DISSERTATION

PARENT MATERIAL-TOPOGRAPHIC-MANAGEMENT CONTROLS ON ORGANIC AND INORGANIC NUTRIENTS IN SEMIARID SOILS

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY RICHARD AGUILAR ENTITLED PARENT MATERIAL-TOPOGRAPHIC-MANAGEMENT CONTROLS ON ORGANIC AND INORGANIC NUTRIENTS IN SEMIARID SOILS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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ABSTRACT OF DISSERTATION

PARENT MATERIAL-TOPOGRAPHIC-MANAGEMENT CONTROLS ON ORGANIC AND INORGANIC NUTRIENTS IN SEMIARID SOILS

Paired native grassland and cultivated landscapes were characterized to evaluate parent material and topographic controls on organic matter and phosphorus along catenary sequences in southwestern North Dakota. Site selection was based on parent material (sandstone, siltstone, and shale residuum), similar cropping history (44-yr wheat-fallow rotation), and uniform range management.

Parent material-soil process relationships were established by evaluating chemical and physical data for soil profiles at the native-summit landscape segments on the three contrasting parent materials. The effects of topography on the amounts and vertical distribution of organic matter and phosphorus were evaluated by studying soil profiles at various geomorphic landscape components along the catenas. The effects of 44 years of cultivation were evaluated by comparing cultivated and virgin soils at each landscape segment using the soils on native pasture as benchmarks.

The finer textured soils weathered in shale were found to have much higher levels of organic C, N and Total P. Soils weathered in sandstone were found to have more uniform decreases in organic matter with profile depth and the highest quantities of organic P. On the native pastures, quantities of organic matter were much higher in the lower landscape segments because of higher moisture contents and/or the deposition of organic matter-enriched soil. Soils at lower landscape segments (lower backslopes, footslopes) have been enriched with Total P at the expense of soils at the upper portions of the catenas.

Changes in organic and inorganic soil constituents resulting from cultivation were found to vary as a function of parent material and topography. Mineralization losses of organic constituents appear to have been higher in the sandstone soils. The fine-textured shale soils, which appear to have a large proportion of highly humified, clay-associated organic matter, lost the lowest quantities of organic constituents relative to total soil loss. Losses of organic matter were generally lower at the lower landscape segments in all three sites, reflecting soil deposition. Redistribution of soil material by both mechanical (tillage practices) and natural processes (wind and water erosion) must be considered when evaluating cultivation-induced changes in soil properties along catenary sequences.

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INTRODUCTION

The semiarid Great Plains of North America comprise over 250 million hectares, of which approximately two-fifths have been cultivated in the last 50 to 100 years. The organic matter content and nutrient supplying power of many of the soils in the Great Plains have seriously declined since they were broken out of native sod. Organic matter losses and soil deterioration resulting from cultivation practices are of major concern in semiarid agroecosystems. In addition to being a primary source of plant available nutrients, soil organic matter is important in maintaining the desirable physical properties of soils.

This study is a part of a five-year cooperative effort between the Science and Education Administration, U.S. Department of Agriculture and Colorado State University. The project's major objective is to develop an integrated evaluation of changes occurring on organic matter and nutrient cycling in agroecosystems found under varying parent material, climatic regimes, vegetation successions and management practices. Field process studies are being conducted at several locations to assess current inputs and losses of carbon and nutrients under selected management systems. Laboratory studies on the nature and turnover of soil organic matter, nitrogen and phosphorus in semiarid soils are also being conducted. This particular study consists of evaluating the quantity and distribution of organic matter and selected plant nutrients on virgin and cultivated soils occurring on landscapes (catenas) of contrasting parent materials.

The "quasi steady state" nutrient cycle of rangeland soils is altered upon plowing of native sod and generally results in a new system where crop removal and other losses of nutrients exceeds inputs by plants. Trudgill (1977) states that this alteration of the nutrient cycle produces an unstable system with internal reactions occurring until the rates of flow are adjusted to the rates of disturbance, or until an entirely new system is obtained. Generally, a rapid decrease in soil organic matter occurs in the early stages of cultivation, and the rate of organic matter loss decreases with time. Results from early studies suggested that a new equilibrium level of organic matter was attained between 20 to 30 years of cultivation (Hass et al., 1957; Unger, 1968). More recently, Martel and Paul (1974) reported that new equilibrium organic matter levels were obtained only after 60 to 70 years of cultivation. And of equal importance, Unger (1968) suggested that the time in which organic matter losses cease is highly dependent upon cropping practices.

A significant reduction in the profile depth of prairie soils can occur through cultivation because of an increase in erosion potential due to the loss of a more permanent cover and the alteration of soil structure. Erosion, therefore, may cause a large portion of the difference in organic matter contents between native grassland and cultivated sites. Profile depth comparisons between native and cultivated sites may aid in distinguishing organic matter losses due to erosion from losses resulting primarily from mineralization.

The four major processes responsible for soil formation include (1) additions of organic and mineral matter to the soil as solids, liquids and gases, (2) losses of these from the soil, (3) translocations of materials within the soil profile, and (4) transformations of mineral and organic substances within the soil (Simonson, 1959). Jenny (1941) defined parent material as "the state of the soil system at time zero of soil formation" and formulated a univocal definition of parent material, along with climate, topography, biota, and time, as the five independent factors of soil formation. Clearly, coarse-textured soils weathered in quartz-rich parent materials will respond differently from finer textured soil with regard to the major driving variables of pedogenesis (temperature, precipitation and other atmospheric inputs, evapotranspiration, and biological activity). Thus, the relative intensity of the major soil forming processes defined by Simonson (1959) will vary within a given environment as a function of parent material. Additionally, the subsequent changes in the soil resulting from cultivation will vary depending upon parent material. Losses of organic matter due to cultivation practices can vary greatly in soils of contrasting textural characteristics. Generally, greater losses have been shown to occur in coarser-textured soils (DeHann, 1977; Herlihy, 1979). Sandy soils, because of their greater susceptibility to wind erosion, undergo extensive losses of organic matter under continuous cultivation. Organic matter losses from sandy soils are more critical than those from finer-textured soils because of lower initial levels prior to cultivation (Reinhorn and Avnimelech, 1974).

On stable landscape positions, the amounts and vertical distribution of organic matter, total, organic and inorganic phosphorus, and nitrogen levels in semiarid soils may result primarily from differences in moisture retention and nutrient supply characteristics of contrasting parent materials. Variations in geomorphic and pedogenic processes along a catenary sequence may modify the processes responsible for the levels of organic and mineral soil constituents and lead to large differences in the amounts and vertical distribution of these in soil profiles at the various landscape positions. To evaluate this, catenary sequences of soils weathered in three distinct and contrasting parent materials were characterized. The catenary sequences are located within the same subclimatic region of the northern Great Plains on native rangeland and cultivated fields in southwestern North Dakota.

The study's primary objectives are (1) to evaluate parent material-landscape interactions which control the levels (concentrations and absolute amounts) of organic matter and selected nutrients on semiarid rangeland, and (2) to assess the long-term effects of cultivation on organic carbon, nitrogen and phosphorus as a function of parent material and topography.

The study will attempt to provide supporting data for some of the project's original hypotheses concerning the distribution and quantity of organic matter and nutrient resources in major soil groups occurring in the Great Plains biome and the subsequent changes in these resulting from long-term cultivation. These hypotheses include:

1. Parent material may control the amounts and vertical distribution of organic and other nutrients in typical soil profiles with native grassland vegetation.

2. Parent material-topographic interactions can lead to large differences in the levels of organic matter and other nutrients at different landscape positions within a given region.

3. The changes in organic matter and nutrient levels resulting from a wheat-fallow management system will vary as function of landscape position within a catena.

The results of this study will be integrated with other studies to develop statistical models which will aid in fine-tuning simulation models on cycling of carbon, nitrogen, and phosphorus in semiarid grassland ecosystems. The project's primary goal is to develop an integrated evaulation of changes occurring in fragile range and cultivated dryland ecosystems as a result of man's activities.

DESCRIPTION OF THE STUDY AREA, SITE SELECTION, AND FIELD AND LABORATORY METHODS

Description of the Study Area

The three study sites are located in Grant County, North Dakota approximately 100 km southwest of Bismarck (Figure 2.1). Legal site location descriptions for the paired native and cultivated catenas are as follows:

	site location
sandstone catenas:	N.W. 1/4 section 11, T133N,R87W
siltstone catenas:	N.E. 1/4 section 6, T133N,R86W
shale catenas:	
native site--	S.W. 1/4 section 16, T131N,R88W
cultiv. site--	N.W. 1/4 section 21, T131N,R88W

Climate

The climate in southwestern North Dakota is extremely continental with a short growing season averaging approximately 122° frost-free days. Climatic data for Grant Count was compiled by Kelly (1984) from U.S. Weather Bureau publications for the period between 1931 and 1961. The mean annual temperature during this 30 year period was 5.7° C (42.3° F). Temperature extremes during this period ranged from a high of 46.7° C (116° F) to a low of -41.7° C (-43° F). Mean maximum and minimum temperatures were 12.8° C (55° F) and -1.4° C (29.5° F), respectively. The mean annual precipitation in Grant County is 396 mm (15.6 in.), with approximately 70% of this occurring during the growing season. The average wind direction and velocity is variable,

Figure 2.1 - The Great Plains of the United States and location of Grant County, North Dakota.

depending upon the season. The wind direction between September and May is predominantly out of the W-NW with an average velocity of 16 km/hr (10.0 mph). During the summer months the predominant wind direction is out of the S-SE with an average velocity of about 10 km/hr (6.2 mph).

Site Selection

Large acreages in southwestern North Dakota remain in native range. Cultivated land in the northern Great Plains is used primarily for small grain production. The most common form of dryland management in Grant County and southwestern North Dakota is a wheat-fallow rotation.

All three native range sites were located upwind from the adjacent cultivated sites and other cultivated fields in the surrounding area. The dominant vegetation on the range sites consists of native grasses and annual forbs. The range condition is considered to be in fair to good condition at all three sites. Production values for the sites were obtained from the Soil Conservation Service at Carson, N.D.[1] Total biomass production on the sandstone range site is estimated to range between 878 and 1317 kg/ha under excellent conditions. The siltstone and shale range sites are estimated to produce 768 to 988 kg/ha and 824 to 1098 kg/ha total biomass, respectively, under excellent conditions.

The dominant plant species found on each native site are listed in Table 2.1.

1 L. Edland. Soil Scientist, USDA-SCS, Carson, North Dakota (personal communication).

Table 2.1 - Dominant plant species on the native portions of the three catenas.

Common Name	Scientific Name
SHALE	
western wheatgrass	*Agropyron smithii*
green needle grass	*Stipa viridula*
blue grama	*Bouteloua gracilis*
Annual Forbs	
SILTSTONE	
western wheatgrass	*Agropyron smithii*
green needle grass	*Stipa viridula*
prairie June grass	*Koeleria cristata*
threadleaf sedge	*Carex filifolia*
western yarrow	*Achillea millefolium*
SANDSTONE	
prairie sandreed	*Calamovilfa longifolia*
needle and thread	*Stipa comata*
threadleaf sedge	*Carex filifolia*
little blue stem	*Andropogon scoparius*
Annual Forbs	

Geology of the Three Study Sites

It was necessary to evaluate the overall geology of the northern Great Plains in order to locate residual soils weathered in three contrasting parent materials with coarse, medium, and fine textural properties within the same subclimatic region (eg. precipitation and temperature regimes). Grant County is located west of both the Missouri River and the glaciated portion of North Dakota. It is also far removed from the heterogeneous Pleistocene outwash on the eastern flanks of the Rocky Mountains. The geology of Grant County consists of flat-lying deposits of sandstone, siltstone, and shale bedrock of Tertiary age (Figure 2.2). Elevations range from 687 M (2255 ft.) above sea level at the shale site to 732 m (2402 ft.) above sea level at the siltstone and sandstone sites.

The sandstone and siltstone sites are in sediments belonging to the Tongue River Formation. These sediments were deposited approximately 65 million years B.P. on a flat, swampy plain similar to parts of the present coastal plains of the southeastern U.S. (Bluemle, 1975). The sandy sediments were deposited as a series of bars in numerous east-flowing rivers and along the shores of large shallow lakes. The siltstone deposits are thought to have settled out of backwaters between individual river channels during periods of flooding or offshore parts of lakes. The clayey sediments comprising the shale site belong to the older Cannonball Formation. These sediments are thought to have been deposited about 75 million years ago, shortly after the invasion of Tertiary Seas into the area.

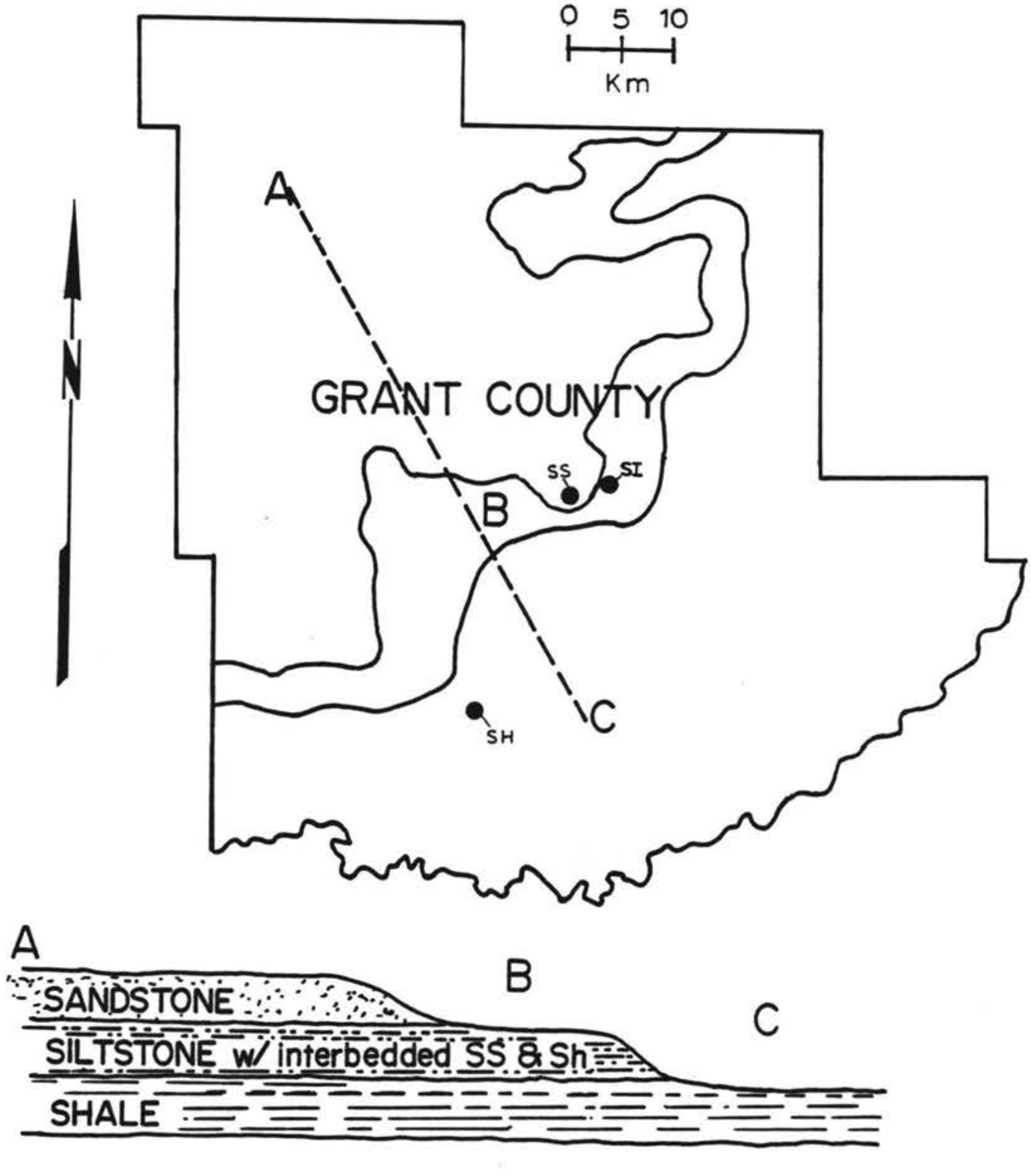

Figure 2.2 - Bedrock geology of Grant County, North Dakota. The locations of the three study sites are indicted on the diagram. (Sandstone - SS, Siltstone - SI, and Shale - SH)

Field Sampling Methodology

The various geomorphic landscape components (summit, shoulder, backslope, footslope, and toeslope) occurring in each catena were identified following the approach outlined by Ruhe and Walker (1968). The various landscape elements are delineated based on discordance of slope. Distinct geomorphic and pedogenic processes are associated with each of the different landscape components and are controlled by the geometric configuration (slope shape, slope length, and slope gradient) at that portion of the hillslope. The shoulder, the convexly rounded component between the summit and the linearly shaped backslope, is usually the most highly eroded portion of the landscape. Within a catena, the shallowest and least pedogenically-developed soil profiles will occur on this segment. The backslope area is usually a transportational zone where inputs and outputs resulting from erosional processes may balance out, with little net change in soil profile depth. Pedogenetic development is generally limited under these conditions. Footslope and toeslope components are continually receiving inputs of material from upslope areas. Soil development in these areas is interrupted by the deposition of fresh sediments. Soils in the summit component are generally the most stable in terms of pedogenic development. Virtually no runon of water and addition of sediments occur on this landscape position because drainage waters are just beginning to accumulate. Pedogenic processes associated with vertical movement of subsurface water play a dominant role in soil development at the summit landscape position, providing that precipitation is not limiting.

Slope gradients, lengths, and shapes of the landscape segments identified at each of our study sites were recorded. Schematic diagrams for the three paired native-cultivated catenas are shown in Figures 2.3-2.5. Each catena has distinct geometric patterns reflecting the weathering characteristics of the underlying bedrock and were characterized accordingly.

The siltstone catena has the most complex landscape geometry of the three sites (Figure 2.3). The lower backslope area was subdivided into three distinct segments because of an inclusion of a weather-resistant sandy mudstone lense in this portion of the hillslope. The sandy lense imparts a convex geometry to the landscape and was segregated from the upper and lower portions of the lower backslope area. A landscape segment occurring on the leeward side of the catena was also characterized and identified as a back shoulder (SH B). The remaining segments on this catena were easily identified following the concepts of Ruhe and Walker (1968).

The sandstone catena was subdivided into seven distinct segments (Figure 2.4). The linear backslope area was separated into upper and lower components. Two landscape segments, the back backslope (BBS) and back footslope (BFS), were characterized on the leeward side of the catena. A rounded convex shoulder was not found on the leeward side of the catena. This type of landscape morphology is typical of areas underlain by sandstone bedrock in Grant County. It was felt that characterization of the segments on the leeward side of this catena would aid in evaluating the effects of wind erosion because it is these segments which are most susceptible to wind deposition.

SILTSTONE SITES

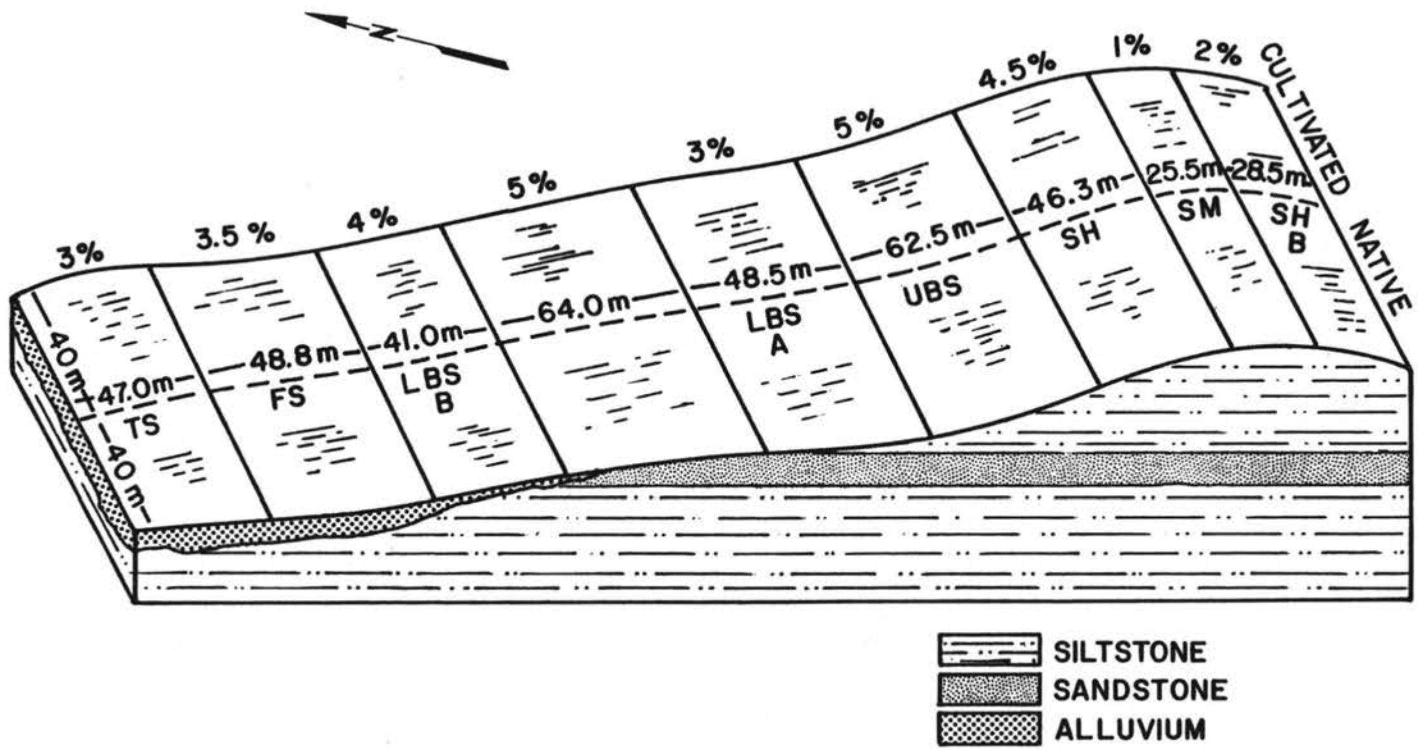

Figure 2.3 - Diagramatic representation of the siltstone catena. Native and cultivated segments at this site include: Back Shoulder - SH B, Summit - SM, Shoulder - SH, Upper Backslope - UBS, Lower Backslope (A) - LBS A, Lower Backslope (B) - LBS B, Footslope - FS, Toeslope - TS. Slope lengths and gradients are indicated for each segment.

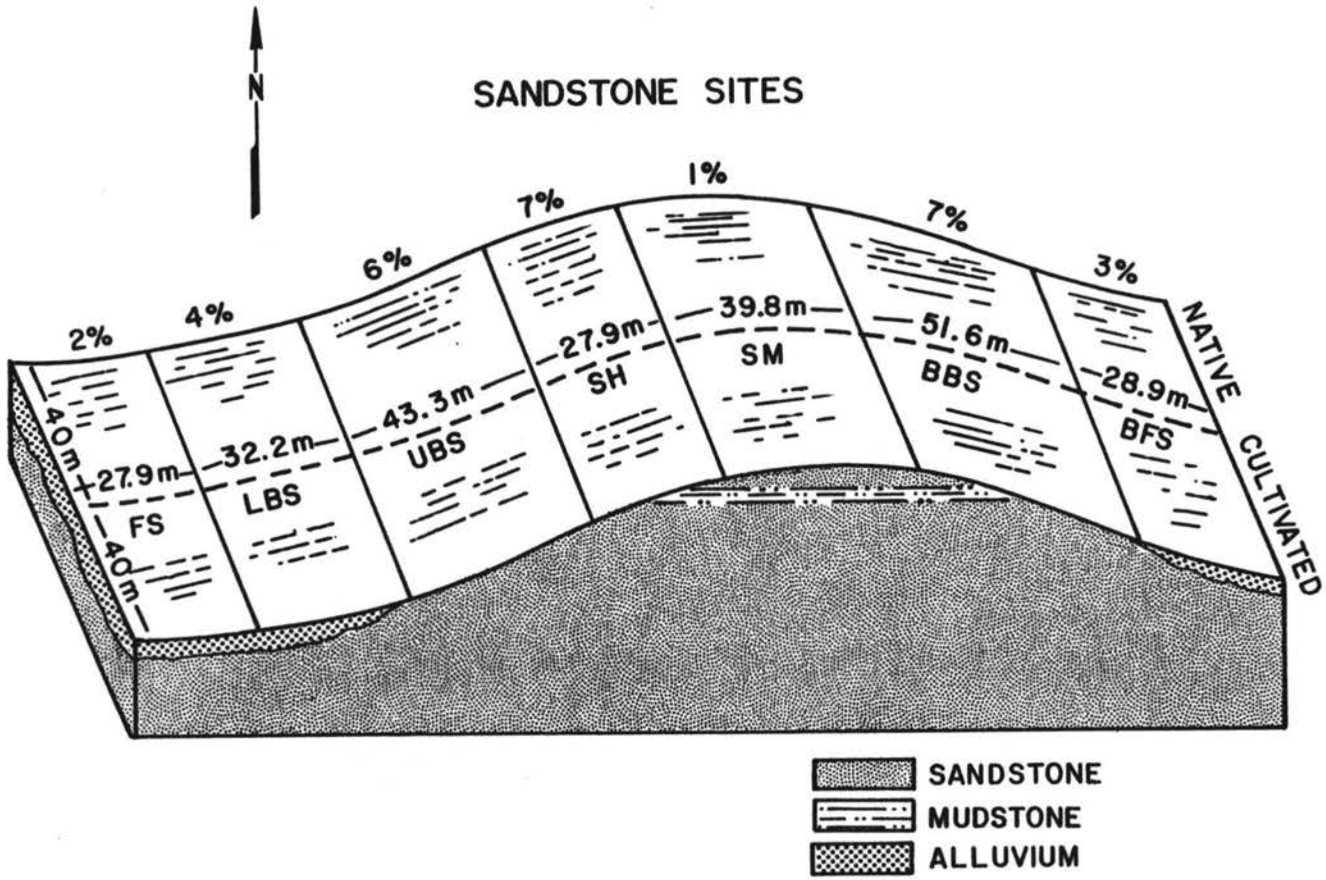

Figure 2.4 - Diagramatic representation of the sandstone catena. Native and cultivated segments at this site include: Summit - SM, Shoulder - SH, Upper Backslope - UBS, Lower Backslope - LBS, Footslope - FS, Back Backslope - BBS, Back Footslope - BFS. Slope lengths and gradients are indicated for each segment.

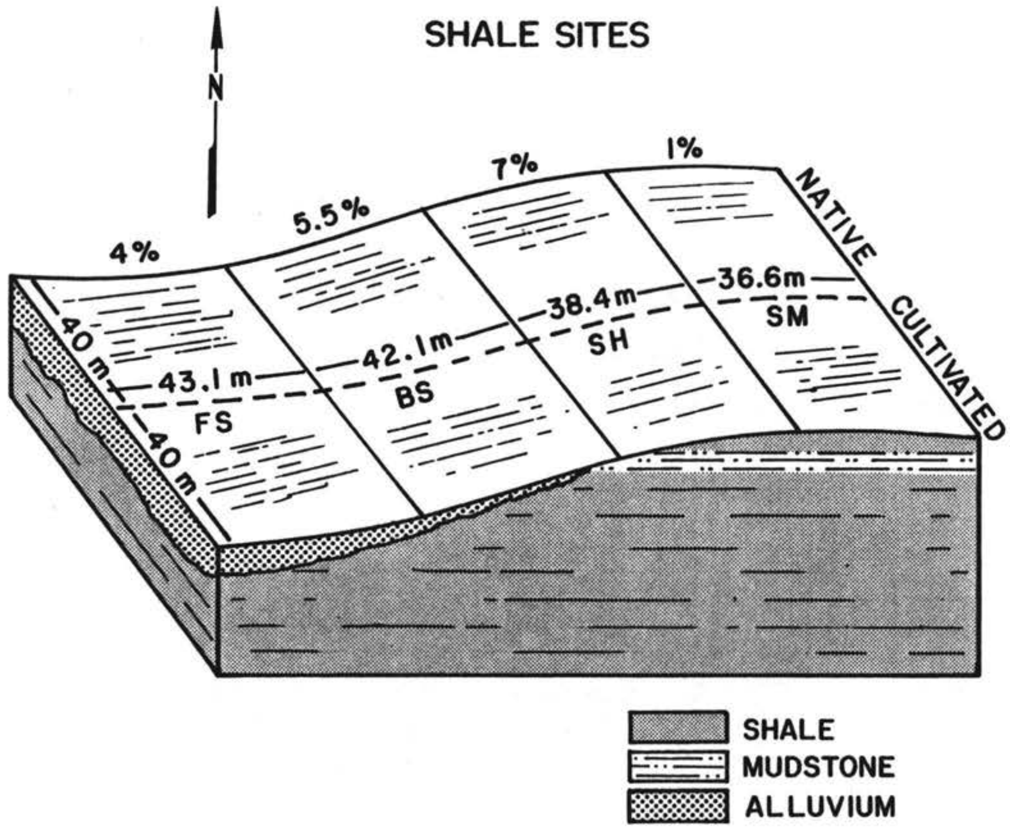

Figure 2.5 - Diagramatic representation of the shale catena. Native and cultivated segments at this site include: Summit - SM, Shoulder - SH, Backslope - BS, Footslope - FS. Slope lengths and gradients are indicated for each segment.

The shale catena is the smallest (by area) of the three and has relatively simple landscape geometry (Figure 2.5). Only four landscape segments were identified on this site. The slope length of the backslope area was relatively short and was not divided into two segments as in the other two study sites. The shale parent material is relatively uniform, with the exception of a thin lense of coarser textured mudstone at the shoulder (SH) area.

Site Characterization

Three pedons, approximately five meters apart, were selected for sampling at each landscape segment. The center point of each segment was sampled, along with two points outward from this point selected at random in a rosette pattern. Complete pedon descriptions were compiled following the procedures outlined in the 1962 USDA Soil Survey Manual (Soil Survey Staff, 1962) and the recently revised Soil Survey Manual (Soil Survey Staff, 1982). Each soil profile was sampled by genetic horizon to a depth of 120-150 cm or to a lithic contact, whichever was encountered first. Horizons with thicknesses greater than 25 cm were split in two for sampling purposes. Other important site characteristics which were noted include the following:

a) topographic characteristics (sufficient contours were delineated to establish slope breaks between landscape segments);

b) general vegetative species list for native sites; and,

c) history of each cultivated site, including length of time under cultivation, fertilizer history, cropping history, and equipment used for tillage practices (Appendix 1).

Soils were classified according the criteria outlined in Soil Taxonomy (Soil Survey Staff, 1975). The soils occurring along the native shale site were classified as fine, montmorillonitic Typic Haplaborolls and Argiborolls. The soils at the siltstone site were identified as fine-silty, mixed Typic Haplaborolls and Argiborolls. At the sandstone site the soils ranged from coarse-loamy, mixed Typic Haplaborolls, in the upper segments of the catena to coarse-loamy, mixed Typic Argiborolls on the lower.

LABORATORY ANALYSES

Soil samples collected for chemical and physical analyses were air-dried and passed through a 2 mm sieve. Samples taken for analyses of organic phosphorus and nitrate were air-dried immediately.

Physical Analyses

Bulk densities were determined using the core method described by Blake (1965). All genetic horizons in each pedon characterized at the various landscape segments were characterized. Particle-size distribution and water-retention data are reported by Kelly (1984).

Chemical Analyses

Chemical analyses included the following:

- -- pH and electrical conductivity
- -- % $CaCO_3$ - equivalent
- -- % organic carbon, total nitrogen, nitrate nitrogen (NO_3-)
- -- total phosphorus, organic phosphorus, acid soluble phosphorus, total inorganic phosphorus, and residual nonextractable phosphorus

Measurements of pH were made with a standard pH meter in 1:1 soil-water suspensions. Electrical conductivity measurements were taken on the extracts of these suspensions. The acid-neutralization method

(U.S. Salinity Laboratory Staff, 1969) was used to estimate percent $CaCO_3$. Two to ten grams of soil were used in the analyses, depending upon the sample's effervescence in dilute HCl. Organic carbon was determined by the modified Walkley-Black method as described by Nelson and Sommers (1975). Total nitrogen was analyzed in Kjeldahl digests as outlined by Bremner and Mulvaney (1982), with slight modifications. A 5.0 g sample was digested at 360° C in 0.5M H_2SO_4 to convert organic N to NH_4^+. The quantity of NH_4^+ in the digest was then determined colorimetrically using a Technicon Autoanalyzer System II. Nitrate nitrogen (NO_3^-) was extracted by leaching 5.0 g of soil with a 2M KCl solution. Total nitrate in the extracts was then determined with the Technicon Autoanalyzer.

Phosphorus was determined according to the method of Murphy and Riley (1962). Total phosphorus digests were obtained by the sodium hydroxide fusion method outlined by Smith and Bain (1982). Organic phosphorus was determined by the difference in 0.5M H_2SO_4 extractable P recovered from samples ignited at 550° C and unignited samples (Saunders and Williams, 1955). Inorganic phosphorus was determined by subtracting the quantity of organic phosphorus from total phosphorus. Acid-soluble phosphorus was that fraction of total P extracted by 0.5M H_2SO_4 following three hours shaking. Residual P was calculated as the difference between total P and the sum of organic P and acid-soluble P, (Residual P = Total P - (Organic P + Acid- soluble P)).

Statistical Analyses

Software programs using DBMS-2000 were written to store and help evaluate the data. Statistical packages including MINITAB software programs (Ryan, et al., 1976) and SPSS - Statistical Package for the Social Sciences (Nie et al., 1975) were used for final data analyses. The quantity (volume-weight basis) of each nutrient was calculated for the three pedons sampled at each segment. The average of these was taken to represent the total quantity of nutrient to a specified depth in the soils representing a given segment. The variability of each nutrient was estimated as the coefficient of standard deviation associated with the mean quantity on each segment. Total phosphorus measurements were not replicated for all landscape segments because of the difficulty in the analysis and time limitations. On some segments, total, inorganic and residual phosphorus indices were calculated for only one pedon. However, three replications of all phosphorus indices were obtained for the native-summit and native-footslope segments on each catena and the standard deviations were consistently low.

Comparisons in the mean quantity of each nutrient along the catenas were made by treating the three replications at each segment as independent from the replications at other segments. TWOSAMPLE t-tests, assuming unequal variances between the populations at the various segments, were performed to contrast the average quantity of the nutrients at the native sites (Ryan, et al., 1976). LINEAR CONTRASTS evaluating landscape-management interactions along the catenas were used to compare the quantity of nutrients in the cultivated vs. virgin soils. Square-root and $\log_{10}$ transformations were employed to stabilize the variance in data where the distribution of the errors were non-normal about the means.

PARENT MATERIAL - SOIL PROCESS RELATIONSHIPS

Background Information

The early pioneers in pedology recognized that the initial parent material was a significant soil-forming factor (Dokuchaev, 1883). Buol, et al. (1980) stated that "the present modern soil as we see and study it owes its properties to (1) the composition of the surficial layer present when the current array of environmental factors started their effect and (2) the modifications resulting from the effect of these environmental factors over time." Many features of the initial parent material are lost as weathering and pedogenic processes proceed and the soil matures in age. However, the influence of the initial material may not diminish with soil age in extremely resistant material such as quartz-rich sandstone. In contrast, mature soils formed in easily weatherable parent material, such as limestone, are generally composed of the more resistant impurities in the limestone. It is these constituents which will ultimately control the pedogenic processes in these types of soils (Buol, et al., 1980). It is therefore important to fully assess the nature of the initial parent material and its influence (or control) on soil forming processes when studying soils of different lithology.

When all other factors are equal, the texture of the parent material has a great influence on the course of soil formation. Textural characteristics influence the rate and depth of leaching in soil profiles. The degree of leaching influences many soil properties and processes including base saturation, pH, and degree of clay translocation within the profile. Birkeland (1984) pointed out textural influence can be so important that soils which generally occur only in different climatic regions can occur side by side, and yet each is stable for the prevailing site conditions.

Additions of organic matter are a natural process in soil development. Soil organic matter is an accumulation of partially decayed and synthesized plant and animal residues. Organic matter is continually being broken down by microorganisms in the soil and thus, is a transitory soil constituent which is constantly renewed to a greater or lesser degree, depending on productivity, by the addition of plant residues. Although the organic matter content in soils is small, commonly three to five percent by weight in surface horizons, its influence on soil properties and subsequently on plant growth is far greater than its low content would indicate (Brady, 1974). Organic matter increases the soil's water-holding capacity and the proportion of plant-available water. It is also a major source of phosphorus and sulfur in soils, and the principal source of nitrogen. Furthermore, organic matter is the main energy source for microbial activity, and without it, biochemical activity in soils would practically cease. The amount of organic matter production in semiarid regions is highly dependent on the total and plant-available soil water. Clearly, soils weathered in parent material of different lithology will vary in their waterholding characteristics.

