of the study area and a second representing points within the study area, were used to construct a DEM. The third objective was to determine if winter wheat yield is related to the primary terrain attributes slope, plan curvature, profile curvature and the secondary attribute wetness index. The two elevation data sets were combined to produce the DEM for this objective. The fourth objective was to determine if a combination of SCS soil mapping units and terrain attributes and treatments better correlate with winter wheat yield than either mapping units or terrain attributes alone. The fifth objective was to determine if winter wheat yields correlate with soil test nitrate-nitrogen at the

sampling points. The final objective was to identify relationships between DEM attributes and soil fertility variables.

LITERATURE REVIEW

Traditional farming practices involve management of fields with little concern for soil or topographic variability. For example, fertilizer and pesticides are generally applied uniformly to all parts of the field. There is a growing body of literature to suggest that this method does not adequately manage the inherent variability for maximum economic return or environmental protection. Several new technologies and techniques developed in the last 10 to 15 years provide new opportunities for verifying the inputs applied to different management units within fields.

The "Farming Soils, Not Fields" Concept

Carr et al. (1991) have shown that the "Farming Soils, Not Fields" concept of matching soils with appropriate yield goals and fertilizer rates has potential economic advantages. Their work measured winter wheat, spring wheat and barley yield differences between contrasting soils within fields at three locations in central Montana. They also investigated the economics of "Farming Soils, Not Fields," where contrasting soils in a field receive variable versus uniform rates and formulations of fertilizer. They reported that grain yield, test weight and returns over variable costs varied greatly among soil units in each field.

Soil fertility data must accurately describe the variation in available nutrients in a field for variable rate fertilizer applications to be successful. Soil-specific fertility recommendations also depend on appropriate yield goals for the soils in a field (Carr et al., 1991). The challenge is to develop quick and cost-effective methods to determine available nutrient levels within a field for fertility management.

Soil Survey and Sampling

Soil sampling methods are available to generate maps which more accurately reflect the variation in soil fertility in a field than traditional methods. Carr et al. (1991) describes sampling by SCS soil mapping unit. These maps are produced at various scales and levels of taxonomic purity. Standard (Order 2) surveys are produced most commonly at scales of about 1:24,000. The consociation is perhaps the most common mapping unit encountered. In a consociation, at least 50% of the pedons in the unit are the same series name as the mapping unit name with the remainder of the pedons having very similar interpretations. This kind of mapping unit allows for no more than 15% dissimilar inclusions if they limit interpretations and 25% dissimilar inclusions if nonlimiting for interpretations (USDA-SCS, 1980). Complexes and associations represent two other kinds of mapping units which contain two or more dissimilar soils, occurring in a regular pattern. Individual soils in a complex cannot be mapped (delineated) at a scale of about 1:24,000, unlike the individual soils in the association. In both cases, the soils are sufficiently dissimilar to preclude being a consociation.

Generally, mapping units are related to geomorphic, geologic or hydrologic features and are defined primarily by morphologic features and by soil series. The soil series concept is the fundamental unit used in designing mapping units. A soil series is a collection of soils with similar kinds and arrangements of horizons. Series are defined on the basis of ranges in morphological, physical and chemical characteristics within horizons. The ranges for some properties, notably physical properties, can vary by an order of magnitude or more. The official series description and interpretive record published by the USDA-Soil Conservation Service (SCS) gives the ranges for these items for each recognized series. Soil fertility data

are not included in these documents primarily due to the spatially and temporally variable nature of these data due to natural or human factors.

SCS Order 2 soil maps based on the series concept and mapping unit designs described above are valuable tools for regional planning, hazard assessment and resource inventories. Only general statements about site-specific suitability for agriculture or urban uses are possible with these maps. Detailed, site-specific soil fertility, physical, chemical and morphological information are not obtainable from these maps. Using SCS soil mapping unit delineations for a fertility sampling scheme is a good approach when nothing else is known about the soils. However, the inherent fertility variation in a mapping unit in addition to annual changes in fertility levels from fertilization, climate and crop removal make predictions impossible. Thus, soil survey maps alone may be poor predictors of soil fertility.

A sampling method practiced by commercial variable-rate fertilizer application firms and others is to grid sample a field (Fairchild and Hammond, 1988). The field is first evaluated using the SCS soils map and infrared photography. Soil samples are then taken on a grid with distances of 33 to 66 m between sample points. Contour maps of soil test data are generated using kriging which interpolate the actual analytical results to areas where there is no soil test data. Fertilizer rates are determined from these maps by subdividing the contour maps into ranges representing high, medium and low soil test results. This method is labor intensive, costly and is most effectively used on high value crops.

Soil Variability and Landscape Position Relationships

There has been much interest in relationships between landscape position (LP), yield and residual NO_3-N over the past two decades. Aandahl (1948) found that slope length was positively related to percent nitrogen (N) extracted from organic matter

and was significant for the virgin Iowa soils studied. He hypothesized that this may be due to greater water and organic matter accumulation in lower slope positions where uphill slopes are longer. Spratt and McIver (1971) investigated the effects of landscape positions, soil test results and fertilizer use on dryland wheat yields in Saskatchewan. Their results show that wheat yields were much less on higher landscape positions (the crown) than at lower landscape positions. They concluded that the arid conditions of the upper slopes limited the yield and that the basic pedological and microclimatological factors of the soil catena affect the yields of wheat more than soil fertility and fertilizers.

Ciha (1984) reported that slope position significantly influenced winter wheat yield in the Palouse region of southeastern Washington. Soils on the broad, flat interfluve had highest yield, thicker A-horizon, thicker solum and less slope than the downslope soils. Yields were lowest at the next lower position and generally increased downslope. He reasoned that the toeslope position received lateral moisture making it more productive than the midslope positions. Ferguson and Gorby (1966) hypothesized that some of the variability in yields of wheat among fields studied in Manitoba, Canada may be due to variation in slope, aspect and size of drainage area although they did not publish any data to support this hypothesis. Stone et al. (1985) reported that the differences in corn grain yields in the North Carolina Piedmont among LP were much more consistent than yield differences among erosion classes. They also noted that yields were higher in those LP receiving water from higher elevations. This suggests that LP has an important impact on yields.

Jones et al. (1989) and Schroeder (1991) also report a general increase in yield for various crops at lower landscape positions. Jones et al. (1989) studied the relationships between landscape position, soil properties, and corn, sorghum and soybeans yields in Nebraska. They report that yields were generally higher on landscape positions with lower slopes. The highest yields were generally on lower

interfluves and footslopes whereas the steep, linear landscape positions had the lowest yields. Schroeder (1991) reported higher available water and higher wheat yields at lower landscape positions than at higher positions on reclaimed mineland in North Dakota.

Sinai et al. (1981) found a strong relationship between moisture content, yield and curvature of the soil surface in the semi-arid area of Israel. Their main conclusion was that the direction of downhill flux of infiltrating water will depend on the degree of anisotropy as well as on the land slope and its changes.

Research relating landscape position to phosphorus (P), potassium (K), pH or organic matter for semi-arid areas is limited. Aguilar and Heil (1988) investigated the relationship between N, P and carbon (C), parent material and landscape position in North Dakota rangeland. They found that the distribution of these constituents varied systematically with parent material and landscape position along three transects and generally increased downslope. They attributed the greater quantities of organic constituents on lower landscape positions to both greater vegetative production and accretion of soil organic matter through sedimentation. The redistribution of soil by wind, water and creep contributed to the changes of P content with time, since P is quickly adsorbed to clay particles and immobilized. Phosphorus movement after immobilization is, therefore, linked to movement of soil particles. Smeck (1973) investigated the vertical distribution of P in a toposequence of soils in southern Illinois. He found that total P in pedons tends to increase in downslope positions.

The literature offers little evidence to expect that pH and K are topographically related. An argument can be made to suggest a relationship, however, since pH and K are, in large part, inherited from the parent material (PM). The proximity of PM to the surface may influence the amount of K present and the pH at a site. Shallow soils may have K amounts and pH more similar to the PM than deeply weathered soils. If one can predict where shallow soils occur on a landscape, then pH, K and

LP may be correlated. In areas of homogenous PM (no bedding planes or changes in lithology), this is conceptually possible. Shallow soils would be expected to occur on the most erosive parts of the landscape.

Soil Water and Landscape Position Relationships

Central to most of the arguments presented above is the concept that water accumulates in lower slope positions. There has been much theoretical and practical work to verify this concept in the last 20 years. Zaslavsky and Rogowski (1969) present a conceptual framework as to why water tends to collect in downslope and concave positions in the landscape. They argued that water moves with a vertical component due to gravitational forces, but the downward flux is also affected by the anisotropic nature of soil horizons. As the downward moving water encounters layers of unequal, and usually lower, hydraulic conductivity, a lateral flux vector is introduced. The resulting soil water flux vector is also a function of the soil surface slope. Soils with a low surface slope will have a smaller lateral soil water flux vector than soils with a steeper slope. Zaslavsky and Sinai (1981a, b and c) present theoretical, mathematic descriptions of the relationship between slope, anisotropy and water movement which illustrate these points. They also postulate that water collects in concave positions because the uphill slope and incoming water flux is greater than the downhill slope and outgoing water flux. As a result, water accumulates in these positions. They present little field evidence to support their claims.

Several workers have noted and attempted to describe soil water and landscape position relationships in the field. Hannah et al. (1982) studied the effect of slope, aspect and landscape position on soil water and its changes throughout the year for dryland farming in southeast Nebraska. They monitored water content on four landscape positions in 30 cm increments to 150 cm weekly for two years. They

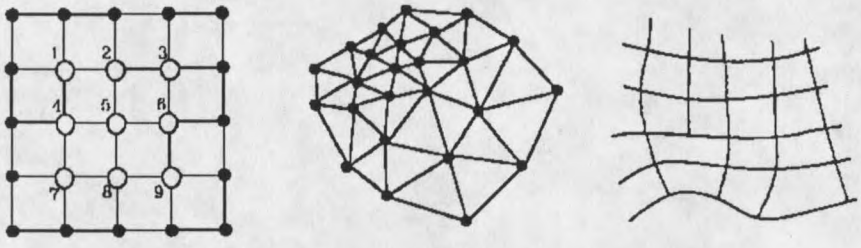
found that soils on the footslopes and backslopes contained, on average, 4 cm more plant available water than soils on summits and shoulders. Additionally, they found that backslope positions were more drastically affected by aspect than summit positions. Hannah et al. (1983) in a related study in Nebraska, measured soil water content for soils with low infiltration under center-pivot irrigation at slopes of 2, 4 and 8 percent during one growing season. They reported that soils on the mid-backslope position (8 percent slope) had higher soil water content than soils on the summit and upper backslope positions (slopes of 2 and 4 percent, respectively). They hypothesized that water moved from the summit and upper backslope positions to the mid-backslope site. Water did collect at lower landscape positions, even though they had higher slopes than higher landscape positions. Sinai et al. (1981) observed a high linear correlation between moisture in the root zone and the soil surface curvature in the semi-arid zone of Israel.

Digital Elevation Models and Terrrain Analysis Techniques

A digital terrain model is a set of numbers that represent the spatial distribution of elevation for points in an area (Collins, 1975). Thus, a digital elevation model (DEM) is one in which the elevation, Z, is given in relation to horizontal coordinates X and Y. There are three ways of handling these data in a DEM. The grid, triangulated irregular network (TIN), and contour-based models are all valid models which describe the same phenomena using different data storage and manipulation techniques (Fig. 1).

The grid-based DEM is the most common model (Moore et al. 1992). In this system, the X, Y and Z elements are generated for a grid network. Values of Z are stored along transects in a regularly spaced square or rectangular mesh. The fitting of a surface to this model consists of using any one of a variety of interpolation

schemes. These include kriging, local interpolation, moving average and spline interpolation. A local interpolation method is often used for the grid-based DEM. The interpolation is local because the surface is fitted by interpolating within a 3 by 3 matrix which is passed over the data (Moore et al., 1993). The surface is fitted using only nine elevations of a submatrix at a time. Zevenbergen and Thorne (1986) proposed using a nine parameter quadratic equation which produces a surface which passes exactly through all nine of the submatrix elevation points. The grid-based DEM has been criticized on several points: 1) abrupt changes in elevation are not easily handled; 2) the computational efficiency and results obtained are determined by the grid mesh size; 3) flow paths used in hydrologic modeling zig-zag and are somewhat unrealistic; 4) specific catchment area definition lacks precision (Moore et al., 1988a).



(a) grid (b) TIN (c) contour

Fig. 1. Three types of digital elevation models. (Moore et al., 1992).

