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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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date April 21, 1993

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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).

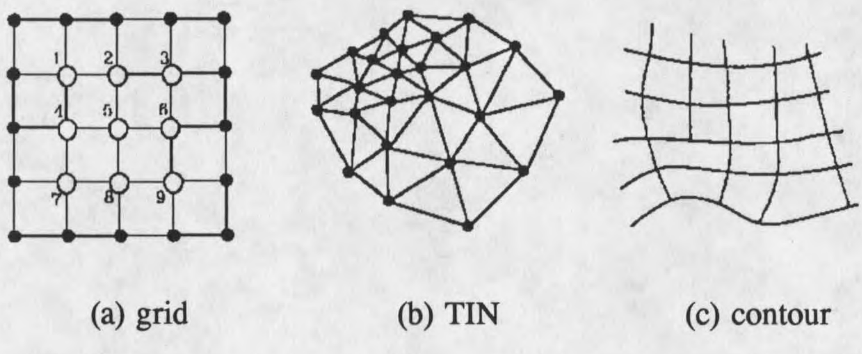

Fig. 1. Three types of digital elevation models. (Moore et al., 1992).

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.

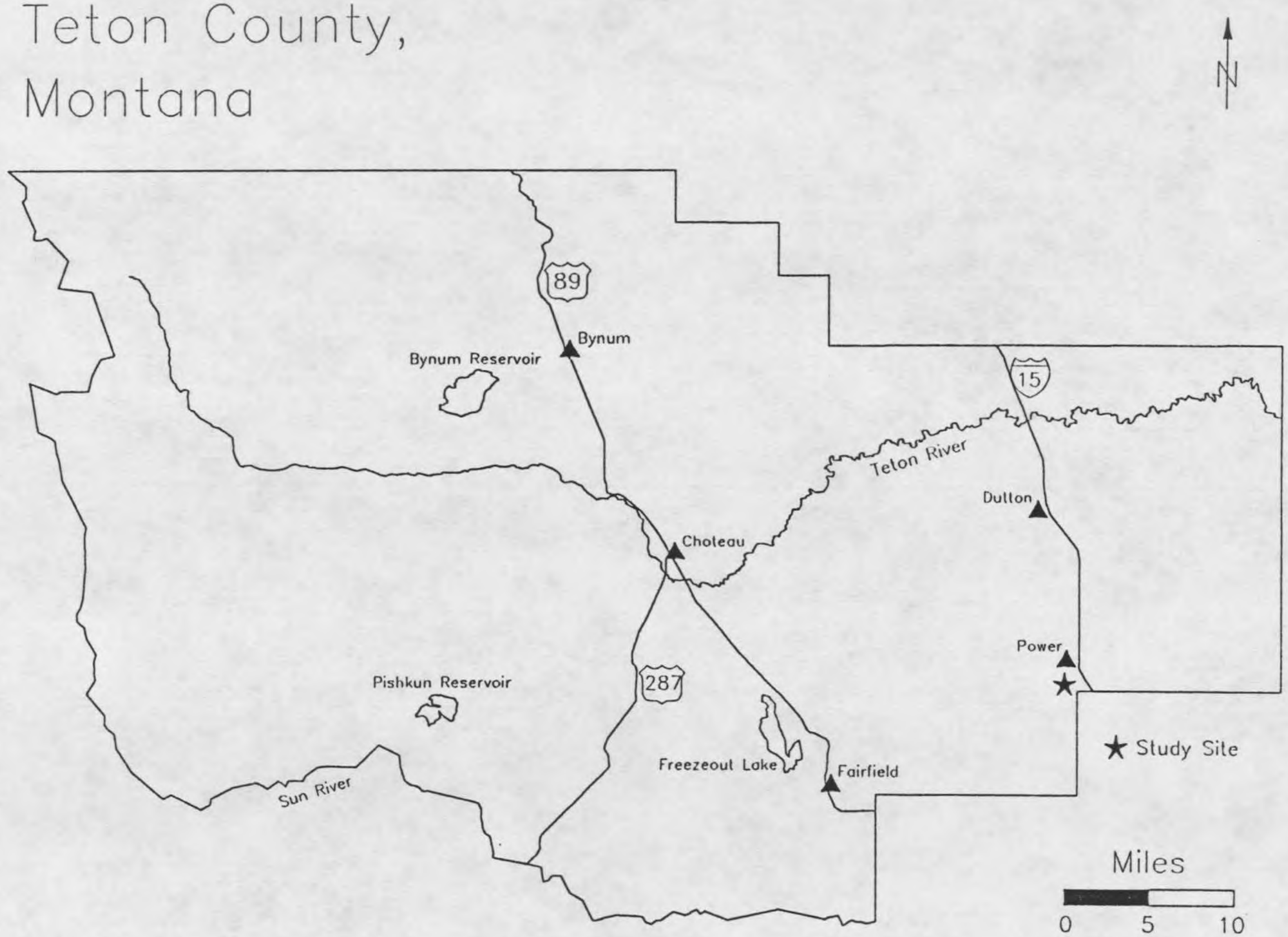

Fig. 2. Location of study site south of Power in Teton County, MT.