The soils at the summit landscape on native range sites were compared in order to evaluate the effects of parent material on soil forming processes and soil property relationships. It was felt that this landscape component would best represent the macroclimatic soil environment because the summit area is generally the most stable in terms of surficial runoff and erosional processes and is least influenced by other landscape segments within a catena.

Physical and chemical data for the soils at each landscape segment at our three sites are listed in tables in Appendix 2. Profile descriptions were compiled for the virgin and cultivated soils at all landscape segments and are reported by Kelly (1984).

Chemical and Physical Characteristics of the Three Contrasting Soils

Particle size distribution data for the three virgin soils at the native-summit landscape segments (Appendix 2) show that the textural characteristics of the soils strongly reflect the grain size characteristics of the initial parent material (Kelly, 1984). In the soil weathered from sandstone the proportion of sand-sized particles (0.05-2.0 mm) ranged from 62 to 73% (by weight) of the total, while the amount of clay (<0.002 mm) and silt-sized particles (0.002-0.05 mm) ranged from only 10 to 23%. Silt-sized particles ranged from 46 to 70% and the clay and sand fractions comprised 18 to 48% and 6 to 20% of the total, respectively, in the siltstone soil. Clay and silt fractions ranged from 38 to 49% in the shale soil, with the proportion of sand-sized particles comprising only approximately 8 to 13% of the total.

Total and plant available water-holding capacity as a function of soil depth are plotted in Figure 3.1. The solid lines and dashed lines indicate the percent water (by volume) held at 1/3-bar and 15-bar tensions, respectively. The shaded area represents the total amount of plant available water. As one would expect, the soils weathered from shale and siltstone have very high plant available water-holding capacities with the shale having the highest total water-holding capacity. The sandstone soil has by far the lowest plant available and total waterholding capacity. This suggests that the sandy soil has a much higher leaching potential and potential limited plant productivity. Moisture retention data also show that the vertical decrease in the amount of plant available water is fairly uniform with profile depth in the sandy soil. Because this soil is very low in clay content, moisture retention is probably highly related to organic matter content. In contrast, the moisture data for both the siltstone and shale soils display higher available water-holding capacity in subsurface horizons due to higher proportions of silt and clay-sized particles. Therefore, the organic fraction may not be as important as the mineral fraction in controlling the overall total and plant available water-holding capacity in these soils.

The pH and calcium carbonate equivalent data for the three contrasting soils are shown in Figures 3.2-3.3. The soil reaction of the surface horizons ranges from moderately acid (pH 5.8) in the siltstone soil to slightly acid (pH 6.6) in the shale soil. Below the organic matter-enriched horizons the pH rapidly increases due to increases in base saturation and calcium carbonate. This pattern is characteristic of soils in arid and semiarid regions where limited leaching results in high base status through most of the profile. A well developed soil in semiarid regions usually has a zone of calcium carbonate accumulation that is greater than that of its initial parent material at some depth in the profile. The lower the effective

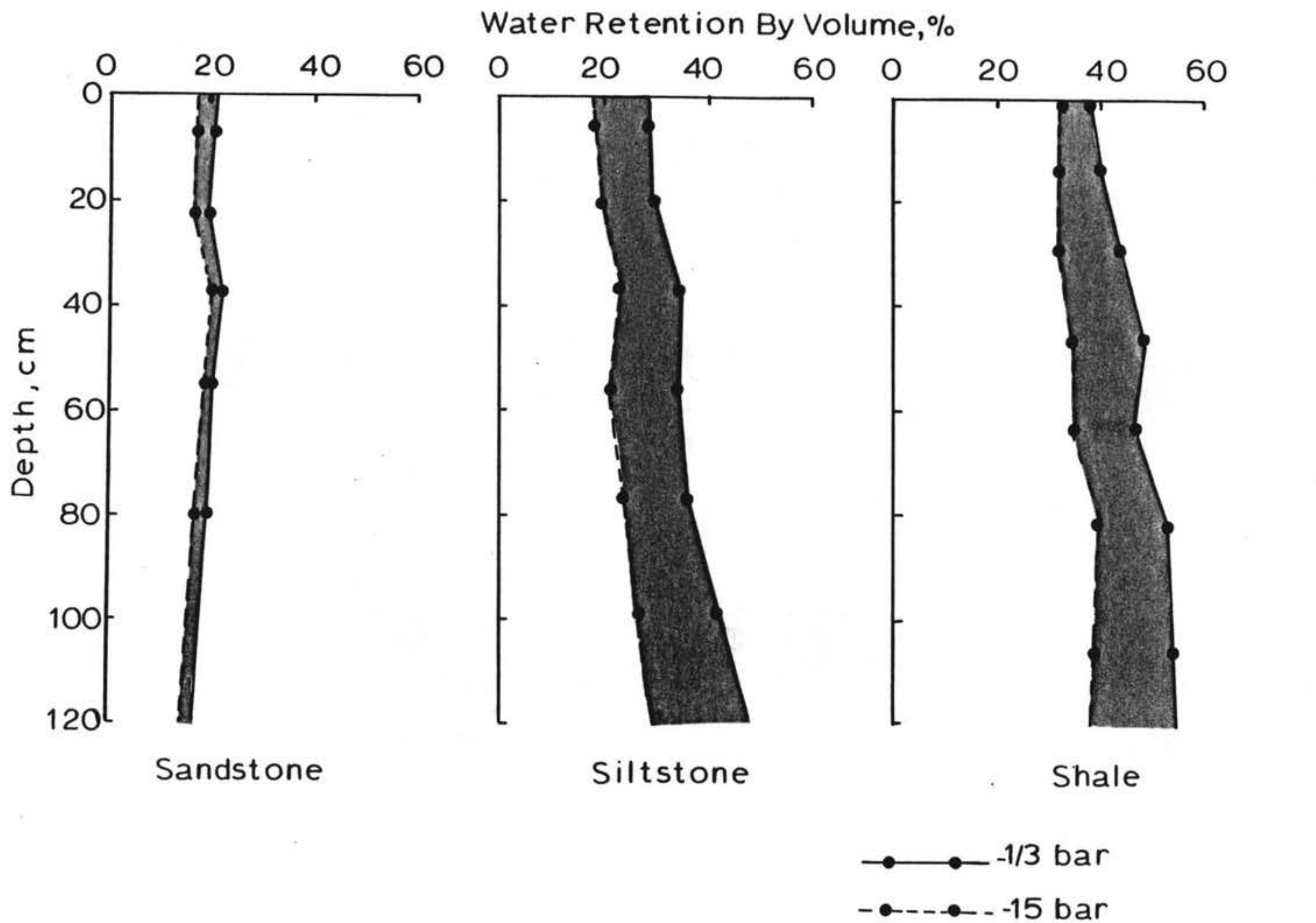

Figure 3.1 - Parent material controls on total and plant available water at the native-summit landscape of the three catenas.

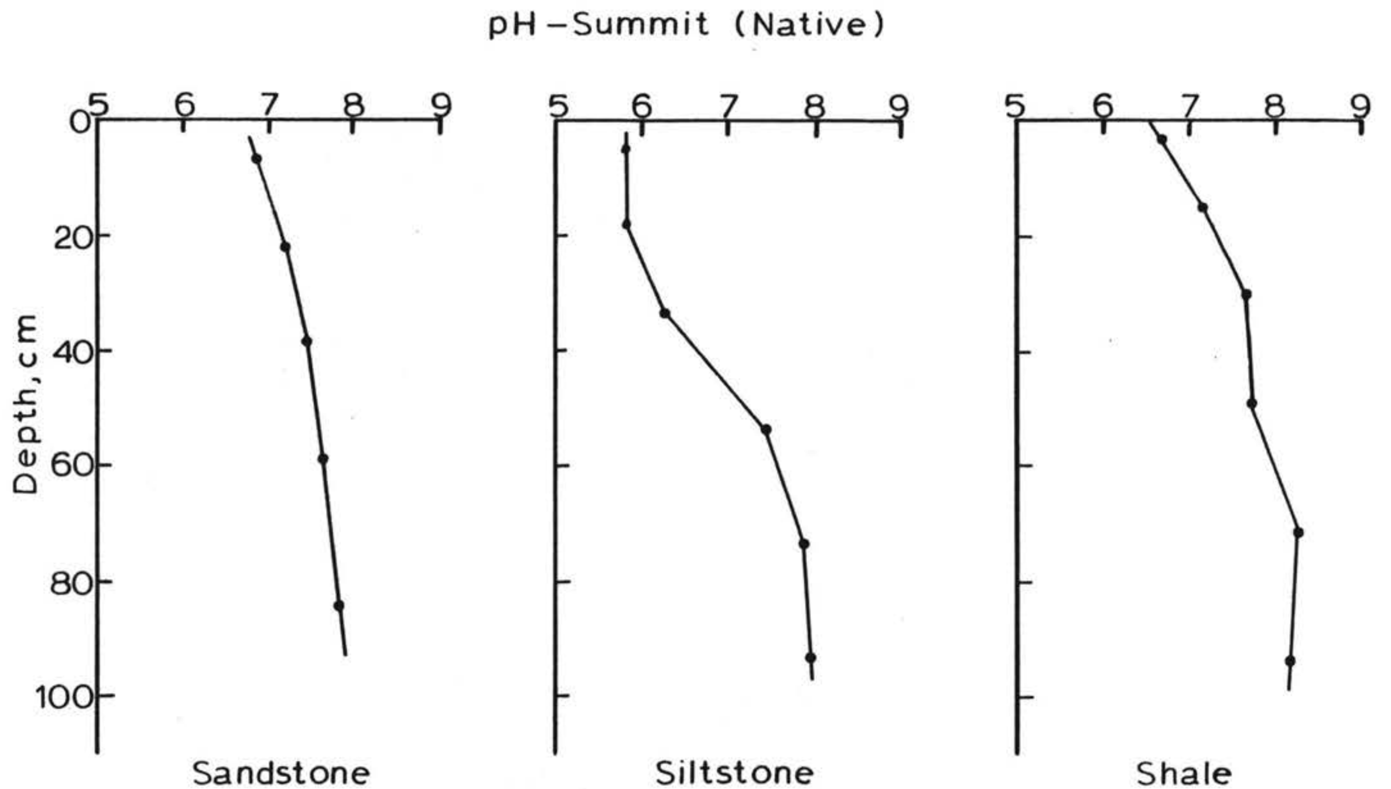

Figure 3.2 - Vertical variation of pH in the soils at the native-summit segment of the three catenas.

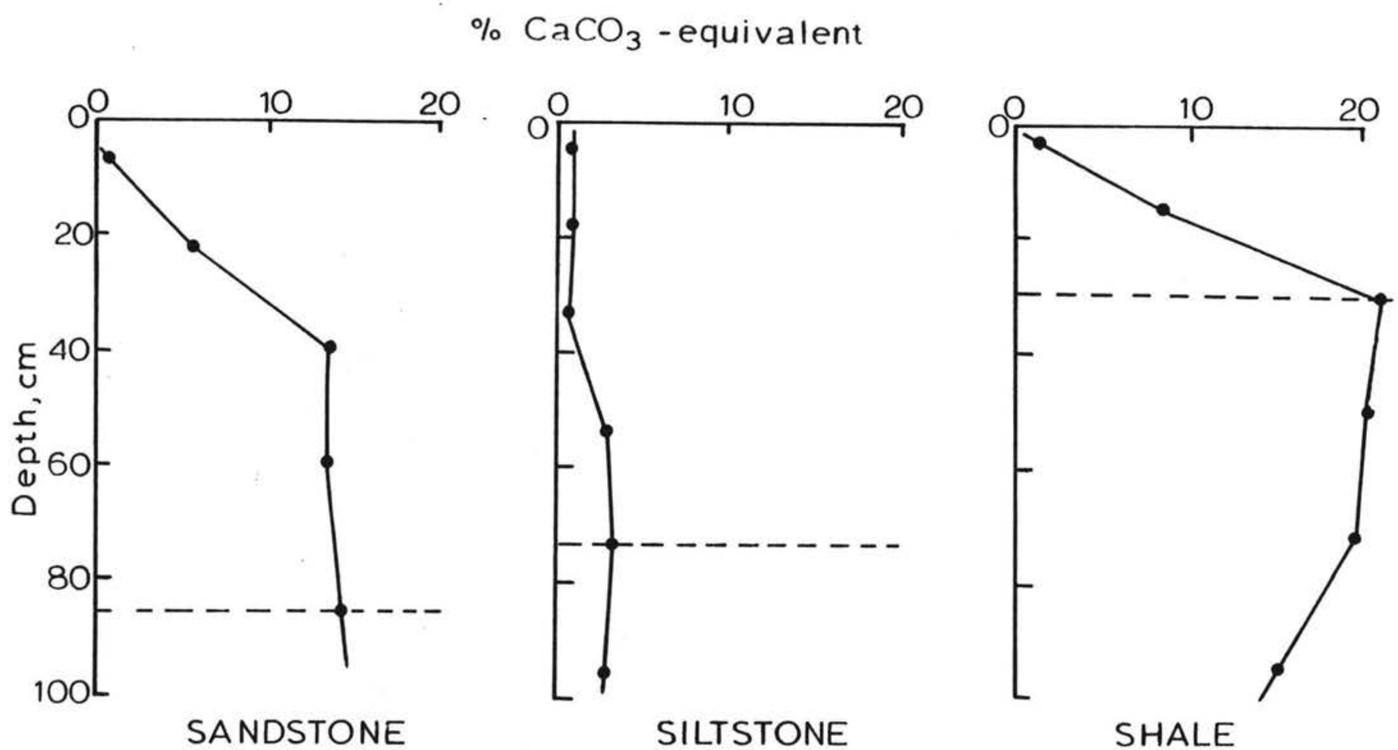

Figure 3.3 - Parent material controls on calcium carbonate distribution, as indicated by the % $CaCO_3$-equivalent index, at the native-summit landscape position of the three catenas.

precipitation and permeability of the soil, the closer to the surface this layer will be.

The depth to the zone of maximum carbonate accumulation differs in the three contrasting soils, reflecting differences in leaching and permeability characteristics (Figure 3.3). This zone occurs at a depth of 25 to 30 cm in the fine-textured shale soil, 70 to 75 cm depth in the siltstone soil and 80 to 85 cm depth in the coarse-textured sandstone soil. The siltstone parent material is lowest in calcium carbonate, with the % $CaCO_3$ -equiv. being only 3 to 4% in the partially weathered C horizon in this soil. The shale parent material is much higher in calcium carbonates, with approximately 15% (by weight) $CaCO_3$ -equiv. in the C horizon material. It is not possible to accurately estimate the initial calcium carbonate content of the sandstone parent material because the increase in % $CaCO_3$ -equiv. does not level off with depth within the horizons sampled. However, it does appear that the sandstone parent material is inherently calcareous. The $CaCO_3$ -equiv. levels are generally greater than 10% in the C horizon of most soils occurring in the sandstone catena, except at the lower landscape positions where removal by higher leaching rates has occurred (Appendix 2). High organic matter contents and low quantities of carbonates are responsible for the slightly acidic nature of the surface horizons in all three soils.

Organic Carbon and Nitrogen

The content and vertical distribution of organic C for the three contrasting soils are shown in Figure 3.4. Higher levels of organic C occur near the surface of each soil where plant residue additions and root production are greatest and decrease rapidly with profile depth.

However, organic C distribution in the sandstone soil displays a more uniform decrease with depth. Roots generally extend to greater depths in sandy soils and this coupled with greater leaching of organic constituents may be responsible for the uniform decrease of organic carbon in the upper 20 cm of the sandstone soil.

Total quantity of organic C for the three pedons characterized at the native-summit landscape of each catena is shown in Table 3.1. Total organic C was calculated on a volume-weight basis by multiplying the percent organic C for each horizon by bulk density and horizon thickness, and summing the total quantity to a depth of one meter. Total organic C increases from 10.2 kg m^{-3} in the upper 1 m of the sandstone soil to 14.7 kg m^{-3} in shale soil. This amounts to a 31% difference between the two texturally extreme soils. The medium-textured siltstone soil has approximately 11% more organic C than the sandstone soil and 20% less than the shale soil. The difference between the mean quantity of organic C in the sandstone and siltstone soils was significant at $\alpha = 0.19$. The test for the significance of the difference between the mean organic C content in the siltstone vs. shale soils was significant at $\alpha = 0.08$, and the difference in the shale vs. sandstone soils was significant at $\alpha = 0.06$.

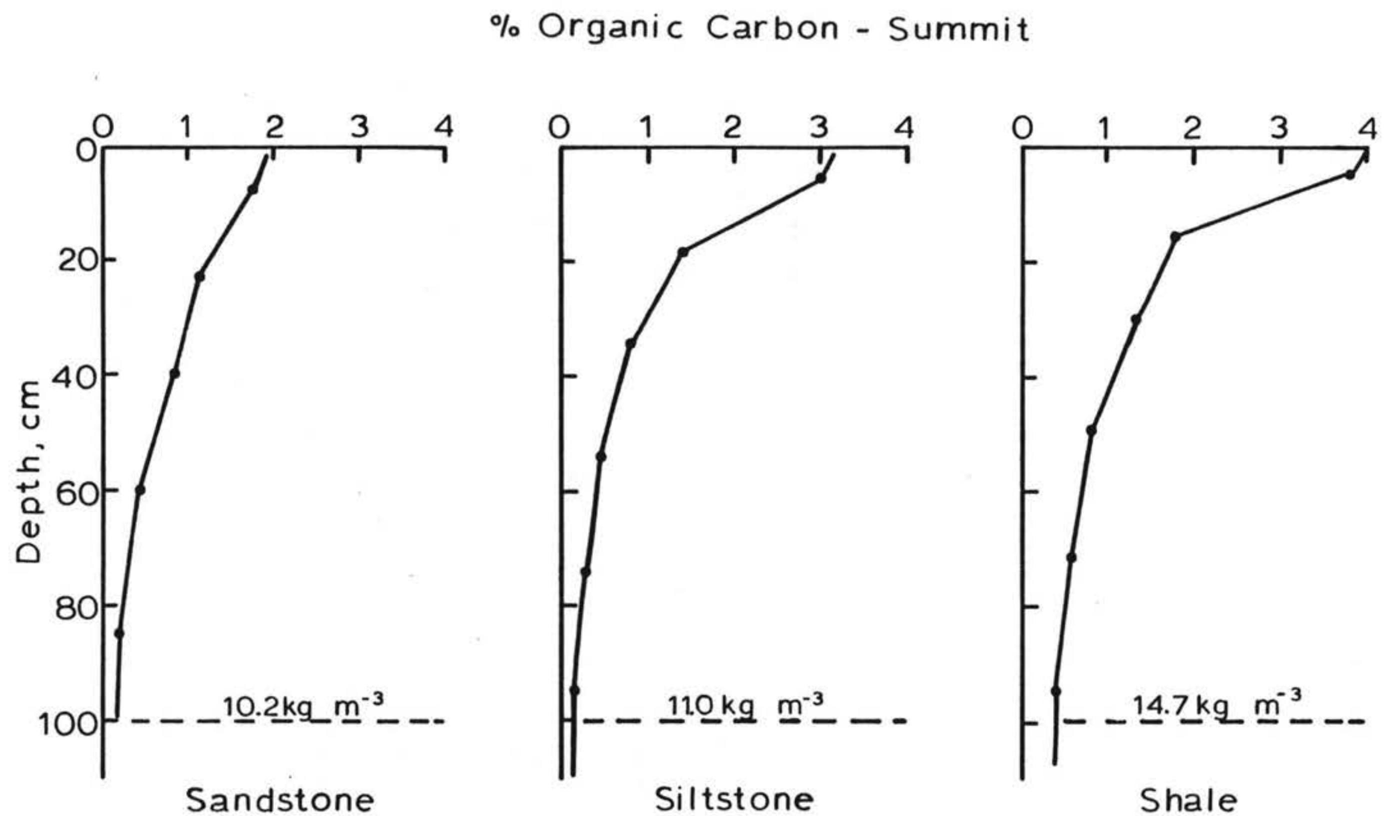

Figure 3.4 - Parent material controls on the amount and vertical distribution of organic carbon at the native-summit segment of the three catenas. The total quantity of organic carbon (vol.-wt. basis) to a depth of 1 m is indicated for the three soils.

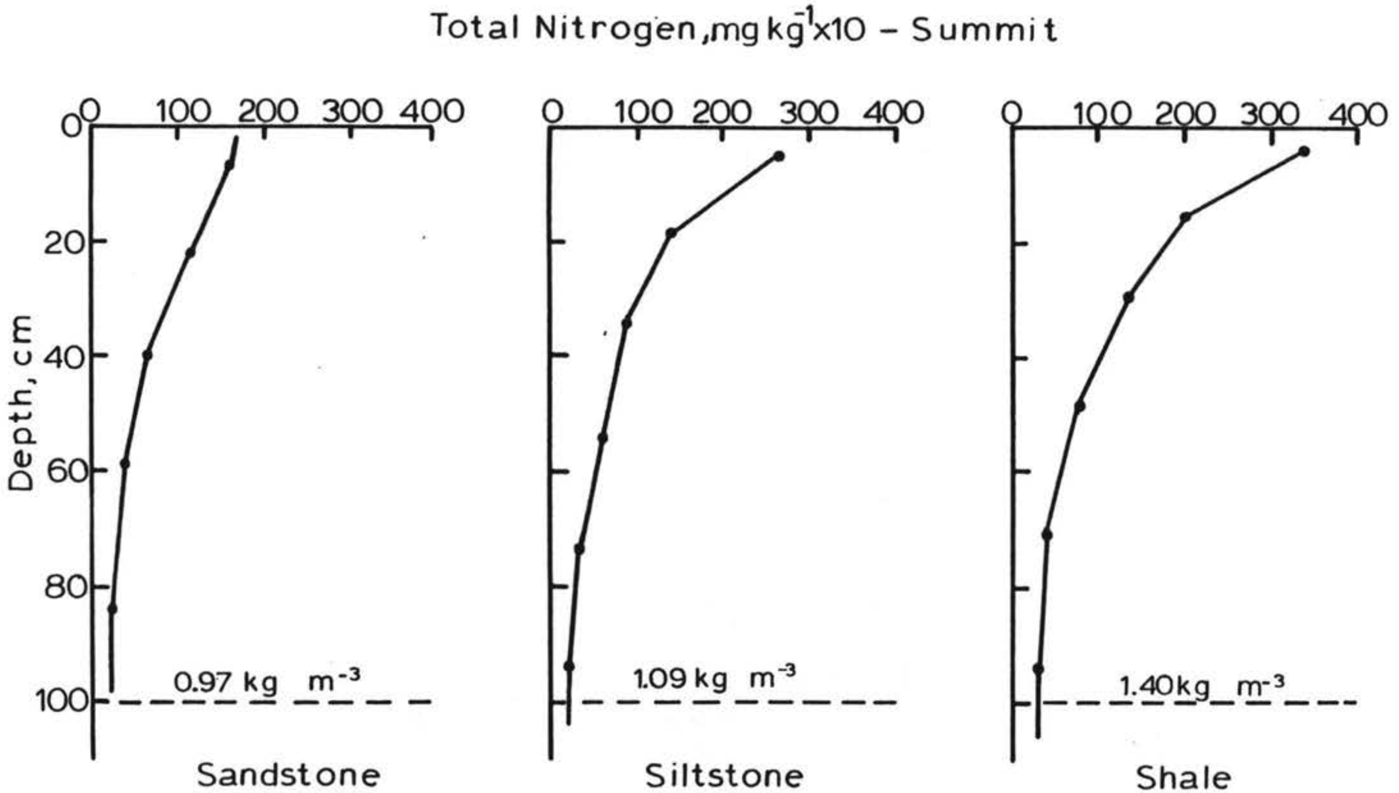

Figure 3.5 - Parent material controls on the amount and vertical distribution of total nitrogen at the native-summit segment of the three catenas. The total quantity of nitrogen (vol.-wt. basis) to a depth of 1 m is indicated for the three soils.

Table 3.1 - Parent material controls on organic carbon at the native-summit landscape segment of the three catenas.

	ORGANIC CARBON kg m-3		
	PARENT MATERIAL		
Pedon	Sandstone	Siltstone	Shale
1	11.129	11.159	13.825
2	9.977	11.130	13.407
3	9.409	11.149	16.727
avg.	10.172	11.146	14.653
SD.	.876	.015	1.810

The lower quantity of organic carbon in the sandy soil is not surprising. Oxidation of organic matter may be higher in this soil because of its lighter texture and better aeration characteristics. However, the differences in organic C between the siltstone and sandstone soils are not as striking as one would expect, based on plant available water-holding capacity. As previously mentioned in Chapter Two, productivity in the sandstone soils is somewhat higher than in the other two soils. Thus, higher productivity may compensate for greater mineralization losses in the sandstone soils, resulting in total quantities of organic C which are not much lower than those in the siltstone soils of higher water-holding capacity. Because the siltstone and shale soils do not differ appreciably in water-holding capacity (Figure 3.1), the higher organic C levels found in the shale soil may reflect physically protected, clay-associated humus. Craswell and Waring (1972) found that nitrogen mineralization increased several-fold when clayey soils were ground up and that this increase was greater when the clay was montmorillonite compared to kaolinite. They suggested that clays play an important role in protecting organic matter from decomposition and that finer textured soils tend to accumulate more organic matter and lose it less readily than coarse-textured soils. The higher levels of organic C in the lower depths of the shale soil may reflect highly humified, physically protected organic matter. Anderson et al. (1981), in a study of particle size fractions and their use in assessing the nature and distribution of C, N and S in soils, reported that 55 to 58% of the organic C was in the clay fraction, with the greatest absolute amounts in the coarse clay (0.2 - 2.0 μm) fraction. These authors concluded that much of this organic carbon was present as a component of strongly aromatic and recalcitrant organic matter.

The vertical distribution of total N in the three contrasting soils appears to parallel the distribution of organic C (Figures 3.4 and 3.5). This indicates that most of the total N in all three soils is a component of the organic matter fraction. Some small quantities of nitrate, nitrite and ammonium are usually present in equilibrium with the organic fraction, but generally constitute only small proportions of the total in surface soils (Schnitzer and Khan, 1978). Bremner (1967) has reported, however, that certain soils high in degraded illite and vermiculite can have significant amounts (>100 g Mg^{-1}) of fixed ammonium in subsurface horizons.

Although ammonium levels were not determined in this study, it appears that they are not significant in the mineral fraction of the three contrasting soils. The quantity of total N closely parallels the quantity of organic C, even at subsurface horizons in all three soils.

Total N in the three soils at the native-summit landscape of each catena is listed in Table 3.2. The means for the sandstone vs. siltstone soils were significantly different at $\alpha = 0.12$, and the difference between the means for the siltstone vs. shale soils was significant at $\alpha = 0.02$. Total N content in the sandstone vs. shale soils was significantly different at $\alpha = 0.01$.

Table 3.2 - Parent material controls on total nitrogen at the native-summit landscape segment of the three catenas.

		TOTAL NITROGEN kg m-3		
		PARENT MATERIAL		
Pedon		Sandstone	Siltstone	Shale
1		1.063	1.088	1.327
2		.931	1.037	1.356
3		.906	1.148	1.509
	avg.	.966	1.091	1.399
	SD.	.084	.056	.096

The levels of nitrate extracted from the soils are listed in Appendix 2. Nitrate is low in each of the three contrasting soils, ranging from about 10 g Mg^{-1} in the organic matter-enriched surface horizons to none in the partially weathered C horizons. Nitrate is lowest in the surface horizon and increases with profile depth in the shale soil. The restricting permeability of the partially weathered shale parent material may be responsible for this slight increase in nitrate at the lower depths in this soil.

Phosphorus

Phosphorus is an essential element for normal plant growth and thus plays an important role in nutrient cycling. In contrast to carbon, nitrogen and sulfur, it must be supplied almost entirely by the parent material. Walker and Syers (1976) reported that atmospheric inputs of phosphorus amount to less than 0.1 kg/ha per year over much of New Zealand. There has been considerable interest in the role that soil phosphorus plays in controlling the distribution and productivity of vegetation, and organic matter production in soils. Cole and Heil (1981) suggest that there are close linkages between organic carbon and nitrogen accumulation in soils and the phosphorus contents of the original parent materials.

Although phosphorus is considered to be essentially immobile in soils, considerable redistribution can occur during the long time-spans over which soil development takes place. Upon the initiation of pedogenic processes on unweathered parent material, essentially all of the phosphorus is in an inorganic form characteristic for a given parent material. As microbial activity is initiated and plants become established, inorganic phosphorus is converted to organic forms which will accumulate through time at the soil surface with increasing soil development. The major process responsible for the redistribution of phosphorus in soil profiles is plant uptake of labile inorganic phosphate forms from the root zone and the subsequent conversion of this phosphorus to organic forms at or near the surface through metabolic processes.

The vertical distribution of total P in soil profiles has been evaluated in numerous studies (Allaway and Rhoades, 1951; Runge and Riechen, 1966; Smeck and Runge, 1971a; Smeck and Runge, 1971b; and Smeck, 1972). Smeck (1972) stated that the relative extent of phosphorus redistribution within a soil profile is a function of the degree of soil development. In well-developed soils, the accumulation of organic P in organic matter-enriched surface horizons results in higher total P levels. Total P decreases to minimum quantities in lower A or upper B horizons, reflecting the zone of maximum plant removal, and then attains maximum quantities in lower B or upper C horizons. Total P will generally decrease to concentrations characteristic of the initial levels of the parent material below the solum. Smeck and Runge (1971b) reported two distinct zones of phosphorus accumulation in the B horizons of well-developed Illinois soils. These zones of accumulation were attributed to two distinct modes of phosphorus immobilization. In the upper portion of the B horizon, higher total P concentrations reflected chemical precipitation by iron and aluminum. It was concluded that the lower zone of phosphorus accumulation was due to precipitation by calcium because it occurred just above the carbonate contact. These accumulation zones, if present in our soils, will probably not be as pronounced because of weaker pedogenic development.

The total P levels in the three contrasting soils are plotted in Figure 3.6. The distribution of total P in the soils reflect both the inherent levels in each parent material and the control of the parent material on soil processes which have modified the initial phosphorus distribution. Concentrations of total P are highest in the shale soil,

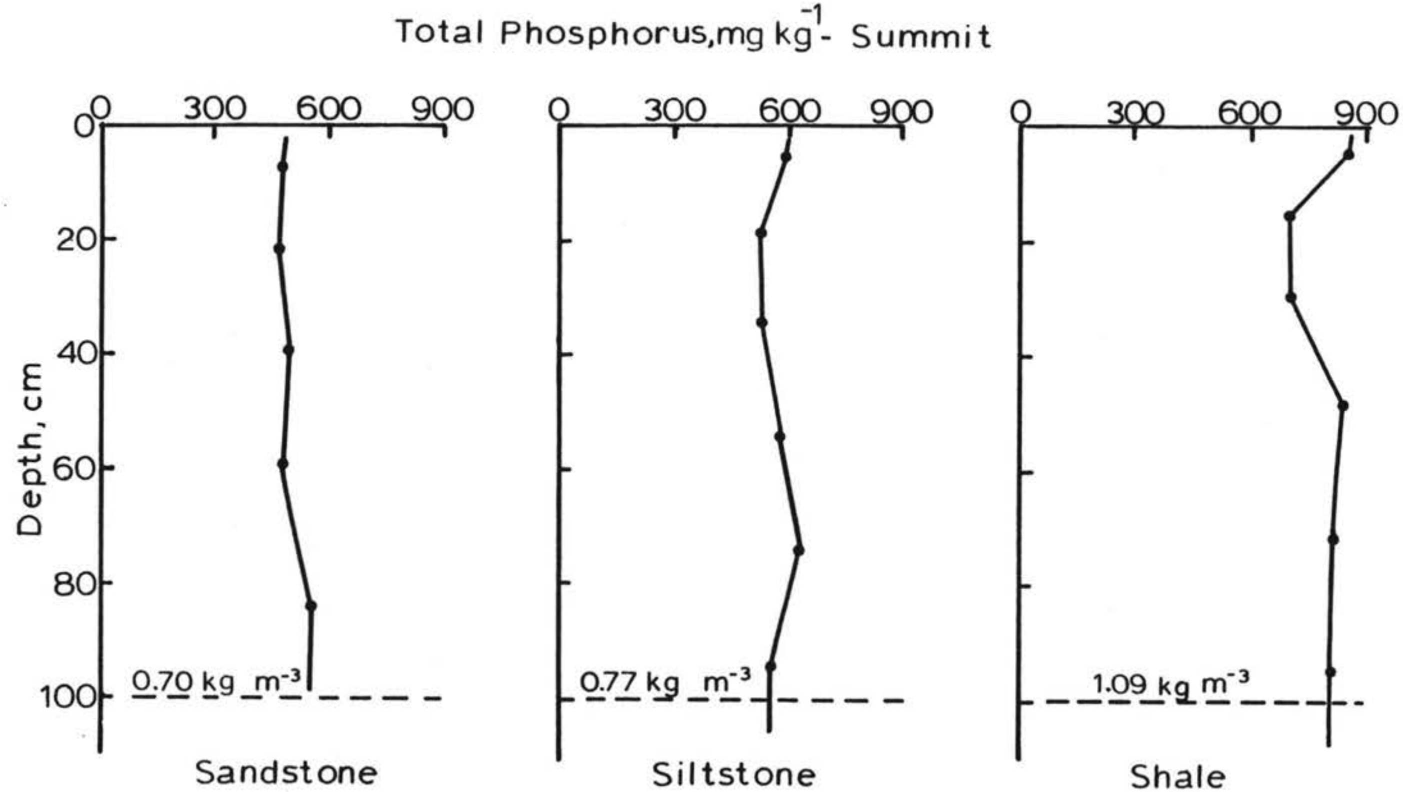

Figure 3.6 - Parent material controls on the amount and vertical distribution of total phosphorus at the native-summit segment of the three catenas. The total quantity of phosphorus (vol.-wt. basis) to a depth of 1 m is indicated for the three soils.

intermediate in the siltstone soil and lowest in the sandstone soil. Quantities of total P (volume-weight basis to 100-cm depth) in the three contrasting soils are listed in Table 3.3. The amounts of total P in the texturally extreme sandstone and shale soils were found to be significantly different at $\alpha = 0.03$. The difference in the total P contents between the siltstone and shale soils was significant at $\alpha = 0.02$, while the difference between the siltstone and sandstone soils was found to be significant at $\alpha = 0.21$.

Table 3.3 - Parent material controls on total phosphorus at the native-summit landscape segment of the three catenas.

		TOTAL PHOSPHORUS kg m-3		
			PARENT MATERIAL	
Pedon		Sandstone	Siltstone	Shale
1		.708	.840	1.057
2		.668	.735	1.199
3		.725	.737	.984
	avg.	.700	.771	1.089
	SD.	.029	.060	.109

As previously mentioned in Chapter Two, the environment of deposition of the shale deposits has been interpreted as shallow marine (Bluemle, 1975). It is likely that these sediments would have been very high in organic constituents during the time of deposition because of the swamp-like vegetation which would have prevailed in this environment. These organic constituents would have contributed to the total P pools of the sediments. Indeed, thin lenses of lignite were intermittently present in the partially weathered parent material (C horizons) at the shale site. The high proportion of clay-sized particles in the shale soils (Appendix 2) is almost certainly responsible for the high total P content. Several studies have shown that total P increases with a decrease in particle size (Williams and Saunders, 1956; Scheffer, et al., 1960; Hanley, et al., 1965; and Syers, et al., 1968; Syers, et al. (1968), in a study involving the fractionation of phosphorus in particle-size separates of two alluvial soils, found that total and organic P were concentrated in the clay separates of both soils. In spite of the dominance of fine sand in these two alluvial soils, silt and clay contributed the greatest proportion of total and organic P in both profiles.

Lower levels of total P in the sandstone and siltstone soils reflect the lower proportion of clay separates and additionally, the fluvial nature of the environment of deposition of the parent material. The somewhat higher total P levels in the siltstone parent material may be due to greater organic P contributions during the time of deposition in addition to the higher proportion of silt and clay separates. A few thin lenses of lignite were also observed in certain landscape segments at this site.

The vertical distribution of total P in all three soils (Fig. 3.6) is similar to that reported in studies by Smeck (1972) and Smeck and Runge (1971b). However, the degree of expression of the characteristic total P pattern appears to vary with soil type. The total phosphorus concentrations are highest in the lower portions (BCk and C horizons) of all three profiles. The zone with the lowest concentrations appears to correspond well with the zone of maximum root activity, reflecting removal by plant uptake. This depletion zone is most strongly expressed in the shale soil, where the root distribution is concentrated closer to the surface, and becomes progressively more evenly distributed with depth and thus weakly expressed in the coarser siltstone and sandstone soils, respectively. The depth to the bottom of this zone of phosphorus depletion could be considered the effective zone of phosphorus uptake within the soil profiles. The zone of highest total P concentration corresponds well with the zone of maximum $CaCO_3$ accumulation (Figure 3.3) and thus, as suggested by Smeck and Runge (1971b), this accumulation must be due to precipitation by calcium. The zone of accumulation which Smeck and Runge (1971b) recognized in the upper portion of the B horizons in their study is not evident in our soils. It appears that chemical precipitation by iron is not a major factor affecting phosphorus in our semiarid soils because of lower effective precipitation and higher base saturation.