The TIN model represents the terrain as a series of triangles. The corners of the triangles are usually representative of peaks, ridges and breaks in slope (Moore et al., 1988b). This model has the conceptual problem of not realistically representing a

landscape. In addition, analysis for plan curvature and profile curvature, to be discussed later, are not possible with TIN's. This method also does not represent slope accurately because the surface is considered to be planar and any slope derivative would thus be an average.

The third alternative of representing terrain in a digital format is the contour-based method proposed by Moore (1988b). The contour method partitions a catchment into natural units based on the flow of water. The units consist of irregularly shaped polygons formed by a section of a contour line and orthogonals extending from this line upslope to the catchment divide. The orthogonals represent stream flow lines and the contour lines represent lines of equal potential. This model is conceptually more appealing than others previously discussed in that it more realistically represents terrain. One disadvantage is that at least an order of magnitude more data storage is required for a contour- compared to a grid-based DEM (Moore et al. 1992).

Attributes can be derived from each type of DEM representing several topographic characteristics (Table 1). Primary properties of terrain generated by DEM's include slope, area, aspect, elevation, maximum and minimum elevations, depressions and divides. Secondary properties include volume, slope changes, profile and plan curvature, stream course and stream course distance, specific catchment area, depression storage and incoming solar radiation.

Table 1. Attribute definition and significance for attributes obtainable from digital elevation models. (Moore et al., 1988b).

Attribute	Definition	Significance
Altitude	Elevation	Climate, vegetation, potential energy
Upslope height	Mean height of upslope area	Potential energy
Aspect	Slope azimuth	Solar insulation, evapotranspiration, flora and fauna distribution and abundance
Slope	Gradient	Overland and subsurface flow velocity and runoff rate, precipitation, vegetation, geomorphology, soil water content, land capability class
Upslope slope	Mean slope of upslope area	Mean slope of upslope area
Dispersal slope	Mean slope of dispersal area	Runoff volume
Catchment slope†	Average slope over the catchment	Time of concentration
Upslope area	Catchment area above a short length of contour	Runoff volume, steady-state runoff rate
Dispersal area	Area downslope from a short length of contour	Soil drainage rate
Catchment area†	Area draining to catchment outlet	Runoff volume
Specific catchment area	Upslope area per unit width of contour	Runoff volume, steady-state runoff rate, soil characteristics, soil water content, geomorphology
Flow path length	Maximum distance of water flow to a point in the catchment	Erosion rates, sediment yield, time of concentration
Upslope length	Mean length of flow paths to a point in the catchment	Flow acceleration, erosion rates
Dispersal length	Distance from a point in the catchment to the outlet	Impedance of soil drainage
Catchment length†	Distance from highest point to outlet	Overland flow attenuation
Profile curvature	Slope profile curvature	Flow acceleration, erosion/ deposition rate, geomorphology
Plan curvature	Contour curvature	Converging/diverging flow, soil water content, soil characteristics

† All attributes except these are defined at points within the catchment.

Moore et al. (1993) have compared data from a grid-based DEM, conventional soil survey sources and extensive soil testing of a 5.4 ha field in Colorado. They examined the correlation between the DEM attributes and soil attributes in the upper 0.1 m of soil profile. Soil attributes investigated on a regular 15.24 m grid included A-horizon thickness, extractable P, organic matter and pH, as well as percent sand, silt and clay. The terrain attributes most highly correlated with soil attributes were slope and wetness index. These results give credence to the hypothesis that the soil catena develops in response to the way water flows through the landscape.

Stepwise linear regression of the terrain variables with the measured soil attributes was performed. The terrain attributes slope, wetness index, stream power index, aspect and profile curvature explained between 41 and 64 percent of the variation in the soil attributes. Slope and wetness index were generally the most important attributes.

MATERIALS AND METHODS

Study Area Description

Location

The study area is a cropped strip along the eastern edge of T23N R1W section 36 southeast of Power in Teton County, MT (Fig. 2). It is bounded on the north by a paved county road and on the east by a gravel county road. The crop/fallow strip is 100 m by 1605 m (16 ha) and is part of a section of land being used for commercial production of small grain crops, primarily winter wheat. The area is in the Brown Glaciated Plains Major Land Resource Area, MLRA 52 (USDA-SCS, 1982).

Climate

The area around Power experiences short, hot summers with long, cold winters. Climatic data were obtained from the Maps Mailbox system (Caprio et al., 1990). Mean annual precipitation is 25.4 to 30.5 cm with 60 percent falling from April to May. Summer precipitation comes primarily in the form of thunder showers with winter precipitation occurring as snow. There are 120 to 125 frost free days with 1,970 growing degree days from May to August using a 10° C (50° F) base and 2,200 to 2,400 growing degree days with a 4.4° C (40° F) base.

Geology and Soils

The bedrock underlying the study area is a member of the upper Cretaceous Colorado Shale group. Colorado Shale is commonly a dark gray to black, fissile, clayey shale with some sandy and silty inclusion in lower portions (Veseth and Montagne, 1980). Continental ice sheets covered the area as recently as the late Illinoian age with the ice sheet terminus probably somewhere north of Power. A terminal moraine is lacking due to the low energy of the ice sheet in this area.

Landscape form in the study area is most likely due to glacial outwash. The landscape is typical of ice marginal outwash plains with two small drainage ways at the north end of the study area and large, gently sloping planar areas in the south intersected by a short, moderately sloping area. Figure 3 depicts the topography of the area around the study site. Readily identifiable outwash deposits occur only in drainage ways. No basal till occurs in the study area. The non-alluvial soils show evidence of shale parent material. Thus, any outwash materials deposited on the ridges and side slopes have been stripped by subsequent erosion or incorporated into current soil profiles.

Most soils in the area have silty clay or clay texture (Fig. 4 and Table 2). All of these soils are classified as fine or clayey (>35% clay) in their subsurface horizon control section (the Soil Taxonomy, USDA-SCS, 1975). Table 3 summarizes selected data from the SCS Soils-5 record for these soils. Depth to a paralithic layer (Cr) is the main difference between these soils. Marvan, Abor and Yawdim form a sequence of soils with high shrink-swell potential varying in depth to a Cr from greater than 152 cm for Marvan, 51 cm to 101 cm for Abor and less than 51 cm to a lithic contact for Yawdim. Pylon is moderately deep (greater than 101 cm), has a moderate shrink-swell potential and a subsurface layer of clay accumulation. Megonot is also moderately deep, has a moderate shrink-swell potential, but no subsurface layer of clay accumulation. All of the soils have surface horizons with neutral to moderately alkaline pH's and low organic matter content. Plant available water (PAW) was calculated to 152 cm or to a lithic or paralithic contact, whichever was shallowest, using the mid-range values from the SCS Soils-5 data sheets. The range in PAW from 6.3 cm to 17.4 cm reflects the range in depth to a lithic or paralithic contact of 38 cm to greater than 152 cm.

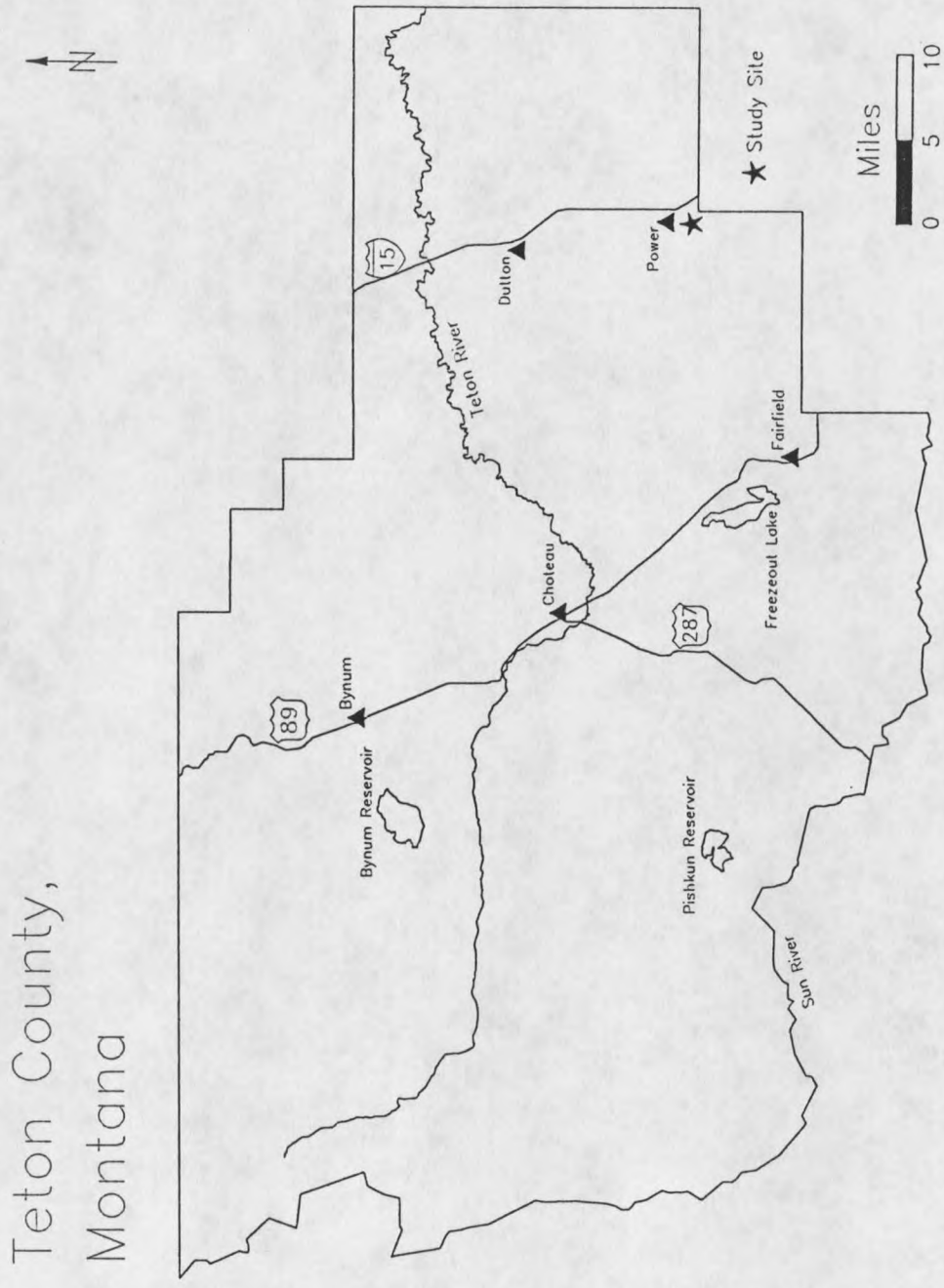


Fig. 2. Location of study site south of Power in Teton County, MT.