The quantity and vertical distribution of organic P in the three contrasting soils are shown in Figure 3.7. Amounts of organic P in each soil are listed in Table 3.4.

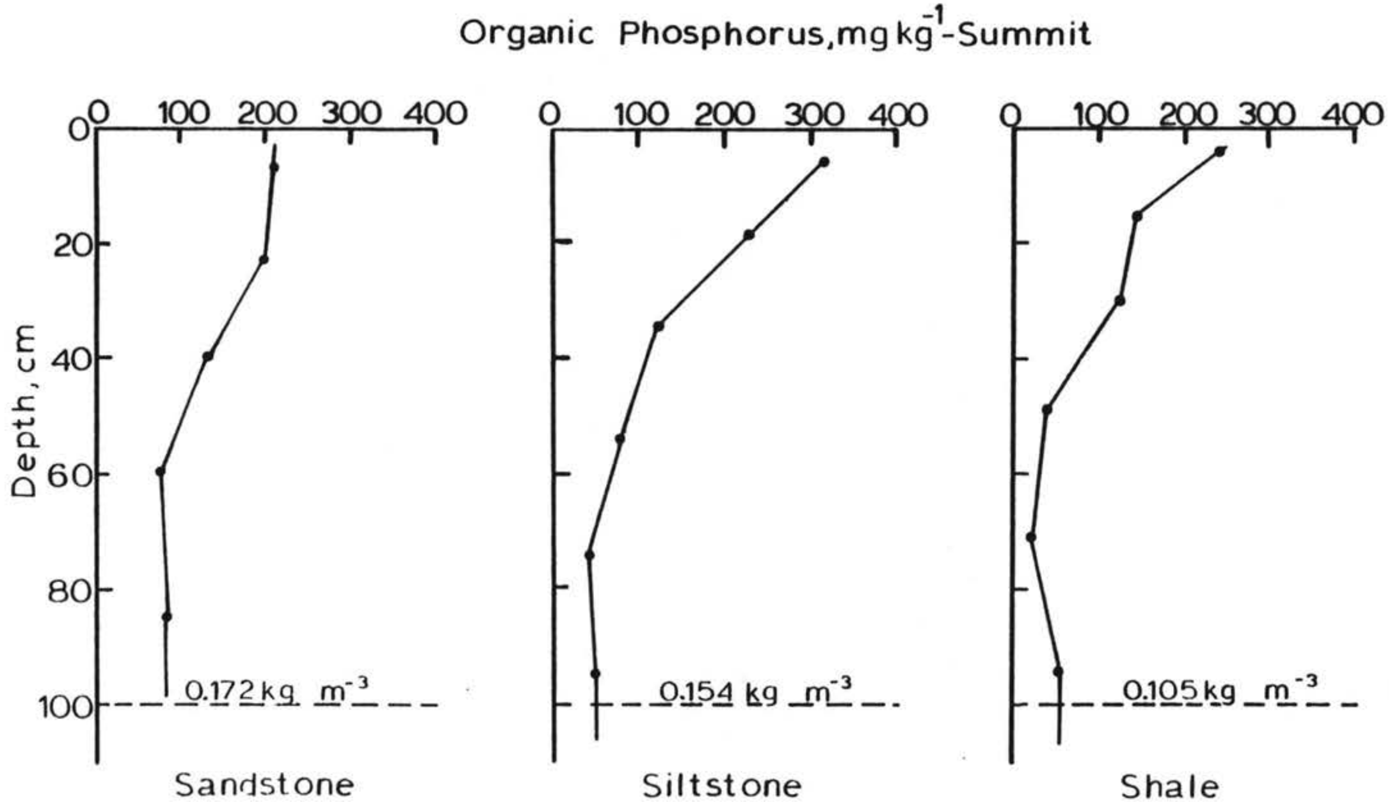

Figure 3.7 - Parent material controls on the amount and vertical distribution of organic phosphorus at the native-summit segment of the three catenas. The total quantity of organic phosphorus (vol.-wt. basis) to a depth of 1 m is indicated for the three soils.

Table 3.4 - Parent material controls on organic phosphorus at the native-summit segment of the three catenas.

		ORGANIC PHOSPHORUS kg m-3		
		PARENT MATERIAL		
Pedon		Sandstone	Siltstone	Shale
1		.195	.136	.071
2		.161	.192	.123
3		.160	.133	.122
	avg.	.172	.154	.105
	SD.	.020	.033	.030

Surprisingly, the coarse-textured sandstone soil has the highest quantity of organic phosphorus and the fine-textured shale soil, which is highest in organic carbon, contains the least. The total quantity of organic P in the sandstone and siltstone soils is not appreciably different. The test for difference between the means of the three pedons sampled in these two parent materials was significant only at $\alpha = 0.47$. The difference between the quantity of organic P in the siltstone and shale soils was found to be significant at $\alpha = 0.15$, while the difference between the texturally extreme sandstone and shale soils was significant at $\alpha = 0.05$. Levels of organic P in the surface horizons of the sandstone soil are much lower than either the siltstone and shale soils, but higher concentrations of organic P are maintained with depth in the sandstone soil. High organic P in the subsoil of the sandstone soil may be due to greater leaching of slightly decomposed organic constituents enriched in phosphorus and/or may reflect greater root incorporation with depth in this soil.

The ratio of organic to total P in the three soils is plotted in Figure 3.8. The medium-textured siltstone soil has the highest organic P/total P ratio in the organic matter-enriched horizons, followed by the sandstone and shale soils, respectively. Below the organic matter-enriched horizons the pattern is different, with the sandstone soil having the highest organic P/total P ratio (0.25). The finer textured siltstone and shale soils have much lower organic P/total P ratios in the subsoil, 0.20 and 0.10, respectively. These data suggest that organic matter may play a major role in the phosphorus dynamics in the sandstone and siltstone soils. It is well documented that organic phosphorus is an important source of labile P under certain conditions (Greb and Olsen, 1967; Dormaar, 1972; and Saunders and Metson, 1971). It appears then, that under the relatively stable "quasi-steady state" conditions of mature grassland soils, soils weathered in coarse-textured sandstone low in inorganic P may sustain high plant productivity by maintaining high levels of organic phosphorus.

The levels of inorganic and acid-soluble phosphorus in the three contrasting soils are shown in Figure 3.9. Total inorganic P and acid-soluble P in soils across the three parent materials on native-summit landscape positions are shown in Tables 3.5-3.6. Total inorganic P and acid-soluble P are highest in the shale soil, followed by the siltstone and sandstone soils, respectively. Differences in total inorganic P and acid-soluble P in the sandstone and siltstone soils were significant at $\alpha = 0.25$ and $\alpha = 0.05$, respectively. Differences between the siltstone and shale soils were significant at $\alpha = 0.02$ and $\alpha = 0.06$, respectively. Differences in the mean quantities of total

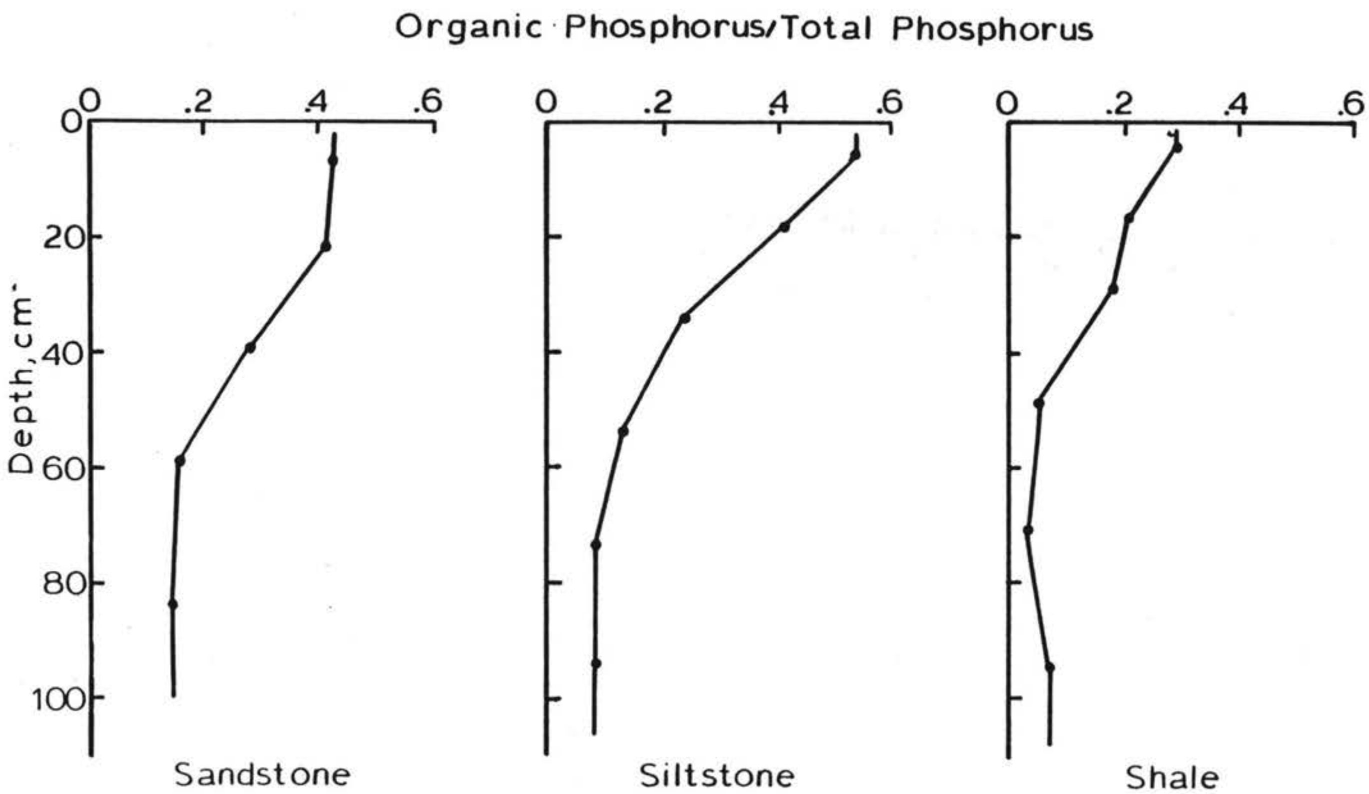

Figure 3.8 - Ratio of organic to total phosphorus with soil profile depth at the native-summit segment in the three catenas.

inorganic P and acid-soluble P between the texturally extreme sandstone and shale soils were both significant at $\alpha = 0.02$.

Table 3.5 - Parent material controls on total inorganic phosphorus at the native-summit segment of the three catenas.

		INORGANIC PHOSPHORUS kg m-3		
		PARENT MATERIAL		
Pedon		Sandstone	Siltstone	Shale
1		.513	.704	.986
2		.506	.534	1.076
3		.565	.604	.868
	avg.	.528	.614	.977
	SD.	.032	.086	.104

Table 3.6 - Parent material controls on acid-soluble phosphorus at the native-summit segment of the three catenas.

		ACID-SOLUBLE PHOSPHORUS kg m^{-3}		
		PARENT MATERIAL		
Pedon		Sandstone	Siltstone	Shale
1		.374	.602	.722
2		.361	.471	.754
3		.321	.542	.620
	avg.	.352	.538	.699
	SD.	.028	.065	.070

The proportion of inorganic P that is soluble in acid differs in the three contrasting soils (Fig. 3.9). In the medium-textured siltstone soil, 88% of the total quantity of inorganic P (kg m-3) is acid-soluble. In the sandstone and shale soils, acid-soluble phosphorus amounts to 67% and 72% of the total, respectively.

Acid-soluble P comprises 96 to 100% of the total inorganic P in the partially weathered C horizons of the siltstone soil. Changes in the levels of this acid-soluble P appear to parallel changes in total inorganic P in the solum (A & B horizons). In contrast, vertical variations in acid-soluble P are not as closely related to changes in total inorganic P in the sandstone and shale soils, particularly in the slightly acidic organic matter-enriched, surface horizons. Total inorganic P vs. acid-soluble P was plotted for the contrasting soils at the native-summit landscape segment (Figure 3.10). Regression analysis was utilized to evaluate the strength of the relationship between these two variables in the three soils. The regression model for the relationship between total inorganic P and acid-soluble P in the siltstone soil is as follows:

$$Y = 166.0 + 0.724X; \quad R^2 = 0.90 \qquad (3.1)$$

where Y is the concentration (g Mg-1) of total inorganic P and X is the concentration of acid-soluble P (g Mg-1). The model shows a strong linear relationship between acid-soluble P and total inorganic P in this soil. In contrast, the regression analysis demonstrated a much weaker relationship between acid-soluble P and total inorganic P in the sandstone and shale soils.

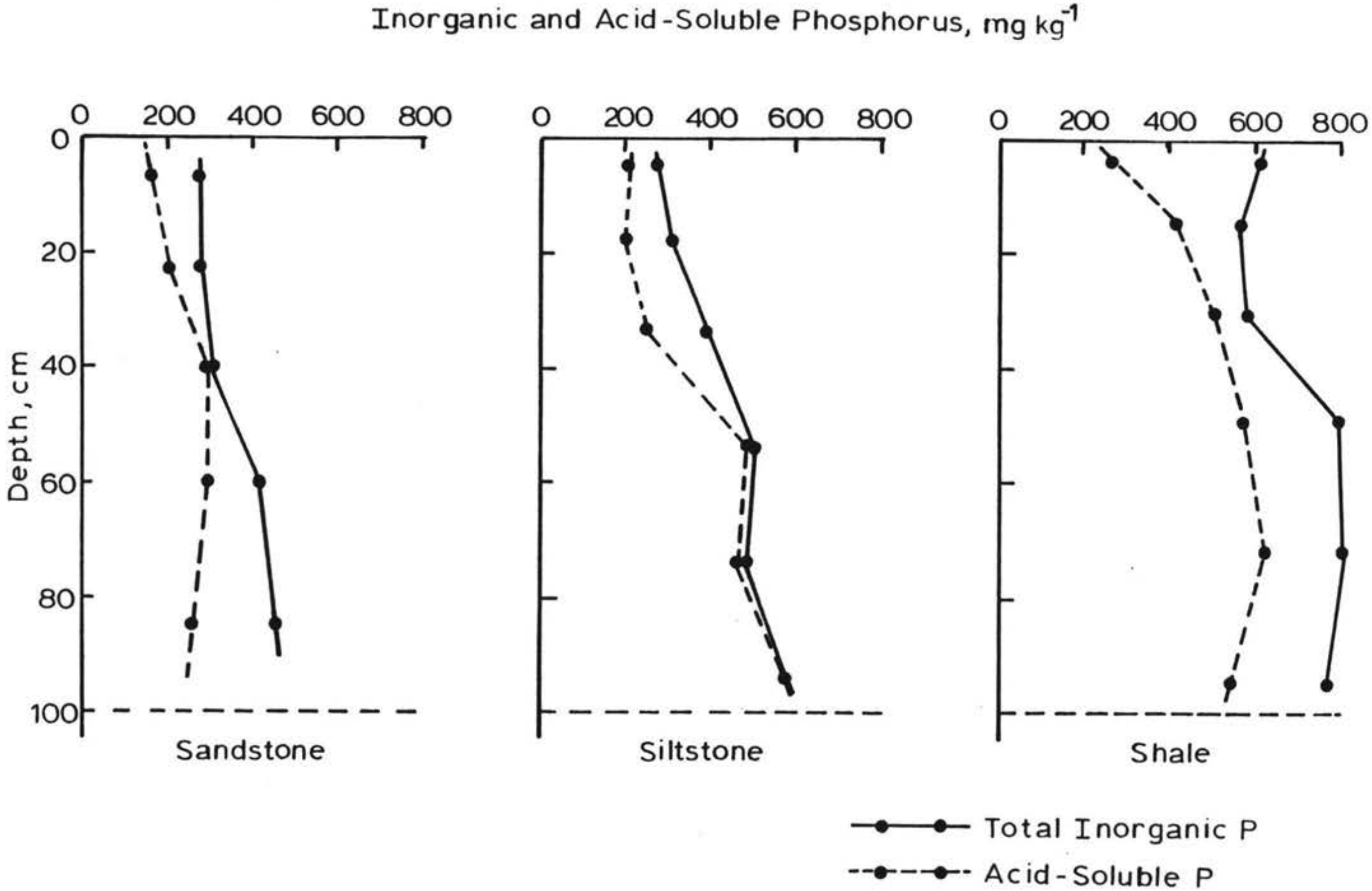

Figure 3.9 - Parent material controls on the amount and vertical distribution of total inorganic and acid-soluble phosphorus at the native-summit segment in the three catenas.

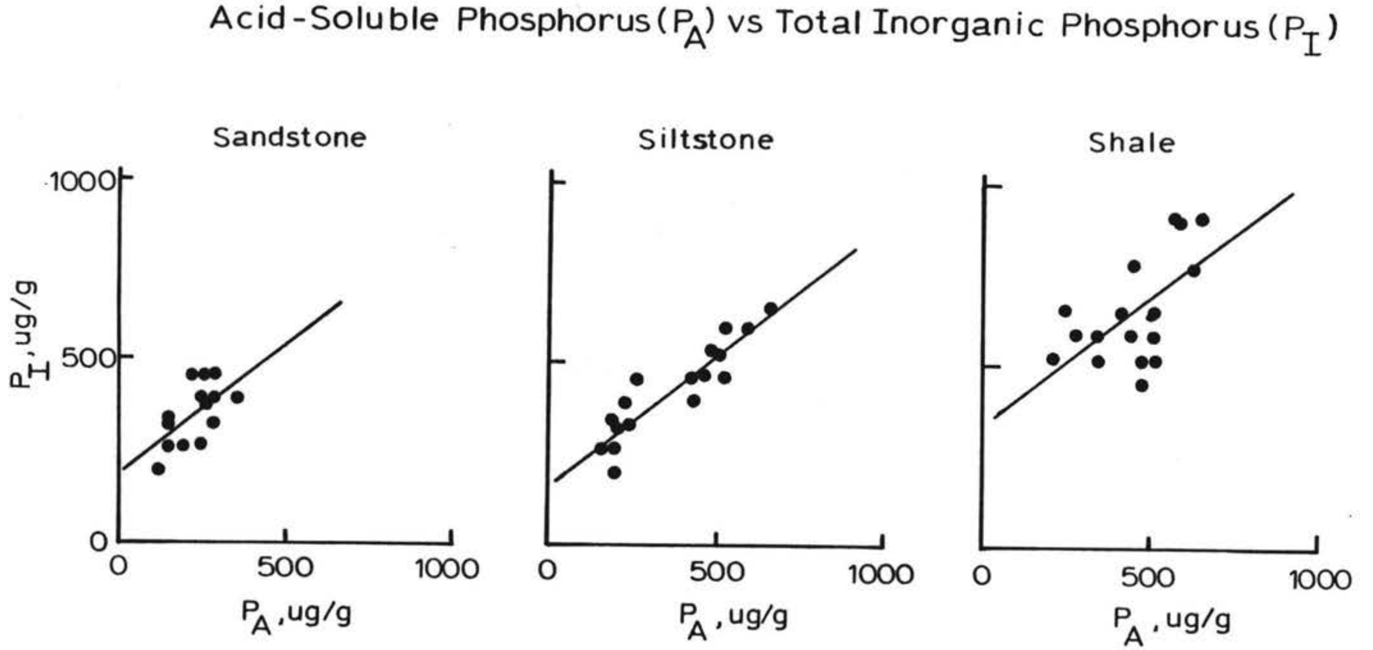

Figure 3.10 - Relationship between acid-soluble phosphorus and total inorganic phosphorus in the three contrasting soils.

The regression models for the sandstone and shale soils are as follows:

SANDSTONE:

$$Y = 186.0 + 0.718X; \quad R^2 = 0.32 \qquad (3.2)$$

SHALE:

$$Y = 340.0 + 0.728X; \quad R^2 = 0.38 \qquad (3.3)$$

The portion of total P that cannot be extracted by acid is generally referred to as one of the following: "residual P", "nonextractable P", "insoluble P", "inert P", or "lattice P" (Kurtz, 1953; Syers, et al., 1967). Studies involving a variety of New Zealand soils and parent materials have shown that this fraction of total P, which will be termed "residual P" in this study, can have both a primary and a secondary origin (Syers, et al., 1969). Apatite included within other minerals and phosphorus distributed throughout mineral lattices generally constitute the primary sources. Nonextractable secondary phosphorus is generally associated with hydrated sesquioxides which accumulate during soil development. The total quantity of residual P (kg m^{-3}) in the three contrasting soils is listed in Table 3.7. The shale soil has the greatest quantity of residual P, followed by the sandstone and siltstone soils, respectively. The difference in the mean quantity of residual P between the sandstone and siltstone soils was significant at $\alpha = 0.15$, while the difference between the sandstone and shale soils was significant at $\alpha = 0.09$. The large difference between the quantity of residual P in the shale and siltstone soils was significant at $\alpha = 0.004$.

Table 3.7 - Parent material controls on residual phosphorus at the native-summit segment of the three catenas.

		RESIDUAL PHOSPHORUS kg m-3		
		PARENT MATERIAL		
Pedon		Sandstone	Siltstone	Shale
1		.120	.102	.264
2		.146	.072	.321
3		.245	.062	.248
	avg.	.170	.079	.278
	SD.	.066	.021	.039

The vertical distribution of residual P in the soils studied is shown in Figure 3.11. In the sandstone soil, residual P levels are highest in the partially weathered C horizons and lowest in the B horizons. In the shale soil, residual P is highest in the surface horizon, drops off to minimum levels in the B horizons, and then increases to higher concentrations in the subsoil. The high levels in the partially weathered, slightly alkaline C material of the sandstone soil are likely due to primary apatite inclusions. Reed (1957) reported apatite inclusions within quartz grains in New Zealand graywakes. Syers et al. (1969) reported significant amounts of included apatite in beach sands in their studies. The high levels of residual P in lower horizons of our shale soil may also reflect primary apatite inclusions, or possibly highly occluded Fe and Al-phosphates which may have formed under conditions of higher acidity. A large portion of the residual P in the organic matter-enriched surface horizons may be

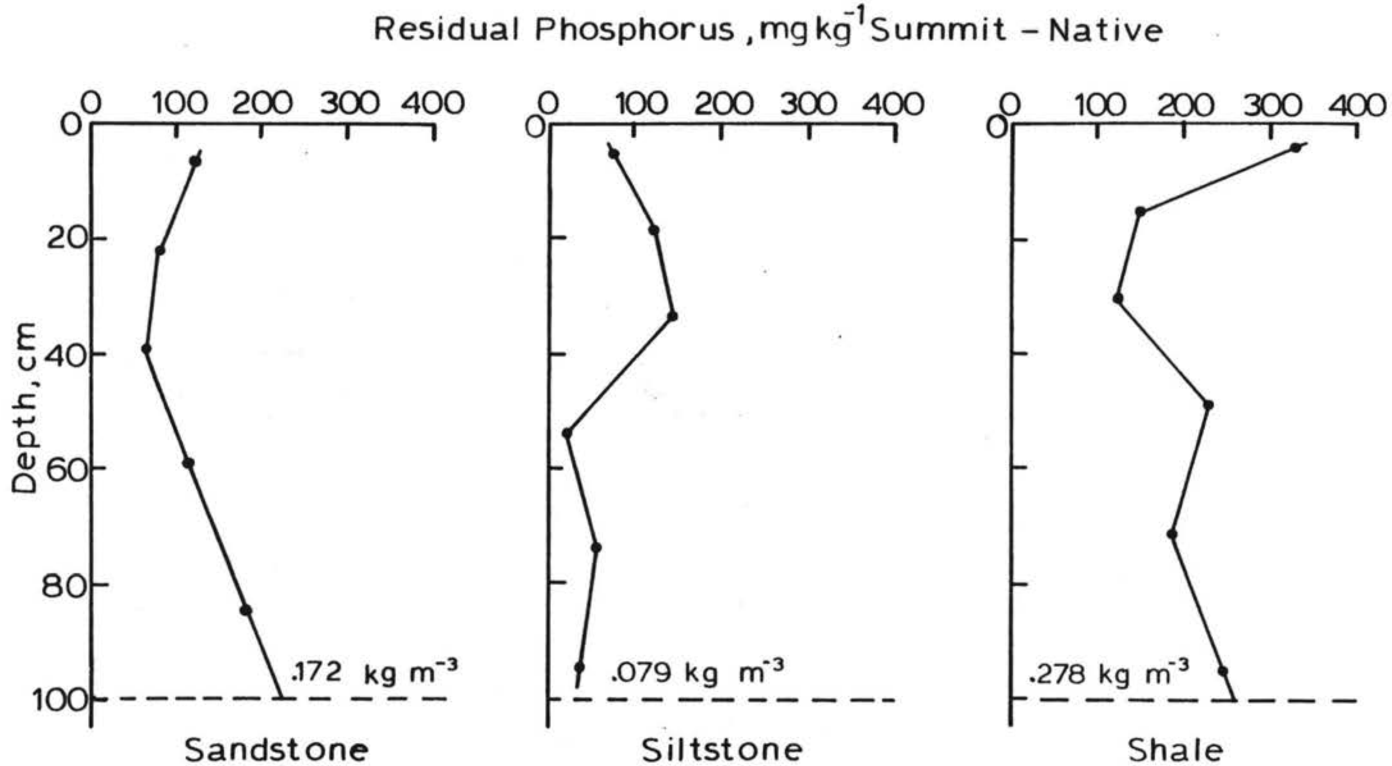

Figure 3.11 - Parent material controls on the amount and vertical distribution of residual phosphorus at the native-summit segment of the three catenas. The total quantity of residual phosphorus (vol.-wt. basis) to a depth of 1 m is indicated for the three soils.

acid-insoluble Fe and Al-phosphates in all three soils. These compounds accumulate in soils as weathering proceeds and are thermodynamically stable at slightly acidic pH range between 5 and 6.5 (Lindsay and Moreno, 1960). Westin and Buntley (1966) reported significant amounts of Fe and Al-phosphates in surface horizons of Ustolls and Udolls in South Dakota. They showed that these fractions comprise a larger proportion of the total inorganic P in the Udolls and decreased significantly with depth in both soils.

The vertical distribution of residual P in the siltstone soil differs from the other two soils. The highest concentrations occur in the lower A and upper B horizons and drop off to very low levels in the partially weathered C horizons. The pH of the lower A and upper B horizons ranges from 5.9 to 6.3, and thus Fe and Al phosphate compounds could account for a large portion of this residual P.

Summary -- Parent Material - Soil Process Relationships

The native-summit landscape component of each catena was selected to contrast the soils weathered in the three parent materials. This portion of the landscape is the most stable in terms of surficial runoff and erosional processes and is least affected by activity at other landscape segments within a catena. The amounts and vertical distribution and the nature of organic carbon, nitrogen, and phosphorus (total, organic, and inorganic) have been shown to vary in the three contrasting soils. Levels of these organic constituents are strongly influenced by the water-holding capacity and permeability characteristics of the soils. These properties are, in turn, determined by the textural characteristics imparted to the soils by the contrasting parent materials. As expected, the coarse-textured sandstone soil, with the lowest total and plant available water-holding capacity, has the lowest quantity of organic C and N. However, this soil has the largest quantity of organic P. A fairly uniform decrease in organic constituents with profile depth occurs in the sandstone soil, reflecting the leaching of organic matter to greater depths and/or greater proliferation of the root system with depth. High levels of organic P at these lower depths account for the soil having the highest organic P content of all the soils studied.

The high levels of organic C in the shale soil may reflect highly humified, physically protected organic matter, in addition to the more active fractions. Clays can play an important role in protecting organic matter from decomposition. Much of the total organic C in this soil may be present as a component of strongly aromatic and recalcitrant organic matter. Thus, cultivation-induced mineralization losses might be expected to be lower in the shale soil than in the sandstone and siltstone soils.

Parent material controls on soil chemical and physical processes, such as the translocation of secondary calcium carbonates, also vary in the three contrasting soils. In the medium-textured siltstone soil, which was shown to have intermediate levels of organic C, N, and P, the depth to the maximum zone of secondary calcium carbonate accumulation is intermediate to that observed in texturally extreme sandstone and shale soils. The textural characteristics imparted to the soils by the three contrasting parent materials, not only control the quantities of organic constituents produced and retained in the soil, but also the degree of translocation of certain mineral constiuents within the soil.

Inorganic phosphorus levels in the three soils reflect the proportion of silt and clay-sized separates and the environment of deposition associated with each of the parent materials. The shale soil, which had the greatest quantity of inorganic P, also had the highest proportion of clay-sized separates. Additionally, the shale parent material was deposited an organic-rich, shallow marine environment. In contrast, the sandstone and siltstone parent materials were deposited in fluvial environments and are much lower in clay-sized separates and total inorganic P. The chemical and physical nature of the inorganic phosphorus varied in the three contrasting soils. Acid-soluble calcium phosphates comprised over 88% of the total quantity of inorganic P in the siltstone soil. Nearly 100% of the total concentration of inorganic P in C horizon of this soil is acid-soluble (Figure 3.9). In the sandstone and shale soils, 24% and 26% of the total P, respectively, was residual in nature (acid-insoluble). Much of the residual P in these two soils probably consists of primary apatite inclusions, particularly in the partially weathered C horizons (Figure 3.11). The presence of included apatite in quartz grains in the sandstone soil may be of particular significance and may exert a considerable influence on the availability of phosphorus. This mineral is quite resistant to weathering under the environment in which the soils are forming. Approximately 40% of the total phosphorus in the surface horizon of the shale soil was residual in nature. A large portion of this residual P may result from the accumulation of secondary Fe and Al phosphates or physically protected, acid-insoluble phosphates. Again, the high levels of residual P in this soil may exert a considerable influence on the availability of phosphorus.

TOPOGRAPHIC - PARENT MATERIAL INTERACTIONS ALONG THE CATENARY SEQUENCES

Soil properties follow systematic patterns of distribution on the landscape. Hillslopes comprise an appreciable portion of the total land surface in the northern Great Plains, and thus, it is important to understand the type and extent of geomorphic and pedological processes occurring on various landscape components and their influence on soil development. Topographic variation along a catenary sequence can have a significant influence on soil processes which promote pedogenesis.

Background Information

Milne (1935a and 1935b) was one of the first pedologists to investigate the interactions among landscapes, soils and erosional-depositional processes. His approach to classifying soils along a catenary sequence as a continuum of three-dimensional, interlinked entities has gained universal acceptance. More recently, numerous investigators have established many important relationships that exist between the various hillslope components and soil characteristics (Aandahl, 1948; Adams, et al., 1975; Dan, et al., 1968; Kleiss, 1970; Malo et al., 1974; and Ruhe and Walker, 1968). Ruhe and Walker (1968) studied morphological, physical and chemical properties of soils along catenary sequences in two Iowa counties and found that as slope gradient increased downslope across the shoulder to the backslope, solum thickness and depth to the zone of maximum accumulation of clay decreased exponentially. These changes were attributed to slope gradient controls on surface runon, runoff, infiltration and subsequent leaching of soil water. Adams et al. (1975), in a study involving a chrono-toposequence of soils weathered in granite in New Zealand, showed that the degree of soil profile development increased with decreasing slope gradients from valley sides to ridge tops. These changes were attributed to increasing landscape stability upon moving towards the ridge tops. Subsequently, more mature, strongly developed soils occurred at the level ridge top area. Malo et al. (1974) studied soil-landscape relationships in a closed drainage system on the glacial drift plain of North Dakota. They found that landscape position and soil properties were significantly related and that erosion and sedimentation exerted a strong influence on the soils and their properties as they occurred on the landscape. Maximum erosion occurred at the shoulder position and was reflected in coarser textured material. Finer textured material accumulated at the lower landscape positions where sedimentation processes predominated. They concluded that in this particular catenary sequence, textural variations observed in the soil profiles were due more to erosional and depositional processes than to pedological activity.

Buol et al. (1980) has stated that the interrelationships between landscape position and soil properties are most strongly expressed in humid regions where precipitation exceeds evapotranspiration. Under these conditions, either slow geologic redistribution of surface soil material or variation in the amount of water percolation produce changes in soil properties along a catena. In semiarid regions, the same topography-soil property relationships exist, but the degree of soil property differentiation within a toposequence is generally not as pronounced. Catenas in dry regions differ from those in humid regions because the amount of precipitation and soil moisture available for surface runoff and sublateral transfer is lower. However, some workers have shown that differences do occur. Nettleton, et al. (1968), in a study involving a toposequence of soils on tonalite grus in southern California Peninsular Range, showed that B horizon properties varied markedly along the catena in arid soils low in organic matter. Soils in lower landscape positions had strongly developed argillic horizons while those in the upper landscape positions had only weak cambic horizons.

Organic matter is generally greater at the footslope and toeslope landscape positions due to increases in effective precipitation and to sedimentation processes. Aandahl (1948) and Malo et al. (1974) have shown that the A horizon not only increases in thickness upon moving downslope, but increases in organic matter and nitrogen content. Aandahl showed that there were big differences in both the total nitrogen in the soil profiles and in the percent nitrogen of any given horizon at the various landscape segments. The nitrogen contents of all soils sampled near the ridge tops were low compared to those on the lower slopes. He concluded that slope segments at the lower portions of the landscape have an opportunity of absorbing runoff from areas above them. Furthermore, any organic debris which is carried in the runoff will tend to accumulate at these lower landscape segments. Aandahl also suggested that lower evaporation rates resulted in lower mineralization rates because there was more protection from winds at these lower landscape positions. Malo et al. (1974) found that the amount of organic carbon in the surface A horizon increased logarithmically from the shoulder to the toeslope position. They concluded that differences in organic carbon content could also be related to varying moisture relationships among the various landscape segments. Recently, it has been suggested that higher litter input resulting from greater production in lower landscape positions might cause a slowing of the rate of mineralization of that litter (Schimel, 1982). Differences in organic matter turnover rates contribute to the varying levels of carbon and nitrogen observed in soil profiles along a catena in a semiarid region.

Birkeland (1984) recently pointed out that differences in morphological, physical and chemical properties of soils along a catena result from a combination of microclimate, pedogenic and surficial geological processes. Assessing the contribution of each process on soil distribution is often a complicated matter.

Topographic Variation in Soil Moisture Dynamics Along the Catenas

Landscape segments at lower elevations within a toposequence will generally receive greater moisture than those at higher elevations because of surface runoff and subterranean water flow. Higher moisture contents and greater depth of penetration generally result in higher plant productivity and stronger pedogenic development at lower landscape segments in semiarid regions (Birkeland, 1984).

The vertical distribution of secondary calcium carbonates in soil profiles along a catena can provide a useful index of the long-term depth of moisture penetration in the soil at each particular landscape position. $CaCO_3$-equivalent indices for the soils along the catenas studied are listed in Appendix 2. The vertical distribution of calcium carbonate, as indicated by the $CaCO_3$-equivalent index has been plotted for soil profiles at selected landscape segments in each catena (Figures 4.1- 4.3). The depth to the maximum zone of secondary calcium carbonate accumulation increases in the sandstone and shale sites upon moving downslope along the catenas, indicating that moisture penetration is greater in the lower landscape segments. At the lower backslope (LBS) and footslope (FS) landscape segments of the sandstone site the carbonates have been leached to a depth of 60 to 80 cm while at the summit and shoulder segments high calcium carbonate levels occur much closer to the surface reflecting shallower depths of moisture penetration. The parent material controls on the leaching potential associated with the three contrasting parent materials are clearly illustrated by the greater depth to the zone of maximum secondary calcium carbonate accumulation in the sandstone vs. shale soils at comparable landscape segments. In the siltstone site, these relationships do not hold, primarily because of variation in the initial $CaCO_3$ content in the parent material. The $CaCO_3$ content is much higher in the sandier soil material at the lower landscape segments than at the summit and shoulder areas at this site. The vertical distribution of $CaCO_3$ along the siltstone toposequence does not correctly reflect changes in soil moisture dynamics due to stratification of medium and coarse-textured geologic materials which comprise the catena.

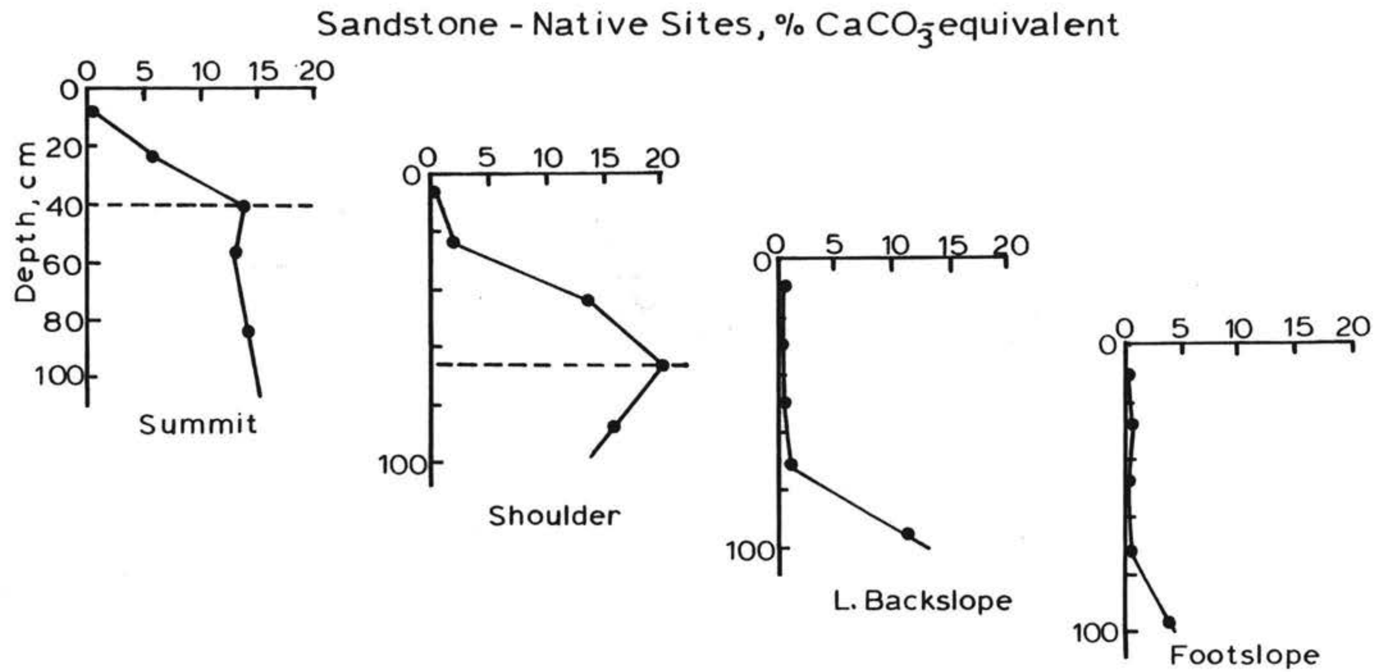

Figure 4.1 - Topographic controls on the vertical distribution of calcium carbonate, as indicated by the % $CaCO_3$-equivalent index, in the native portion of the sandstone catena.

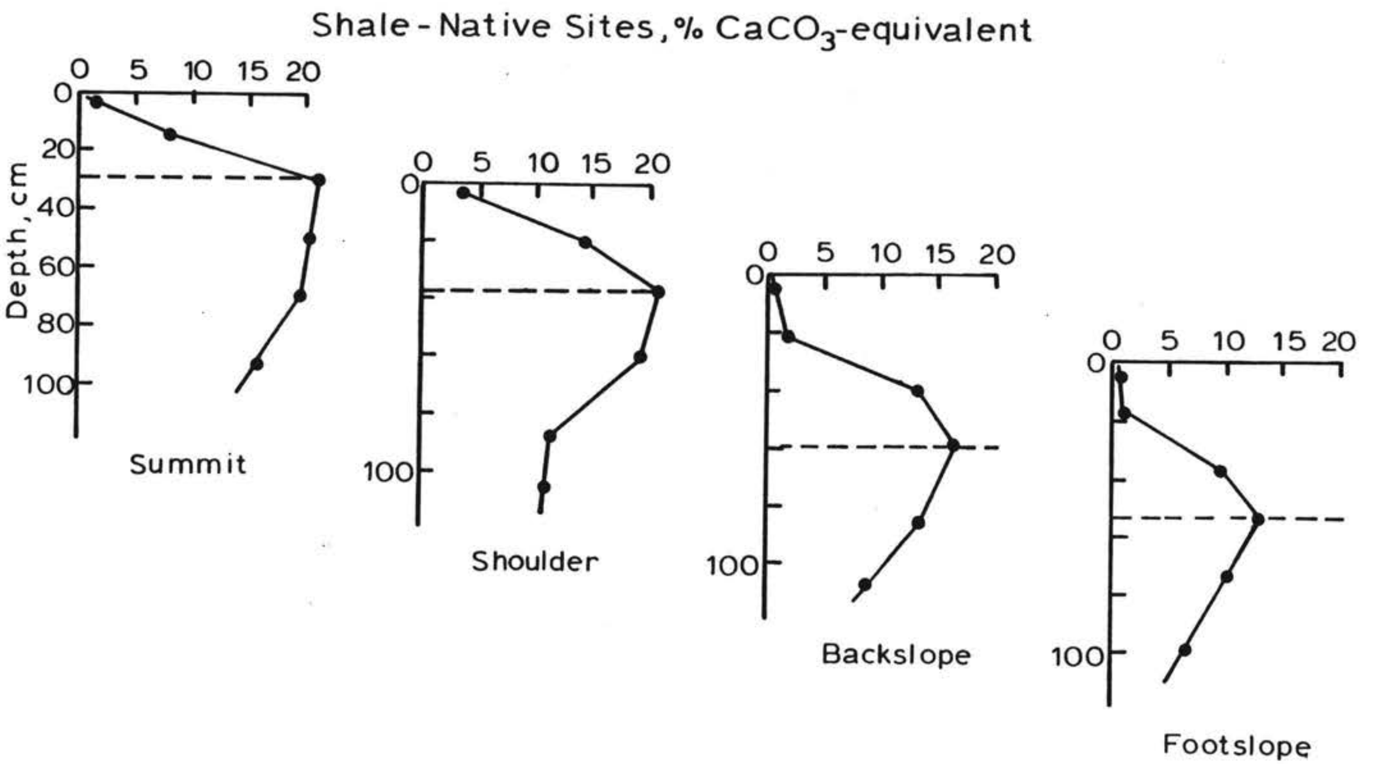

Figure 4.2 - Topographic controls on the vertical distribution of calcium carbonate, as indicated by the % $CaCO_3$-equivalent index, in the native portion of the shale catena.

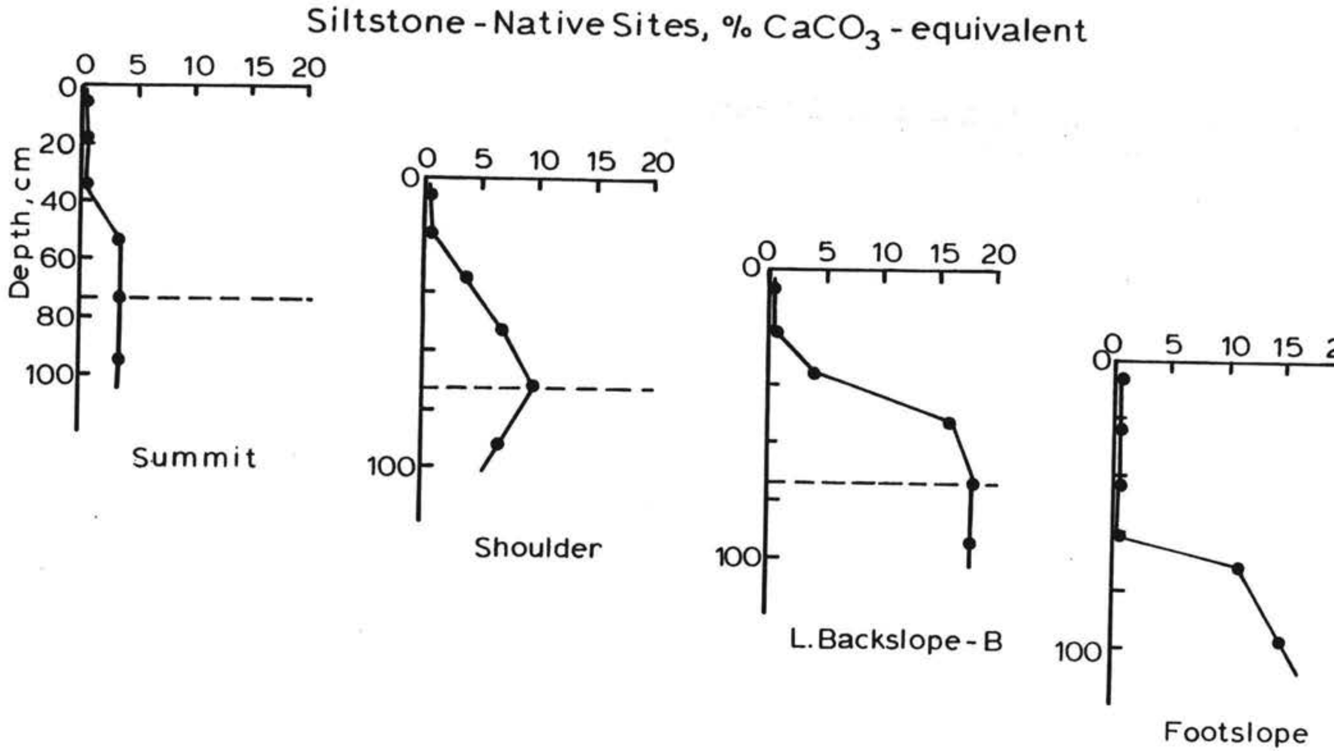

Figure 4.3 - Topographic controls on the vertical distribution of calcium carbonate, as indicated by the % $CaCO_3$-equivalent index, in the native portion of the siltstone catena.

Variation in Morphological Properties and Organic Matter Along the Catenas

Selected morphological features observed in the soils at each landscape segment on the three native catenas are listed in Tables 4.1-4.3. Solum and A horizon thickness all tend to increase upon moving downslope along the catenas. Solum thickness is appreciably less at the shoulder than at the two adjacent segments (summit and upper backslope) in the sandstone site. This probably reflects the slow erosional loss of surface material and/or less percolation of water through the soil profile due to greater surface runoff on the convex shoulder area. Similar characteristics are observed in the native siltstone site. In contrast, solum thickness is greater at the shoulder segment than at the summit in the shale site. The presence of more readily weatherable mudstone lense in the subsoil at this landscape segment may cause this anomaly (Figure 9).

Table 4.1 - Selected morphological data for soil pedons characterized at the native-sandstone catena (Kelly,1984).

Landscape Segment	Depth to $CaCO_3$	Solum Thickness	B horizon Thickness	A horizon Thickness
	----------	cm	----------	
Summit	23	53	40	14
Shoulder	34	43	27	16
Upper Backslope	75	54	36	18
Lower Backslope	100	74	53	21
Footslope	104	81	60	21
B Backslope	62	72	64	18
B Footslope	105	86	66	20

Table 4.2 - Selected morphological data for soil pedons characterized at the native-siltstone catena (Kelly, 1984).

Landscape Segment	Depth to $CaCO_3$	Solum Thickness	B horizon Thickness	A horizon Thickness
	cm			
B Shoulder	58	57	47	10
Summit	65	69	58	11
Shoulder	44	49	36	13
Upper Backslope	42	58	46	12
Lower Backslope (A)	47	63	50	13
Lower Backslope (B)	42	58	45	13
Footslope	67	69	53	16
Toeslope	70	85	55	30

Table 4.3 - Selected morphological data for soil pedons characterized at the native-shale catena (Kelly, 1984).

Landscape Segment	Depth to $CaCO_3$	Solum Thickness	B horizon Thickness	A horizon Thickness
	cm			
Summit	22	39	30	9
Shoulder	13	75	62	13
Backslope	32	88	73	15
Footslope	40	99	85	14

The quantity of organic carbon, total nitrogen, and organic phosphorus all generally increase upon moving downslope along the catenas in the three parent materials due to increases in moisture content. Amounts of organic carbon in the three pedons sampled for each landscape segment on the native catenas is listed in Table 4.4. Vertical distribution at selected landscape segments is plotted in Figures 4.4-4.6. The vertical distribution of organic carbon changes most noticeably at the lower landscape segments (lower backslopes and footslopes) of all three catenas. The higher quantities (kg m-3) in the soils at these landscape segments appear to be due to higher concentrations of organic carbon in subsurface horizons. The concentrations of organic carbon do not vary appreciably in the surface horizons of the siltstone site upon moving downslope, and actually decrease slightly in the shale site. At the lower landscape segments higher quantities of organic carbon are due primarily to greater accumulations of organic matter in subsurface horizons either through deeper root incorporation or accumulation of organic matter-enriched matter due to depositional processes. In contrast, the organic carbon concentration in the mollic epipedon does increase from about 1.7% to 2.0% upon moving from the summit to the footslope segments at the sandstone site. This trend probably reflects greater organic matter production and accumulation in surface horizons at the lower segments (see Tables - Appendix 2).

It appears that depositional processes resulting in the accumulation of organic-matter enriched sediments at lower elevations have been more active over geologic time in the finer textured shale

Table 4.4 - Parent material - topographic controls on organic carbon along the native segments of the three catenas. (quantities listed for each segment represent the average of three pedons)

SANDSTONE:

Landscape Segment	Org C kg m-3	SD.
Summit	10.17	.88
Shoulder	11.70	.56
Upper Backslope	11.61	.94
Lower Backslope	12.60	.69
Footslope	14.00	1.02
B Backslope	12.48	.81
B Footslope	15.41	1.64

SILTSTONE:

Landscape Segment	Org C kg m-3	SD.
Summit	11.15	.01
Shoulder	13.57	1.80
Upper Backslope	15.79	1.43
Lower Backslope(A)	18.98	.56
Lower Backslope(B)	15.23	1.45
Footslope	16.24	.90
Toeslope	17.66	.97
B Shoulder	14.23	1.31

SHALE:

Landscape Segment	Org C kg m-3	SD.
Summit	14.65	1.81
Shoulder	14.78	2.63
Backslope	16.12	1.40
Footslope	18.53	1.71

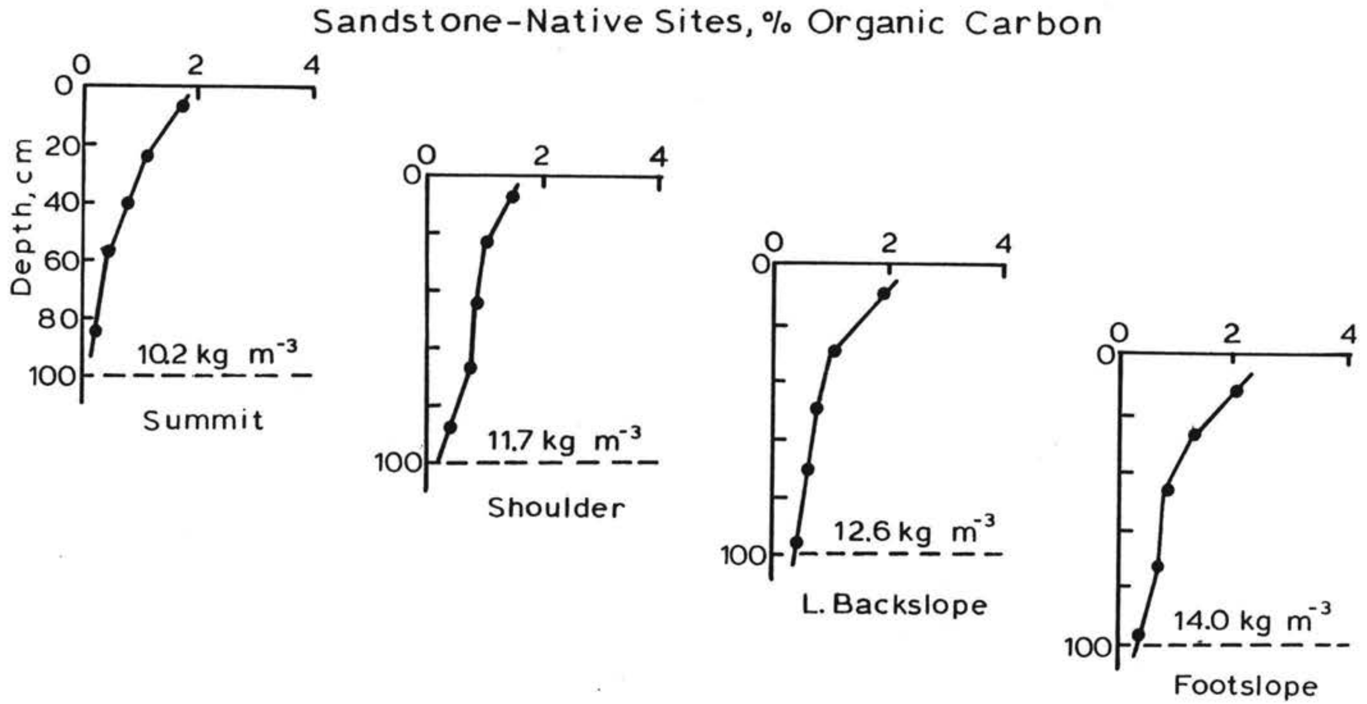

Figure 4.4 - Topographic controls on the amounts and vertical distribution of organic carbon in the native portion of the sandstone catena.

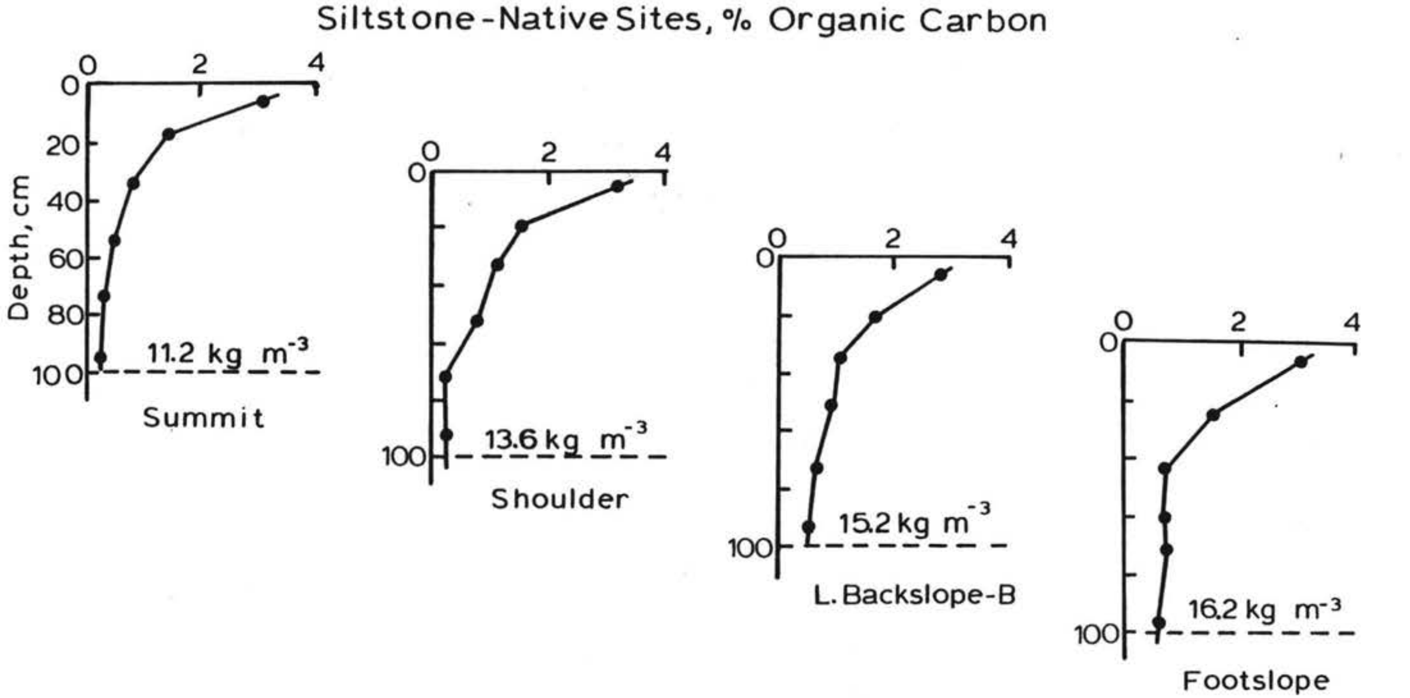

Figure 4.5 - Topographic controls on the amounts and vertical distribution of organic carbon in the native portion of the siltstone catena.

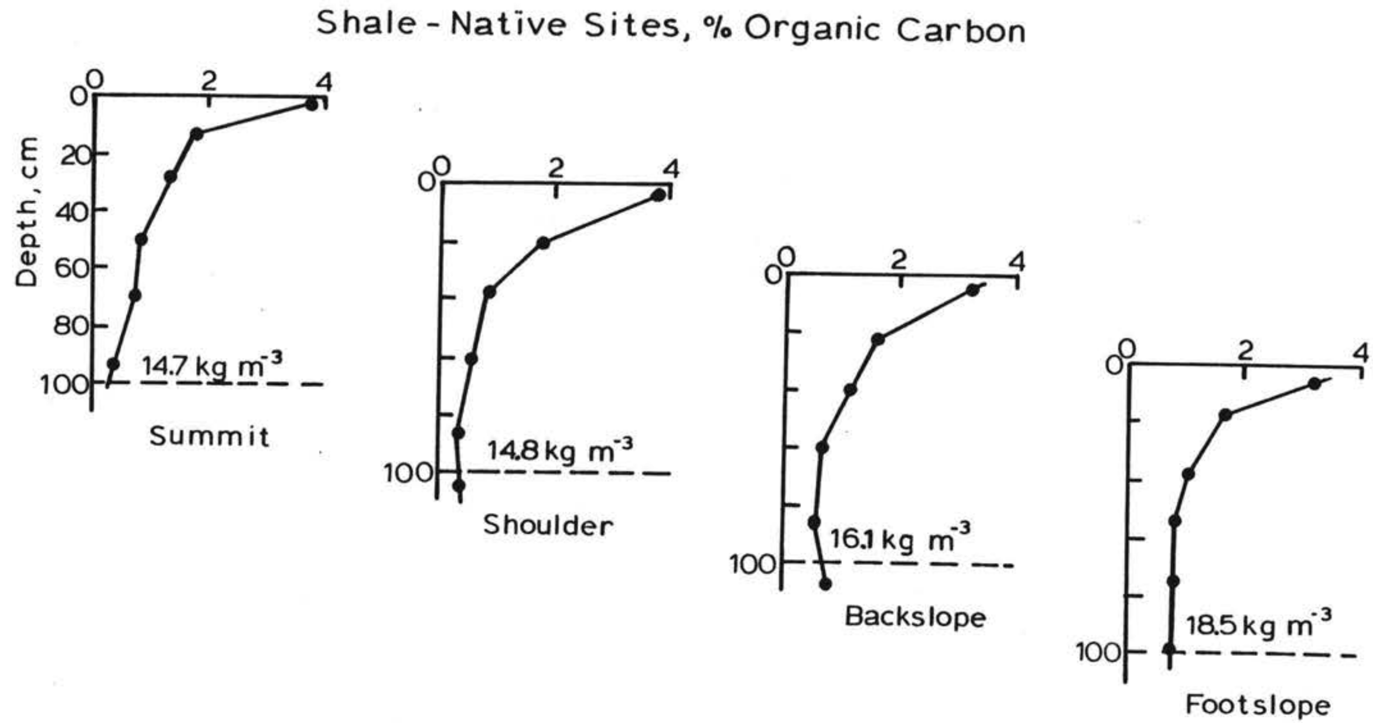

Figure 4.6 - Topographic controls on the amounts and vertical distribution of organic carbon in the native portion of the shale catena.

and siltstone catenas because the greater organic C quantities (kg m-3) are not reflected by higher concentrations in surface horizons.

In both the sandstone and shale sites the organic carbon content in the soils increases by approximately 3.8 kg m-3 upon moving from the summit to footslope segments (Figures 4.4 and 4.6). Comparing the total quantity of organic C in the summit and footslope segments it was found that the quantity at the footslope segment was significantly greater at $\alpha = 0.07$ and $\alpha = 0.01$ in the shale and sandstone sites, respectively.

The greatest quantity of organic C in the sandstone site was found at the back footslope (BFS) segment (Figure 2.4). The difference between the mean quantity of organic C in the back footslope (BFS) vs. footslope (FS) segments was significant at $\alpha = 0.29$ at this site. This difference might be due to the effects of an east vs. west aspect resulting in higher effective precipitation and thus greater primary production at the back footslope (BFS) segment. Deposition of wind-blown material enriched with organic matter may also be a contributing factor to these greater quantities of organic matter.

Organic C increases most dramatically along the siltstone toposequence (Figure 4.5). An increase of 5.0 kg m-3 occurs in the upper one meter depth of soil upon moving from summit (Sm) to footslope (Fs) segments at this site. The larger increase at the siltstone site is likely due to greater accumulations of soil water in the lower landscapes segments because of larger shoulder and backslope segment lengths compared to the other two catenas. The coarser parent material below the sandy mudstone lense at the mid-portions of the lower backslope area exerts some influence on organic matter production and accumulation. At any segment below this portion of the hillslope, the quantity of organic carbon is lower than at the segment directly above the sandy mudstone lense. The difference in the mean total organic C between the lower backslope (A) above the sandier lense and the lower backslope (B) below the lense was significant at $\alpha = 0.05$. The difference in total organic C at the lower backslope (A) and the footslope segment was significant at $\alpha = 0.02$.

One of the project's initial hypotheses was that differences in total organic matter within a toposequence can be as great as the differences among contrasting parent materials at comparable landscape segments. It was pointed out in Chapter Three that the difference in total mass of organic C (to a depth of 1 meter) between the texturally extreme sandstone and shale soils at the native-summit area was approximately 31%. Organic C increases from summit to footslope segments amount to 27%, 31%, and 21%, in the sandstone, siltstone and shale catenas, respectively. These results support our initial hypothesis that differences in organic matter quantities within a toposequence of relatively uniform parent material can be as large as differences among contrasting parent materials. Similar trends are observed with total N along the catenas (Table 4.5).

Table 4.5 - Parent material - topographic controls on total nitrogen along the native segments of the three catenas. (quantities listed for each segment represent the average of three pedons)

SANDSTONE:

Landscape Segment	Tot N kg m-3	SD.
Summit	0.97	.08
Shoulder	1.11	.03
Upper Backslope	1.14	.08
Lower Backslope	1.30	.04
Footslope	1.36	.12
B Backslope	1.34	.07
B Footslope	1.43	.04

SILTSTONE:

Landscape Segment	Tot N kg m-3	SD.
Summit	1.09	.06
Shoulder	1.31	.17
Upper Backslope	1.55	.04
Lower Backslope(A)	1.65	.01
Lower Backslope(B)	1.52	.03
Footslope	1.58	.03
Toeslope	1.74	.05
B Shoulder	1.36	.12

SHALE:

Landscape Segment	Tot N kg m-3	SD.
Summit	1.40	.10
Shoulder	1.47	.10
Backslope	1.57	.08
Footslope	2.09	.07

Organic P in the soils along the three native sites is listed in Table 4.6. Large differences in organic P are observed on all three parent materials as a function of landscape position (Figures 4.7-4.9).

Table 4.6 - Parent material - topographic controls on organic phosphorus in the native segments of the three catenas. (quantities listed for each segment represent the average of three pedons)

SANDSTONE:

Landscape Segment	Org P kg m^{-3}	SD.
Summit	0.172	.020
Shoulder	0.187	.014
Upper Backslope	0.233	.024
Lower Backslope	0.228	.011
Footslope	0.256	.010
B Backslope	0.204	.013
B Footslope	0.239	.010

SILTSTONE:

Landscape Segment	Org P kg m^{-3}	SD.
Summit	0.154	.033
Shoulder	0.171	.044
Upper Backslope	0.213	.010
Lower Backslope(A)	0.252	.014
Lower Backslope(B)	0.181	.010
Footslope	0.195	.023
Toeslope	0.232	.008
B Shoulder	0.168	.009

SHALE:

Landscape Segment	Org P kg m^{-3}	SD.
Summit	0.105	.030
Shoulder	0.177	.020
Backslope	0.172	.005
Footslope	0.240	.014

The largest increase upon moving downslope is observed at the shale site. Organic P increases by approximately 56% from the summit to the footslope segment in this catena. The ratio of organic C to organic P, (org C/org P), decreases from 143 to 77 from the summit to the footslope segments at the shale site, while increasing slightly at

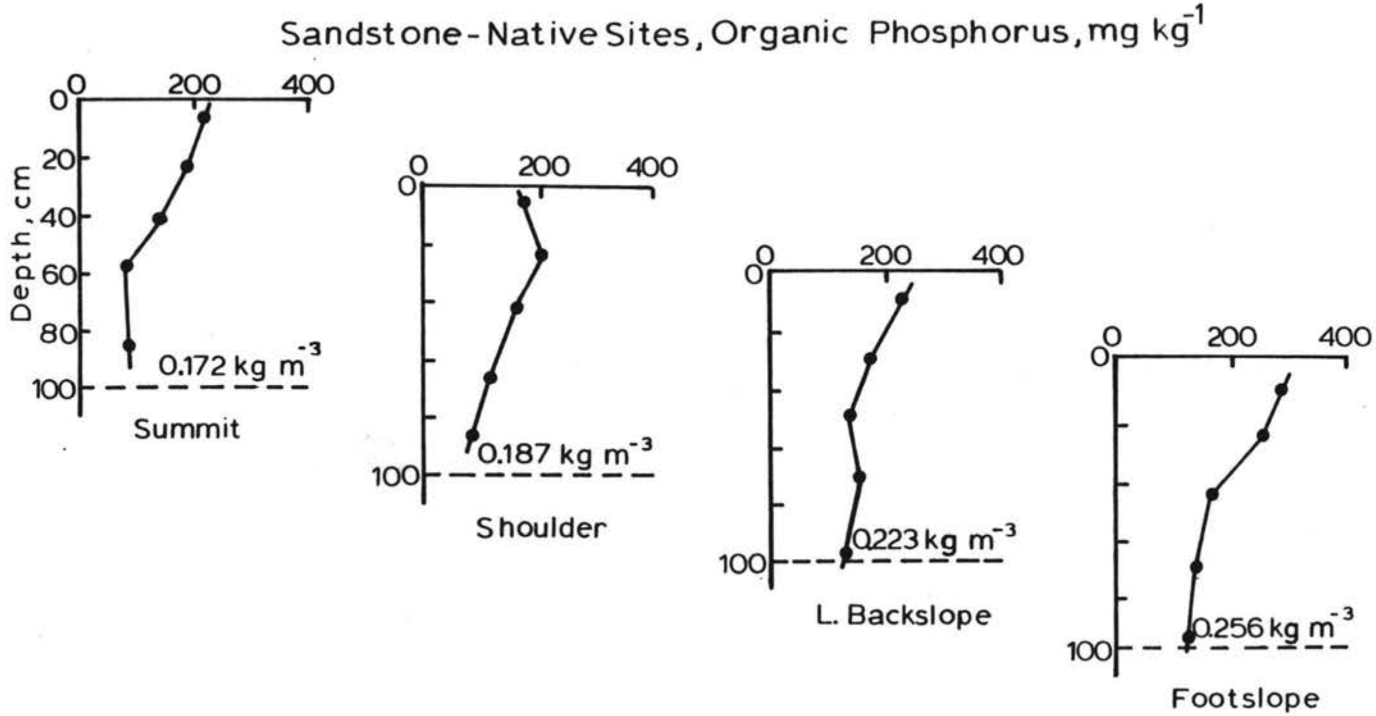

Figure 4.7 - Topographic controls on the amounts and vertical distribution of organic phosphorus in the native portion of the sandstone catena.

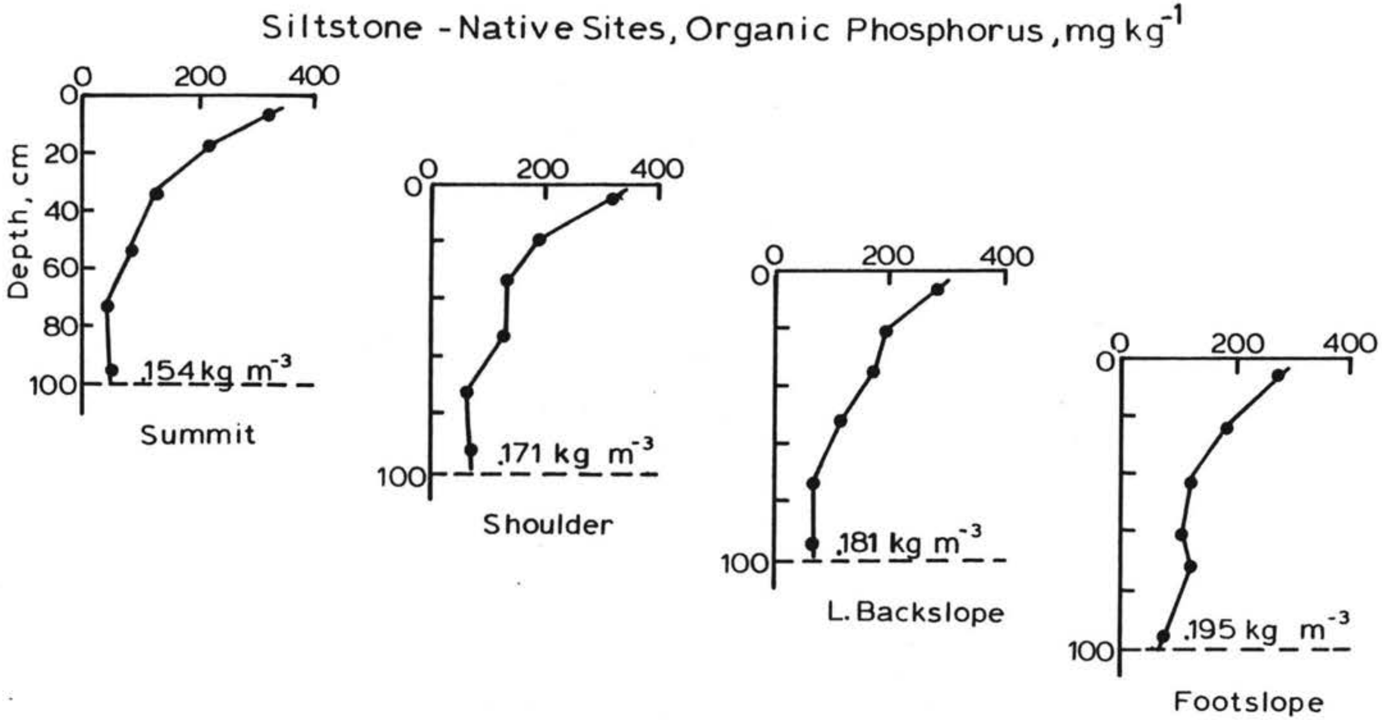

Figure 4.8 - Topographic controls on the amounts and vertical distribution of organic phosphorus in the native portion of the siltstone catena.

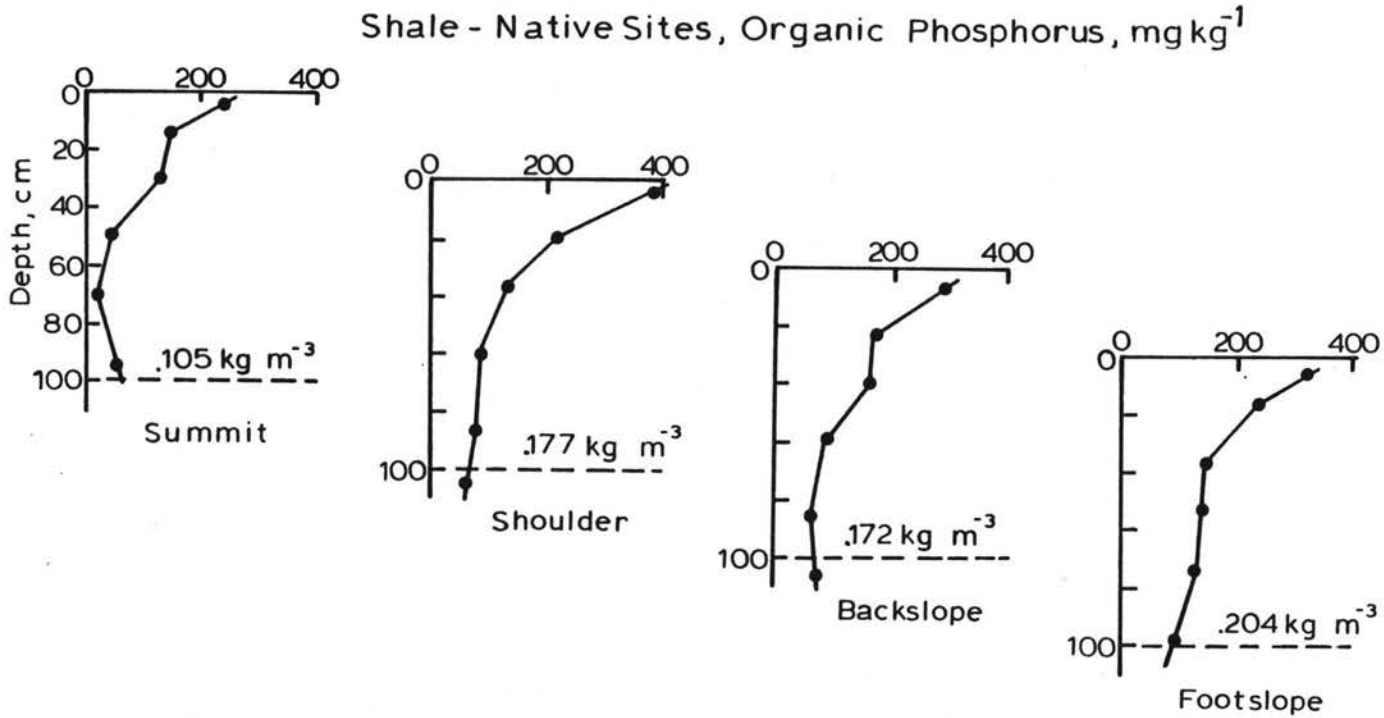

Figure 4.9 - Topographic controls on the amounts and vertical distribution of organic phosphorus in the native portion of the shale catena.

the siltstone site and decreasing slightly at the sandstone site (Table 4.7). In a study evaluating the changes in organic and inorganic phosphorus in particle size fractions of soils following 60 and 90 years of cultivation, Tiessen et al. (1983) showed that highly recalcitrant NaOH-extractable organic phosphorus tended to be associated with fine silts and coarse clays. This organic P fraction was found to be quite stable to further mineralization. The greater increase in organic P relative to organic C upon moving from the summit to the footslope segments in the shale site may reflect greater accumulations of physically protected, highly recalcitrant organic P fractions in the footslope area due to depositional processes.