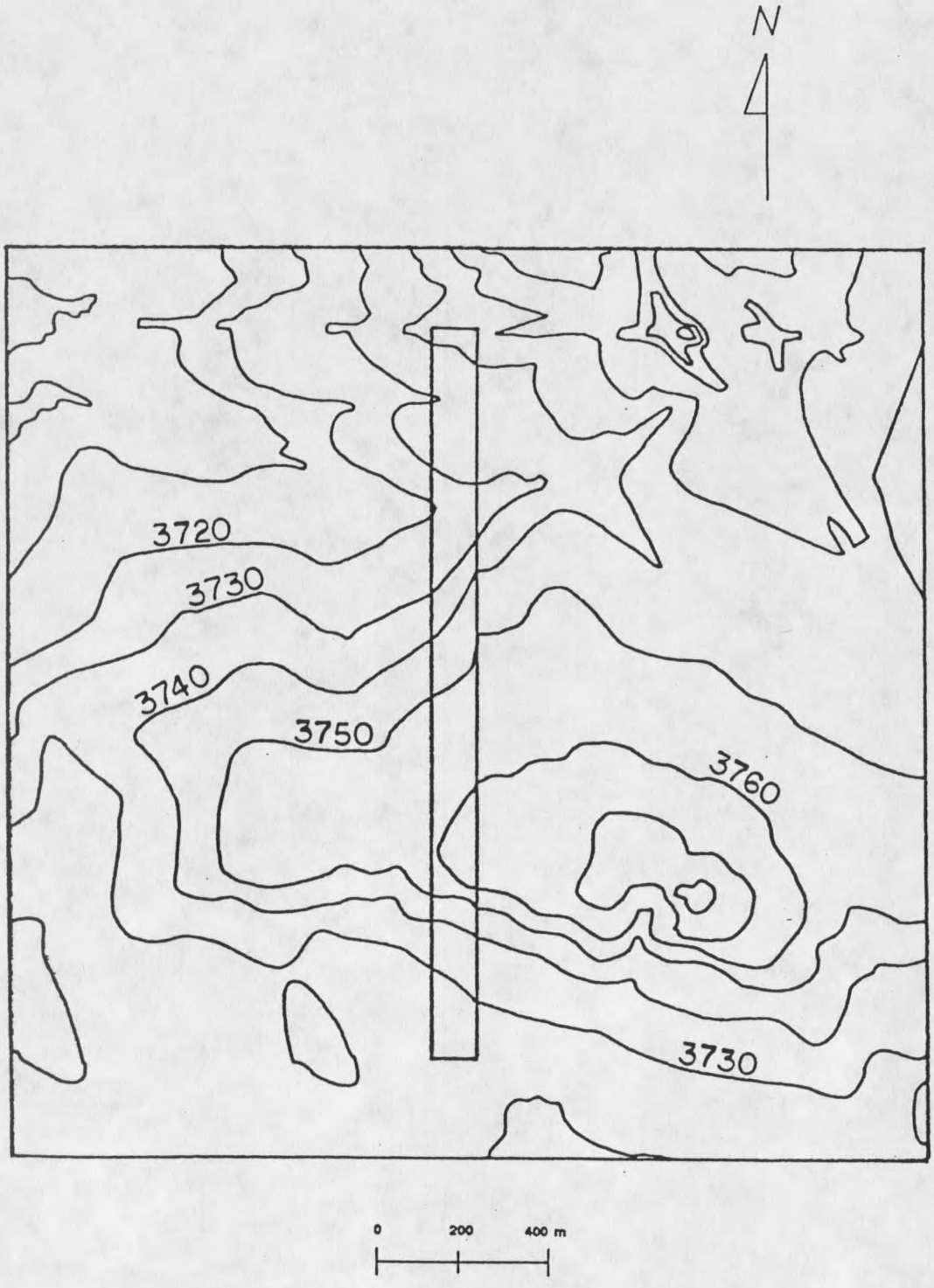


Fig. 3. Contour map of the area surrounding the study site. Digitized from the Power 7.5 minute United States Geological Survey topographic quadrangle. The rectangle delineates the study site. Contour interval is 10 feet.

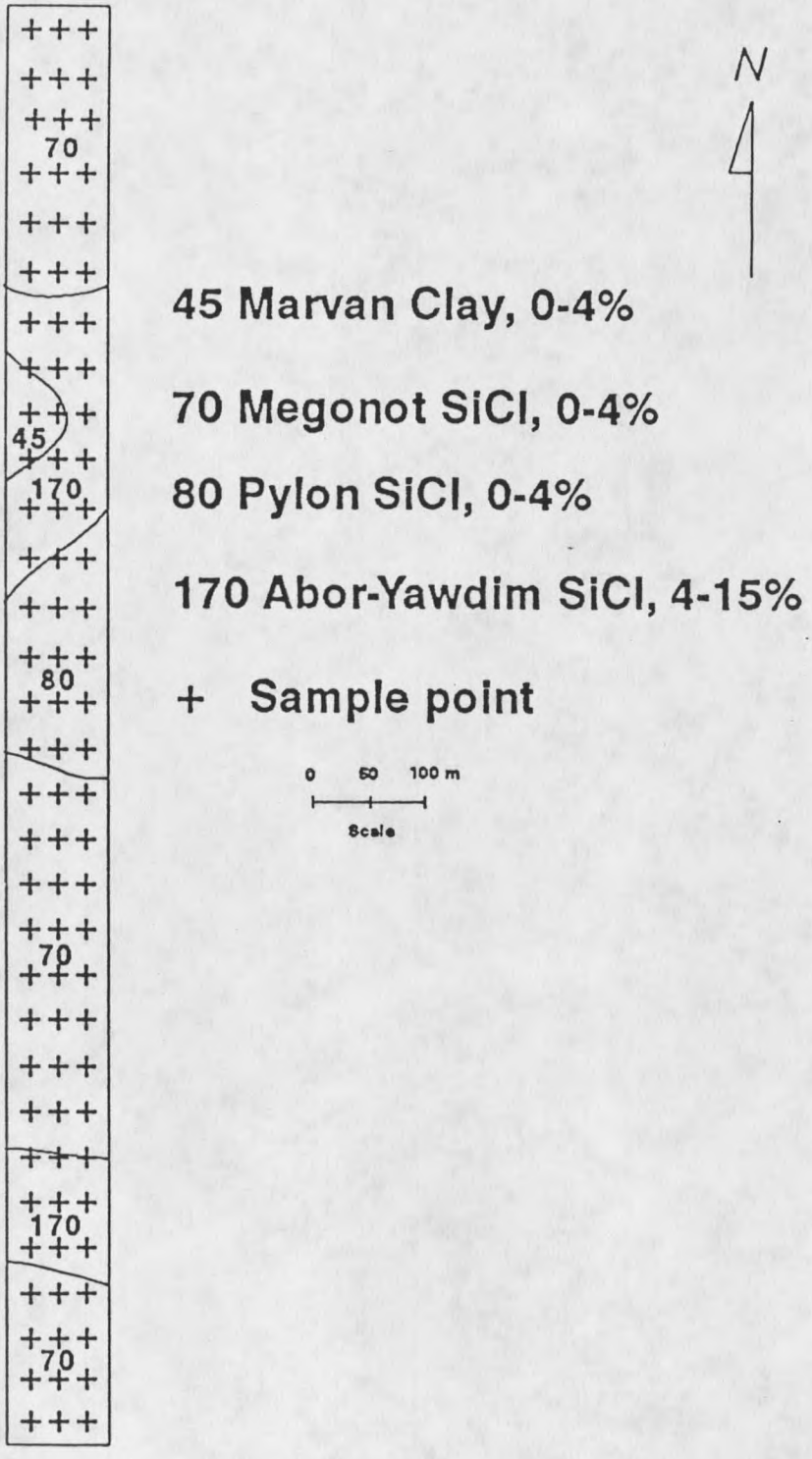


Fig. 4. Map of the study site showing the SCS mapping units and sample point locations.

Table 2. USDA-SCS soils mapping units and classification (USDA-SCS, 1975) of the soils in the study area.

Mapping unit ID	Series	Classification
45	Marvan	Fine, montmorillonitic, frigid, Udorthentic Chromustert
80	Pylon	Fine, montmorillonitic, Typic Eutroboralf
70	Megonot	Fine, montmorillonitic, Borollic Camborthid
170*	Abor-	Fine, montmorillonitic, frigid Udorthentic Chromustert
	Yawdim	Clayey, montmorillonitic (calcareous), frigid, shallow, Ustic Torriorthent

* Mapping unit 170 is a complex of Abor and Yawdim soils.

Table 3. Selected soil attribute values from the SCS Soils-5 form for the soils in the study area.

Soil Series	pH†	Organic matter†	PAW‡	Depth to		
				carbon-ates	gypsum or salts	para-lithic
		%		----------cm----------		
Abor	7.4-8.4	1-2	4.56	41	66	76§
Marvan	7.4-8.4	.5-1	6.86	none	28	>152
Megonot	6.6-7.8	1-3	3.78	31	53	74
Pylon	6.1-7.3	0-1	4.78	43	none	86
Yawdim	6.6-7.8	.5-1	2.48	23	38	38

† pH and organic matter values are for surface layers only.
‡ Plant available water (PAW) values are to 152 cm or to lithic or paralithic contact and are mid-range values from Soils-5.
§ Lithic contact.

Treatments

Three fertilizer treatments were applied in August, 1990 using a variable rate fertilizer applicator (McEachern et al., 1990). The treatments represented a "Farm Soils, Not Fields" scheme (FSNF), the same rate plus sulfur (FSNF+S), and a "field average" (FA) treatment. Figure 5 shows placement of the treatments in the field and Table 4 summarizes the fertilizer treatments. The FSNF and FSNF+S treatments were based on inspection of kriged maps of the 1990 pre-plant NO_3-N, P and K soil test data developed by Max Hammond of Cenex. Figure 6 shows the pre-plant NO_3-N distribution. The fertilizer rates were also derived with reference to the yield goals summarized in Table 5.

Table 4. Fertilizer rates for the treatments.

Treatment	N	P_2O_5	K_2O	S
	----------kg/ha----------			
A FSNF	29	17	22	-
B FSNF	45	28	22	-
C FSNF	56	39	22	-
D FSNF+S	29	17	22	17
E FSNF+S	45	28	22	17
F FSNF+S	56	39	22	17
G FA	45	17	22	-

Table 5. Yield goals for soils in the study area.

Mapping unit ID	Yield goal kg/ha
45	1209
70	2352
80	1680
170	1880

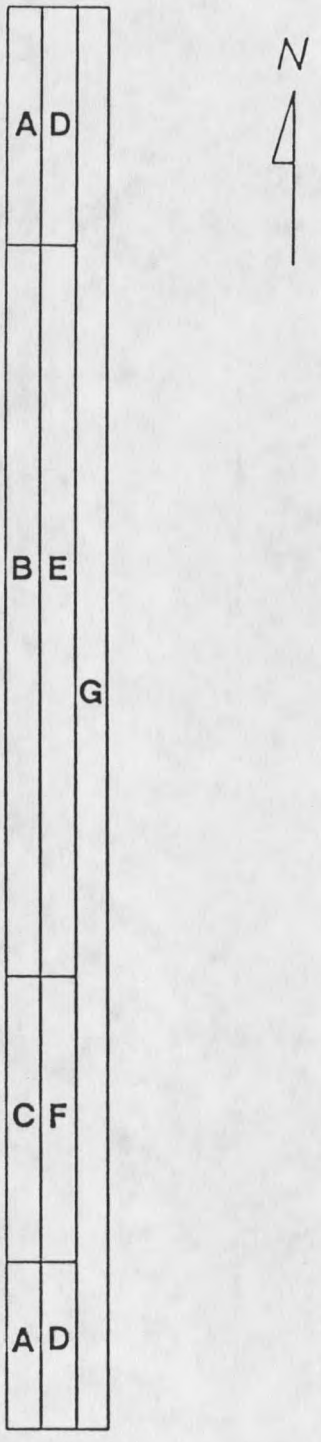


Fig. 5. Fertilizer treatment location blocks A, B and C represent the "Farm Soils, Not Fields" treatment; blocks D, E and F represent the "Farm Soils, Not Fields" treatment plus sulfur; block G represents the field average treatment. Table 4 lists the rates for the different blocks.

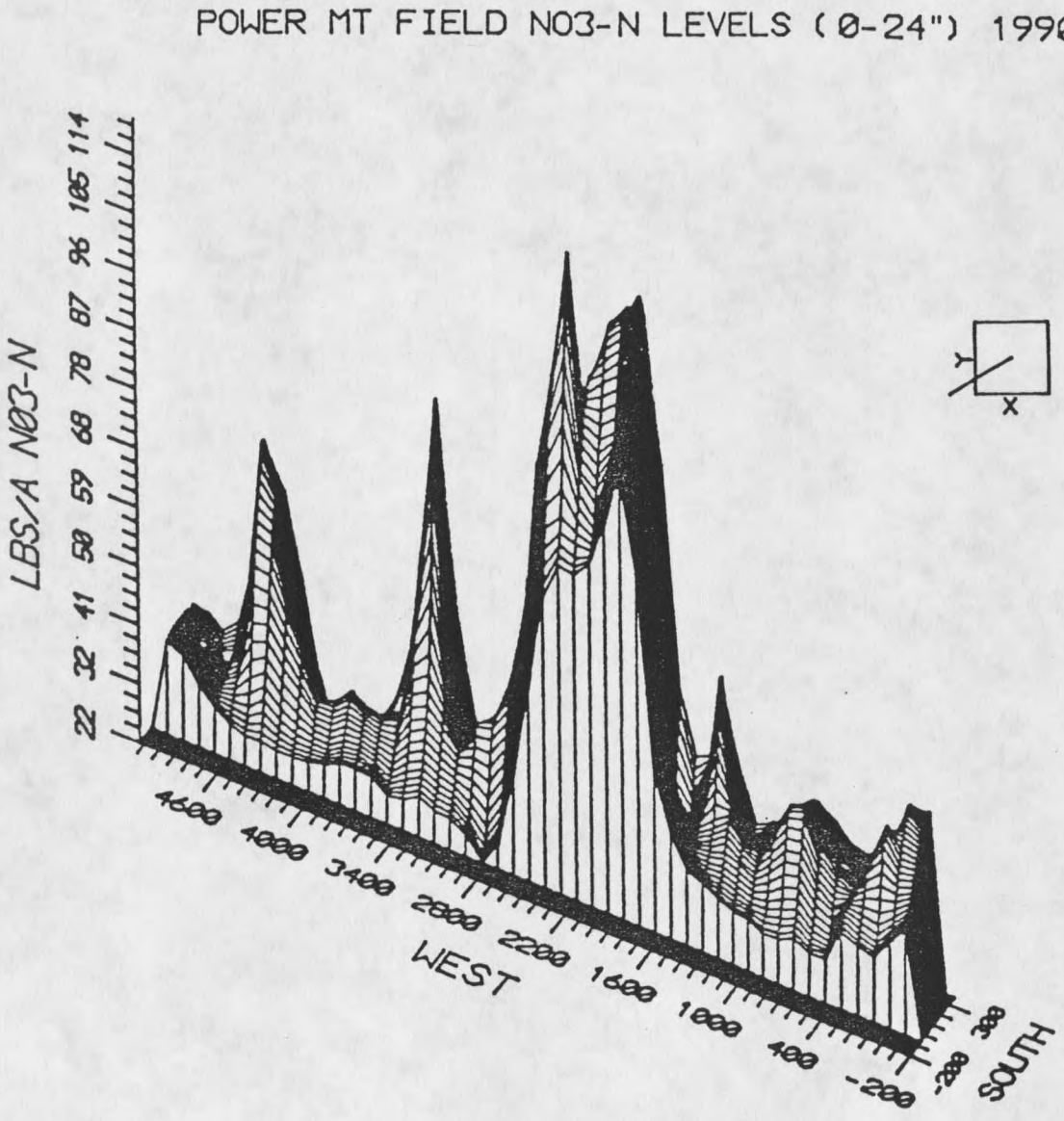


Fig. 6. Pre-plant NO_3-N distribution. This map was generated by kriging the NO_3-N values at the 93 sample points. Map generated by Max Hammond of Cenex/ Land O' Lakes.