Table 4.7 - Average quantities of organic C, organic P and organic C/organic P ratios at the native-summit and footslope segments of the three catenas.

	Org C	Org P	Org C/Org P
		kg m^{-3}	
SANDSTONE:			
Summit -	10.171	0.172	58.8
Footslope -	13.995	0.256	55.6
SILTSTONE:			
Summit -	11.146	0.154	71.4
Footslope -	16.244	0.195	83.3
SHALE:			
Summit -	14.653	0.105	142.9
Footslope -	18.532	0.240	76.9

It was previously shown, while comparing the native-summit landscape segments on the three contrasting parent materials (Chapter Three), that total organic P was highest in the sandstone soil, although this soil had the lowest quantity of organic C and total P. Organic P is higher in the sandstone catena than in the other two sites at any comparable landscape segment along the toposequences (Figures 4.7-4.9). Apparently, high productivity in these soils is sustained by maintaining a larger pool of organic P. Independent of landscape position, the organic matter fraction may be more important in providing a source of labile P in the sandy soils than in the finer textured shale and siltstone soils.

Changes in Inorganic Soil Constituents Along the Catenary Sequences

Walker and Syers (1976) pointed out that the nature of phosphorus in the initial parent material will influence transformations and losses of phosphorus during pedogenesis. Smeck (1973) suggested that in addition to serving as an index for two-dimensional (vertical) translocation of soil constituents, as was discussed in Chapter Two, phosphorus can also provide a useful index of three-dimensional (landscape) redistribution. In a study involving the redistribution of phosphorus along a toposequence in Cass County, Illinois, Smeck and Runge (1971b) found that soils at lower landscape positions had accumulated more phosphorus in the B horizons than was due to illuviation from overlying A horizons. Soils at higher landscape positions were found to have lost more phosphorus from the surface horizons than was gained by underlying B horizons. Phosphorus redistribution along the landscape was attributed to the movement of organic matter-enriched material by surface runoff and to slow sublateral movement by soil water. Although it is generally considered immobile over short time spans, phosphorus is mobile enough to provide an index of redistribution of soil constituents within a landscape during the long time spans involved in soil development.

The average quantity (kg m-3) of total P at each landscape segment along the native pasture in the three catenas is listed in Table 4.8. The vertical distribution of total P in the soils at selected segments along the catenas is plotted in Figures 4.10-4.12. The lowest quantities in the sandstone and shale catenas are observed on the convex shoulder segment. This is not surprising, given that the shoulder segment is generally considered the most highly erosive landscape on the hillslope (Ruhe and Walker, 1968). The lower backslope and footslope segments appear to have been enriched with total P at the expense of the less stable shoulder segment in these two sites. In contrast, similar trends are not observed at the siltstone site (Figure 4.11). The presence of the coarser textured mudstone lense at the lower backslope has apparently resulted in the deposition of local alluvium which is lower in total P at the footslope and toeslope segments (Table 4.8).

Statistical analyses to contrast the quantity of total P along the catenas was limited to the comparison of the summit vs. footslope segments in the shale and siltstone sites because total P was measured for only one pedon in the other landscape segments.

Total P was measured for all three pedons at all landscape segments in the sandstone catena, except for the upper and lower backslopes (Table 4.8). It was found that the average quantity of total P was significantly lower at the shoulder segment than on any other segment. The difference in total P in the summit vs. shoulder segments was significant at $\alpha = 0.06$, while the difference between shoulder and footslope segments was significant at $\alpha = 0.05$. The

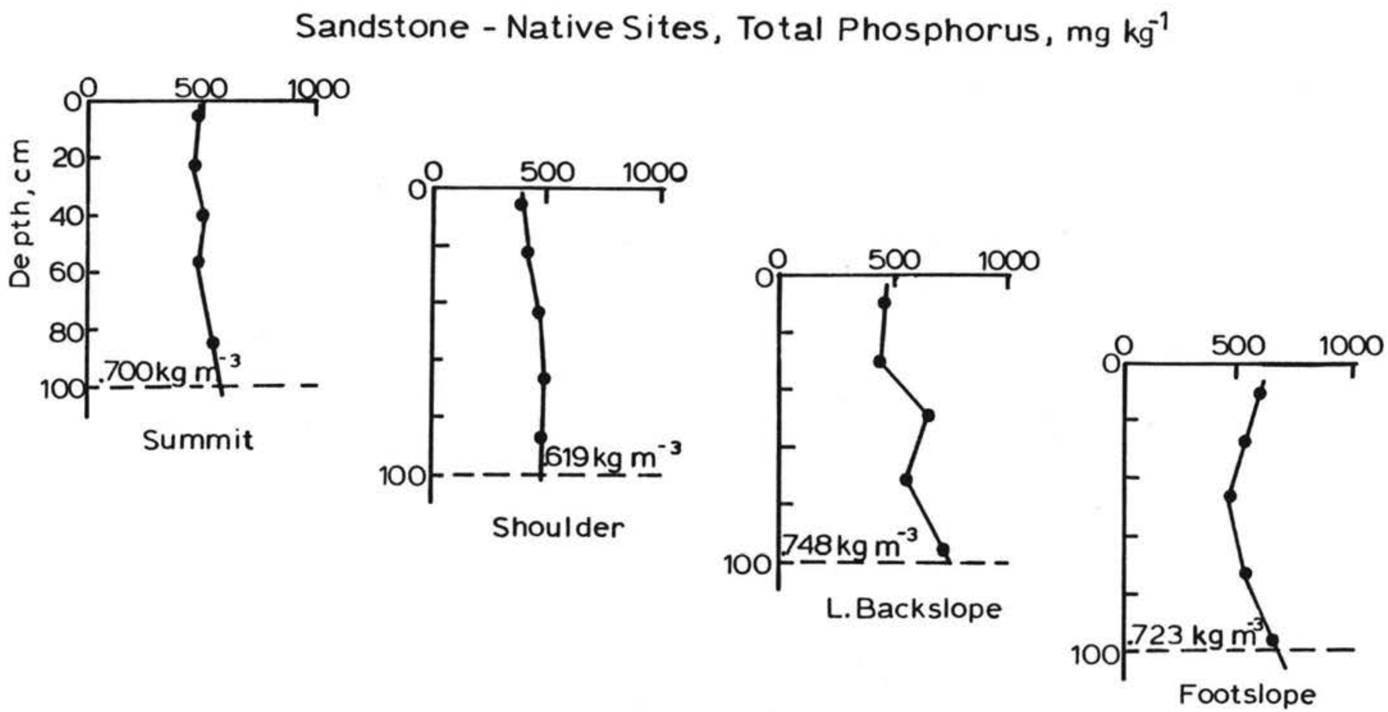

Figure 4.10 - Topographic controls on the amounts and vertical distribution of total phosphorus in the native portion of the sandstone catena.

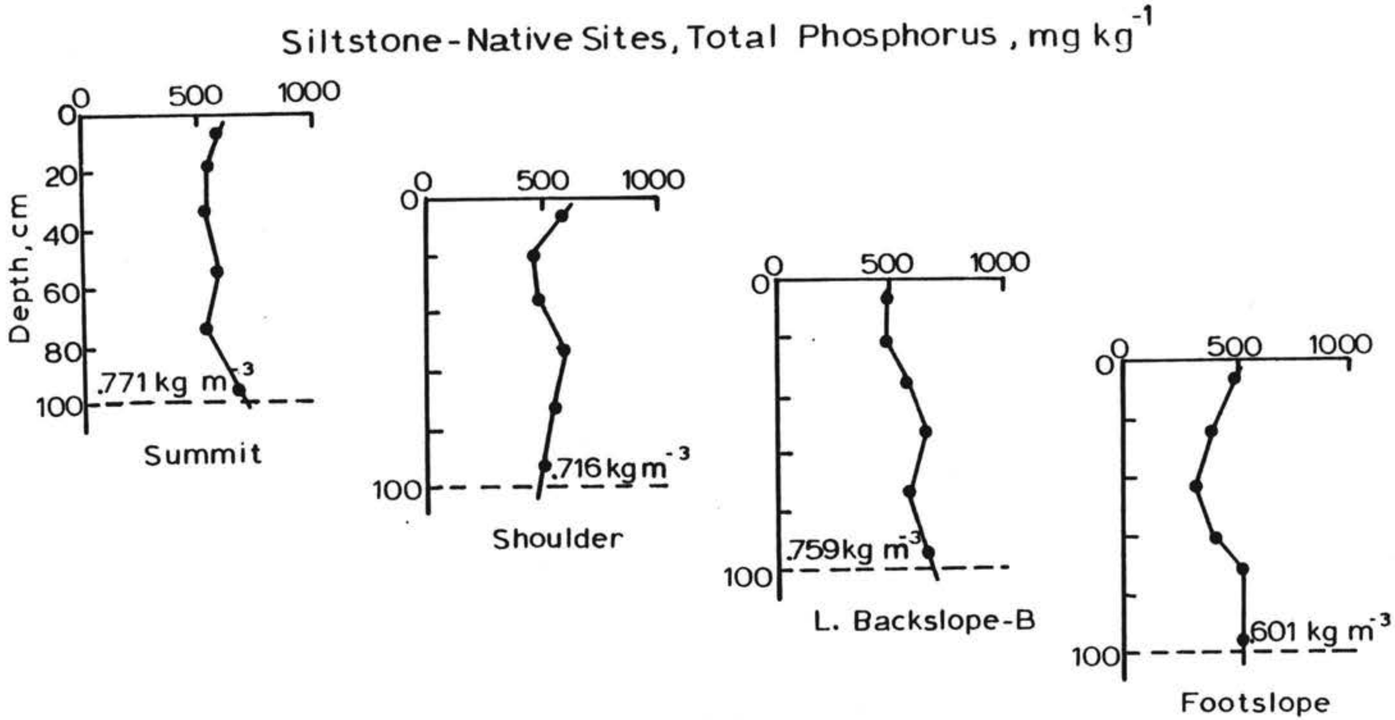

Figure 4.11 - Topographic controls on the amounts and vertical distribution of total phosphorus in the native portion of the siltstone catena.

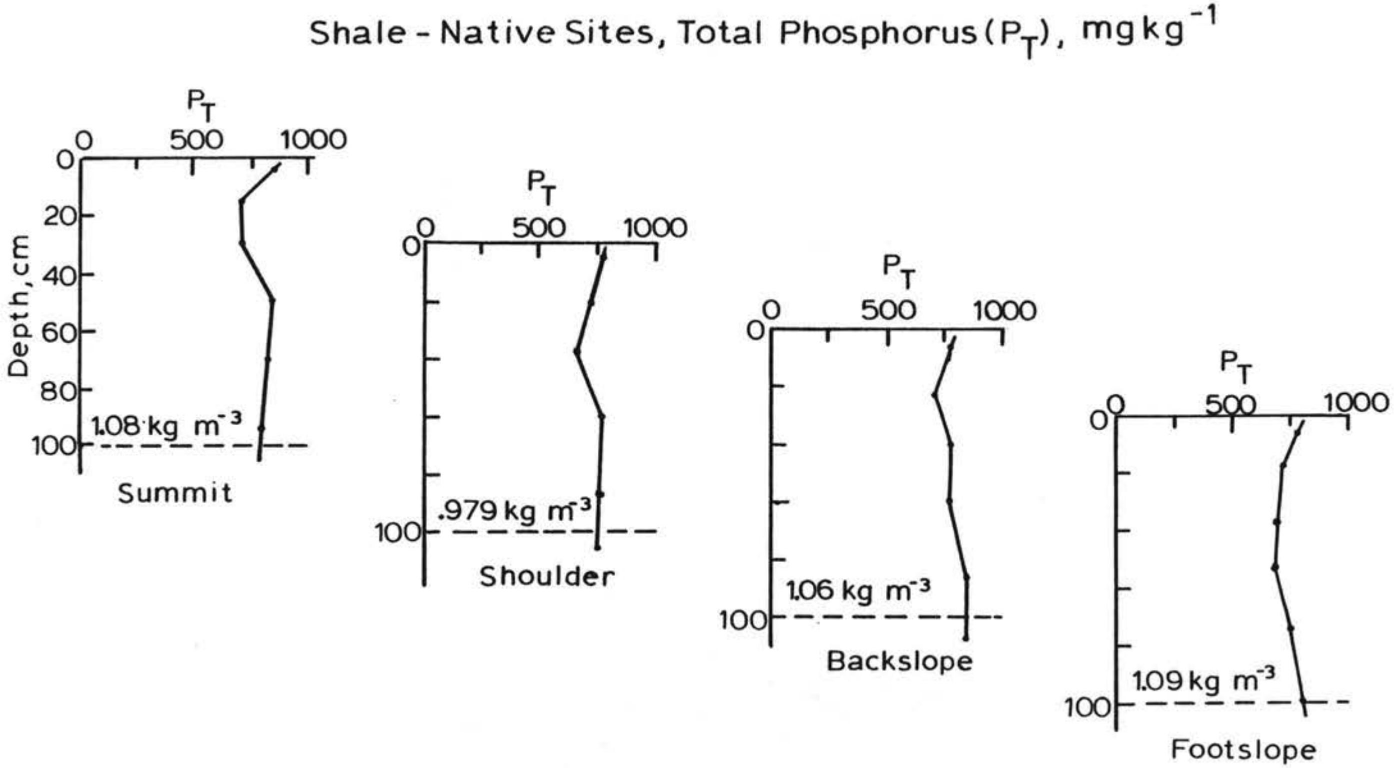

Figure 4.12 - Topographic controls on the amounts and vertical distribution of total phosphorus in the native portion of the shale catena.

greatest difference was found between the shoulder and back footslope segments (test significant at $\alpha = 0.007$).

The difference in the mean quantity of total P on the summit vs. footslope segments at the shale and sandstone sites was found to be significant only at $\alpha = 0.95$ and $\alpha = 0.52$, respectively. In contrast, at the siltstone site total P at the footslope segment was significantly lower than at the summit ($\alpha = 0.04$), likely due to the difference in parent material above and below the sandy mudstone lense.

Ruhe and Walker (1968) defined an open drainage system as one where drainage waters and soil material are ultimately flushed (moved) out of temporary storage compartments into a trunk stream and out of the immediate area. Under these conditions the sedimentologic record relating to the erosion of valley hillslopes is often incomplete. In contrast, a closed drainage system is encircled such that all erosional debris is trapped within a common depository at the lower elevations (footslopes and toeslopes) with no net loss of material from the system. All three of our paired native-cultivated catenas are components of open drainage systems. It is not surprising then, that the apparent losses of total P from the shoulder landscape segments are not reflected by significantly greater total P quantities at the footslope segments, when compared to the relatively stable summit segments.

Table 4.8 - Parent material - topographic controls on total phosphorus in the native segments of the three catenas. (quantities listed for the each segment represent the average of three pedons, unless otherwise indicated)

SANDSTONE:

Landscape Segment	Tot P kg m-3	SD.
Summit	0.700	.029
Shoulder	0.619	.036
Upper Backslope*	0.616	--
Lower Backslope*	0.748	--
Footslope	0.723	.046
B Backslope	0.676	.067
B Footslope	0.819	.036

SILTSTONE:

Landscape Segment	Tot P kg m-3	SD.
Summit	0.771	.060
Shoulder*	0.716	--
Upper Backslope*	0.872	--
Lower Backslope(A)*	0.759	--
Lower Backslope(B)*	0.778	--
Footslope	0.601	.057
Toeslope*	0.697	--
B Shoulder*	0.593	--

SHALE:

Landscape Segment	Tot P kg m^{-3}	SD.
Summit	1.080	.109
Shoulder*	0.993	--
Backslope*	1.053	--
Footslope	1.085	.080

*data represents 1 pedon on these landscape segments

The quantity of inorganic P in the soils along the native catenas is listed in Table 4.9. The vertical distribution of inorganic P at selected landscape segments on each catena is plotted in Figures 4.13-4.15. Total inorganic P generally decreases upon moving downslope along the catenas, except for slight increases in the backslope segments. It

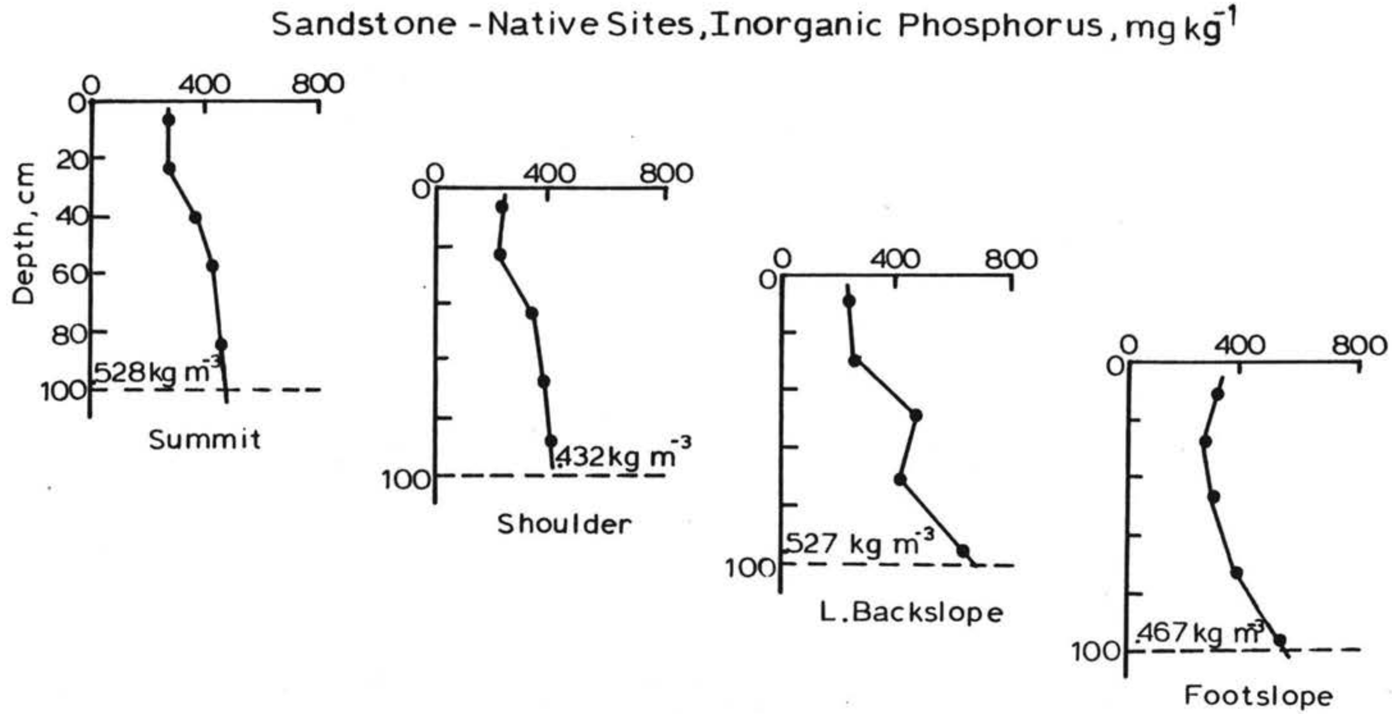

Figure 4.13 - Topographic controls on the amounts and vertical distribution of inorganic phosphorus in the native portion of the sandstone catena.

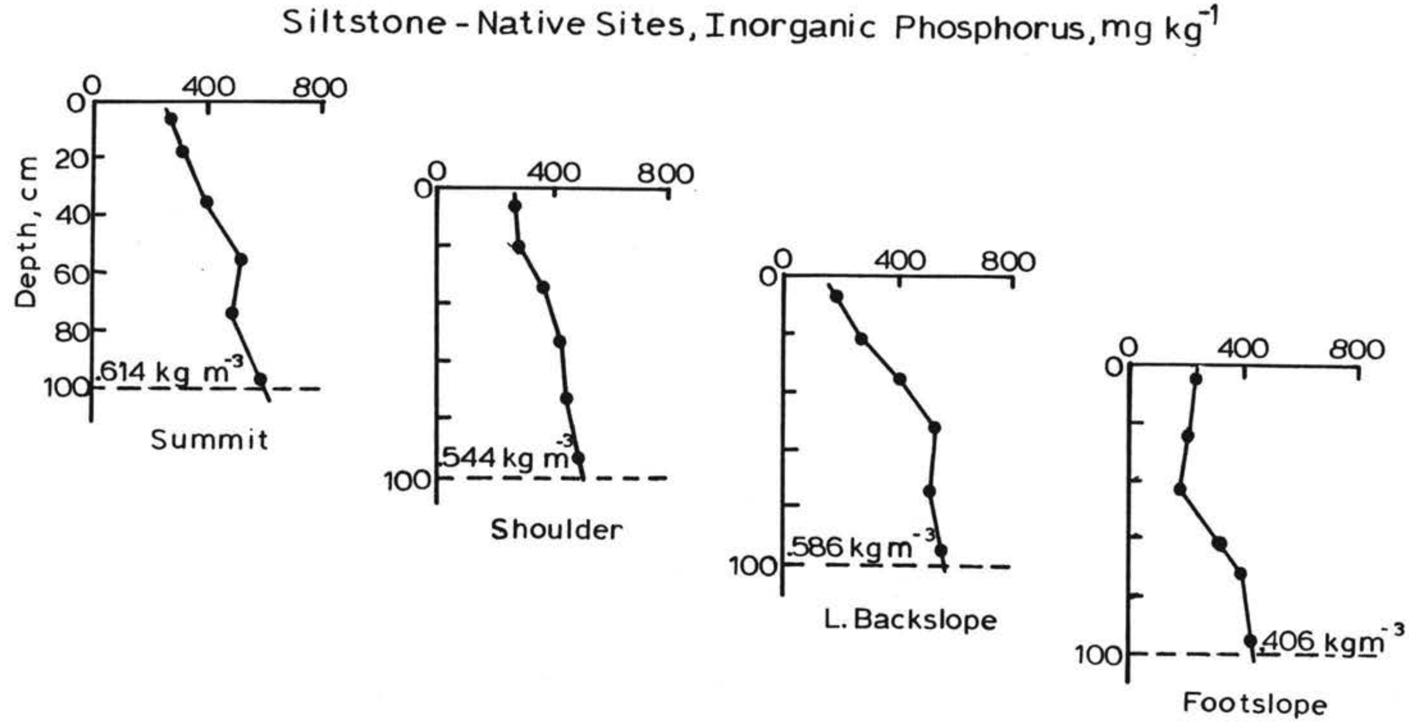

Figure 4.14 - Topographic controls on the amounts and vertical distribution of inorganic phosphorus in the native portion of the siltstone catena.

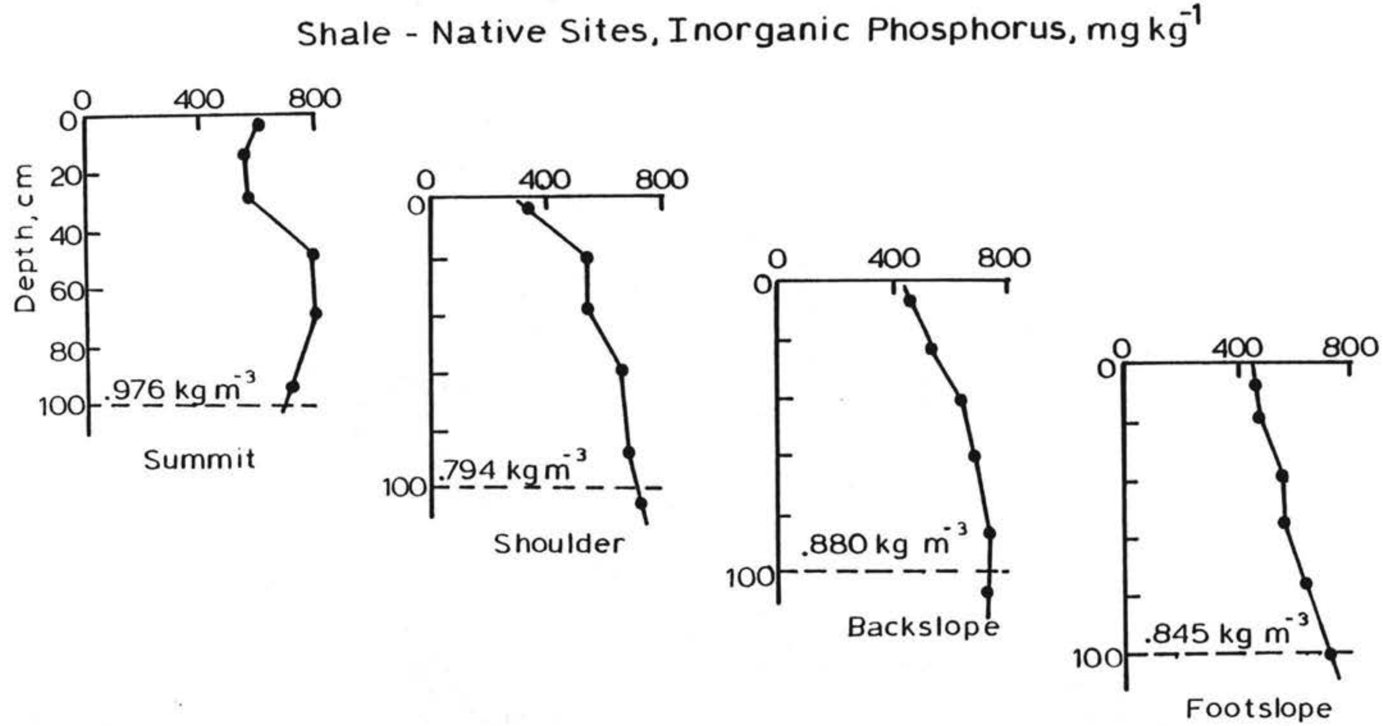

Figure 4.15 - Topographic controls on the amounts and vertical distribution of inorganic phosphorus in the native portion of the shale catena.

was shown earlier (Figures 4.7-4.9) that organic P progressively increases upon moving downslope along the catenas, because of higher plant productivity and the deposition of organic matter-enriched soil at lower elevations. The lower quantities of inorganic P at the footslope segments are likely due to greater transformations of inorganic to organic forms by plant activity. The reciprocal relationship between organic and inorganic P along the catenas is reflected nicely in the plots showing the vertical distribution of inorganic P (Figures 4.13-4.15). Increases in inorganic P at the lower backslope (sandstone and siltstone sites) and backslope (shale site) segments reflect the accumulation of soil from higher elevations. Plant productivity is not as high in these segments as in footslope areas and thus, depositional accumulations of inorganic P are not as completely masked by transformations to organic forms. The high quantity of inorganic P at the back footslope in the sandstone site also reflects accretion of phosphorus-enriched soil material. Increases of inorganic P resulting from soil accretion at this segment are not totally masked by transformations to organic forms.

Table 4.9 - Parent material - topographic controls on inorganic phosphorus in the native segments of the three catenas. (quantities listed for each segment represent the average of three pedons, unless otherwise indicated)

SANDSTONE:

Landscape Segment	Inorg P kg m-3	SD.
Summit	0.528	.032
Shoulder	0.432	.035
Upper Backslope*	0.389	--
Lower Backslope*	0.527	--
Footslope	0.467	.036
B Backslope	0.471	.058
B Footslope	0.580	.026

SILTSTONE:

Landscape Segment	Inorg P kg m-3	SD.
Summit	0.614	.086
Shoulder*	0.544	--
Upper Backslope*	0.650	--
Lower Backslope(A)*	0.519	--
Lower Backslope(B)*	0.586	--
Footslope	0.406	.080
Toeslope*	0.467	--
B Shoulder*	0.435	--

SHALE:

Landscape Segment	Inorg P kg m^{-3}	SD.
Summit	0.976	.104
Shoulder*	0.794	--
Backslope*	0.880	--
Footslope	0.845	.067

*data represents 1 pedon on these landscape segments

The quantity and vertical distribution of acid-soluble phosphorus at the three native sites are listed in Table 4.10 and shown in Figures 4.16-4.18. Unlike total inorganic P, changes in the levels in acid-soluble P along the catenas is influenced as much by the nature of the parent material as by topography. Acid-soluble P at the sandstone site

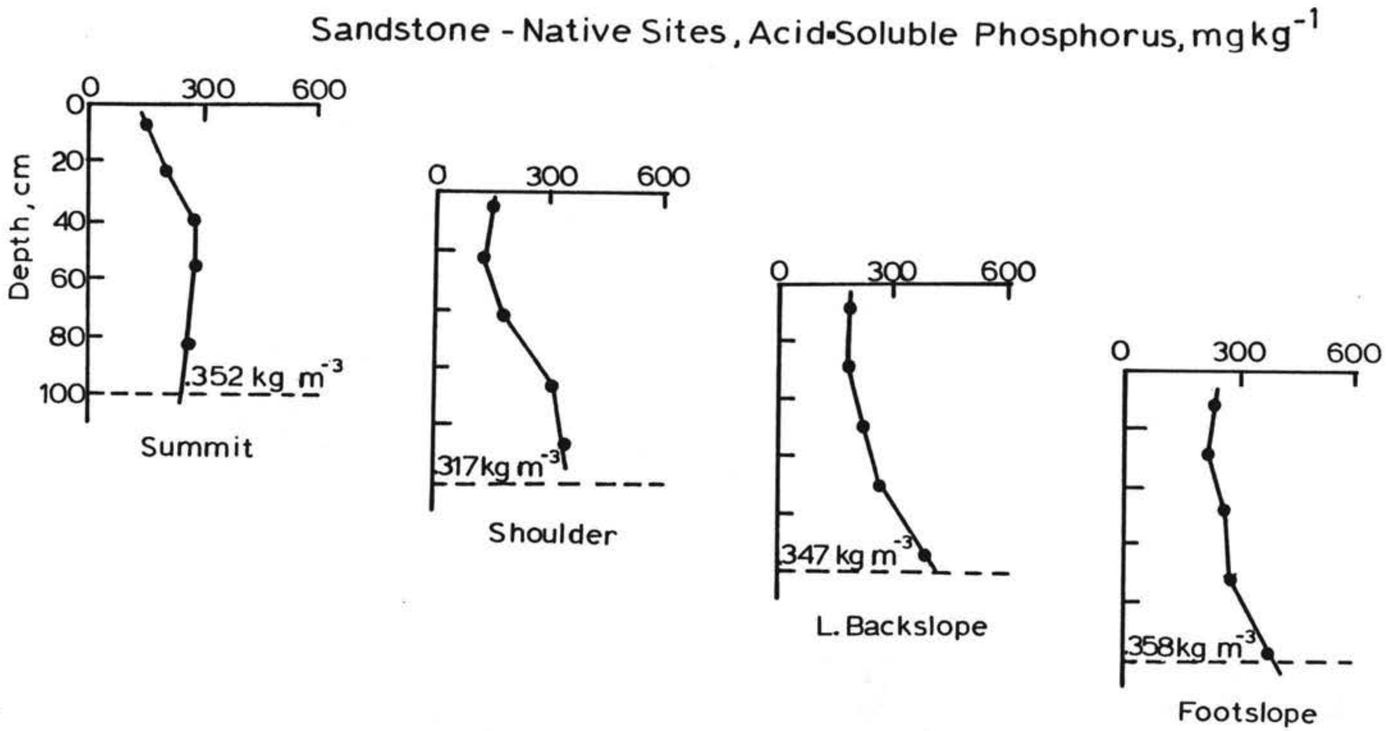

Figure 4.16 - Topographic controls on the amounts and vertical distribution of acid-soluble phosphorus in the native portion of the sandstone catena.

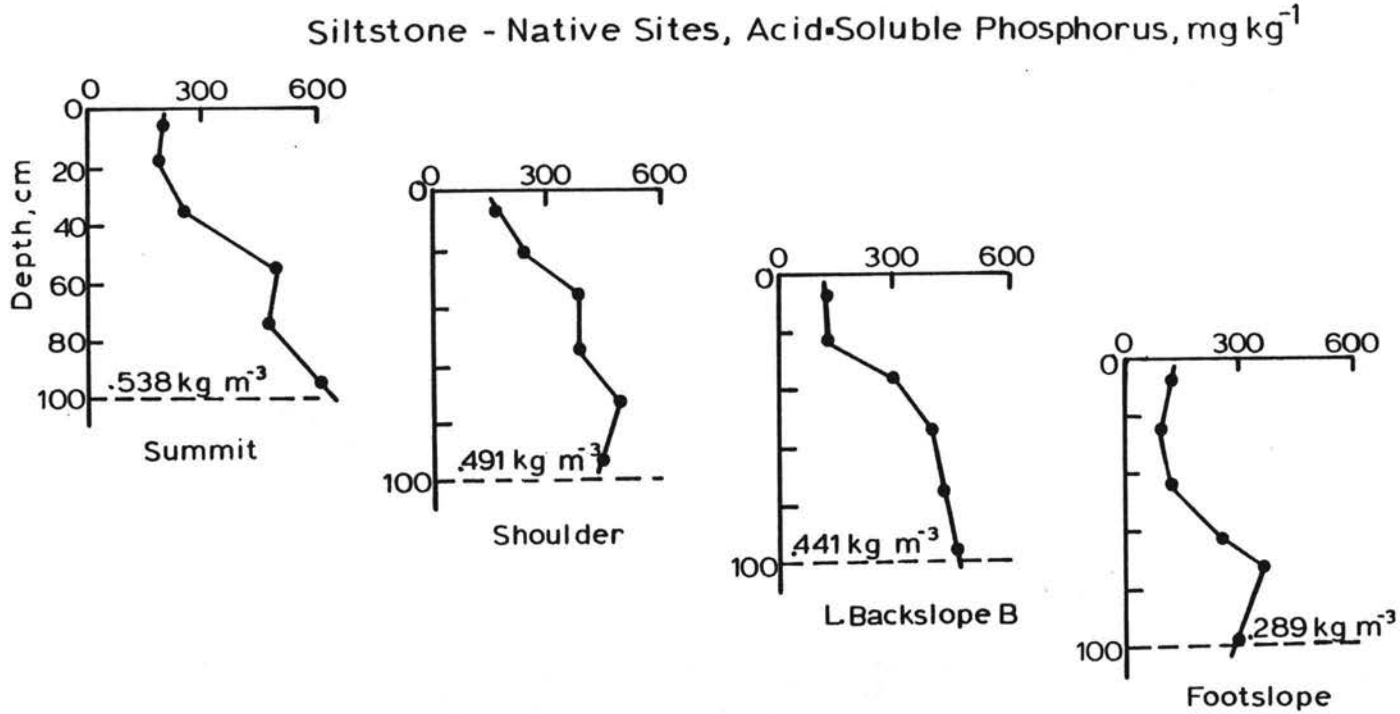

Figure 4.17 - Topographic controls on the amounts and vertical distribution of acid-soluble phosphorus in the native portion of the siltstone catena.

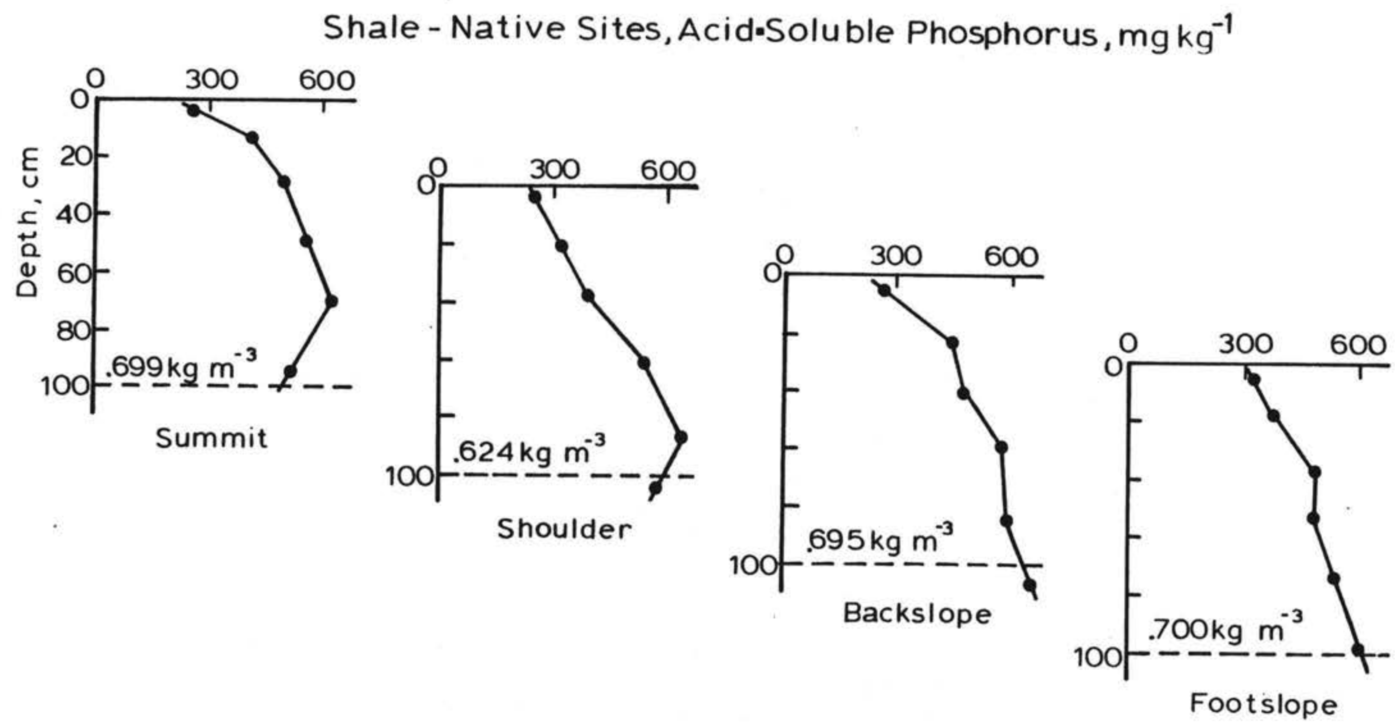

Figure 4.18 - Topographic controls on the amounts and vertical distribution of acid-soluble phosphorus in the native portion of the shale catena.

decreases in the shoulder and upper backslope segments relative to the summit, and subsequently increases upon moving further downslope (Figure 4.16). This suggests that other forms of inorganic P (residual P) have been important in the overall transformation of inorganic to organic P at the lower elevations in this site. Similar trends are observed at the shale site (Figure 4.18).

In contrast, large decreases in acid-soluble P are observed upon moving downslope at the siltstone site, with the exception of the upper backslope. It was previously shown in Chapter Three that most of the inorganic P in the siltstone parent material was acid-soluble (Figure 3.9). It is not surprising then that the total quantity of acid-soluble P would decrease appreciably as the quantity of organic P increases in the lower elevations at this site. The higher quantities of total, inorganic and acid-soluble P in the upper backslope segment are likely due to higher levels in the original parent material at this portion of the hillslope.

Changes in the levels of residual P along the three catenas are much more difficult to interpret and are probably due to a number of site specific processes. As discussed in the previous chapter, the quantity of residual P at the native-summit segments is greatest in the shale soil and this, apparently is independent of landscape position. The quantity of residual P is greater at the shale site than at the other two native catenas on any comparable landscape (Table 4.11). However, the patterns within either of the three toposequences are not consistent. This is probably due to changes in the chemical nature of the residual P resulting from microclimatic differences (effective precipitation and leaching characteristics) along the catenas and variation in parent material (residuum vs. alluvium) with elevation changes.

Table 4.10 - Parent material - topographic controls on acid-soluble phosphorus in the native segments of the three catenas. (quantities listed for the each segment represent the average of three pedons)

SANDSTONE:

Landscape Segment	Acid P kg m-3	SD.
Summit	0.352	.028
Shoulder	0.317	.023
Upper Backslope	0.308	.017
Lower Backslope	0.347	.025
Footslope	0.358	.015
B Backslope	0.347	.067
B Footslope	0.303	.009

SILTSTONE:

Landscape Segment	Acid P kg m-3	SD.
Summit	0.538	.065
Shoulder	0.491	.108
Upper Backslope	0.570	.016
Lower Backslope(A)	0.443	.032
Lower Backslope(B)	0.441	.021
Footslope	0.289	.045
Toeslope	0.310	.024
B Shoulder	0.438	.056

SHALE:

Landscape Segment	Acid P kg m-3	SD.
Summit	0.699	.070
Shoulder	0.624	.038
Backslope	0.695	.017
Footslope	0.700	.037

Table 4.11 - Parent material - topographic controls on residual phosphorus in the native segments of the three catenas. (quantities listed for each segment represent the average of three pedons, unless otherwise indicated)

SANDSTONE:

Landscape Segment	Resid P kg m-3	SD.
Summit	0.170	.066
Shoulder	0.115	.041
Upper Backslope*	0.090	--
Lower Backslope*	0.198	--
Footslope	0.109	.035
B Backslope	0.125	.018
B Footslope	0.277	.017

SILTSTONE:

Landscape Segment	Resid P kg m-3	SD.
Summit	0.079	.021
Shoulder*	0.107	--
Upper Backslope*	0.083	--
Lower Backslope(A)*	0.112	--
Lower Backslope(B)*	0.139	--
Footslope	0.117	.055
Toeslope*	0.145	--
B Shoulder*	0.057	--

SHALE:

Landscape Segment	Resid P kg m^{-3}	SD.
Summit	0.278	.039
Shoulder*	0.171	--
Backslope*	0.203	--
Footslope	0.145	.041

*data represents 1 pedon on these landscape segments

Summary -- Topographic - Parent Material Interactions Along The Catenary Sequences

The amounts and vertical distribution of organic and inorganic soil constituents along the native grassland portions of the three catenas were shown to vary as a function of landscape position. Much of the variation in organic soil constituents has resulted from variations in soil moisture resulting in differences in plant productivity along the catenas. The redistribution of soil by erosional processes has also contributed to the enrichment of organic and inorganic constituents at lower landscape segments at the expense of the soils at higher landscape segments.

The vertical distribution of calcium carbonate in the soils, as indicated by the $CaCO_3$-equivalent index, was used to establish changes in soil moisture dynamics along the three catenas. The depth to the zone of maximum calcium carbonate accumulation increased upon moving downslope in the sandstone and shale catenas reflecting greater infiltration and leaching of moisture at the lower landscape segments. A similar pattern was not observed at the siltstone site because of variations in the initial calcium carbonate content of the parent material.

Both solum and A horizon thickness increased upon moving downslope along the catenas. Greater surface runoff and erosion have resulted in shallower solum thicknesses at the shoulder segment of the sandstone and siltstone sites. At the shale site, the presence of a more readily weatherable mudstone lense has resulted in greater solum thickness at the shoulder segment compared to the summit.

Greater organic matter concentrations in the mollic epipedon at the lower landscape segments of the sandstone site suggest higher plant productivity. A similar trend is not observed at the siltstone and shale sites. In these catenas the increase in organic C has resulted primarily through greater accumulations of organic matter in subsurface horizons. Depositional processes resulting in the accumulation of organic matter-enriched sediments appear to have been more active over time in the finer textured soils on the shale and siltstone catenas. Total organic C contents increased by 27%, 31% and 21% upon moving from the summit to footslope segments on the sandstone, siltstone and shale sites, respectively.

The quantity of organic P was highest in the sandstone site at every comparable landscape segment in the three catenas. However, the greatest increase in organic P, upon moving from the summit to the footslope segments, was found at the shale site due to greater accumulations of physically protected, highly recalcitrant organic P fractions associated with finer mineral fractions (silt and clay).

Variations in the quantities of total and inorganic phosphorus along the catenas reflect the redistribution of soil material by erosional processes. Shoulder landscape segments were found to have lower quantities of total and inorganic P than adjacent segments, indicating the loss of phosphorus over time. However, these losses were not reflected by significantly higher total P quantities at the footslope segments. Phosphorus has apparently moved out of the lower landscape segments of the catenas over time.

MANAGEMENT (CULTIVATION) EFFECTS ON SOIL - PARENT MATERIAL - LANDSCAPE - INTERACTIONS

The application of stability and change to soil-vegetation systems is complicated due to the multicomponent nature of these systems. Trudgill (1977) states that each system component will have a different lability to an external disturbance and that each disturbance may stress different causal links that exist between the components. A system's sensitivity to fluctuations in external factors increases in proportion to the importance of these factors in maintaining that state of the system. Upon disturbance, a system will change until the reaction is adjusted to the action or an entirely new system is attained and new relationships and adjustments are seen. Speculation exists as to whether soils subject to continuous cultivation will eventually reach new organic matter equilibrium levels and nutrient cycling dynamics or continue to degrade. Organic matter losses resulting from cultivation practices have greatly altered the nutrient cycling component of semiarid prairie soils. The "quasi-steady state" nutrient cycle of grassland soils is destroyed and converted to a system where crop removal, mineralization and erosional losses of nutrients far exceeds inputs by plants. Organic matter losses and soil deterioration resulting from cultivation have become a serious problem in semiarid agroecosystems.

Background information

Previous work evaluating the effects of cultivation on soils in the U.S. and Canadian Great Plains has shown that these practices have substantially reduced organic matter quantity and quality. (Newton et al., 1945; Haas et al., 1957; Martel and Paul, 1974; DeHann, 1977; Herlihy, 1979; and Tiessen et al., 1981). Generally, a rapid decrease in organic matter occurs when soils are initially cultivated, and the rate of loss subsequently decreases with time upon continued cultivation (Haas et al., 1957; Martel and Paul, 1974). Results from early studies suggested that a new equilibrium level of organic matter was attained after 20 to 30 years of cultivation. Martel and Paul (1974) reported that new equilibrium levels were obtained only after 60 to 70 years of cultivation. More recently, Tiessen et al. (1981) have shown that losses of organic matter may continue even after 90 years of cultivation due to erosional processes.

Tiessen et al. (1981) have shown that the effects of cultivation on the amounts and vertical distribution of organic carbon, nitrogen and phosphorus in soils differs as a function of parent material and soil textural characteristics. Native rangeland and adjacent cultivated soils were sampled in the Canadian prairies and their organic C, nitrogen and phosphorus contents, bulk densities and horizon depths were compared. Reductions of 35%, 18-34% and 12% of organic C, nitrogen and phosphorus, respectively, were found when clayey and silt loam virgin and cultivated soils were compared. Greater reductions were found to have occurred during a similar period of cultivation on a coarser sandy loam soil. Losses of organic C, nitrogen and total P in this soil amounted to 46%, 46% and 29%, respectively. Results of their studies showed that phosphorus losses occurred from both the organic and inorganic fractions in the coarser textured soil, whereas all phosphorus losses in the finer silty and clayey soils occurred in the organic fraction.

Recent studies in the Canadian prairies have focused on evaluating the nature of organic and inorganic P in the various particle size fractions of soils and the effects of continued cultivation on these. As previously mentioned in Chapter Four, Tiessen et al. (1983), in a study evaluating the changes in organic and inorganic P in particle size fractions of soils following 60 and 90 years of cultivation, found that highly recalcitrant organic P associated with coarse clays was found to increase. Organic P and labile inorganic P were depleted during cultivation, while acid extractable P (apatite) was found to increase in all soils studied. It is apparent that changes in soil phosphorus pools resulting from cultivation are highly dependent on the textural properties of the soil.

Comparison of our Native Rangeland and Cultivated Soils

Profile reconstruction has been utilized to evaluate the morphological, physical and chemical changes in our soils following 44 years of cultivation using a method which was initially tested by Muhaimeed (1981) on a catenary sequence in eastern Colorado. This method uses virgin soils as benchmarks to assess the changes in adjacent cultivated soils. The following assumptions about the soils along the paired native-cultivated sequences must be made in order to use profile reconstruction to evaluate changes in soil properties brought about by cultivation:

1. Soils on matched native and cultivated landscape segments were homogeneous in terms of morphological, physical and chemical properties prior to cultivation.

2. All differences in soil properties between the virgin and cultivated soils along the catenas have resulted from the cultivation practices.

3. The cultivated soils have a higher potential for soil removal and redistribution resulting from erosional and agricultural activities. However, the potential for wind deposition is similar on both virgin and cultivated sites.

The use of profile reconstruction allows the assessment of the quantity of mineral and organic soil constituents lost by erosion in addition to crop removal and mineralization. The method allows more realistic comparisons of virgin and cultivated soils.

Figure 5.1 illustrates the changes which occur in soil profiles when cultivated over time. The erosion potential is greatly increased in the Ap horizon of the cultivated soil. The Ap horizon will subsequently become incorporated deeper and deeper into the profile with continued cultivation and surface soil loss. In addition to organic matter losses from the surface through induced mineralization and erosion, the Ap horizon is incorporated into subsurface soil of lower organic matter content. Thus, it is clear that comparison of chemical and physical properties of the Ap horizon with the A horizon of the virgin benchmark soil is unrealistic without accounting for erosion and mixing effects. Changes in the total quantity (vol.-weight basis) of organic C, nitrogen and phosphorus are best estimated by comparing the total quantities present in the solum (A and B horizons) of the virgin and cultivated soils. In this manner, losses of these

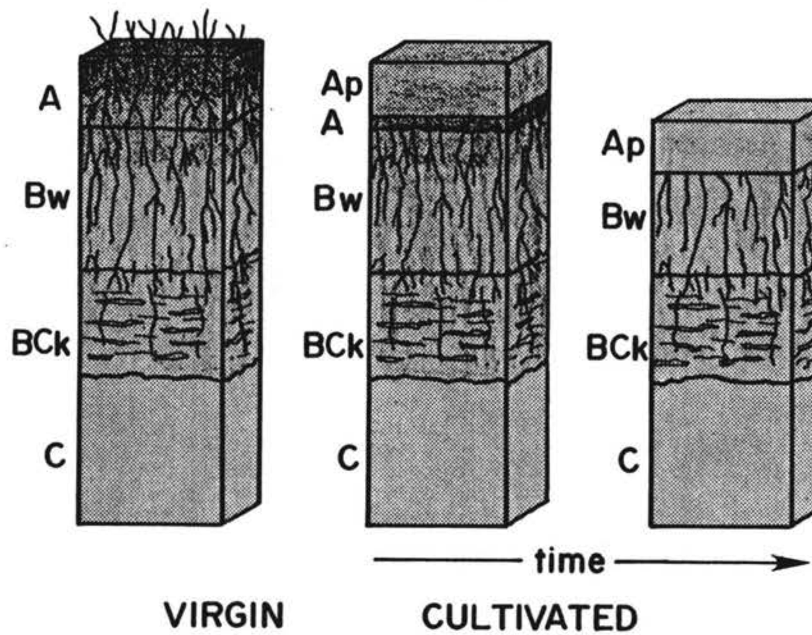

Figure 5.1 - Changes in native grassland soil profiles resulting from long-term cultivation.

soil constituents by erosion can also be taken into account. Similarly, in those landscape segments where soil accretion has taken place, the gains of organic and inorganic matter (vol.-weight basis) resulting from deposition can be assessed.

Kelly (1984) used a discriminate analysis procedure to verify the accuracy of our identification of genetic horizons in the soils at our study sites. Chemical, physical and morphological data were combined in the procedure to discriminate between genetic horizons. Upon establishing a sufficient level of accuracy, the virgin pedons were used as benchmarks to evaluate the changes in soil properties resulting from 44 years of cultivation at each landscape segment.

The changes in solum thickness and B/A horizon ratios are listed in Tables 5.1-5.3. The loss of surface soil and subsequent incorporation of the Ap horizon into the B horizon is reflected by an overall reduction in B/A ratios on every landscape segment, except for the shoulder segment in the siltstone site. Accretion of soil material has apparently taken place at this landscape segment. Tables 5.4-5.6 show the quantity of soil lost (or gained) at each landscape segment in the three paired native-cultivated catenas as calculated by Kelly (1984). Soil loss determinations on the shale catena indicated that the greatest losses have occurred in the convex shoulder segment. These losses (74.7 T/ha/yr) are greater than the weighted average loss for the entire catena (Table 5.4). Surprisingly, losses from the footslope segment were much greater than the losses from the backslope and were also higher than the weighted average for the entire catena.

Soil loss patterns are somewhat more complicated in the siltstone and sandstone sites (Tables 5.5-5.6). On the siltstone catena (Table

5.5) soil losses range from 62.7 T/ha/yr on the summit and upper backslope segments to 27.3 T/ha/yr on the back shoulder. The landscape segments that are generally considered depositional (footslope and toeslopes) have lost more soil than the calculated weighted average for the entire catena. Losses from the back shoulder were well below the average for the entire catena, suggesting deposition, as this segment does occur on the leeward side (prevailing wind direction) of the catena (see Figure 2.3). Soil accretion has occurred on the cultivated shoulder segment, which is generally considered the most active from the standpoint of erosional processes. Kelly (1984) has concluded that over-thickening and compaction of the plow layer accounts for the increase on this landscape segment, because little change in the B/A ratio has occurred (Table 5.2). Mechanical (by farm machinery) and wind deposition may have played a major role in the accretion of soil on this landscape segment.

Table 5.1 -- Comparison of B/A ratios for native shale and cultivated shale catenas (Kelly, 1984).

Landscape segment	% Change solum depth	Native B/A	Cultivated B/A
Summit	-27	3.35	2.40
Shoulder	-42	4.76	2.60
Backslope	-8	4.85	4.04
Footslope	-18	6.10	4.33

Table 5.2 -- Comparison of B/A ratios for native siltstone and cultivated siltstone catenas (Kelly, 1984).

Landscape segment	% Change solum depth	Native B/A	Cultivated B/A
Back Shoulder	-19	4.70	1.90
Summit	-36	5.30	2.40
Shoulder	+22	2.76	2.85
Upper Backslope	-43	3.76	1.62
Lower Backslope (A)	-27	3.84	1.69
Lower Backslope (B)	-30	3.76	2.00
Footslope	-28	3.29	1.76
Toeslope	-32	1.83	1.15

Table 5.3 -- Comparison of B/A ratios for native sandstone and cultivated sandstone catenas (Kelly, 1984).

Landscape segment	% Change solum depth	Native B/A	Cultivated B/A
Summit	-34	2.85	1.42
Shoulder	-34	1.71	0.89
Upper Backslope	-21	2.00	0.06
Lower Backslope	-10	2.56	2.28
Footslope	-20	2.86	1.74
Back Backslope	-27	3.61	3.20
Back Footslope	+20	3.30	3.20

Table 5.4 -- Soil loss calculated by profile reconstruction for cultivated shale catena (Kelly, 1984).

Landscape segment	Soil loss T/ha/yr	Area m2	% of area
Summit	-32.3	1268	19.8
Shoulder	-74.7	1560	24.3
Backslope	-13.2	1940	30.3
Footslope	-66.0	1636	25.6
	*44.0 T/ha/yr	6406 m^2	

*Weighted average for entire field based on area of each landscape segment.

Table 5.5 -- Soil loss calculated by profile reconstruction for cultivated siltstone catena (Kelly,1984).

Landscape segment	Soil loss T/ha/yr	Area m2	% of area
Back Shoulder	-27.3	1160	8.2
Summit	-62.7	840	5.9
Shoulder	+36.9	2180	15.4
Upper Backslope	-62.7	2480	17.6
Lower Backslope (A)	-44.2	2460	17.4
Lower Backslope (B)	-49.7	1600	11.3
Footslope	-54.3	1520	10.8
Toeslope	-59.3	1880	13.4
	*44.0 T/ha/yr	14,120 m^2	

*Weighted average for entire field based on area of each landscape segment.

Table 5.6 -- Soil loss calculated by profile reconstruction for cultivated sandstone catena (Kelly, 1984).

Landscape segment	Soil loss T/ha/yr	Area m^2	% of area
Summit	-47.3	1520	14.9
Shoulder	-53.7	1152	11.2
Upper Backslope	-30.5	1332	13.0
Lower Backslope	-20.1	1080	10.6
Footslope	-43.3	812	7.9
Back Backslope	-63.0	2752	26.0
Back Footslope	+71.3	1572	15.4
	*39.6 T/ha/yr	10,000 m^2	

*Weighted average for entire field based on area of each landscape segment.

Similar trends were observed on the sandstone catena (Table 5.6). The back backslope, summit and shoulder segments have lost 63.0, 47.3 and 53.7 T/ha/yr of soil, respectively. Losses in the lower backslope amounted to 20.1 T/ha/yr, well below the weighted average for the entire catena, suggesting some redistribution of soil to this landscape segment. Soil accretion has also occurred on the back footslope segment located on the leeward side of the catena (Figure 2.4).

Some similarities in soil loss-landscape relationships existed in all three sites. Greater losses occurred in the footslope and toeslope segments than some portions of the backslope, although the former are generally considered to be more depositional in nature than the latter. It has been concluded that, given the complexity of the erosion-depositional patterns observed, the redistribution of soil material by both mechanical and natural processes must be considered when evaluating cultivation-induced soil losses along catenary sequences.

Changes in Organic Soil Constituents Following 44 Years of Cultivation

Organic C, nitrogen, and organic P in the solum (A and B horizons) of the soils in the three paired native-cultivated catenas are listed in Tables 5.7-5.9. The values reported represent the average of the three pedons sampled at each landscape segment. Greatest losses of organic matter in the sandstone and shale catenas have occurred in the summit and convex shoulder areas. Losses of organic C on these landscape segments have amounted to 61%, 33% and 49%, 49% at the sandstone and shale sites, respectively. Somewhat lower losses of nitrogen and organic P have occurred on these landscapes, but the pattern of change is similar. A similar trend is observed in the siltstone site on the summit and back shoulder segments. During mineralization of organic matter there will usually be a narrowing of organic C to N and organic P ratios. This is generally observed, with a few exceptions, at all three sites on those landscape segments having net losses of organic C.

The landscape segments which were shown to have had possible soil deposition (Kelly, 1984) have the lowest losses of organic constituents, and even gains in certain cases. The shoulder segment at the siltstone site, which was shown to have had a net gain of soil material following the 44 years of cultivation, has had a 10%, 14% and 28% increase in organic C, nitrogen and organic P, respectively. Losses of organic C at the shale and sandstone sites are lower in the

Table 5.7 -- Changes in organic constituents at the various landscape segments at the sandstone catena following 44 years of cultivation.

Landscape Segment	kg-m^2 (solum)								
	Organic Carbon			Total Nitrogen			Organic Phosphorus		
	Nat.	Cult.	% Change	Nat.	Cult.	% Change	Nat.	Cult.	% Change
Summit	7.500	2.920	-61***	0.721	0.305	-58***	0.113	0.049	-56***
Shoulder	7.858	5.299	-33***	0.785	0.628	-20***	0.125	0.100	-20**
Upper Backslope	7.935	5.560	-30***	0.751	0.626	-17**	0.130	0.109	-16**
Lower Backslope	10.498	9.810	-7*	1.074	1.000	-7**	0.169	0.208	+23***
Footslope	13.046	9.235	-29***	1.260	0.971	-23***	0.228	0.161	-29***
Back Backslope	11.392	6.938	-39***	1.145	0.748	-35*	0.186	0.134	-28***
Back Footslope	14.223	13.479	-5*	1.285	1.336	+4*	0.215	0.247	+15***

Significance of contrasts based on the means of the three pedons (virgin vs. cultivated)

*** -- $<$ 0.10
** -- 0.10 - 0.40
* -- $>$ 0.40

Table 5.8 - Changes inorganic constituents at the various landscape segments in the siltstone catena following 44 years of cultivation.

Landscape Segment	kg-m^2 (solum) Organic Carbon			Total Nitrogen			Organic Phosphorus		
	Nat.	Cult.	% Change	Nat.	Cult.	% Change	Nat.	Cult.	% Change
Back Shoulder	11.149	6.940	-38***	1.038	0.681	-34***	0.131	0.102	-22***
	9.702	5.964	-39***	0.936	0.609	-35***	0.131	0.084	-36***
Shoulder	10.354	11.392	+10*	0.985	1.124	+14*	0.122	0.156	+28***
Upper Backslope	12.212	6.264	-49***	1.170	0.549	-53***	0.162	0.093	-43***
Lower Backslope (A)	12.522	6.719	-46***	1.153	0.585	-49***	0.181	0.098	-46***
Lower Backslope (B)	12.412	5.515	-56***	1.254	0.564	-55***	0.148	0.088	-41***
Footslope	12.905	7.814	-39***	1.246	0.735	-41***	0.151	0.101	-33***
Toeslope	15.776	10.335	-34***	1.488	1.050	-29*	0.201	0.159	-21***

Significance of contrasts based on the means of the three pedons (virgin vs. cultivated)

*** -- < 0.10
** -- 0.10 - 0.40
* -- > 0.40

Table 5.9 -- Changes in organic constituents at the various landscape segments in the shale catena following 44 years of cultivation.

Landscape Segment	kg-m^2 (solum)								
	Organic Carbon			Total Nitrogen			Organic Phosphorus		
	Nat.	Cult.	% Change	Nat.	Cult.	% Change	Nat.	Cult.	% Change
Summit	10.916	5.622	-49***	1.115	0.666	-40***	0.080	0.067	-16*
Shoulder	13.548	6.934	-49***	1.326	0.797	-40***	0.158	0.089	-44***
Backslope	13.868	9.884	-29***	1.374	1.106	-20***	0.151	0.159	+5*
Footslope	19.092	12.670	-34***	2.163	1.489	-31***	0.248	0.216	-13**

Significance of contrasts based on the means of the three pedons (virgin vs. cultivated)

*** -- < 0.10
** -- 0.10 - 0.40
* -- > 0.40

backslope and lower backslopes, respectively, as was observed with total soil loss on these segments (Kelly, 1984). Current research in the Canadian prairies evaluating changes in organic matter along native and cultivated toposequences suggests that mineralization rates are higher in footslope segments than in backslopes. Anderson[2] attributes these differences to higher moisture contents and therefore greater biological activity at the footslope segment. Greater soil losses and higher mineralization rates were probably responsible for the higher organic P losses in the footslope vs. backslope segments at our sandstone and shale sites.

Net gains in organic P are observed in every landscape segment that was shown to be depositional in nature. These segments are the backslope in the shale catena, the lower backslope and back footslope in the sandstone catena and shoulder segment in the siltstone site. The probable cause for this may be the deposition of coarse clay and fine silt material enriched with highly humified organic matter with a larger proportion of recalcitrant organic P.

Mineralization losses, crop removal of nutrients released from decomposing organic matter and erosional losses all contribute to the total quantity of nutrients lost when soils are subjected to continuous cultivation. Mineralization rates in soils within a given environment vary appreciably as a function of soil textural characteristics. As pointed out earlier in Chapter Three, the total amount of water held is much lower in the coarse-textured sandstone soils than in the finer soils weathered from siltstone and shale.

2 Darwin W. Anderson, Professor of Soils, Dept. of Soils, Univ. of Saskatchewan, Saskatoon (personal communication).

The sandy soils are thus subjected to more frequent and extreme changes in moisture contents than the finer textured soils found on the siltstone and shale sites.

Birch (1960) showed that frequent wetting and drying cycles cause fluctuations in carbon, nitrogen and other nutrients in soils. Black (1968) suggested that some of the active microbial cells are killed when the soil is dried out. Upon rewetting, new microbial populations will utilize this additional source of organic matter for their energy sources and, subsequently, microbial populations will greatly increase resulting in higher mineralization rates. In addition, wetting and drying cycles can cause swelling and shrinking of the soil which may physically disrupt some of the otherwise stable organic matter causing the exposure of new surfaces for microbial attack.

Recently, Schimel (1982) reported that organic matter turnover rates were greater in the coarser textured soils along a catena in a short-grass prairie steppe. Apparently deeper penetration of precipitation during the infrequent, often violent thunderstorms resulted in overall greater moisture storage at depth in the sandier soils. Schimel (1982) suggested that water vapor gradient flows towards the surface during cool night time temperatures were greater in the coarser textured soils resulting in increased mineralization. Mineralization rates within a catena with relatively uniform parent material are likely to vary as a function of landscape position because changes in soil moisture content.

Schimel has been studying N-mineralization rates of soils on various slope positions at our three study sites under controlled laboratory conditions. He has found that the coarse-textured soils at the sandstone site have the highest mineralization rates at field capacity moisture conditions.[3] These findings further support our hypothesis that the turnover rates of organic pools are higher in the coarser sandstone soils. The organic matter fractions would tend to be younger and less humified in the soils at our sandstone site if these pools are being turned over (mineralized) more rapidly than at the other two sites.

The total amount of organic constituents lost or gained in the soils at our three sites was plotted against the total quantity of soil lost or gained. The relationship between the losses of organic C, N and P and soil losses at each landscape segment was then tested with simple linear regression analysis (Table 5.10). Although losses of soil organic constituents are not directly proportional to soil losses, we feel that evaluating the strength of a simple linear relationship between these two variables can provide some useful information. If losses by mineralization and crop removal have varied in the three sites over the 44 year period in which they have been cultivated, the strength of the relationship between organic matter and soil loss should vary accordingly. The sites with the lowest amounts of mineralization and crop removal should have the strongest relationship between the organic C, N, and P loss vs. soil loss. I acknowledge that many more data points are necessary on our nutrient vs. soil loss plots in order to make strong statistical inferences based on the regression models generated. However, the regression analyses do represent an approach that could be further evaluated in a

3 David S. Schimel. Research Ecologist, Natural Resources Ecology Laboratory, Colorado State University (personal communication).

study designed specifically for this purpose. By sampling a larger number of pedons at specific landscape segments in catenas of similar parent material, this approach could distinguish changes in organic matter resulting from soil redistribution, mineralization and crop removal.

Table 5.10 - Summary of regression models for the relationship between nutrient losses and soil loss at the three catenas.

Organic C vs. Soil Loss:		
Sandstone:	$Y = 2.07 + 0.006X$;	$R^2 = 0.52$
Siltstone:	$Y = 2.47 + 0.013X$;	$R^2 = 0.75$
Shale :	$Y = 3.66 + 0.009X$;	$R^2 = 0.96$
Total N vs Soil Loss:		
Sandstone:	$Y = 0.121 + 0.001X$;	$R^2 = 0.62$
Siltstone:	$Y = 0.127 + 0.002X$;	$R^2 = 0.70$
Shale:	$Y = -0.230 + 0.127X$;	$R^2 = 0.83$
Organic P vs. Soil Loss:		
Sandstone:	$Y = 0.004 + 0.0002X$;	$R^2 = 0.51$
Siltstone:	$Y = 0.014 + 0.0002X$;	$R^2 = 0.75$
Shale:	$Y = -0.023 + 0.0002X$;	$R^2 = 0.88$
Total P vs. Soil Loss:		
Sandstone:	$Y = 0.034 + 0.0005X$;	$R^2 = 0.76$
Siltstone:	$Y = -0.021 + 0.0008X$;	$R^2 = 0.79$
Shale:	$Y = 0.014 + 0.0008X$;	$R^2 = 0.93$

Figure 5.2 shows the relationship between the total quantity of organic C loss (kg m-2 in solum) and soil loss (kg m-2 in solum) at our three sites. The differences in erosional patterns which were observed by Kelly (1984) are nicely reflected in the three plots. The pattern of organic C loss relative to soil loss in the shale site (Figure 5.2), which was shown to have the simplest erosional-depositional patterns, reflects a strong linear relationship, $R^2 = 0.96$. Recall, the shoulder segment was shown to have lost the greatest quantity of soil at this site, while the backslope was shown

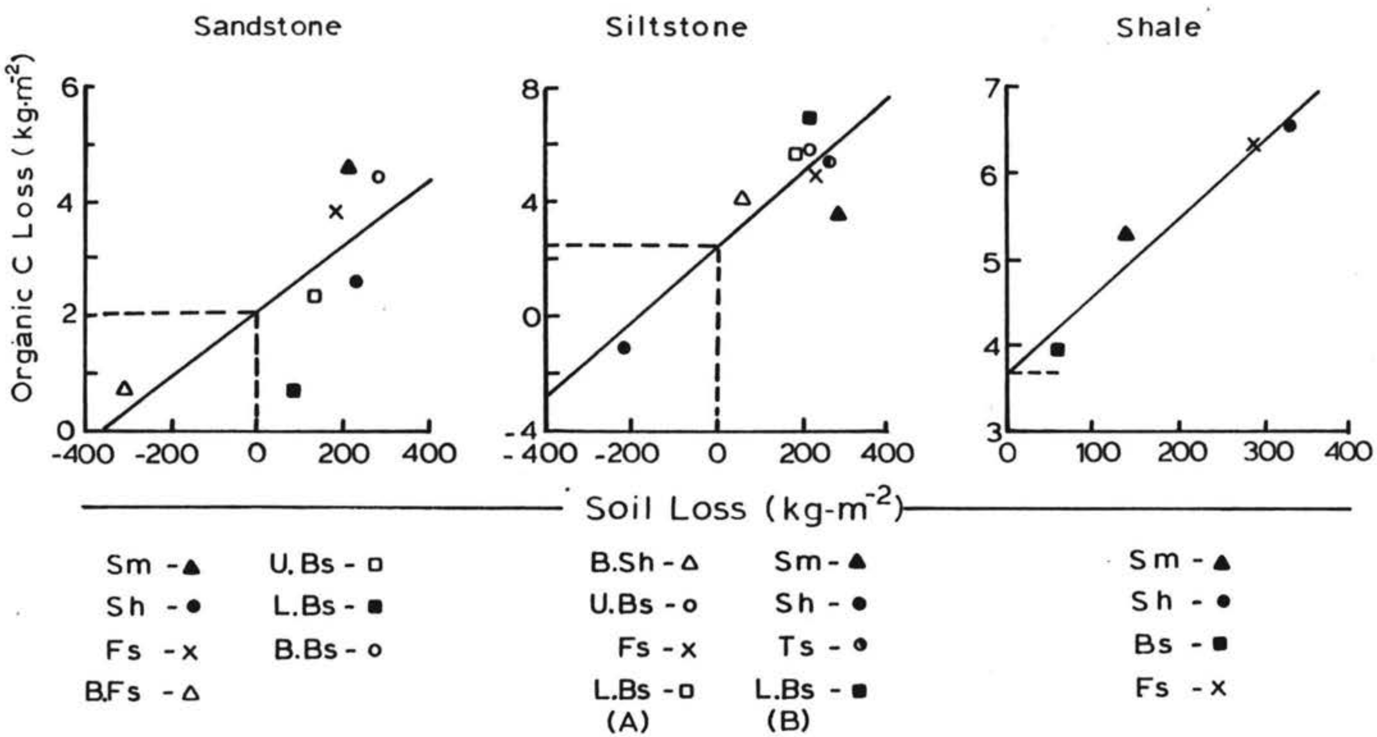

Figure 5.2 - Relationship between organic carbon and soil loss (or gain) in the three catenas.

to have lost lower quantities than the footslope segment. Mineralization losses of organic C may be much higher in the footslope segment at this site due to higher moisture contents. This, coupled with lower losses of soil at the backslope segment may account for the apparent anomaly of greater organic C loss relative to soil loss at the footslope segment. It is interesting to note that, based on this relatively simple regression model, average losses of organic C over the entire catena following 44 yr of cultivation would amount to about 3.6 kg m^{-2}, if no soil losses had occurred (Y-intercept at 0 soil loss). Furthermore, the model can also predict the amount of organic C losses that would be offset by gains in soil (negative soil loss).

Sorting of the initial parent material by erosional processes may also contribute to the changes in the organic matter content of soils following cultivation. In those landscape segments where deposition of organic matter-enriched sediments have occurred there will be an increase in the total quantity of organic C, N, and P. Similarly, where erosional processes have resulted in the preferential removal of the finer textured particles with a subsequent increase in coarser particle-size fractions, there may be a dilution of the organic matter content in the soils. The relationship between organic matter and soil loss will be weakened somewhat if these processes have occurred to a large extent. Thus, even if mineralization and crop removal losses were minimal, sorting of soil material and its associated organic constituents will tend to weaken the overall relationship between nutrient and soil losses. Sorting, resulting in the deposition of finer soil material may explain the apparent lower losses of organic C on the backslope of the shale site.

At the siltstone site, the overall relationship between organic C and soil losses is somewhat weaker, $R^2 = 0.75$. This site was shown to have the overall greatest amount of soil losses and a very complex erosional-depositional pattern. The large gain (accretion) in soil material at the shoulder segment is accompanied by a gain in organic matter. The back shoulder segment has lost approximately 0.5 kg m^{-2} more organic C than the summit, which has had a greater loss of soil. Slightly higher effective precipitation resulting in higher mineralization losses at the back shoulder may account for the difference because Kelly's (1984) data showed that both of these segments have experienced similar changes in textural properties. Both of these landscape segments have had an overall reduction in solum depth and an increase in clay content in the surface horizons resulting from the incorporation of finer subsurface material. Furthermore, based on solum depth comparisons with the adjacent virgin benchmark soils, the back shoulder and the summit were shown to have had a net loss (vol.-weight basis) of sand and silt-sized particles. The lower backslope (B) segment has had a net gain of 31% in the total quantity of sand compared to the virgin site. This may partly explain the higher losses of organic C relative to soil loss, based on the overall predictive model for the entire catena. The organic C vs. soil loss relationships in the other segments at this site are more difficult to interpret and may reflect a number of site specific soil loss - sorting - mineralization relationships because the nature of the soil parent material does vary within these landscape segments. The regression model again predicts that an appreciable quantity of organic C (2.47 kg m-2) would have been lost if no losses of soil would have occurred in the catena during the 44 yr of cultivation (Figure 5.2).