The field average rate was based on the average soil test result and the average yield goals for the soils in the strip. In all except the field average treatment, areas with high pre-plant nutrient status were given less fertilizer than those areas with less pre-plant nutrient status. The field average treatment was based on an average nutrient status for that strip. In all cases, the fertilizer rate assigned to a portion of the field was influenced also by the yield goals of the soils in that area of the field. Winter wheat (Triticum aestivum L.) was seeded in October, 1990.

Soil and Grain Sample Collection

A permanent sampling grid (Fig. 4) consisting of 93 sample points separated by 30 m east to west and 50 m north to south was established in the field using a 1 m diameter measuring wheel. The northwest point was used as the starting point and was 36.6 m south of the centerline of the paved county road and 15.2 m east of the crop/fallow border. All subsequent sample points were measured from this point.

Soil samples were taken pre- and post-harvest (June, 1990 and August, 1991) in 0-15, 15-30, and 30-60 cm increments. Nitrate-N was analyzed at all depths in both years while P, K, pH and organic matter were analyzed in 1990 for the 0-15 cm samples only. The sample points were re-established in June, 1991 after the field was disked and seeded in October, 1990. Four-fifths of the flagged sample points were still in place at this time with the remainder measured using the same measuring wheel from extant sample points.

Soil samples were collected in August, 1990 by Centrol technicians using a 3.8 cm diameter hydraulic probe mounted in a truck cab. Multiple cores were collected within one foot of each point and combined by depth increment to ensure sufficient material for analysis. Samples were placed in drying ovens the same day. Samples were collected in 1991 with a 5.0 cm, truck-mounted Giddings probe and were

likewise separated into sampling increments in the field. Samples were refrigerated prior to transportation to Bozeman where they were air dried.

Depth of moist soil was determined by the feel method in 1990 and soil moisture was determined gravimetrically in 1991. All samples from both years were ground and screened through a 2 mm sieve after drying and prior to shipment to Centrol Laboratories in Lincoln, Nebraska for analysis.

Grain samples were collected August 19, 1991 in 192 50 m strips which paralleled the sample point transects and extended from one sample point to the next. Replicate yield samples taken for each sample cell were separated by approximately 1 m and lay east and west of the sample point transect. The yield sample transects began at the south end of the field and extended to the northern end of the field. In any one sample transect there were 64 yield observations giving a total of 192 yield observations. The Hege plot combine employed had a 1.2 m header giving a sampling cell of 0.006 ha. An average yield for each sample point was obtained by averaging the four sample cells surrounding a sample point. Thus, sample points north and south of each other had two common yield sample cells.

Grain yield was determined by weighing each of the samples on a large capacity beam balance. Sub-samples were taken for test weight and protein determination at this time. Percent protein was determined by the Montana State University Cereal Quality Laboratory using infrared reflectometry techniques. Test weight was determined by weighing a known volume of grain using either a one quart or one pint Buro test weight cylinder and converting to pounds per bushel.

Elevation Data Collection

Two sets of elevation data were collected. The first set used high precision global positioning system (GPS) receivers manufactured by Trimble Navigation (model

4000ST). A Trimble representative (Cheryl Quirion) and Dr. David Tyler from the University of Maine at Orono performed this survey. This data set was collected in August, 1990 and followed the perimeter of the study site as well as the roads north and east of the study site.

Global Positioning System Survey

In its simplest form, GPS surveying is accomplished by a receiver determining distance (ranging) from an array of at least 3 satellites by calculating how long it takes a radio signal to travel from the satellite to the receiver (Hurn, 1989). Triangulation is then used to generate coordinates for the receiver. The receiver is able to determine distance because both the receiver and the satellite generate identical pseudo-random binary codes simultaneously which repeat every millisecond. The distance to the receiver is calculated from the length of time the radio signal takes to reach the receiver. The timing of when this signal is generated is therefore crucial. Timing is accomplished in the satellite by atomic clocks and in the receiver by quartz clocks. Errors in the receiver's clock and those caused by atmospheric interference are accounted for, in practice, by ranging four satellites. This arrangement allows for the receiver to resolve where the receiver is in three dimensions using trigonometry.

The GPS elevation data were collected in the field using continuous kinematic surveying techniques. Kinematic surveying allows for the collection of data while one of a pair of receivers is mounted on a moving vehicle. The second receiver is left stationary and functions as a temporary benchmark (TBM). Coordinates were collected every five seconds while driving around the field. There are several problems encountered in this type of survey. One is the resolution of initial ambiguities between the two receivers. The method employed in this survey to resolve this is through an antennae swap (Hurn, 1989). The antennas of the two receivers, one of which occupies a known point and the other which is within 10 m,

are swapped for a few minutes. This allows the receivers to collect several signals from each other's position and allows for the resolution of the ambiguities.

The other major source of error in a kinematic survey is from cycle slips. A cycle slip occurs when fewer than the minimum number of satellites are being tracked, if even for a few seconds. If this occurs, the receivers are no longer ranging enough satellites to resolve position with any degree of precision. This problem is resolved by returning to the last known point the moving receiver occupied, which in this case is the TBM, and beginning the survey again. A second way to avoid this problem is to collect data with no fewer than 5 satellites being tracked. One satellite can then be lost with little loss of precision.

In kinematic surveying, coordinates are calculated for the moving receiver by comparing when the pseudo codes were received by the moving receiver versus when the codes were received by the receiver at the TBM. The time differences between when the signals were received by the two receivers is used to calculate where the moving receiver was in relation to the TBM receiver. This operation is accomplished after the survey is complete.

The second data set was collected in March, 1992 using an SCS Geodemeter total station survey instrument under the direction of Jerry Davis, Civil Engineer, PE. These data were collected with an approximate spacing of 10 m within the study area and on the roads north and east of the study area. Neither survey was based on geodetic control and the points were relative in the vertical and horizontal dimensions only to points in each data set. Both the GPS and geodemeter data sets contained coordinates for the road intersection at the NE corner of the study site. Linkage of the data sets was accomplished by scaling the data in each data set to the x, y and z coordinates at this intersection. The coordinates of this intersection were measured on the Power 7.5' U.S.G.S. topographic quadrangle. The intersection is a third-order elevation benchmark.

DEM and GIS Database Development

The SCS soils map of the study area was digitized in PC ARC/INFO (Environmental Systems Research Institute, Inc., Redlands, CA) from a compiled 1:24,000 orthophoto, mylar, half-tone sheet. The study area was extracted from this map by entering the coordinates of the limits of the study area. The limits were the coordinates of road intersections at the NE and SE corners of the study area and points 100 m west of these points. Coordinates of the road intersections were determined by scaling the orthophoto and measuring from tic marks to the road intersections. The study area was measured and determined to be 100 m from east to west, so the western coordinates of the clip coverage were set to be 100 m west of the road intersections. The Universal Transverse Mercator system in meters was used for all GIS coverages.

A point coverage representing the soil sample points (Fig. 4) was generated from the coordinates of the northwestern-most sampling point. This point was 36.6 m south of the center line of the paved road and 85.3 m west of the gravel road on the east side of section 36. An ASCII file of x and y coordinates for the northern three sample points was generated by adding 30 m and 60 m to the x value of the NW. In addition, 50 m was subtracted from the y value of each of these sample points sequentially 30 times and the x value copied 30 times to generate x,y coordinate pairs for each sample point. A shift in the x coordinate of 9.2 m from due north over the 1,605 m of the study area was noted on the orthophoto. This shift was incorporated by dividing the x shift into 31 increments and subtracting this amount from each x value. The sample points were then labeled 1 through 93 and these ID's became the user-ID's when the point coverage was generated in PC ARC/INFO using this ASCII file.

All crop and soil fertility variables were entered into a spreadsheet using the same sample point ID's as used to generate the sample point coverage. This file was then transferred to dBase format and appended to the soil sample point coverage.

The data from the GPS and the geodemeter survey were interpolated separately and in combination, to a regular 10 m by 10 m grid using a Fortran program, ANUDEM (Hutchinson, 1989), which takes irregularly spaced data and interpolates them to a regular grid spacing specified by the user. The resulting database contained triplets of data representing elevation and horizontal coordinates for 2,294 points. These data were then entered into Moore's TAPES-G program (Moore, 1988b) which calculated values for profile curvature, plan curvature, specific catchment area and slope for each of the 2,294 cells. Wetness index (WI) values were generated from the slope and specific catchment area (SA) values using Equation 1. Specific catchment area is the area of a cell divided by the width of a cell.

$$WI = \ln(SA/(\tan(\text{percent slope}/100))) \quad (1)$$

A polygon coverage representing the 10 m by 10 m DEM cells covering the study area was generated using the coordinates of the intersection of the paved and gravel roads at the NE corner of the study area as the origin. Values for the TAPES-G output variables plan curvature, profile curvature, slope and wetness index were appended to the polygon attribute table of the grid coverage.

A polygon coverage representing the three fertilizer treatments was generated from the map of the study area by entering coordinates for lines representing treatment boundaries.

A point-in-polygon overlay of the soil sample point and DEM polygon coverages was performed. The resulting point coverage contained only those DEM attributes which corresponded to the soil sampling points. The new point coverage was sequentially overlain with the soil map and treatment polygon coverages. This operation preserves all items from the point, soil and treatment polygon attribute

tables. The resulting database contained crop, soil fertility, soil mapping unit ID, DEM attribute values and treatment ID's for each sample point. This database was transferred from PC ARC/INFO to an ASCII file for statistical analysis.

Statistical Analysis

The yields by fertilizer treatment and mapping unit were analyzed with PROC ANOVA (SAS Institute, Inc., 1988). PROC ANOVA uses two mean separation tests depending on the data structure. When the subdivided data contained a low number of yield observations, the students T test was used. When the data are unbalanced the least significant difference was used. Since this work was exploratory in nature, an alpha of 0.1 was used in all analyses to determine differences between means.

The relationships between the DEM attributes, crop and soil variables were analyzed using the multiple linear regression routine in MSUSTAT (Lund, 1987). The yield and soil data were regressed against profile curvature, plan curvature, wetness index and slope values.

Cumulative frequency plots of slope, elevation, profile curvature, plan curvature and upslope contributing area were generated for the two DEM data sets both when they were analyzed individually and when they were joined.

All of the crop, soil and DEM data are presented in Appendix 1. The elevation data used to develop the DEM are not presented.

RESULTS

The northern 500 m of the study area was reseeded to spring wheat on June 4 due to severe winter kill. As a result, all data pertaining to the northern 9 sampling rows (27 sample points) were eliminated from the data set for statistical analysis. Only one sample point remained from mapping unit 45 and it was combined with mapping unit 170 for analysis. The resulting data set contained 66 sampling points and was used in all subsequent statistical analysis. The producer, Jack Toeckes, reported an average yield for the field of 4,152 kg/ha (62 bu/ac) which is almost twice the county average of 2,217 kg/ha (33 bu/ac) for dryland winter wheat. This is almost identical to the average yield of 4,102 kg/ha (61 bu/ac) for the 192 sample cells measured. Mr. Toeckes also commented that he has not usually made the county average in this field.

Abundant June precipitation as well as fertilizer treatments are responsible for these high yields. Weather records from the Great Falls airport, which is 32 km south of the study area, show that summer fallow precipitation of 20.1 cm was near normal with most falling early in the period. The resulting dry conditions in the surface horizons allowed for some winter kill to occur. April and May precipitation of 3.9 cm each was adequate for the tillering and flag leaf stages. Almost twice the normal June precipitation of 10.5 cm came during the heading-out and soft-dough stages and was most likely the cause of the high yields. July and August precipitation were near normal with a total growing season precipitation excess of 0.4 cm over the long-term average.

The average yields by SCS mapping unit were almost twice the predicted yields (Tables 5 and 6C). The rank order of measured yields by mapping unit did not match the rank order of yield goals by mapping unit. However, the mapping unit predicted to be the highest (70) was higher than those predicted to be lower (80 and 170).

Effects of Fertilizer Treatments and SCS Mapping Unit on Yield

The first task in analyzing the data was to determine the effects of the variable rate fertilizer treatments on winter wheat yield. Analysis of the treatment effects was complicated by the size of the treatments. The treatments were a mile in length and crossed several different soil mapping units and the analysis was tailored to ascertain what variation in yield was due to these different soil conditions as well as treatments. Table 6 presents ANOVA results using yield as the dependent variable, and mapping unit and treatment ID's as class variables. Greater variation in yields occurred between mapping units than between treatments (Table 6A). This variation results in significant differences within mapping units and treatments, as can be noted from the last two columns. No significant differences are noted for the interactions between the two class variables, however. Treatment differences were noted between the FSNF and the other two treatments (Table 6B). The FSNF+S and FA treatments were not significantly different from each other. The FSNF treatment yielded the lowest with the FSNF+S and the FA treatments being roughly equal. All of the mapping units were significantly different from each other (Table 6C).

The previous two-way analysis was performed to ascertain if there were interaction differences. Since there were none, the data were further subdivided by treatment to determine if there were mapping unit differences within a treatment (Table 7A). The data were also subdivided by mapping unit to determine if there were treatment differences within a mapping unit (Table 7B).

Table 6. Results of two-way ANOVA of yields using mapping unit ID (MUID) and treatment (TREAT) and the interaction between the two (MUID*TREAT) as class variables.

A. ANOVA analysis.

Source	DF	Type I SS	Mean Square	F value	Pr > F
MUID	2	46377314.8	23188657.4	23.44	0.0001
TREAT	2	5965549.7	298277.4	3.82	0.0569
MUID* TREAT	4	2232979.5	558244.9	8.56	0.6859

B. Treatment affects.

Treatment	n	Mean yield	Mean Separation
		kg/ha	
FSNF	31	3688	A*
FSNF+S	31	4346	B
FA	31	4424	B

C. Mapping unit differences.

Mapping unit			
70	36	4857	A
80	14	3303	B
170	16	3082	C

* Treatments and mapping units with the same letter under grouping are not significantly different at the $P<0.10$ level of significance.

Results differed from when the treatments were not grouped by mapping unit (Table 6B and C). In this analysis, the FSNF treatment differs from the other two treatments only in mapping unit 70. None of the yields are significantly different between any of the treatments within either mapping unit 80 or 170 (Table 7A).

Table 7. Wheat yield differences for one-way ANOVA within treatments and mapping units.

A. Winter wheat yield differences between mapping units within a treatment.

Treatment	Mapping unit		
	70 (n)	80 (n)	170 (n)
FSNF	4256 B* (12)	3130 A (4)	2925 A (6)
FSNF+S	5187 B (12)	3924 A (5)	2946 A (5)
FA	5124 B (12)	3861 A (5)	2854 A (5)

B. Wheat yield differences between treatments within a mapping unit.

Mapping unit	Treatment		
	FSNF (n)	FSNF+S (n)	FA (n)
70	4256 A** (12)	5187 B (12)	5124 B (12)
80	3130 A (4)	3924 A (5)	3861 A (5)
170	2925 A (6)	2946 A (5)	2854 A (5)

* Letters after mean yield in rows following treatment which are the same denote no significant mapping unit differences for yields within that treatment at $P<0.10$ level of significance.

**Letters after mean yield in rows following mapping unit which are the same denote no significant treatment differences for yields within that mapping unit at $P<0.10$ level of significance.

The data were also analyzed for differences in yield between mapping units within a treatment (Table 7B). Separate one-way ANOVA for yield differences between mapping units within a treatment were performed and combined in Table 7. Results here differ from when the data are not grouped by mapping unit (Table 6C). Mapping unit 70 is significantly different from 80 and 170 within each treatment while mapping units 80 and 170 are not significantly different in any of the treatments.

Sensitivity of TAPES-G to Number and Pattern of Elevation Data Points

The cumulative frequency plot for elevation (Fig. 7) indicates that the combined elevation data set is essentially identical to the geodemeter data set alone. The GPS curve has a smoother S-shape than the geodemeter. In addition, the GPS data set underestimates the area with elevations less than 3,715 ft and overestimates the area with elevations greater than 3,715 ft.

The cumulative frequency plot for slope (Fig. 8) indicates that the GPS data set consistently underestimates slope in the study area compared to the geodemeter data. The cumulative frequency distribution plot for profile curvature (Fig. 9) has similarly shaped curves for both data sets. The GPS data set overestimates the area with concave terrain (profile curvature values < 0 degrees/meter) and underestimates the area with convex terrain (values > 0 degrees/meter) when compared to the combined data set curve. The cumulative frequency plot for plan curvature (Fig. 10) indicates that the GPS data set underestimates the area with plan curvature values < 0 degrees/meter and overestimates the area with plan curvature values > 0 degrees/meter when compared to the geodemeter data set.

The GPS data consistently overestimates the parts of the field in the cumulative frequency plot for upslope contributing area (Fig. 11). The lines do not have similar shapes. The slope of the GPS curve decreases at about 600m^2 and the other line increases in slope at about 1,000m^2.

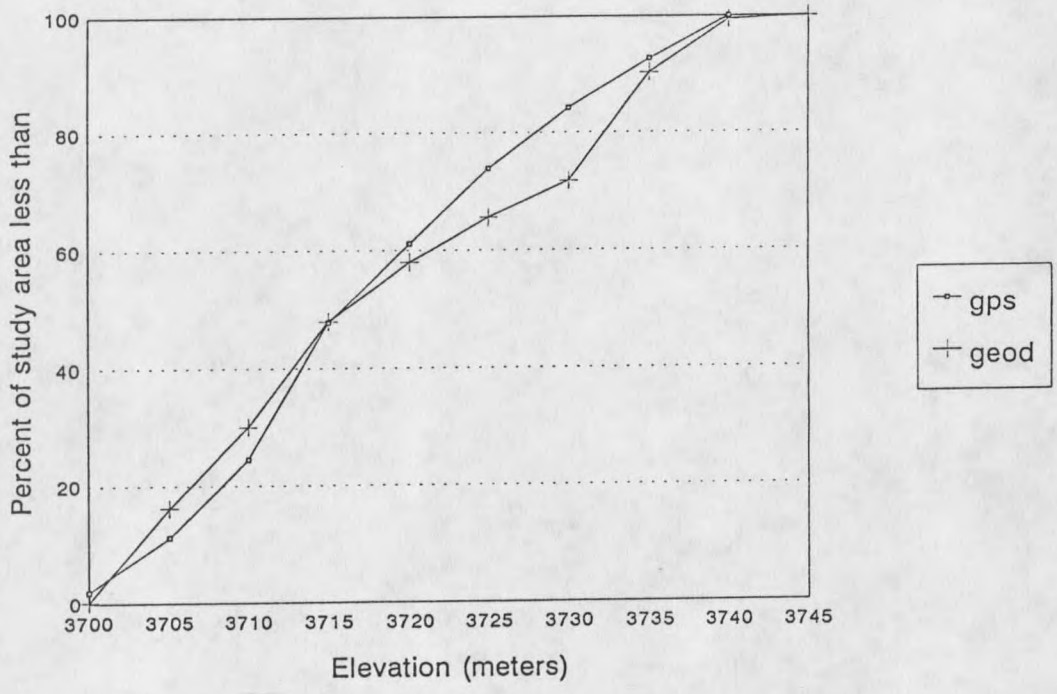


Fig. 7. Cumulative frequency plot of elevation for the GPS and geodemeter data sets.

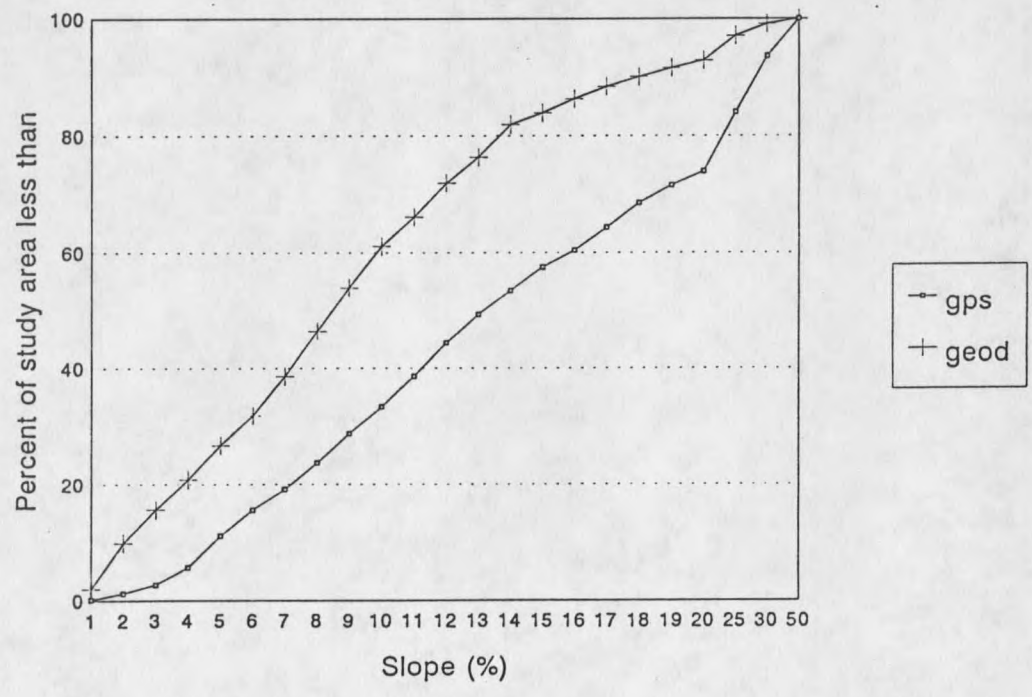


Fig. 8. Cumulative frequency plot of slope for the GPS and geodemeter data sets.

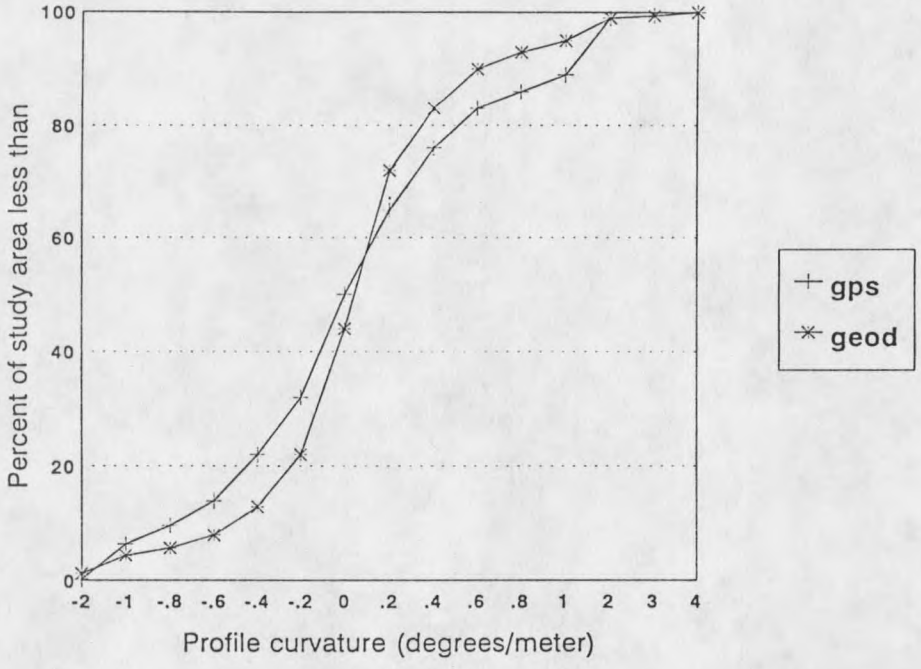


Fig. 9. Cumulative frequency plot of profile curvature for the GPS and geodemeter data sets.