The organic C vs. soil loss pattern at the sandstone site reflects a much weaker linear relationship than the other two sites, $R^2 = 0.52$. As discussed earlier, the coarse-textured soils at this site probably have had the overall highest turnover rates of organic matter. Mineralization rates are probably more variable along the segments of this catena because of greater variability in moisture conditions. These conditions may be responsible for a large portion of the variability observed in the organic C - soil loss relationship for the entire catena (Figure 5.2).

The back footslope in the sandstone site has likely gained substantial quantities of organic matter through deposition. However, mineralization rates are probably much higher in this segment because of greater moisture available for biological activity, due to its position in the landscape and its east aspect (Figure 2.4). Greater mineralization losses of organic C have probably occurred at this segment offsetting the gains resulting from soil accretion. The large losses in organic C at the summit segment may, in part, be due to the loss of finer soil particles with a subsequent increase in coarser material of lower organic matter content. Kelly (1984) reported an 88% net loss of clay (vol.-wt basis) from the solum at this segment. Again, the regression model predicts that a substantial amount of organic C would have been lost from the soils at this site even if no net soil loss had occurred during the 44 years of cultivation (Y-intercept = 2.07 kg m^{-2} at 0 soil loss).

Nitrogen-soil loss patterns are similar to organic C on the three sites. However, organic P is cycled more conservatively than carbon and nitrogen, which are more readily lost by leaching and volatilization (Stewart and Tiessen, 1984). Batsula and Krivonosova (1973) reported that the proportion of non-hydrolyzable to hydrolyzable organic P in humic and fluvic acids doubled upon cultivation. The quantity of organic P losses or gains relative to soil losses (or gains) at each landscape segment along the three catenas is plotted in Figure 5.3. A weaker relationship between these two variables is observed at the sandstone site, $R^2 = 0.51$, than at the shale and siltstone sites, $R^2 = 0.88$ and $R^2 = 0.75$, respectively. Higher losses of organic P at the footslope vs. summit and backslope segments in the shale catena probably reflect greater mineralization losses. However, less organic P appears to have been lost at the footslope segment relative to organic C. The ratio of organic C to organic P loss decreases from about 400 at the summit segment to 200 at the footslope. Thus, it appears that less organic P is lost by mineralization relative to organic C in the finer textured shale soils, particularly in the lower elevations where older, more humified organic matter may have accumulated through deposition.

The strength of the relationship between organic P and soil loss in the sandstone and siltstone sites is not much different than those observed for organic C (Table 5.10). This suggests that organic C and P cycling and redistribution by erosional processes are somewhat more closely linked with one another in the sandstone and siltstone soils. As pointed out earlier, much of the total quantity of organic P in the finer shale soil may be associated with highly humified,

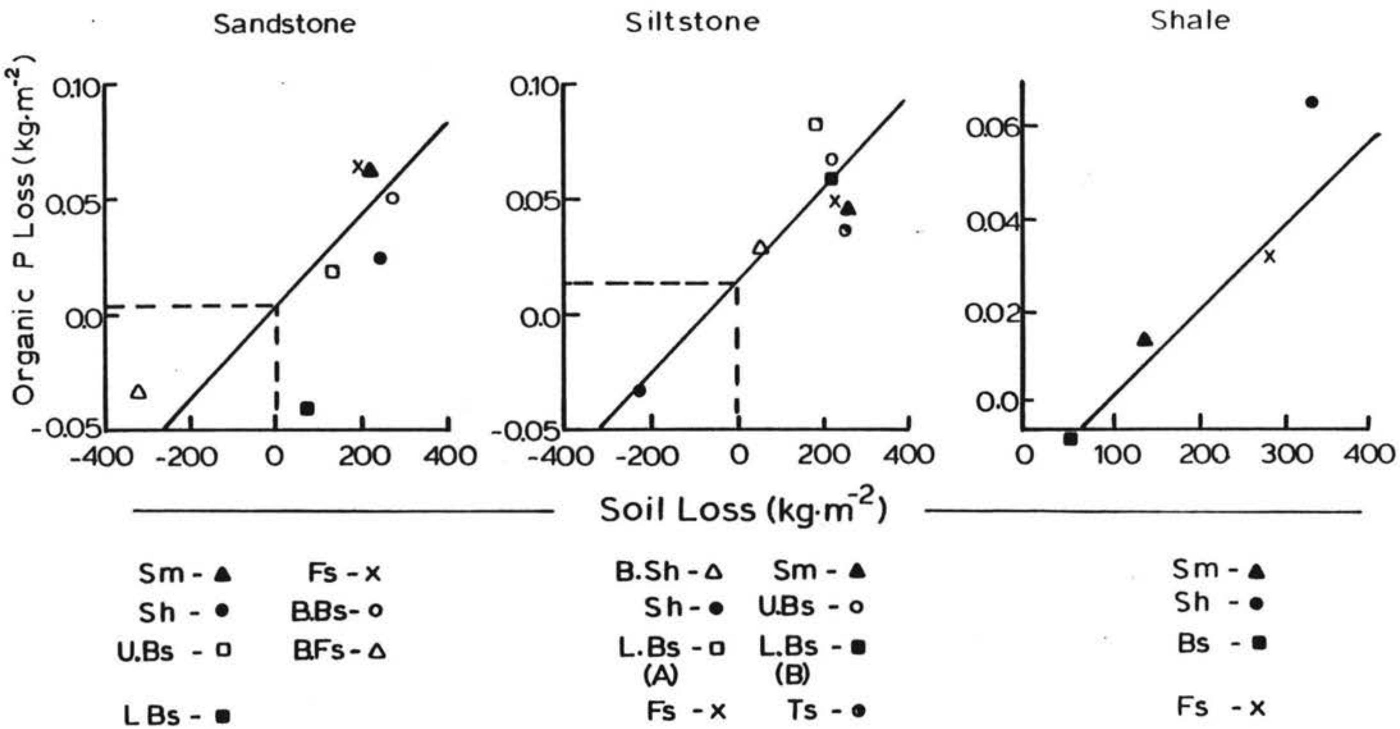

Figure 5.3 - Relationship between organic phosphorus and soil loss (or gain) in the three catenas.

physically protected organic matter that is quite resistant to further mineralization upon cultivation.

Changes in Total and Inorganic Phosphorus Following 44 Years of Cultivation

The quantities (vol.-wt. basis) of total and inorganic P in the three paired native-cultivated catenas are listed in Tables 5.11-5.13. Unless otherwise noted, values reported represent only one pedon at the various landscape segments.

Changes in the levels of total P are more closely linked to erosion and depositional processes than changes in organic soil constituents because total P is independent of mineralization losses. Mineralization processes merely affect the ratios of organic and inorganic P to total P, but not the total quantity of phosphorus in the soils. The data in Tables 5.11-5.13 show that total and inorganic P have increased in those landscape segments which were shown to have had net gains (accretion) of soil material due to depositional processes. These segments are the back footslope in the sandstone site and the shoulder segment in the siltstone catena. Total P and inorganic P have increased by 63% and 62%, respectively, in the shoulder segment of the siltstone site and by 15% and 16%, respectively, in the back footslope of the sandstone site. The landscape segments which were shown to have the greatest quantities of soil loss have experienced the highest losses of total and inorganic P. The summit, shoulder and back backslope segments on the sandstone catena have had average reductions in total P of 59%, 29% and 38%, respectively, while inorganic P has been reduced by 47%, 39% and 41% on these segments. The siltstone site has had average reductions in

Table 5.11 -- Changes in total and inorganic phosphorus at the various landscape segments in the sandstone catena following 44 years of cultivation.

	kg-m2 (solum)					
	Total Phosphorus			Inorganic Phosphorus		
Segment	Nat.	Cult.	% Change	Nat.	Cult.	% Change
Summit	0.312	0.129	-59	0.199	0.106	-47
Shoulder	0.313	0.222	-29	0.188	0.114	-39
Upper Backslope	0.270	0.252	-7	0.151	0.129	-15
Lower Backslope	0.624	0.516	-17	0.418	0.338	-19
Footslope	0.586	0.485	-17	0.358	0.306	-15
Back Backslope	0.557	0.346	-38	0.372	0.220	-41
Back Footslope	0.679	0.781	+15	0.464	0.537	+16

Table 5.12 -- Changes in total and inorganic phosphorus at the various landscape segments in the siltstone catena following 44 years of cultivation.

	kg-m2 (solum)					
	Total Phosphorus			Inorganic Phosphorus		
Segment	Nat.	Cult.	% Change	Nat.	Cult.	% Change
Back Shoulder	0.311	0.291	-6	0.196	0.189	-4
Summit	0.463	0.248	-46	0.332	0.183	-45
Shoulder	0.324	0.529	+63	0.208	0.337	+62
Upper Backslope	0.470	0.227	-52	0.304	0.137	-55
Lower Backslope (A)	0.363	0.205	-44	0.206	0.104	-50
Lower Backslope (B)	0.460	0.230	-50	0.306	0.131	-57
Footslope	0.363	0.242	-33	0.212	0.147	-31
Toeslope	0.436	0.353	-19	0.252	0.189	-25

Table 5.13 -- Changes in total and inorganic phosphorus at the various landscape segments in the shale catena following 44 years of cultivation.

	kg-m2 (solum)					
	Total Phosphorus			Inorganic Phosphorus		
Segment	Nat.	Cult.	% Change	Nat.	Cult.	% Change
Summit	0.498	0.392	-21	0.418	0.315	-25
Shoulder	0.781	0.530	-32	0.601	0.378	-37
Backslope	0.778	0.709	-9	0.626	0.561	-10
Footslope	1.155	0.875	-24	0.907	0.662	-27

total and inorganic P ranging from 6% to 52% and 4% to 57%, respectively, with the greatest losses occurring in those landscapes which were shown to have lost the largest quantities of soil (compare Table 5.5 and Table 5.12).

Similar total P-soil loss patterns are observed in the shale site (Table 5.13). The greatest losses of total and inorganic P have occurred on the highly eroded shoulder segment. Although the backslope segment on this site has had a net loss of soil, Kelly (1984) showed that there has also been deposition of soil material offsetting the overall erosional losses. This is reflected by lower losses of total and inorganic P at this segment.

Simple linear regression analyses were employed to evaluate the strength of the relationship between total and inorganic P loss and soil loss in the three catenas. Figure 5.4 shows the relationship between the quantity of total P loss vs. soil loss on each landscape segment at the three sites. A much stronger relationship between the two variables is observed compared to the relationship previously shown for organic constituents. The overall relationship between total P and soil loss is strongest in the fine-textured soils at the shale site, $R^2 = 0.93$. The same relationship is somewhat weaker in the medium and coarse-textured soils at the siltstone and sandstone sites, $R^2 = 0.79$ and 0.76, respectively.

Cultivation induced accumulations of coarser soil material may account for the higher losses in total P relative to soil loss at the footslope segment on the shale site than was predicted by the total P - soil loss model for the entire catena. Kelly (1984) has shown that the soils on this landscape segment have had a net gain of sand

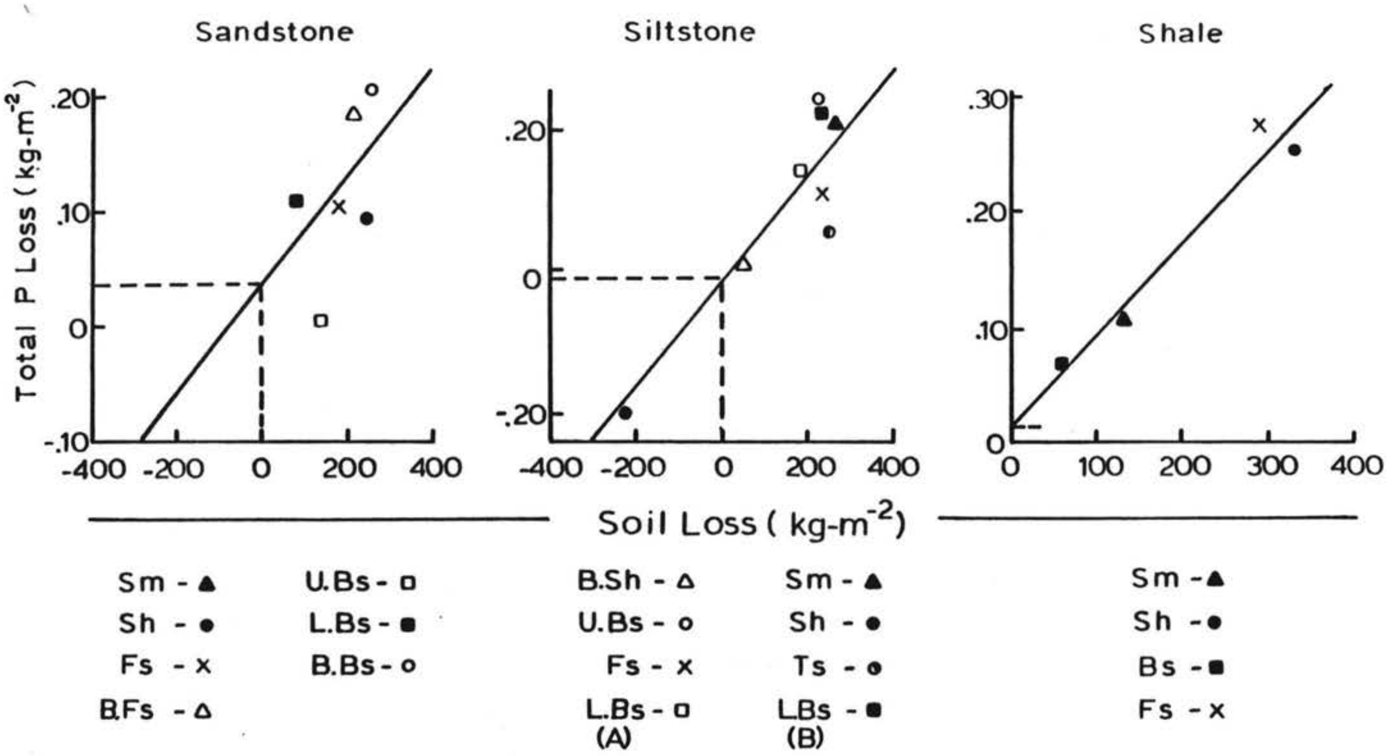

Figure 5.4 - Relationship between total phosphorus and soil loss (or gain) in the three catenas.

relative to their native counterparts. It was also shown that the cultivated soils at the summit and shoulder segments have had greater proportionate losses in sand content, 37% and 58%, respectively, than clay content (24% loss from summit and 25% loss from shoulder) as a result of erosional processes. This may explain why these two segments have had lower losses of total P than is predicted by the regression model (Figure 5.4). Note that the predicted average losses of total P across all landscape segments on this site are very small if no losses of soil had occurred ($Y = 0.014$ kg m^{-2} at 0 soil loss). These losses are likely attributable to crop removal.

Patterns of total P and soil loss are more difficult to interpret in the siltstone and sandstone sites. As previously mentioned, the parent material is not entirely homogeneous at the siltstone site and thus sorting of soil material by erosional processes will have a large influence on changes in the quantities of total P. Those landscapes receiving inputs of coarser material with lower total P concentrations will experience an accompanying dilution in total P relative to their native counterparts. Similarly, those landscapes receiving inputs of finer material with higher total P concentrations will become enriched in total P relative to the native benchmark soils. Sorting by erosional and depositonal processes has resulted in disproportional losses or gains of total P relative to soil losses or gains at numerous segments along the siltstone and sandstone catenas. Mechanical movement by tillage equipment is likely responsible for some of the sorting which has occurred on these two sites. Kelly (1984) concluded that sorting by wind erosion has been more active on these two sites than on the shale site. The combination of all these processes explain the overall weaker relationships between total P and soil loss indicated by the regression models for the sandstone and siltstone sites (Table 5.14). It is interesting to note that the regression model for the siltstone catena predicts a slight gain in total P (0.021 kg m^{-2}) if no soil losses had occurred (Y = -0.021 kg m-2 at 0 soil loss). If this prediction were valid one would suspect that these gains in phosphorus would have come about from fertilizer inputs. However, very little fertilizer inputs have taken place on the siltstone site (see Appendix 1 - Site Histories). The apparent discrepancy of predicting small gains in phosphorus is probably due to "noise" in the regression model resulting from the extensive sorting of soil material which has occurred on the site.

Summary -- Management (Cultivation) Effects on Soil - Parent Material - Landscape Interactions

Profile reconstruction was used to assess changes in organic and mineral soil constituents along the catenas resulting from 44 years of a wheat-fallow rotation. The method allowed more realistic comparisons between our virgin and cultivated soils because losses (or gains) resulting from erosion-depositional processes could also be taken into account. Redistribution of soil material by both natural and mechanical (tillage practices) processes must be considered when evaluating changes in nutrients resulting from cultivation.

The greatest losses of organic and inorganic soil nutrients were shown to have occurred on those landscape segments where the greatest losses of soil had occurred. These were generally the upland positions (summits, shoulders, and upper backslopes) in the catenas. One exception to this was the shoulder in the siltstone catena which has had a substantial increase in soil material accompanied by a net gain in organic C, N and P, total and inorganic P. Losses of organic C and nitrogen were higher than losses of organic P in those landscape segments having net organic matter losses. Organic P cycling is generally more conservative than organic C and N because the latter two are more readily lost from the soil by volatilization and leaching. In general, nitrogen losses were lower than organic C, reflecting greater gaseous losses of carbon.

Mineralization of organic soil constiuents appears to vary as a function of parent material. It appears that mineralization losses from the finer shale soils are lower than losses from the siltstone and sandstone soils. This is consistent with our previous suggestions that a higher proportion of the organic pools in the shale soils consists of highly humified, physically protected organic matter. Based on the weak relationship between organic C and soil loss in sandstone site it appears that a larger proportion of the organic matter in these soils has been lost through mineralization and/or crop removal. This further suggests that the organic matter fractions in the sandstone soils are less humified (younger pools) because of overall more rapid turnover rates. Mineralization losses have apparently been greater at the wetter, lower landscape segments in all three sites.

Changes in total P at all three sites are much more closely linked to the redistribution and sorting of soil material. This was not unexpected because the total quantity of phosphorus is independent of transformations between organic and inorganic pools in soils. In addition to changes resulting from soil redistribution and sorting, losses of phosphorus must be due almost entirely to crop removal. The nature of soil redistribution and sorting appears to be strongly related to the textural properties imparted to the soils by parent material. This in turn has played a major role in the extent of redistribution of both organic and inorganic nutrients within the catenas.

SUMMARY AND CONCLUSIONS

A large portion of the semiarid Great Plains of North America has been cultivated in the last 50 to 100 years. The organic matter content and nutrient status of many soils in the Great Plains region have seriously declined since they were first plowed. Soil organic matter losses are a major concern because in addition to being a primary source of plant nutrients, organic matter is essential in maintaining important soil physical properties such as water-holding capacity and tilth. Because of an increase in erosion potential due to the disruption of grass cover and alteration of soil structure, a significant reduction in profile depth can occur in soils subjected to long-term cultivation. Profile comparisons between virgin and cultivated soils can aid in assessing the changes in the total quantity of organic and inorganic soil constituents resulting from cultivation.

The use of profile reconstruction to evaluate changes in soils resulting from cultivation practices allows the assessment of the quantity of mineral and organic soil constituents lost by erosion, in addition to crop removal and mineralization. Furthermore, comparing the chemical and physical properties of Ap horizons in cultivated soils with those of A horizons in similar virgin soils to assess the changes brought about by cultivation is unrealistic. Mixing of surface horizons high in organic matter content with subsurface material will in itself alter chemical and physical properties and lower the organic matter content of the surface soil.

Paired native and cultivated soils on catenas weathered in three distinct and contrasting parent materials were characterized and sampled in southwestern North Dakota in order to evaluate the changes brought about by 44 years of a wheat-fallow rotation. Primary objectives of the study included (1) evaluating the parent material and landscape interactions which control the levels of organic C, N, P and total and inorganic P in these semiarid grassland soils, and (2) assessing the long-term effects of cultivation on these nutrients as a function of parent material and topography. The results of this study will aid in developing and fine-tuning simulation models on nutrient cycling in semiarid grassland ecosystems.

Parent Material Controls on Soil Processes

The amounts, vertical distribution and the nature of organic C, N and phosphorus (total, organic and inorganic) were shown to vary in the soils of three contrasting parent materials. The levels of these constituents were strongly influenced by the total and plant-available water-holding capacity and permeability characteristics of the soils. These physical properties were largely controlled by textural characteristics imparted to the soils by the contrasting parent materials. The highest levels of organic C were observed in the fine-textured shale soils. Much of this organic C appears to be associated with highly humified, physically protected organic matter, particularly in the subsurface horizons. Clays play an important role in protecting organic matter from decomposition. This process has resulted in greater quantities of organic C in the shale soils.

The coarse-textured sandstone soils, with the lowest water-holding capacity, were found to have the lowest quantities of organic C and N. However, these soils were found to have the highest quantities of organic P at every comparable landscape in the three catenas. It appears that the organic matter pools are generally less humified (younger) in the sandy soils because of more rapid turnover rates. Although they were found to have the lowest quantities of total and inorganic P, high productivity appears to be sustained in the sandy soils by the high levels of organic P.

The nature of the inorganic P pools is different in the three contrasting soils. The medium-textured soils weathered in siltstone have a much higher proportion of acid-soluble P, particularly in the partially weathered C horizons. The sandstone and shale soils are lower in acid-soluble P and contain larger proportions of residual P. Approximately 40% of the total phosphorus in the surface horizon of the shale soil at the native-summit segment is residual in nature. Much of this residual P was possibly due to the accumulation of secondary Fe and Al phosphates or physically protected, acid-insoluble phosphate.

A large proportion of the residual P in the partially weathered C horizon of the sandstone soils probably consisted of primary apatite inclusions within the quartz grains. Quartz minerals are quite resistant to weathering and the large proportion of inorganic P in this form may significantly affect the overall availability of phosphorus in the sandstone soils. This may become particularly important if the organic P pools are further depleted from these soils through cultivation practices.

Topographic Controls on the Levels of Organic and Inorganic Constituents in the Three Catenas

Much of the topographic variation in organic matter on the native portions of the three catenas is due to increasing moisture, resulting in higher plant productivity in the lower landscape segments. However, the redistribution of soil material by erosional processes has played a role in the enrichment of organic and inorganic constituents at the lower elevations of all three sites. These processes appear to have been more active over time in the finer textured soils on the shale and siltstone catenas. Total organic C contents increase by 27%, 31%, and 21% upon moving from the summit to footslope segments on the sandstone, siltstone and shale sites, respectively. Organic matter concentrations in the mollic epipedon increase significantly in the sandstone site upon moving from the summit to footslope segments, but not in the shale and siltstone sites. This suggests that greater accumulations of organic matter-enriched material through time at the lower segments in the finer textured soils may have caused the greater quantities of organic C.

The shoulder segment was found to have lower quantities of total and inorganic P than adjacent segments at all three sites, indicating the loss of phosphorus over time. These losses could be accounted for by significantly greater total P quantities at the footslope segments because all three sites are components of open drainage systems. Phosphorus has apparently moved out of the lower landscape segments of the catenas and into the major drainage systems of the surrounding areas in association with finer textured soil material.

Cultivation Effects on the Levels of Organic and Inorganic Soil Constituents

Long-term cultivation practices have resulted in considerable changes in the vertical distribution and total quantity of organic and inorganic soil constituents along the three catenas. The greatest depletions of organic and inorganic matter have occurred in those landscape segments experiencing the greatest losses of soil. These were generally the upland positions in the catenas. One exception to this was the siltstone site where a substantial increase in soil material at the shoulder segment, probably due to mechanical movement, has resulted in net gains in every organic and inorganic nutrient measured. Losses of organic P have generally been much lower than organic C and N. Organic C and N are more readily lost from the soil by volatilization and leaching while phosphorus is not subject to volatilization or leaching losses and is readily retained in the soil. Nitrogen losses were generally lower than organic C in those landscape segments experiencing a net loss of soil, reflecting much greater gaseous losses of organic C.

Mineralization losses of organic matter were shown to vary as a function of parent material. Losses from the finer shale soils were lower than losses in the medium and coarse-textured siltstone and sandstone soils, respectively. This suggested that the shale soils have a greater proportion of highly humified, physically protected organic matter. The weak relationship between organic C and soil loss in the sandstone catena suggested that the organic constituents in these soils were more readily lost through mineralization and/or crop removal. Mineralization losses at all three sites appear to have been greater in the wetter segments at lower elevations.

Changes in total P were more closely linked to erosion and depositional processes because the quantity of total P is independent of mineralization losses. Mineralization processes affect the ratios of organic and inorganic P to total P, but not the total quantity of phosphorus in soils. Major losses of total P from the soils at our three sites have therefore been attributed to soil losses and some crop removal.

Sorting of soil material by erosion and depositional processes has apparently contributed to some of the change in the levels of both organic and inorganic soil constituents along the catenas. The extent and mode of soil redistribution and sorting appears to be strongly related to the textural properties of the soils. These processes have been more active in the medium and coarse-textured siltstone and sandstone soils which are more susceptible to wind erosion.

Parent material and topography are important in determining the morphological, physical, and chemical characteristics of soils in semiarid grassland ecosystems. Changes in these soil properties brought about by long-term cultivation will also vary as a function of parent material and topography. The results of this study have shown that it is important to establish the nature of the initial parent material and its influence on soil-forming processes. Textural characteristics imparted to soils by contrasting parent materials can have a considerable influence on processes controlling the accumulation and turnover of organic matter in semiarid regions. Variations in geomorphic and pedogenic processes, resulting from changes in topography, can have an equally important influence on the accumulation of organic matter along a catena with relatively uniform parent material. On landscapes displaying large topographic variation, the effects of cultivation can be more adequately assessed by evaluating the entire landscape sequence. Changes imposed on soils at any landscape segment will likely affect others along a catena.

The study of agroecosystems at the catena level can provide invaluable information about the modifications of topography on soil processes influencing nutrient cycling and organic matter production. Furthermore, because many areas that are currently being cultivated display some degree of topographic variation, studying the entire toposequence is essential when assessing the overall effects of these practices on soil properties.

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APPENDIX 1 - MANAGEMENT AND FERTILIZER HISTORIES FOR THE THREE CULTIVATED SITES

All three cultivated sites where broken out of native sod approximately 44 years ago. Aerial photographs taken in 1936 and a second flight in 1940 showed that all sites were first plowed sometime during this four year period. The predominant use for the sites has been wheat production. However, the sandstone site was used for sunflower, oats and corn production between 1978 and 1982, and barley was grown on the shale site during the 1980 growing season. The siltstone site has predominantly been used for wheat production in the last 20 years, but some barley and oats where grown on this site during the 11 year period between 1947 and 1958. Fertilizer inputs have been minimal on the sandstone and siltstone site since 1962, while the shale site has had only small amounts of fertilizer inputs in the past three years.

SANDSTONE SITE --

Owner or Manager	Crop	Tillage Equip.	Fertil. Inputs
(1978-82) John Meier Carson, N.D.	Wheat, Fallow, Sunflowers, Oats, Corn	Mold-Board Plow, Drill, Noble Plow	56 kg/ha 18-46-0 on Fallow 56 kg/ha 25-25-0 on Stubble
(1939-78) Ed Johnson Carson, N.D.	Wheat, Fallow	Mold-Board Plow, Chisel Plow	56 kg/ha 25-25-0 or 56 kg/ha 18-46-0 1962-77 None, Prior to 1962

SILTSTONE SITE --

Owner or Manager	Crop	Tillage Equip.	Fertil. Inputs
(1980-82) Lyle Zimerman Carson, N.D.	Wheat, Fallow	Chisel Plow, Noble Plow	None
(1964-80) Darwin Deihl Carson, N.D.	Wheat, Fallow	Mold-Board Plow, Chisel Plow	56 kg/ha 18-46-0 or 56 kg/ha 11-48-0 1962-77
(1958-64)	---- Owner or Manager Unknown ----		
(1947-58) Emil Miller Carson, N.D.	Wheat, Fallow, Oats, Barley	Mold-Board Plow	None
(prior to 1947)	---- Owner or Manager Unknown ----		

SHALE SITE --

Owner or Manager	Crop	Tillage Equip.	Fertil. Inputs
(1979-82) Jim Hauge Leith, N.D.	Wheat, Barley, Fallow	Chisel Plow, Press Drill	67 kg/ha 18-46-0 1980-82 None on Fallow
(1958-79) Ellis Sabin Morrison, N.D.	Wheat, Fallow	Mold-Board Plow,	None
	Site was in Soil Bank between 1958-63 and was seeded to Broome Grass in 1963. Wheat-fallow rotations were started again in 1968.		
(1945-58) Bob Well Elgin, N.D.	Wheat, Fallow	Chisel Plow	None
(prior to 1945)	---- Owner or Manager Unknown ----		

APPENDIX 2 -- PHYSICAL AND CHEMICAL DATA FOR THE SOILS ALONG THE CATENARY SEQUENCES

The physical and chemical data listed in this Appendix represent the average of three pedons for each landscape segment. Pedon data was averaged by genetic horizon. Total P measurements were made for only one pedon per landscape segment, except at the summit and footslope segments in the native portions of each catena. At these landscape segments all three pedons characterized in the field were analyzed for Total P. The phosphorus data marked by an asterisk (*) in the following tables represent the pedon sampled at the center point of the rosette pattern in the landscape segments where Total P was measured for only one pedon. Particle-size data and textural class names were taken from Kelly (1984).

TABLE A-1 -- PHYSICAL AND CHEMICAL DATA FOR THE SANDSTONE - NATIVE - SUMMIT SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-14	A	1.29	71.0	15.7	13.3	SL	6.9	0.4	0.61
14-32	Bw	1.30	65.9	12.5	21.6	SCL	7.3	6.0	0.48
32-48	BCk	1.37	61.9	18.7	19.4	SCL	7.5	13.8	0.31
48-71	Ck1	1.47	66.6	10.7	22.7	SCL	7.7	12.9	0.31
71-99	Ck2	1.46	72.7	12.7	14.6	SL	7.8	14.5	0.29

			mg kg^{-1}						
Depth (cm)	Horiz	% Org. C	Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-14	A	1.73	1610	8.3	490	212	278	156	121
14-32	Bw	1.12	1150	1.4	476	193	282	202	80
32-48	BCk	0.77	698	0.7	502	141	361	289	289
48-71	Ck1	0.48	415	0.6	489	76	413	294	294
71-99	Ck2	0.25	249	0.5	542	83	459	263	263

TABLE A-2 -- PHYSICAL AND CHEMICAL DATA FOR THE SANDSTONE - CULTIVATED - SUMMIT SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-19	Ap	1.29	70.4	26.0	3.6	SL	7.4	16.0	0.34
19-39	Ck1	1.43	73.3	23.5	3.2	SL	7.5	20.7	0.29
39-63	Ck2	1.40	74.5	21.7	3.8	SL	7.7	19.1	0.32
63-88	Ck3	1.41	81.8	15.4	2.8	LS	8.0	19.7	0.25

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-19	Ap	0.89	984	7.1	471	85	387	181	180
19-39	Ck1	0.45	482	2.2	383	54	329	173	162
39-63	Ck2	0.27	321	1.3	267	29	238	200	29
63-88	Ck3	0.15	188	1.1	339	11	328	256	55

TABLE A-3 -- PHYSICAL AND CHEMICAL DATA FOR THE SANDSTONE - NATIVE - SHOULDER SEGMENT.

Depth (cm)	Horiz	B.D. ($Mg\ m^{-3}$)	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC ($dS\ m^{-1}$)
0-15	A	1.32	72.0	15.7	12.3	SL	6.7	0.2	0.44
15-34	AC1	1.32	71.3	19.7	9.0	SL	7.3	2.1	0.47
34-54	AC2	1.33	63.3	18.0	18.7	SL	7.7	13.7	0.33
54-78	Ck1	1.40	60.3	22.0	17.7	SL	7.7	20.7	0.29
78-99	Ck2	1.38	65.7	20.0	14.3	SL	7.7	15.8	0.26

Depth (cm)	Horiz	% Org. C	$mg\ kg^{-1}$ Tot. N	NO_3^-	Tot P	Org P	Inorg P	Acid P	Resid P
0-15	A	1.44	1395	5.7	392	167	225	144	80
15-34	AC1	1.04	1060	1.3	419	202	217	128	89
34-54	AC2	0.87	888	1.1	476	154	322	196	126
54-78	Ck1	0.77	607	0.8	490	110	380	305	75
78-99	Ck2	0.42	407	0.7	480	82	398	340	58

TABLE A-4 -- PHYSICAL AND CHEMICAL DATA FOR THE SANDSTONE - CULTIVATED - SHOULDER SEGMENT.