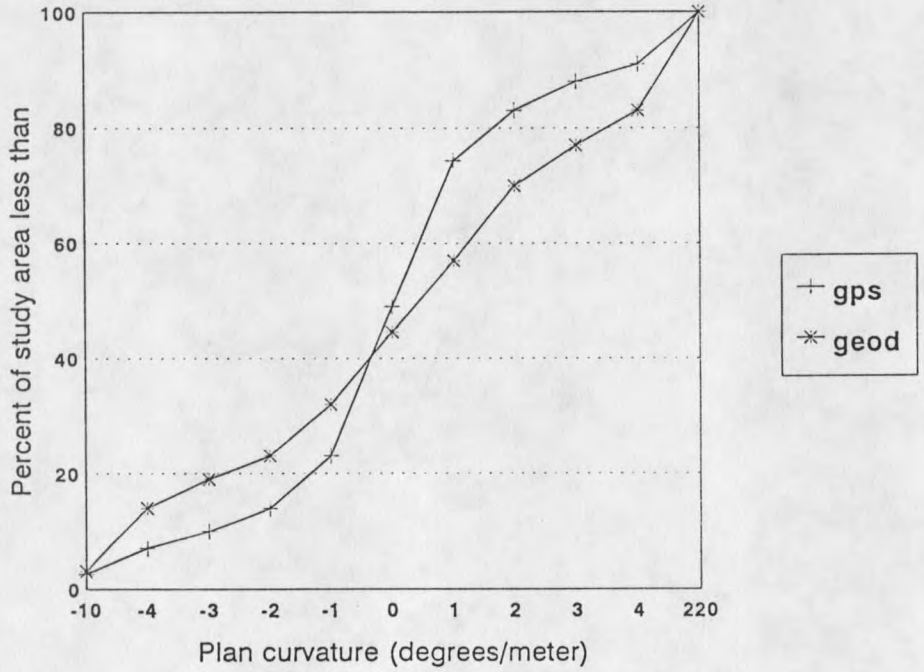


Fig. 10. Cumulative frequency plot of plan curvature for the GPS and geodemeter data sets.

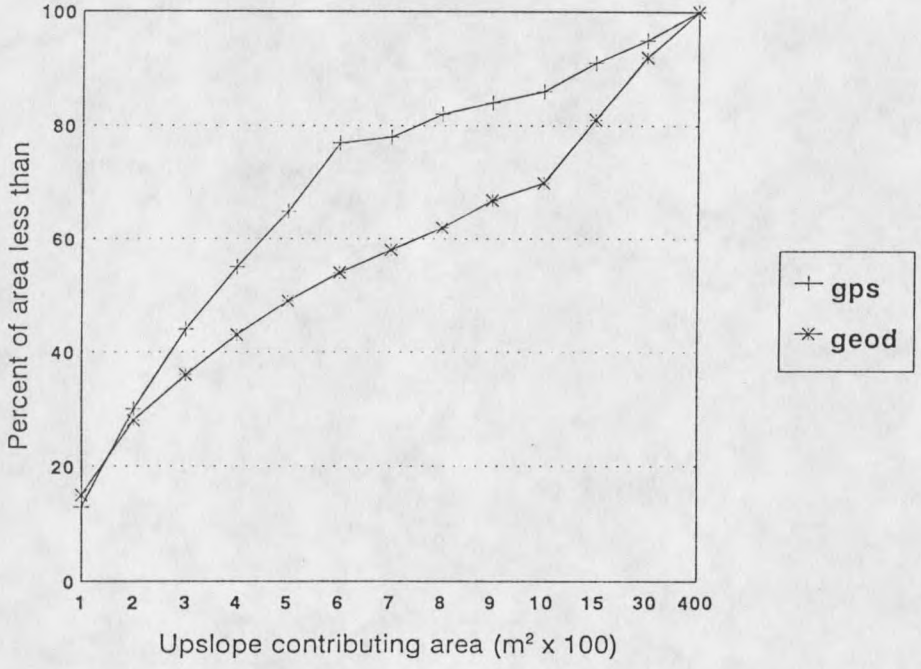


Fig. 11. Cumulative frequency plot of upslope contributing area for the GPS and geodemeter data sets.

Yield Differences by DEM Attribute Class and Treatment

DEM attributes from the combined GPS and geodemeter data set only were investigated for relationships to yield. Class variables for mapping unit, treatment and DEM attribute were added to the yield data for analysis of variance (ANOVA). The yield data were divided into three classes for each of the DEM attributes slope, profile curvature, plan curvature and wetness index. These DEM classes and treatment ID's were used as class variables for analysis of variance (Table 8). There were no significant yield differences for the interaction between any of the DEM attribute and treatment classes. The main effect differences for treatment were already described in Table 6. Main effect differences for slope class, profile curvature class, plan curvature class and wetness index class are presented in Table 8A,B,C,D.

Table 8. Yield differences when grouped by treatment and terrain attribute class.

A. Slope class differences.

Slope class	Treatment		
	FSNF (n)	FSNF+S (n)	FA (n)
%		kg/ha	
≤ 5.0	4240 (9)	5211 (10)	5217 (9)
5.1 - 9.9	3650 (5)	3634 (6)	4572 (5)
≥ 10	3091 (8)	3614 (6)	3440 (8)

B. Profile curvature class differences.

°/m			
≤ - 0.05	4385 (8)	4402 (9)	4701 (5)
-0.051 - 0.9	3612 (8)	4541 (8)	4005 (6)
≥ 0.1	2860 (6)	3993 (5)	4528 (11)

C. Plan curvature class differences.

°/m			
≤ - 0.5	4066 (10)	4148 (8)	4482 (2)
-0.51 - 1.49	3220 (8)	4176 (5)	4041 (11)
≥ 1.5	3680 (4)	4617 (9)	4881 (9)

D. Wetness index class differences.

≤ - 0.5	4063 (5)	3569 (6)	3769 (9)
-0.51 - 1.49	3546 (8)	4130 (7)	4449 (8)
≥ 1.5	3607 (9)	5032 (9)	5566 (5)

Yield Differences by DEM Attribute Class and Mapping Unit

Yields were analyzed to determine if there were differences between DEM attribute classes and mapping units (Table 9). The same DEM classes and analysis techniques were used as in the test for differences between treatments. There were no

significant differences for the interactions between any of the DEM attribute classes and mapping units.

Table 9. Yield differences when grouped by mapping unit and terrain attribute class.

A. Slope class differences.

Slope class (%)	Mapping unit 70 (n)	80 (n)	170 (n)
		kg/ha	
≤ 5.0	4901 (28)	-*	-*
5.1 - 9.9	4703 (8)	4046 (4)	2275 (4)
≥ 10	5066 (1)	3482 (9)	3128 (12)

B. Profile curvature class differences.

°/m			
≤ - 0.05	5089 (14)	3455 (4)	3289 (4)
-0.051 - 0.9	4454 (17)	3905 (2)	1907 (3)
≥ 0.1	5497 (6)	3699 (7)	3085 (9)

C. Plan curvature class differences.

°/m			
≤ - 0.5	4622 (14)	4130 (2)	2461 (4)
-0.51 - 1.49	4857 (12)	2891 (4)	2655 (8)
≥ 1.5	5177 (11)	3957 (7)	3890 (4)

D. Wetness index class differences.

≤ - 0.5	4850 (6)	4123 (7)	2526 (7)
-0.51 - 1.49	5032 (12)	2684 (4)	3106 (7)
≥ 1.5	4760 (19)	3961 (2)	3612 (2)

* These combinations of mapping unit and terrain attribute class contained no yield observations.

Main Effect Differences by DEM Class

Differences in yield between the DEM attribute classes were noted in the main effects of the two-way ANOVA. Subsequently, one-way ANOVA was performed for each of the DEM attribute classes to ascertain how well these attributes alone differentiated yield. The one-way ANOVA was performed because main effect differences for the DEM classes were not consistent between the two-way ANOVA's for mapping unit and treatment. The inconsistencies occurred when the different mean square errors generated in the different two-way ANOVA were used to calculate the F statistic.

Results for the slope classes (Table 10) indicate that there is a trend of decreasing yield with increasing slope class. Yields are significantly higher ($P<0.10$) on the lowest slope class compared to the higher slope classes.

Table 10. Yield differences by DEM attribute class.

DEM attribute class[†]	Slope[‡]	Profile curvature[‡]	Plan curvature[‡]	Wetness index[‡]
	Mean yield kg/ha			
1	4901 A	4464 A	4140 AB	3782 A
2	3932 B	4057 A	3795 A	4038 AB
3	3361 B	3938 A	4554 B	4590 B

[†] DEM attribute class limits are: Slope; ≤5, 5.1-9.9, ≥10; Profile curvature; ≤-0.05, -0.051-0.89, ≥0.9; Plan curvature; ≤-0.5, -0.51-1.49, ≥1.5; Wetness index; ≤6.79, 6.8-7.6, ≥7.6.
[‡] Mean yields followed by the same letter in columns under the DEM attributes are not significantly different at the $P<0.10$ level of probability.

Analysis of variance of yields by profile curvature class (Table 10) indicates that there is a trend of decreasing yield with increasing profile curvature class, although these differences were not significant ($P<0.10$). Results of ANOVA of yield differences by plan curvature class (Table 10) show some significant differences but

do not reveal a consistent relationship. Differences in yield between wetness index classes (Table 10) indicate a trend of increasing yield with increasing wetness index class. Yields in the highest and lowest wetness index classes are significantly different at the $P < 0.10$ level of significance.

Yield Differences by Treatment and Combination of DEM Class and Mapping Unit

Combination of DEM attributes and mapping unit was accomplished by determining the median value of each DEM attribute from the $n=66$ data set. These median values were then used to group yields into high and low classes for each DEM variable within each mapping unit for analysis. The FSNF and FSNF+S treatments were combined in an attempt to ensure a sufficient number of yield observations within each cell in the two-way ANOVA. This combination is deemed valid because there was no significant difference between these two treatments (Table 7). Even so, some cells in the analysis contained no yield observations. The resulting database contained yield values coded by DEM group and mapping unit in addition to treatment groupings.

None of the interactions between the combination of DEM attribute and mapping unit and treatment were significantly different for yield ($P < 0.10$) given the constraints of small sample size. Results of the analysis are presented in Table 11.

Table 11. Yield differences when grouped in high and low terrain attribute classes within each mapping unit.

A. Slope class differences.

Slope class (%)	Mapping unit	FSNF (n)	FSNF+S and FA (n)
<8	70	3938 (11)	4783 (22)
>8	70	3419 (1)	3973 (3)
<8	80	(0)	4474 (2)
>8	80	3952 (4)	4310 (7)
<8	170	(0)	(0)
>8	170	2987 (6)	3672 (10)
B. Profile curvature. (°/m)			
<0.017	70	4398 (10)	5178 (15)
>0.017	70	3683 (2)	4623 (10)
<0.017	80	(0)	3752 (4)
>0.017	80	2862 (4)	3466 (5)
<0.017	170	(0)	2696 (4)
>0.017	170	2819 (6)	3071 (6)
C. Plan curvature. (°/m)			
<-0.23	70	4264 (9)	4926 (7)
>-0.23	70	4563 (3)	5184 (18)
<-0.23	80	(0)	3659 (2)
>-0.23	80	2862 (4)	3492 (7)
<-0.23	170	3686 (2)	2214 (4)
>-0.23	170	2385 (4)	3643 (6)
D. Wetness index.			
<7.26	70	5064 (5)	4845 (10)
>7.26	70	3820 (7)	5289 (15)
<7.26	80	2641 (3)	3424 (7)
>7.26	80	3525 (1)	3900 (2)
<7.26	170	3139 (4)	2827 (8)
>7.26	170	2178 (2)	4050 (2)

Winter Wheat Yield Regression With Total Available NO_3-N

The main difference between treatments was the amount of nitrogen applied (Table 4). The relationship between the total amount of nitrogen available at each sample point and yield was investigated. The amount of nitrogen mineralized (NO_3MIN) was calculated from percent organic matter using the approximation of 22 kg/ha of N mineralized per percent organic matter per year. Terms for pre-plant (N90T) and post-harvest (N91T) NO_3-N, organic matter and NO_3-N applied at each sample point were regressed against the yield at the sample points. Only terms significant at the 0.10 level of probability were included. The result is given in Equation 2 and the R^2 is 0.183.

$$\text{Yield(kg/ha)} = 2339 + -26.8(\text{N90T}) + 115.2(\text{NO}_3\text{MIN}) \quad (2)$$

The yield data were also regressed with the other soil fertility variables, but the results were not improved over those reported here.

DEM Relationships to Soil Fertility

The final objective of this work was to determine whether any relationships occurred between DEM attributes and soil fertility. The values for the DEM attributes elevation, slope, profile curvature, plan curvature and wetness index were regressed against the total pre-plant NO_3-N at each sample point and the soil fertility values P, K, pH and organic matter (Table 12).

Table 12. Results of regression of soil fertility values against DEM attributes. $P<0.10$.

N90T	=	41.04+(1.2)(slope)+(29.15)(profc)	r2=.1983
K	=	693.1+(19.7)(slope)	r2=.2401
pH	=	50.2+(-.027)(slope)+(.007)(planc)+(-.126)(WI)	r2=.2082
OM	=	-23.5+(.022)(slope)+(.218)(profc)+(.007)(elev)	r2=.1729

About 20% of the pre-plant nitrogen variation was explained by slope and profile curvature. None of the DEM terms were significant in the regression with P. The most predictive model was for potassium, in which 24% of the variability was accounted for by slope alone. The model for pH indicates that approximately 21% of the variability was explained by slope, plan curvature and wetness index. About 17% of the variation in organic matter was explained by slope, profile curvature and elevation.

DISCUSSION

Effects of Fertilizer Treatments and SCS Mapping Unit on Yield

The differences in yields are attributable primarily to mapping unit differences. Treatment differences were noted, but were not as great as those within and between mapping units (Table 6A).

Mapping unit 70 had the highest average yield (Table 6C) and the highest average yield within each treatment (Table 7). This is consistent with the projected yield goals (Table 5). This unit contained soils that had moderate water holding capacity and was in the middle of the range for surface pH, percent organic matter and depth to carbonates and gypsum as compared to the other soils in the study area (Table 3). Mapping unit 70 may have out-yielded the other units due to its having fewer constraints to high yields. This unit's high yield may also be due to all of the sample points with slopes less than 5% that occur in this unit. Even with a moderate plant available water holding capacity, the nearly level slopes in this unit may have had increased water infiltration and decreased water runoff, thereby increasing the amount of available water and consequently producing greater yield.

The measured yield goals were almost twice the projected yield goals in each mapping unit (Table 6C). The timely rainfall received in 1991 probably accounts for these results. The fact that the yield goals were almost half of what was harvested, illustrates the difficulty of assigning realistic yield goals for fertilizer recommendations. This observation reiterates those made by Carr et al. (1991).

Treatment differences were noted (Table 6B) between the FSNF treatment and the other two treatments. A trend is noted where the FA treatment had the highest yields followed by the FSNF+S treatment, with the FSNF treatment yielding the least.

Without an economic analysis, it cannot be said which fertilization scheme is best for the producer.

The lack of significant interaction implies that the fertilizer treatments had no significant effect on mapping unit yields and that the mapping units had no significant effect on fertilizer treatment yields.

Definitive statements about soil-specific fertilization results are difficult to make from the data presented here due to the lack of replication of fertilizer treatments on each soil type and the unique year experienced. However, it appears that in this study the SCS mapping units explain most of the yield variation. Soil-specific farming endeavors should therefore use the SCS soil map as a starting point for fertility management. Additionally, further work should concentrate on using the SCS mapping unit as the blocks for replicated fertilizer treatments to better distinguish differences by treatments and mapping units.

Sensitivity of TAPES-G Output to Number and Pattern of Data Density

Examination of the cumulative frequency plots for the DEM attributes generated from the GPS data and the geodemeter data (Figs. 7-11) reveals that the GPS data is consistently different from the geodemeter data set. If the geodemeter data set is considered to be closer to reality than the GPS data set due to its having a much higher data density within the study area, then it can be stated that the GPS elevation data points collected around the edge of the study area are inadequate.

The differences between the GPS and geodemeter outputs from the DEM are due to the interpolation which takes place in Hutchinson's (1989) routine. This FORTRAN routine interpolates irregularly spaced data into regularly spaced (grid) data. Since there are no elevation data within the study site in the GPS data set, the routine interpolates all values for the study site. Thus, all output from the DEM is

based on interpolated and not observed data for the GPS data set. This explains why the output from the GPS data alone was different from that of the geodemeter output. Therefore, future use of the DEM TAPES-G should avoid using data collected around only the perimeter of the area of interest.

Relationship of Yield to DEM Attributes

Investigation of yield differences by slope, profile curvature, plan curvature, wetness index classes and treatment were inconclusive. Yields decrease with increasing slope class, but differences were not significant (Table 10). This trend fits with the intuitive concept that yields increase with less runoff and more water availability on level areas. Although not consistent for all treatments, the same trend is confirmed by increasing yield with increasing wetness index for the FSNF+S and the FA treatments (Table 8D). Moore's wetness index (WI) accounts for the area upslope which is capable of contributing water to an area of the landscape. The index also accounts for the slope of that area. Areas with larger WI would conceivably have greater water concentration and less water loss downslope than areas with smaller WI. The trend of increasing yield with increasing WI is consistent with the concept of increasing yield with increasing water availability.

Results of analysis of yield differences profile curvature class reveals no consistent trends or significant differences. None of the results of analysis for differences by treatment and DEM attribute were statistically significant.

However, when yield is analyzed without regard to treatment or mapping unit, sample points with slopes of 5% or less generally outyield points with slopes greater than 5% and are statistically different ($P<0.10$) from sample points with slopes greater than 5% (Table 10). This is intuitively acceptable because decreased water runoff, increased water concentration and resulting higher yields are expected on areas with less slope.

Yield differences between the profile curvature classes were not significant. The observed trend of increased yield with decreased profile curvature may be expected (Table 10). Profile curvature values < 0 degrees/meter represent areas concave in cross section while areas > 0 represent areas convex in cross section. Concave areas may be expected to yield higher than convex areas since water will tend to accumulate in these areas.

The noted differences in the plan curvature classes are also not conclusive. The relationship between plan curvature values and landscape shape are the same as for profile curvature. Although the plan curvature classes do show significant differences (Table 10), they are not the differences expected. They do not follow the pattern expected of increasing yield with increasing concavity (i.e. smaller values of plan curvature). Concave forms are associated with converging water flow and greater water availability for plants.

These results do not agree with the conclusions of Sinai et al. (1981). The lack of correlation in this study of the curvature values to yield may be due to the subdued terrain of the study site. Changes in slope shape are gradual both across slope and downslope. The resulting curvature value ranges reflect this with few extreme values (Figs. 10 and 11).

Yield differences analyzed by WI class (Table 10) show a trend of increasing yield with increasing WI. Yield for the wettest class was significantly higher than the driest class. DEM attributes generally did not explain yield differences when combined with soil mapping units. No trends or obvious patterns are discernable in the ANOVA results except for the combination of slope and mapping units. Within each mapping unit, the higher slope class tends to have the higher yield. But again, the differences are not significant. These results may be due in large part to the small number of yield observations per mapping unit and DEM attribute combinations.

There are insufficient observations for a valid ANOVA test of differences between means.

In short, the DEM variables slope and wetness index showed the most promise of being significantly related to yield.

Winter Wheat Yield Regression With Total Available NO_3-N

Measures of NO_3-N availability explained only about 19% of the yield variation (Equation 2). This suggests that other factors are controlling yield. Regression of yield with the other soil fertility data (data not presented) exhibited equally low regression coefficients. The lack of strong correlation of yield with any of the soil fertility values suggests that some other physical or chemical property, or combination of chemical or physical property is influencing yield to a greater degree.

The negative correlation of the pre-plant NO_3-N to yield is difficult to explain (Equation 2). One possible explanation is that the fertilizer recommendations were not sufficient given the outstanding yields obtained. The areas of the field which were originally high in NO_3-N were not given as much fertilizer as areas of the field with lower pre-plant NO_3-N. The increased crop demand due to optimum growing conditions may have required more NO_3-N than was available.

DEM Relationships to Soil Fertility

The regression of the DEM attributes with the soil fertility variables suggests that slope is the attribute most likely to predict fertility (Table 12). It was significant in regressions for total available nitrogen, K, pH and organic matter. Slope is related to and controls water movement across a landscape. It is not reasonable to expect N and organic matter to be positively related to slope. As percent slope increases, N and organic matter should decrease. Potassium and pH may be related to slope by way of

depth to parent material. This regression does hint that this may be true for K. The positive relationship of slope to K suggests that as slope increases, so does K. The converse is true for pH.

The negative relationship of slope to pH is not what would be expected. Soils in the study area generally increase in pH with depth. Thus, soils found on steeper slopes would be expected to have higher pH's due to the proximity of parent material to the surface.

The positive relationship of organic matter to slope is also converse to what is expected. Soils with less slope should conceptually have greater organic matter due to increased water run-on and plant growth.

The results here are somewhat similar to those reported earlier by Moore et al. (1993). In their study, slope and wetness index had the strongest relationship with the soil attributes measured. This study confirms that slope is most likely to predict NO_3-N, K, pH and organic matter. However, the relationships here are not as strong. More troubling is that some of the relationships here are inverse from those of Moore et al. (1993) or are not explained at all. Twenty-one and 18% of the variation in pH and organic matter, respectively, were explained in this study where their study explained 41 and 48% of the variation in pH and organic matter, respectively. They obtained equally strong results for A-horizon depth, extractable P, percent sand and percent silt.

The differences between the two sets of results may be due to the sizes of the sample areas and sampling distance. Their sample area was roughly one-third the size of this study area and their sample points were much more closely spaced. However, results presented here are encouraging and more work needs to be done to determine an optimum sampling density based on chemical, physical and other attributes.

A different approach to investigating these relationships may be to extrapolate the soil fertility and DEM variables to the size of the yield cells instead of relating the

point data to a DEM cell. This could be accomplished with the use of kriging and other related interpolation routines.

In spite of having a moderately dense sample of fertility yield and a detailed DEM, there were no single parameters which predicted yield or fertility with much precision. The SCS mapping unit did show promise as did slope and wetness index of the DEM. Identification of terrain or nutrient parameters for soil-specific farming applications is still a challenge. The SCS mapping unit as a management unit warrants further study since the delineations did segregate some of the variation in yield. The question of which characteristics of the SCS mapping units were responsible for this was not answered in this work.

CONCLUSION

The SCS soil mapping unit was responsible for most of the variation in yield in this study. The implication of this is that many soil-specific farming endeavors may be able to use the SCS soils map as the starting point for soil fertility management and yield goal delineation. This advice must be tempered by pointing out the difficulty in assigning realistic yield goals. The yield goals in this study were approximately 50% of actual yields. The unique rainfall distribution may explain these large yields.

Comparison of DEM attributes with soil fertility variables and yield showed that slope has the most promise of predicting these variables. Moderately good correlation was obtained between yield and slope, wetness index and plan curvature. Some of the relationships were converse to that expected, however.

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APPENDIX

Soil Fertility and Yield Data for Study Area

Table 13. Residual NO_3-N, P and K data for the n=67 data set.

Sample Point ID	Pre-plant NO_3-N depth increment (cm) 0-15	15-30	30-60	0-60	P 0-15	K 0-15
	ppm					
10	16	8	12	36	28	820
41	12	8	16	36	18	638
72	12	10	16	38	16	572
11	16	8	16	40	24	658
42	14	10	20	44	26	774
73	14	10	16	40	14	780
12	24	18	60	102	40	1260
43	30	22	48	100	50	1262
74	22	20	76	118	42	1214
13	18	16	52	86	44	1116
44	26	24	44	94	66	1274
75	20	18	72	110	30	1076
14	18	16	40	74	48	1422
45	24	22	44	90	48	1318
76	24	22	64	110	44	1008
15	18	18	44	80	52	1370
46	30	26	68	124	58	1418
77	22	18	28	68	34	1016
16	18	14	32	64	28	804
47	22	20	64	106	44	1092
78	14	12	36	62	28	1008
17	16	10	12	38	40	896
48	18	12	28	58	48	1034
79	14	14	36	64	18	760
18	10	4	8	22	20	516
49	20	12	16	48	30	832
80	16	8	16	40	20	688
19	10	6	12	28	30	638
50	14	8	20	42	60	528
81	12	6	12	30	24	784
20	10	8	12	30	24	718
51	16	8	16	40	42	744
82	10	8	16	34	58	418
21	10	10	12	32	30	816
52	14	8	24	46	48	568
83	14	16	64	94	28	662
22	12	8	8	28	48	882
53	14	10	16	40	24	790
84	10	8	20	38	38	622
23	10	8	12	30	42	766
54	14	10	12	36	42	1036
85	12	8	12	32	20	788
24	12	6	12	30	48	570
55	14	10	16	40	54	612

Table 13 continued.

Sample Point ID	Pre-plant NO_3-N depth increment (cm) 0-15	15-30	30-60	0-60	P 0-15	K 0-15
	ppm					
86	12	8	12	32	50	618
25	10	6	12	28	30	1024
56	12	8	16	36	38	1088
87	10	6	12	28	18	1044
26	10	6	12	28	28	822
57	20	10	12	42	30	1098
88	8	8	12	28	22	972
27	10	8	12	30	32	684
58	22	12	16	50	32	1074
89	12	8	32	52	26	962
28	10	8	12	30	30	468
59	20	12	24	56	38	922
90	14	12	48	74	24	972
29	10	8	12	30	34	684

Table 14. Pre-plant pH, organic matter (OM), post-harvest NO_3-N and NO_3-N applied at each sample point.

Sample Point ID	pH	OM	-Post-harvest NO_3-N-			NO_3-N applied
	depth increment (cm)					
	0-15	0-15	0-15	15-30	30-60	0-15
	ppm					kg\ha
10	8.0	2.4	36	4	16	13
41	8.3	2.0	38	6	12	20
72	8.4	2.6	44	4	0	25
11	8.3	2.0	12	4	12	13
42	8.2	2.2	30	6	28	20
73	8.3	2.7	28	12	44	25
12	8.1	2.3	10	4	12	13
43	8.0	2.5	10	2	8	20
74	7.9	2.9	8	8	28	25
13	8.1	2.5	16	4	8	13
44	7.9	3.3	6	2	4	20
75	7.9	3.2	6	2	4	25
14	8.0	2.6	20	6	4	13
45	7.9	3.2	4	4	8	20
76	7.8	3.0	4	2	8	25
15	8.1	2.4	6	6	12	13
46	7.9	3.1	12	10	8	20
77	7.8	3.2	4	4	24	25
16	8.3	2.5	10	4	8	13
47	7.9	3.1	18	20	16	20
78	8.0	3.0	10	6	8	25
17	8.0	2.3	12	12	12	13
48	7.5	2.8	24	6	20	20
79	7.9	3.0	8	6	48	25
18	8.3	2.1	10	6	12	13
49	7.9	2.9	8	8	20	20
80	8.2	2.7	14	6	24	25
19	8.4	2.5	8	6	12	13
50	7.9	2.5	16	8	12	20
81	8.0	2.6	12	4	40	25
20	8.3	2.0	10	6	28	13
51	7.7	2.6	8	6	40	20
82	7.8	2.3	8	2	12	25
21	7.9	1.9	4	4	8	13
52	7.1	2.6	4	2	4	20
83	7.5	2.3	4	2	28	25
22	7.9	2.3	6	6	8	13
53	7.6	2.6	6	8	8	20
84	7.4	2.5	4	2	4	25
23	8.1	1.8	10	2	16	25
54	7.3	2.7	4	2	4	20
85	7.9	2.8	6	2	8	25
24	7.7	2.3	4	2	8	25
55	7.2	2.3	4	2	4	20
86	7.7	2.7	14	12	24	25
25	7.5	2.3	6	4	4	25

Table 14 continued.

Sample Point ID	pH 0-15	OM 0-15	-Post-harvest NO_3-N- depth increment (cm) 0-15	15-30	30-60	NO_3-N applied 0-15
			ppm			kg\ha
56	7.5	2.8	6	2	8	20
87	7.6	2.8	10	10	12	25
26	7.7	2.6	6	4	8	25
57	7.1	3.0	20	22	4	20
88	7.5	2.7	36	2	4	25
27	8.1	2.5	10	4	8	25
58	7.3	3.1	6	2	4	20
89	7.5	2.7	4	4	24	25
28	8.1	2.3	6	2	4	13
59	7.4	2.9	6	4	4	20
90	7.6	2.9	4	2	16	25
29	7.7	1.9	4	4	12	13
60	8.1	2.5	10	2	4	20
91	7.5	2.4	18	2	12	25
30	7.6	1.9	4	2	4	13
61	8.3	2.6	4	2	4	20
92	8.3	2.4	4	6	8	25
31	8.3	2.1	12	6	12	13
62	8.1	2.8	6	2	4	20
93	7.8	2.3	4	2	52	25

Table 15. Yield, percent protein and test weights for the n=67 data set. The yield, protein and test weight samples were replicated twice with the replicate yield samples being northeast and northwest of a sample point.

ID	----Yield------ east	west	----Protein---- east	west	-Test weight- east	west
	-----kg\ha----		------%-------		----lbs\bu---	
10	1689	1779	12.2	12.7	53.6	54.8
41	2082	1992	11.7	10.8	54.0	56.2
72	3082	3181	10.0	9.1	59.1	61.3
11	1713	1730	11.2	12.0	52.4	52.8
42	902	1000	12.9	12.0	50.8	51.2
73	1033	861	15.4	15.8	0.0	52.4
12	2533	2672	9.0	9.0	58.4	61.1
43	746	820	12.9	13.1	55.1	54.8
74	1410	1271	13.2	14.0	40.0	56.1
13	321	2336	8.1	8.3	62.6	62.3
44	1976	1803	10.2	11.5	56.4	54.4
75	3189	286	9.0	12.1	60.6	58.7
14	1435	1443	9.4	10.4	57.6	58.0
45	3738	2967	7.7	9.0	63.3	60.9
76	3435	4427	9.7	10.3	61.2	61.9
15	3328	3689	8.8	7.5	60.7	63.0
46	5607	3845	9.9	8.6	62.0	61.6
77	4197	4664	13.8	10.0	60.9	60.7
16	3555	3820	11.6	11.1	57.6	60.4
47	4550	3172	13.4	11.8	61.0	60.1
78	5312	4787	11.1	11.2	61.5	60.4
17	4501	3541	13.6	13.6	58.8	60.0
48	5259	5794	13.8	13.8	60.0	59.2
79	4443	3940	13.0	13.6	60.9	59.1
18	5853	5123	13.8	13.9	60.1	59.8
49	5550	6910	13.3	13.1	61.4	61.3
80	5689	4894	13.3	14.0	61.3	58.4
19	6550	5468	13.0	13.0	61.4	62.0
50	6148	5992	13.2	12.9	61.4	61.7
81	5960	5337	13.5	13.6	54.4	60.7
20	6091	5230	13.0	12.9	60.7	62.5
51	5550	6230	14.4	13.5	60.8	60.9
82	5558	5238	13.7	13.8	60.6	59.0
21	4673	3517	10.4	11.2	62.1	60.7
52	5451	5910	7.9	12.6	63.5	61.9
83	4664	5115	8.4	11.9	63.3	61.6
22	4730	3418	7.6	8.0	62.3	62.1
53	4984	4902	7.5	7.3	63.4	63.5
84	4459	4820	9.1	10.1	63.0	63.1
23	4386	3246	7.0	7.7	62.9	62.2
54	4632	4467	7.6	6.9	62.8	63.0
85	4984	4369	9.5	9.2	62.4	63.2
24	3986	3058	6.9	8.0	62.8	62.2

Table 15 continued.

ID	---Yield------ east	west	---Protein---- east	west	-Test weight- east	west
	-----kg\ha----		------%-------		----lbs\bu---	
55	4640	4935	7.9	7.3	62.3	63.1
86	4353	4295	8.0	9.8	61.2	61.1
25	3689	3189	6.4	7.0	62.5	62.7
56	4271	4107	6.8	6.8	62.7	63.0
87	4894	4418	8.0	7.8	62.9	62.5
26	4348	4468	6.7	9.3	62.4	0.0
57	5328	4763	7.8	7.2	63.3	62.3
88	5566	5287	8.6	8.1	62.5	62.6
27	3386	2476	7.8	8.3	61.3	61.1
58	4509	4500	8.6	8.4	62.3	61.9
89	3861	3254	10.3	9.5	60.0	59.2
28	3804	3528	10.1	8.7	59.1	61.9
59	4714	4279	8.6	8.2	61.8	61.1
90	4066	3566	9.8	8.2	61.4	61.7
29	3528	4846	11.4	9.7	60.7	58.8
60	5525	5410	8.5	7.9	63.4	63.0
91	5927	4738	8.6	7.4	62.2	62.8
30	2697	3822	12.7	11.3	57.1	57.2
61	4623	4812	10.4	8.8	60.1	61.6
92	6033	5107	9.4	9.1	63.6	63.3
31	2763	3518	12.1	10.0	56.8	58.4
62	4213	4492	11.4	8.3	59.8	61.5
93	6484	5722	8.9	10.2	63.2	52.8

Table 16. Terrain attributes slope, profile curvature, plan curvature and wetness index by sample point ID.

ID	slope %	profile curvature °/m	plan curvature °/m	wetness index
10	9.263369	0.176046	1.313591	7.39
11	10.217630	0.082668	-0.038810	6.92
12	10.488680	0.567391	2.986265	8.17
13	13.018830	0.273906	0.453964	6.90
14	12.262650	-0.253500	0.238483	6.93
15	9.750512	0.151457	1.808913	7.71
16	11.643990	0.046866	2.595138	6.72
17	6.688796	-0.172430	-1.291820	5.83
18	0.761577	-0.138520	-5.444690	7.23
19	1.920937	-0.136020	-0.203150	7.07
20	1.463728	-0.086630	-1.594370	6.91
21	1.612452	-0.005230	2.805093	9.61
22	2.400000	0.019983	-1.666670	7.83
23	2.804015	0.013742	-2.987090	7.60
24	4.188078	-0.046820	1.120967	8.11
25	20.479260	-1.190730	0.910290	6.35
26	18.873920	0.153630	-2.129450	5.95
27	11.315920	0.304221	-0.796070	7.22
28	9.727537	0.043430	-0.247220	7.67
29	6.758143	-0.188490	-2.370740	7.87
30	2.951694	0.011990	-0.745530	9.62
31	1.303840	-0.255550	-8.005760	6.64
41	8.710052	-0.034540	-3.732130	6.87
42	12.377600	-0.066360	-0.421030	6.46
43	8.335766	0.219277	-8.176420	6.33
44	15.857570	-0.472040	3.531153	6.80
45	11.773810	-0.140890	-1.071630	6.50
46	8.057606	0.722434	11.796540	7.84
47	13.262160	1.043187	11.831930	6.72
48	0.250000	-0.150000	-72.000000	8.29
49	1.600781	0.064122	1.615065	7.68
50	2.598557	-0.058870	2.652769	7.34
51	2.592778	-0.354570	-19.094100	6.23
52	4.732071	-0.318100	-2.764860	7.64
53	4.638965	-0.025610	2.278261	7.17
54	3.757659	-0.007460	-2.462210	7.21
55	4.964876	-0.003610	1.281375	7.43
56	28.467260	-0.425840	2.594716	5.82
57	16.958550	0.288219	-0.417140	6.81
58	9.359086	0.210983	-0.040180	7.76
59	7.438077	0.042220	1.847642	8.59
60	6.726812	-0.011590	1.957434	8.46
61	4.491102	-0.034370	-1.904280	8.21
62	0.863134	-0.051190	12.882270	11.51
72	10.873130	0.025906	-0.058560	6.16
73	12.886520	0.243291	0.160042	5.98
74	21.986360	0.371285	0.370550	5.24

Table 16 continued.

ID	slope %	profile curvature °/m	plan curvature °/m	wetness index
75	5.634048	0.007134	12.119740	7.49
76	11.136990	0.283966	-0.891320	5.94
77	7.915807	0.264016	0.675841	6.56
78	10.804630	-0.128690	3.248165	6.39
79	2.147673	0.039631	-3.243440	7.50
80	0.650000	-0.054610	19.171600	8.17
81	1.916377	0.133221	6.089890	8.15
82	4.562072	0.121372	0.619206	6.53
83	2.728095	0.193190	0.608259	7.65
84	4.543677	-0.035880	0.792035	6.39
85	5.523133	0.082078	1.766141	6.79
86	4.416163	0.014715	0.345133	6.98
87	26.153060	-1.616380	1.433958	5.36
88	16.259300	0.860815	2.366798	6.91
89	10.336830	-0.095730	1.908356	7.59
90	8.633077	-0.089550	-0.572720	6.86
91	8.194204	0.311762	0.550302	7.13
92	3.900321	0.280307	4.847126	8.71
93	2.451530	0.112511	3.564618	8.78