Depth (cm)	Horiz	B.D. ($Mg\ m^{-3}$)	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC ($dS\ m^{-1}$)
0-22	Ap	1.30	71.7	14.6	13.7	SL	7.3	12.0	0.6
22-36	AC	1.45	67.7	19.9	12.4	SL	7.6	24.3	0.4
36-59	Ck1	1.37	77.7	16.9	5.4	SL	7.7	27.4	0.3
59-82	Ck2	1.41	57.6	27.5	14.9	SL	7.9	21.7	0.3
82-107	Ck3	1.42	54.9	33.2	11.9	SL	7.9	22.3	0.3

Depth (cm)	Horiz	% Org. C	mg kg^{-1}						
			Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-22	Ap	1.20	1410	11.9	437	193	244	185	84
22-36	AC	0.94	1140	5.6	480	258	222	159	122
36-59	Ck1	0.50	523	1.9	381	129	251	207	67
59-82	Ck2	0.18	321	2.2	377	96	281	266	53
82-107	Ck3	0.20	278	2.2	396	148	247	293	63

TABLE A-5 -- PHYSICAL AND CHEMICAL DATA FOR THE SANDSTONE - NATIVE - UPPER BACKSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-18	A	1.28	63.6	17.0	19.4	SL	6.3	0.5	0.42
18-35	Bw1	1.29	67.3	16.4	16.3	SL	6.6	0.3	0.30
35-52	Bw2	1.39	71.9	17.8	10.3	SL	6.9	0.7	0.27
52-76	C	1.42	66.9	17.9	15.2	SL	7.2	1.3	0.39
76-103	Ck	1.38	58.9	22.9	18.2	SL	7.6	12.8	0.36

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO$_3$-	Tot P	Org P	Inorg P	Acid P	Resid P
0-18	A	1.74	1545	5.6	450*	226*	224*	172	26*
18-35	Bw1	0.91	962	2.5	451*	179*	273*	188	102*
35-52	Bw2	0.79	759	1.4	422*	178*	245*	195	71*
52-76	C	0.58	626	1.1	449*	133*	317*	232	81*
76-103	Ck	0.52	555	0.9	516*	172*	343*	304	53*

TABLE A-6 -- PHYSICAL AND CHEMICAL DATA FOR THE SANDSTONE - CULTIVATED - UPPER BACKSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-19	Ap	1.50	60.7	25.4	13.9	SL	7.1	0.2	0.46
19-37	Bw	1.53	61.7	24.8	13.5	SL	7.1	0.3	0.29
37-56	C	1.39	55.0	32.9	12.1	SL	7.4	9.0	0.39
56-84	Ck1	1.42	40.2	40.1	19.7	L	7.7	22.0	0.34
84-103	Ck2	1.49	31.2	44.7	24.1	L	7.8	32.4	0.34

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-19	Ap	1.11	1285	9.3	427	214	213	151	57
19-37	Bw	0.98	962	2.8	377	177	200	173	110
37-56	C	0.73	872	1.9	361	211	250	170	77
56-84	Ck1	0.45	576	3.2	685	159	526	367	169
84-103	Ck2	0.31	419	3.3	600	46	554	511	47

TABLE A-7 -- PHYSICAL AND CHEMICAL DATA FOR THE SANDSTONE - NATIVE - LOWER BACKSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-20	A	1.23	59.5	22.5	18.0	SL	6.2	0.5	0.38
20-38	BA	1.21	59.2	19.9	20.9	SL	6.5	0.3	0.27
38-61	Bw	1.37	61.4	20.4	18.2	SL	6.7	0.3	0.20
61-83	BC	1.41	61.1	17.7	21.2	SCL	7.0	1.3	0.27
83-108	Ck	1.43	61.3	19.7	19.0	SL	7.5	12.0	0.42

Depth (cm)	Horiz	% Org. C	Tot. N (mg kg^{-1})	NO_3- (mg kg^{-1})	Tot P (mg kg^{-1})	Org P (mg kg^{-1})	Inorg P (mg kg^{-1})	Acid P (mg kg^{-1})	Resid P (mg kg^{-1})
0-20	A	1.90	1860	5.3	496*	255*	241*	187	69*
20-38	BA	1.09	1005	1.6	442*	190*	252*	185	80*
38-61	Bw	0.71	757	0.9	622*	147*	475*	216	260*
61-83	BC	0.60	644	0.6	547*	140*	407*	258	130*
83-108	Ck	0.46	511	0.7	716*	90*	626*	389	170*

TABLE A-8 -- PHYSICAL AND CHEMICAL DATA FOR THE SANDSTONE - CULTIVATED - LOWER BACKSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-20	Ap	1.36	51.9	31.4	16.7	L/SL	6.2	0.2	0.43
20-44	Bw1	1.40	49.9	32.0	18.1	L	6.4	0.1	0.22
44-68	Bw2	1.45	46.7	34.4	18.9	L	6.8	3.9	0.37
68-87	Ck1	1.70	67.1	20.7	12.2	SL	7.4	13.5	0.46
87-108	Ck2	1.45	61.7	35.5	2.8	SL	7.5	18.9	0.35

Depth (cm)	Horiz	% Org. C	Tot. N (mg kg^{-1})	NO_3- (mg kg^{-1})	Tot P (mg kg^{-1})	Org P (mg kg^{-1})	Inorg P (mg kg^{-1})	Acid P (mg kg^{-1})	Resid P (mg kg^{-1})
0-20	Ap	1.48	1510	10.2	543	291	252	181	84
20-44	Bw1	0.90	890	2.4	524	205	319	171	169
44-68	Bw2	0.76	804	3.1	527	104	423	266	115
68-87	Ck1	0.54	538	2.5	564	173	391	329	70
87-108	Ck2	0.30	362	2.1	641	104	537	526	109

TABLE A-9 -- PHYSICAL AND CHEMICAL DATA FOR THE SANDSTONE - NATIVE - FOOTSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-21	A	1.22	53.2	29.8	17.0	SL	6.1	0.2	0.37
21-37	BA	1.27	55.1	28.1	16.8	SL	6.3	0.4	0.21
37-61	Bw1	1.40	52.4	27.2	20.4	SL	6.5	0.1	0.18
61-85	Bw2	1.34	49.7	33.3	17.0	L	6.7	0.2	0.26
85-108	C	1.45	59.7	23.2	17.1	SL	7.6	3.9	0.41

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-21	A	2.05	2005	6.6	597	293	304	228	75
21-37	BA	1.33	1240	1.5	528	256	272	210	62
37-61	Bw1	0.84	798	0.7	460	162	298	254	45
61-85	Bw2	0.70	709	0.6	523	140	383	280	103
85-108	C	0.45	478	0.8	647	132	515	378	137

TABLE A-10 -- PHYSICAL AND CHEMICAL DATA FOR THE SANDSTONE - CULTIVATED - FOOTSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-16	Ap1	1.17	55.5	27.7	16.8	SL	6.8	0.4	0.39
16-30	Ap2	1.49	53.9	33.3	12.8	SL	6.7	0.3	0.36
30-48	Bw1	1.44	55.9	25.2	18.9	SL	6.8	0.5	0.24
48-67	Bw2	1.48	59.5	23.9	16.6	SL	7.0	2.2	0.25
67-86	C	1.57	77.1	11.3	11.6	SL	7.3	10.0	0.39
86-107	Ck	1.53	77.8	10.4	11.8	SL	7.6	14.5	0.37

Depth (cm)	Horiz	% Org. C	Tot. N (mg kg^{-1})	NO_3- (mg kg^{-1})	Tot P (mg kg^{-1})	Org P (mg kg^{-1})	Inorg P (mg kg^{-1})	Acid P (mg kg^{-1})	Resid P (mg kg^{-1})
0-16	Ap1	1.40	1425	8.1	535	201	334	196	145
16-30	Ap2	1.30	1355	8.9	442	186	256	185	46
30-48	Bw1	0.79	834	1.9	498	142	356	194	105
48-67	Bw2	0.65	721	2.0	498	204	294	228	23
67-86	C	0.43	436	2.0	638	119	519	384	0
86-107	Ck	0.32	340	2.2	622	74	548	472	7

TABLE A-11 -- PHYSICAL AND CHEMICAL DATA FOR THE SANDSTONE - NATIVE - BACK BACKSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-18	A	1.34	69.8	17.2	13.0	SL	6.8	0.5	0.42
18-40	Bw1	1.31	72.9	12.8	14.3	SL	7.1	0.6	0.28
40-63	Bw2	1.39	71.2	13.4	15.4	SL	7.2	1.2	0.36
63-88	BCk	1.41	43.8	27.9	28.3	CL	7.4	13.5	0.33
88-110	Ck	1.44	26.3	34.8	38.9	CL	7.5	15.4	0.28

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-18	A	1.46	1410	4.0	494	196	298	187	111
18-40	Bw1	0.98	987	1.3	468	175	293	180	113
40-63	Bw2	0.82	924	0.9	469	171	298	234	64
63-88	BCk	0.76	830	0.7	542	115	427	362	65
88-110	Ck	0.57	788	0.8	501	89	412	314	98

TABLE A-12 -- PHYSICAL AND CHEMICAL DATA FOR THE SANDSTONE - CULTIVATED - BACK BACKSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (g/cc)	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-16	Ap1	1.39	76.3	12.3	11.4	SL	7.7	2.8	0.17
16-31	Ap2	1.52	74.5	12.2	13.3	SL	7.6	5.3	0.31
31-59	AC	1.42	74.2	13.1	12.7	SL	7.6	8.2	0.33
59-83	Ck1	1.42	72.1	13.9	14.0	SL	7.6	11.9	0.30
83-108	Ck2	1.42	70.8	12.2	17.0	SL	7.9	12.9	0.23

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-16	Ap1	1.07	1100	8.0	444	158	286	165	101
16-31	Ap2	0.82	948	3.4	342	191	151	161	15
31-59	AC	0.67	728	2.3	406	115	291	222	62
59-83	Ck1	0.53	545	1.9	437	180	257	257	0
83-108	Ck2	0.34	411	1.6	445	121	324	272	84

TABLE A-13 -- PHYSICAL AND CHEMICAL DATA FOR THE SANDSTONE - NATIVE - BACK FOOTSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-20	A	1.15	63.5	21.5	15.0	SL	6.2	0.6	0.39
20-41	Bw1	1.20	64.8	20.9	14.3	SL	6.3	0.6	0.20
41-65	Bw2	1.33	67.3	16.8	15.9	SL	6.6	0.6	0.18
65-86	BC	1.45	67.7	17.6	14.7	SL	6.7	0.8	0.16
86-107	Ck	1.64	53.5	22.3	24.2	SCL	7.4	2.7	0.39

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-20	A	2.68	2095	11.1	692	298	394	189	205
20-41	Bw1	1.31	1335	3.1	583	197	386	182	204
41-65	Bw2	0.92	907	1.3	589	180	409	208	201
65-86	BC	0.61	600	1.1	603	136	467	252	215
86-107	Ck	0.53	655	0.5	616	112	504	321	183

TABLE A-14 -- PHYSICAL AND CHEMICAL DATA FOR THE SANDSTONE - CULTIVATED - BACK FOOTSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-19	Ap1	1.35	63.3	21.6	15.1	SL	6.9	0.4	0.37
19-38	Ap2	1.40	64.4	18.8	16.8	SL	6.7	0.4	0.20
38-60	Bw1	1.44	63.0	18.3	18.7	SL	7.0	0.3	0.25
60-82	Bw2	1.50	56.1	25.8	18.1	SL	7.2	0.6	0.21
82-107	Bw3	1.63	47.7	29.7	22.6	SCL	7.6	2.1	0.32

			mg kg^{-1}						
Depth (cm)	Horiz	% Org. C	Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-19	Ap1	1.34	1360	11.9	457*	158*	299*	181	118*
19-38	Ap2	1.08	1035	4.8	451*	186*	265*	188	88*
38-60	Bw1	0.71	703	2.4	479*	131*	348*	210	131*
60-82	Bw2	0.73	689	3.6	636*	128*	508*	240	228*
82-107	Bw3	0.62	625	3.5	479*	173*	306*	265	31*

TABLE A-15- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - NATIVE - BACK SHOULDER SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-10	A	1.13	18.3	54.7	27.0	SiL/SiCL	5.9	0.3	0.51
10-23	BA	1.28	17.2	54.4	28.4	SiCL	5.9	0.1	0.35
23-40	Bw	1.25	12.6	55.4	32.0	SiCL	6.2	0.5	0.32
40-57	BC	1.14	10.7	61.9	27.4	SiCL	7.3	2.3	1.70
57-81	Ck	1.38	10.7	66.3	23.0	SiL	7.7	7.1	3.30
81-103	C	1.45	9.5	75.2	15.3	SiL	8.0	6.0	8.80

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-10	A	3.65	3105	13.6	625*	268*	357*	202	154*
10-23	BA	1.85	1685	8.4	499*	183*	316*	185	73*
23-40	Bw	1.20	1130	1.8	505*	188*	317*	226	77*
40-57	BC	0.65	812	3.7	422*	134*	288*	306	40*
57-81	Ck	0.60	686	2.9	490*	158*	332*	428	0*
81-103	C	0.42	363	1.3	507*	---	---	504	---

TABLE A-16 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - CULTIVATED - BACK SHOULDER SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-14	Ap1	1.20	13.1	51.2	35.7	SiCL	7.2	1.0	0.38
14-25	Ap2	1.30	10.2	55.5	34.3	SiCL	7.3	10.1	0.38
25-44	AC	1.35	11.5	51.7	36.8	SiCL	7.5	16.9	0.39
44-63	Ck	1.44	10.2	63.7	27.1	SiL	7.9	13.6	1.74
63-88	C1	1.46	17.8	55.9	26.3	SiL	7.9	10.6	3.79
88-111	C2	1.46	16.9	58.2	24.9	SiL	7.8	5.9	4.80

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-14	Ap1	1.91	1710	9.2	444*	255*	189*	147	65*
14-25	Ap2	1.20	1265	6.3	447*	225*	222*	195	58*
25-44	AC	0.77	843	3.9	529*	145*	384*	367	3*
44-63	Ck	0.40	482	2.5	414*	76*	338*	330	6*
63-88	C1	0.34	343	2.5	454*	72*	382*	346	35*
88-111	C2	0.27	251	2.9	406*	---	---	---	

TABLE A-17 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - NATIVE - SUMMIT SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-10	A	1.13	19.8	56.1	24.1	SiL	5.9	0.5	0.44
10-26	BA	1.23	16.8	56.6	26.6	SiL	5.9	0.5	0.36
26-43	Bw	1.36	6.7	62.5	30.8	SiCL	6.3	0.4	0.30
43-65	BC	1.34	6.7	66.7	26.6	SiL	7.4	3.5	0.67
65-83	Ck	1.41	12.0	70.2	17.8	SiL	7.9	3.9	5.90
83-106	Cy	1.53	5.8	57.0	37.2	SiCL	7.9	3.7	10.10

Depth (cm)	Horiz	% Org. C	Tot. N (mg kg^{-1})	NO_3- (mg kg^{-1})	Tot P (mg kg^{-1})	Org P (mg kg^{-1})	Inorg P (mg kg^{-1})	Acid P (mg kg^{-1})	Resid P (mg kg^{-1})
0-10	A	3.04	2600	16.8	597	318	279	200	79
10-26	BA	1.48	1405	3.8	521	212	309	189	121
26-43	Bw	0.79	842	1.9	525	127	398	254	144
43-65	BC	0.49	555	2.3	582	78	504	481	24
65-83	Ck	0.33	356	1.2	536	45	491	472	56
83-106	Cy	0.25	256	0.9	655	588	587	605	0

TABLE A-18 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - CULTIVATED - SUMMIT SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-16	Ap1	1.26	11.3	52.4	36.3	SiCL	6.3	0.8	0.35
16-27	Ap2	1.37	6.1	57.1	36.8	SiCL	7.0	4.2	0.33
27-42	AC	1.33	4.0	70.8	25.2	SiL	7.7	9.5	0.57
42-59	Ck	1.39	5.4	63.6	31.0	SiCL	7.8	13.5	2.65
59-84	Cy	1.46	9.2	73.9	16.9	SiL	7.8	13.1	4.10
84-118	C	1.48	1.9	66.2	31.9	SiCL	7.9	9.7	6.05

			mg kg^{-1}						
Depth (cm)	Horiz	% Org. C	Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-16	Ap1	1.54	1485	11.3	462*	135*	327*	142	192*
16-27	Ap2	0.89	1030	7.4	682*	199*	483*	236	366*
27-42	AC	0.74	764	4.1	590*	172*	418*	502	0*
42-59	Ck	0.43	491	4.2	666*	93*	573*	477	81*
59-84	Cy	0.27	329	3.0	632*	35*	597*	591	6*
84-118	C	0.18	245	1.1	567*	25*	542*	521	21*

TABLE A-19 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - NATIVE - SHOULDER SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-13	A	1.16	18.8	55.7	25.5	SiL	6.0	0.6	0.42
13-26	Bw	1.27	14.3	49.7	36.0	SiCL	5.9	0.7	0.31
26-43	BC	1.36	7.4	57.5	35.1	SiCL	6.9	3.9	0.45
43-62	Ck	1.39	11.2	62.7	26.1	SiL	7.6	7.4	0.70
62-83	Cy1	1.41	9.6	69.7	20.7	SiL	7.9	9.6	2.85
83-103	Cy2	1.38	9.2	65.2	25.6	SiL	8.0	6.7	6.60

			mg kg^{-1}						
Depth (cm)	Horiz	% Org. C	Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-13	A	3.17	2830	9.4	583*	311*	272*	170	98*
13-26	Bw	1.53	1545	2.0	456*	161*	295*	228	66*
26-43	BC	1.06	1040	1.3	482*	110*	372*	382	70*
43-62	Ck	0.74	679	1.4	577*	149*	428*	381	179*
62-83	Cy1	0.39	425	1.3	509*	64*	445*	482	0*
83-103	Cy2	0.29	310	1.0	498*	---	---	338	---

TABLE A-20 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - CULTIVATED - SHOULDER SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-20	Ap	1.29	18.2	55.1	26.7	SiL	6.1	0.3	0.36
20-35	Bw	1.37	9.5	61.2	29.3	SiCL	6.7	1.6	0.36
35-52	BC	1.42	10.1	58.4	31.5	SiCL	7.4	14.0	0.40
52-81	Ck	1.44	9.0	58.9	32.1	SiCL	7.9	19.0	0.39
81-100	Cy	1.41	9.6	60.2	30.2	SiCL	8.0	19.8	2.19

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-20	Ap	2.10	1945	10.2	452*	270*	182*	193	0*
20-35	Bw	1.19	1285	3.4	560*	234*	326*	276	116*
35-52	BC	1.06	1140	3.3	632*	178*	454*	431	102*
52-81	Ck	0.63	646	2.0	522*	58*	464*	476	135*
81-100	Cy	0.52	427	1.1	398*	34*	364*	405	90*

TABLE A-21 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - NATIVE - UPPER BACKSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-12	A	1.05	24.4	57.9	17.7	SiL	6.1	0.7	0.39
12-21	Bw1	1.25	17.5	52.3	30.2	SiCL	6.1	0.6	0.31
21-37	Bw2	1.20	14.4	53.9	31.7	SiCL	7.0	1.7	0.52
37-57	BCk	1.34	11.4	57.2	31.4	SiCL	7.7	19.3	0.38
57-83	Ck1	1.35	5.9	71.5	22.6	SiL	7.9	19.0	0.40
83-107	Ck2	1.33	8.9	68.2	22.9	SiL	8.1	16.6	0.60

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-12	A	3.65	3225	7.3	754*	417*	337*	193	151*
12-21	Bw1	1.82	1765	1.3	642*	329*	313*	251	80*
21-37	Bw2	1.39	1415	1.2	648*	225*	423*	426	69*
37-57	BCk	1.09	1095	1.3	646*	146*	500*	434	38*
57-83	Ck1	0.72	717	0.9	710*	94*	616*	554	68*
83-107	Ck2	0.45	529	1.0	685*	67*	618*	553	40*

TABLE A-22 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - CULTIVATED - UPPER BACKSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-14	Ap	1.21	17.6	76.4	6.0	SiL	7.5	5.3	0.5
14-33	ACk	1.27	8.0	59.1	32.9	SiCL	7.9	33.4	0.3
33-59	Ck1	1.37	6.6	66.8	26.6	SiL	8.0	35.6	0.4
59-81	Ck2	1.52	3.2	68.1	28.7	SiCL	7.9	27.2	3.4
81-103	Cy	1.52	7.5	66.9	25.6	SiL	8.0	19.5	3.8

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-14	Ap	2.17	1650	10.7	477*	253*	224*	163	54*
14-33	ACk	1.07	1080	4.0	563*	167*	396*	357	6*
33-59	Ck1	0.58	629	2.7	627*	90*	537*	494	9*
59-81	Ck2	0.31	318	1.6	578*	18*	560*	550	5*
81-103	Cy	0.25	215	0.8	756*	27*	729*	513	219*

TABLE A-23 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - NATIVE - LOWER BACKSLOPE (A) SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-13	A	1.02	19.6	64.3	16.1	SiL	6.2	0.6	0.36
13-31	Bw	1.23	16.7	53.1	30.2	SiCL	6.3	0.3	0.31
31-47	BC	1.30	12.7	55.9	31.4	SiCL	7.3	2.4	0.52
47-68	Ck1	1.28	7.7	59.5	32.8	SiCL	7.7	16.0	0.49
68-87	Ck2	1.34	19.8	46.7	33.5	SiCL	8.1	18.7	0.49
87-105	Ck3	1.32	11.2	61.0	27.8	SiCL	8.3	17.0	2.48

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-13	A	3.14	2915	5.6	642*	329*	313*	186	118*
13-31	Bw	1.79	1715	2.1	602*	285*	317*	233	75*
31-47	BC	1.38	1300	1.7	715*	214*	501*	350	143*
47-68	Ck1	1.49	1230	1.6	615*	205*	410*	404	1*
68-87	Ck2	1.06	781	1.0	571*	91*	480*	429	93*
87-105	Ck3	0.79	581	0.8	583*	80*	503*	459	142*

TABLE A-24 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - CULTIVATED - LOWER BACKSLOPE (A) SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-17	Ap	1.13	18.3	66.9	14.8	SiL	7.1	0.6	0.43
17-39	AC	1.30	8.5	60.0	31.5	SiCL	7.6	13.5	0.38
39-55	Ck1	1.32	2.7	64.7	32.6	SiCL	7.8	27.6	0.69
55-68	Ck2	1.39	4.9	60.6	34.5	SiCL	7.8	23.2	2.32
68-85	Cy	1.53	9.8	63.4	26.8	SiL	7.7	14.4	3.15
85-105	C	1.50	4.8	64.8	30.4	SiCL	7.7	11.3	4.00

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-17	Ap	1.83	1540	10.9	549*	263*	286*	149	133*
17-39	AC	1.17	1045	3.5	463*	234*	229*	251	37*
39-55	Ck1	0.47	616	3.2	725*	146*	579*	448	109*
55-68	Ck2	0.33	386	2.5	630*	51*	579*	544	48*
68-85	Cy	0.31	278	1.2	574*	16*	558*	560	28*
85-105	C	0.25	249	1.0	606*	---	---	---	---

TABLE A-25 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - NATIVE - SANDY MUDSTONE LENSE.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-20	A	1.23	59.5	22.5	18.0	SL	6.2	0.5	0.38
20-38	BA	1.21	59.2	19.9	20.9	SCL	6.5	0.3	0.27
38-61	Bw	1.37	61.4	20.4	18.2	SL	6.7	0.3	0.20
61-83	BC	1.41	61.1	17.7	21.2	SCL	7.0	1.3	0.27
83-108	Ck	1.43	61.3	19.7	19.0	SL	7.5	12.0	0.42

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-20	A	1.90	1860	5.3	496	255	241	187	69
20-38	BA	1.09	1005	1.6	442	190	252	185	80
38-61	Bw	0.71	757	0.9	622	147	475	216	260
61-83	BC	0.60	644	0.6	547	140	407	258	130
83-108	Ck	0.46	511	0.7	716	90	626	389	170

TABLE A-26 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - CULTIVATED - SANDY MUDSTONE LENSE.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-20	Ap	1.36	51.9	31.4	16.7	L/SL	6.2	0.2	0.43
20-44	Bw1	1.40	49.9	32.0	18.1	L	6.4	0.1	0.22
44-68	Bw2	1.45	46.7	34.4	18.9	L	6.8	3.9	0.37
68-87	Ck1	1.70	67.1	20.7	12.2	SL	7.4	13.5	0.46
87-108	Ck2	1.45	61.7	35.5	2.8	SL	7.5	18.9	0.35

Depth (cm)	Horiz	% Org. C	mg kg^{-1}						
			Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-20	Ap	1.48	1510	10.2	543	291	252	181	84
20-44	Bw1	0.90	890	2.4	524	205	319	171	169
44-68	Bw2	0.76	804	3.1	527	104	423	266	115
68-87	Ck1	0.54	538	2.5	564	173	391	329	70
87-108	Ck2	0.30	362	2.1	641	104	537	526	109

TABLE A-27 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - NATIVE - LOWER BACKSLOPE (B) SEGMENT.

Depth (cm)	Horiz	B.D. ($Mg\ m^{-3}$)	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC ($dS\ m^{-1}$)
0-13	A	1.12	25.2	52.7	22.1	SiL	6.2	0.6	0.52
13-29	BA	1.32	19.4	56.0	24.6	SiL	6.1	0.5	0.36
29-44	Bw	1.36	16.6	38.8	44.6	C	7.1	4.3	0.46
44-63	BCk	1.39	12.8	47.4	39.8	SiCL	7.6	16.4	0.44
63-84	Ck1	1.40	14.0	56.2	29.8	SiCL	7.6	17.8	0.33
84-106	Ck2	1.30	14.0	45.2	40.8	SiC	7.7	17.5	0.39

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3^-	Tot P	Org P	Inorg P	Acid P	Resid P
0-13	A	2.88	2915	11.2	495*	301*	194*	122	68*
13-29	BA	1.61	1630	1.2	492*	204*	288*	125	148*
29-44	Bw	1.15	1190	0.7	574*	170*	404*	303	86*
44-63	BCk	0.94	919	0.7	634*	101*	533*	408	155*
63-84	Ck1	0.62	595	0.6	587*	74*	513*	437	110*
84-106	Ck2	0.50	463	1.6	628*	75*	553*	459	40*

TABLE A-28 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - CULTIVATED - LOWER BACKSLOPE (B) SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-15	Ap	1.41	48.6	31.7	19.7	L	5.8	0.2	0.28
15-28	Bw	1.49	34.6	32.9	32.5	CL	6.3	0.4	0.30
28-49	BCk	1.49	28.5	38.4	33.1	CL	6.8	1.1	0.36
49-64	Ck1	1.43	29.1	42.3	28.6	CL	7.5	9.9	0.48
64-91	Ck2	1.36	25.3	50.9	23.8	SiL	7.8	18.3	0.47
91-113	Ck3	1.34	23.7	48.7	27.6	CL	7.9	18.7	0.41

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-15	Ap	1.34	1290	8.4	379*	198*	181*	79	98*
15-28	Bw	0.71	811	2.8	337*	114*	223*	65	169*
28-49	BCk	0.63	657	1.6	264*	106*	158*	87	91*
49-64	Ck1	0.57	663	1.4	293*	104*	189*	205	39*
64-91	Ck2	0.50	516	1.1	536*	72*	464*	267	191*
91-113	Ck3	0.50	446	1.0	530*	42*	488*	323	145*

TABLE A-29 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - NATIVE - FOOTSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-16	A	1.19	20.2	58.6	21.2	SiL	6.2	0.6	0.37
16-32	BA	1.34	24.5	46.2	29.3	CL	6.1	0.4	0.27
32-54	Bw	1.53	26.1	42.5	31.4	CL	6.4	0.4	0.27
54-67	BC	1.54	17.2	50.1	32.7	SiCL	7.3	0.3	0.47
67-87	Ck1	1.44	17.1	52.5	30.4	SiCL	7.7	10.8	0.43
87-105	Ck2	1.45	13.9	44.9	41.2	SiC	7.9	14.6	0.39

Depth (cm)	Horiz	% Org. C	mg kg^{-1}						
			Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-16	A	3.02	2600	8.3	492	273	219	117	103
16-32	BA	1.55	1420	1.9	389	187	202	83	119
32-54	Bw	0.74	876	0.8	310	118	192	128	64
54-67	BC	0.73	813	1.0	416	102	314	248	66
67-87	Ck1	0.75	763	0.9	507	111	396	361	53
87-105	Ck2	0.66	633	0.9	508	73	435	296	138

TABLE A-30 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - CULTIVATED - FOOTSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-13	Ap	1.31	42.4	36.4	21.2	L	5.8	0.4	0.30
13-27	Bw	1.42	36.2	32.1	31.7	CL	6.1	0.3	0.25
27-43	BC	1.55	31.9	34.5	33.6	CL	6.5	1.7	0.22
43-61	Ck1	1.42	26.4	46.5	27.1	CL	7.4	9.9	0.44
61-85	Ck2	1.45	22.8	44.3	32.9	CL	7.7	18.2	0.45
85-111	Ck3	1.44	19.7	50.7	29.6	SiCL	7.8	20.0	0.40

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-13	Ap	1.64	1510	9.4	418*	193*	225*	111	132*
13-27	Bw	1.29	1210	5.1	296*	99*	197*	96	86*
27-43	BC	0.76	775	2.0	329*	110*	219*	126	47*
43-61	Ck1	0.78	768	1.6	516*	160*	356*	221	102*
61-85	Ck2	0.54	607	1.2	493*	72*	421*	341	50*
85-111	Ck3	0.52	478	0.9	626*	84*	542*	512	0*

TABLE A-31 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - NATIVE - TOESLOPE SEGMENT.

Depth (cm)	Horiz	B.D. ($Mg\ m^{-3}$)	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC ($dS\ m^{-1}$)
0-17	A1	1.11	23.9	51.2	24.9	SiL	6.1	0.6	0.39
17-30	A2	1.24	26.0	46.2	27.8	CL	6.1	0.4	0.31
30-52	Bw1	1.54	20.9	43.8	35.3	CL	6.5	0.4	0.38
52-70	Bw2	1.65	21.0	45.5	34.5	CL	7.4	0.4	1.13
70-89	Ck1	1.57	13.7	51.0	35.3	SiCL	7.9	8.4	3.37
89-110	Ck2	1.28	15.0	48.0	37.0	SiCL	8.2	12.4	4.51

Depth (cm)	Horiz	% Org. C	$mg\ kg^{-1}$						
			Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-17	A1	3.64	3335	10.9	621*	397*	224*	132	90*
17-30	A2	1.83	1725	2.5	496*	199*	297*	123	172*
30-52	Bw1	0.84	893	0.7	363*	130*	233*	140	91*
52-70	Bw2	0.86	733	0.7	414*	111*	303*	200	106*
70-89	Ck1	0.53	695	0.8	532*	112*	420*	360	56*
89-110	Ck2	0.63	730	1.7	565*	68*	497*	351	139*

TABLE A-32 -- PHYSICAL AND CHEMICAL DATA FOR THE SILTSTONE - CULTIVATED - TOESLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-12	Ap1	1.18	27.2	56.9	15.9	SiL	5.6	0.1	0.36
12-24	Ap2	1.34	27.7	42.8	29.5	CL	5.7	0.1	0.30
24-36	Bw	1.36	28.5	41.3	30.2	CL	6.0	0.3	0.24
36-59	BC	1.51	25.6	39.4	35.0	CL	6.3	1.6	0.34
59-79	Ck1	1.59	31.0	45.1	23.9	L	7.2	3.6	0.57
79-106	Ck2	1.47	19.9	55.2	24.9	SiL	7.6	15.3	0.39

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-12	Ap1	2.07	2015	13.5	471*	260*	211*	131	80*
12-24	Ap2	1.82	1760	9.6	451*	269*	182*	125	59*
24-36	Bw	1.14	1230	4.8	392*	235*	157*	140	30*
36-59	BC	0.78	816	3.0	375*	116*	259*	131	145*
59-79	Ck1	0.72	791	4.6	464*	145*	319*	240	76*
79-106	Ck2	0.66	661	2.2	539*	81*	458*	368	127*

TABLE A-33 -- PHYSICAL AND CHEMICAL DATA FOR THE SHALE - NATIVE - SUMMIT SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0- 9	A	1.01	12.6	49.1	38.3	SiCL	7.7	1.4	0.55
9-22	Bt1	1.21	9.1	42.2	48.7	SiC	7.2	8.1	0.50
22-38	Bt2	1.39	8.6	44.5	46.9	SiC	7.5	21.0	0.40
38-61	BCk	1.40	8.8	43.1	48.1	SiC	7.6	20.4	0.36
61-82	Ck1	1.43	7.5	45.9	46.6	SiC	8.3	19.9	0.62
82-107	Ck2	1.49	11.8	42.4	45.8	SiC	8.1	15.3	3.36

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO3-	Tot P	Org P	Inorg P	Acid P	Resid P
0- 9	A	3.76	3395	0.7	850	247	603	267	336
9-22	Bt1	1.78	2000	1.6	707	148	559	408	151
22-38	Bt2	1.34	1405	1.7	715	128	587	501	128
38-61	BCk	0.80	784	0.6	842	42	800	560	239
61-82	Ck1	0.59	426	3.3	826	24	802	613	189
82-107	Ck2	0.39	333	3.5	814	53	761	514	246

TABLE A-34 -- PHYSICAL AND CHEMICAL DATA FOR THE SHALE - CULTIVATED - SUMMIT SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-13	Ap	1.23	13.2	60.9	25.9	SiL	7.6	8.3	0.45
13-26	Bt	1.27	6.6	46.2	47.2	SiC	7.6	17.1	0.35
26-42	BCk	1.33	7.0	43.5	49.5	SiC	7.9	16.2	0.37
42-65	Ck	1.38	6.8	46.9	46.3	SiC	8.1	11.2	0.53
65-90	Cy1	1.41	9.6	51.3	39.1	SiCL	7.9	10.7	3.83
90-109	Cy2	1.55	10.7	46.2	43.1	SiC	7.8	10.7	4.63

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-13	Ap	1.69	2000	6.3	694*	182*	512*	381	118*
13-26	Bt	1.00	1215	4.7	663*	114*	549*	509	48*
26-42	BCk	0.62	698	5.2	677*	110*	567*	548	90*
42-65	Ck	0.32	456	4.9	762*	52*	710*	671	80*
65-90	Cy1	0.23	317	7.1	776*	35*	741*	583	146*
90-109	Cy2	0.24	290	4.3	837*	87*	750*	639	54*

TABLE A-35 -- PHYSICAL AND CHEMICAL DATA FOR THE SHALE - NATIVE - SHOULDER SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-13	A	1.03	17.2	45.9	36.9	SiCL	6.9	3.5	0.64
13-30	Bt1	1.24	9.1	42.2	48.7	SiC	6.7	14.1	0.60
30-45	Bt2	1.34	8.6	44.5	46.9	SiC	7.7	20.5	0.36
45-75	BCk	1.35	8.8	43.1	48.1	SiC	8.0	19.0	0.38
75-100	Ck	1.44	7.5	45.9	46.6	SiC	8.1	11.8	0.55
100-115	C	1.47	11.7	42.4	45.9	SiC	8.1	10.4	0.88

			mg kg^{-1}						
Depth (cm)	Horiz	% Org. C	Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-13	A	3.84	3700	5.0	785*	429*	356*	251*	130*
13-30	Bt1	1.89	1845	2.7	731*	190*	541*	314*	222*
30-45	Bt2	0.98	1010	3.6	669*	125*	544*	399*	106*
45-75	BCk	0.56	552	3.8	771*	100*	671*	531*	107*
75-100	Ck	0.34	401	3.3	759*	67*	692*	630*	87*
100-115	C	0.42	380	4.0	749*	21*	728*	---	---

TABLE A-36 -- PHYSICAL AND CHEMICAL DATA FOR THE SHALE - CULTIVATED - SHOULDER SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-14	Ap	1.20	10.9	49.8	39.3	SiCL	7.5	5.6	0.40
14-30	Bt	1.32	5.7	41.1	53.2	SiC	7.7	12.3	0.36
30-48	BCk	1.40	4.7	45.8	49.5	SiC	7.9	19.4	0.41
48-69	CK1	1.40	4.9	41.6	53.5	SiC	8.2	16.3	0.50
69-90	Ck2	1.52	6.7	46.8	46.5	SiC	8.3	13.3	0.62
90-112	C	1.64	16.5	41.6	41.9	SiC	8.3	12.0	1.18

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-14	Ap	1.52	2060	5.5	667*	229*	438*	337	138*
14-30	Bt	1.23	1340	4.7	701*	146*	555*	425	122*
30-48	BCk	0.74	730	5.4	772*	118*	654*	508	104*
48-69	Ck1	0.49	490	8.0	813*	47*	766*	560	42*
69-90	Ck2	0.26	399	8.7	841*	78*	763*	586	49*
90-113	C	0.37	336	5.5	875*	27*	848*	686	136*

TABLE A-37 -- PHYSICAL AND CHEMICAL DATA FOR THE SHALE - NATIVE - BACKSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-15	A	1.06	16.6	48.8	34.6	SiCL	6.3	0.4	0.42
15-33	Bt1	1.37	10.1	47.3	42.6	SiC	6.8	2.1	0.53
33-47	Bt2	1.42	11.1	47.5	41.4	SiC	7.6	12.8	0.42
47-73	BCk	1.47	8.3	52.0	39.7	SiCL	7.9	16.9	0.37
73-99	Ck	1.46	11.0	49.0	40.0	SiC	8.2	13.0	0.44
99-118	C	1.37	11.2	51.1	37.7	SiCL	8.2	8.7	0.87

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-15	A	3.25	3130	5.1	773*	297*	476*	268	214*
15-33	Bt1	1.54	1790	4.5	712*	172*	540*	443	166*
33-47	Bt2	1.22	1110	4.5	772*	127*	645*	472	142*
47-73	BCk	0.64	580	4.5	776*	82*	694*	576	121*
73-99	Ck	0.58	491	4.7	790*	59*	731*	586	135*
99-118	C	0.69	642	4.7	783*	57*	726*	650	58*

TABLE A-38 -- PHYSICAL AND CHEMICAL DATA FOR THE SHALE - CULTIVATED - BACKSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-15	Ap	1.09	13.1	48.3	38.6	SiCL	7.1	0.9	0.50
15-31	Bt1	1.39	13.5	44.6	41.9	SiC	7.1	3.7	0.42
31-44	Bt2	1.46	12.1	43.5	44.4	SiC	7.7	10.1	0.35
44-68	BCk	1.57	14.5	42.8	42.7	SiC	7.8	13.5	0.37
68-93	Ck	1.55	13.3	43.9	42.8	SiC	7.9	12.8	0.42
93-112	C	1.48	14.8	42.9	42.3	SiC	8.1	10.7	0.52

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-15	Ap	1.81	1945	7.4	748*	235*	513*	278	242*
15-31	Bt1	1.19	1490	5.4	718*	224*	494*	427	95*
31-44	Bt2	0.96	1005	5.6	937*	135*	802*	520	262*
44-68	BCk	0.65	712	5.7	783*	153*	630*	547	106*
68-93	Ck	0.41	514	6.4	820*	70*	750*	616	150*
93-112	C	0.61	509	5.9	811*	51*	760*	649	25*

TABLE A-39 -- PHYSICAL AND CHEMICAL DATA FOR THE SHALE - NATIVE - FOOTSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-14	A	1.20	15.1	52.6	32.3	SiCL	6.3	0.7	0.47
14-28	BA	1.43	9.3	44.3	46.4	SiC	6.8	1.0	0.53
28-45	Bt1	1.53	8.2	42.4	49.4	SiC	7.7	9.4	0.43
45-64	Bt2	1.52	8.5	43.5	48.0	SiC	7.9	12.8	0.44
64-87	Bt3	1.54	4.7	48.3	47.0	SiC	8.1	10.1	0.62
87-113	BCk	1.53	2.2	47.8	50.0	SiC	7.8	6.7	1.22

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-14	A	3.29	3615	4.9	783	316	467	309	158
14-38	BA	1.65	2085	4.5	720	238	482	371	111
28-45	Bt1	1.05	1325	4.8	702	149	553	489	64
45-64	Bt2	0.85	952	4.2	696	137	559	484	75
64-87	Bt3	0.82	839	4.1	750	124	626	528	97
87-113	BCk	0.83	804	3.7	812	94	718	603	115

TABLE A-40 -- PHYSICAL AND CHEMICAL DATA FOR THE SHALE - CULTIVATED - FOOTSLOPE SEGMENT.

Depth (cm)	Horiz	B.D. (Mg m^{-3})	%Sand	%Silt	%Clay	Texture Class	pH	$CaCO_3$ equiv.	EC (dS m^{-1})
0-12	Ap	1.26	14.2	49.4	36.4	SiCL	6.5	0.6	0.48
12-30	Bt1	1.35	11.2	44.7	44.1	SiC	6.8	2.2	0.36
30-48	Bt2	1.52	7.2	43.9	48.9	SiC	7.6	7.5	0.43
48-73	BCk	1.57	2.8	42.9	54.3	SiC	7.9	12.4	0.41
73-97	Ck1	1.54	7.5	44.9	47.6	SiC	7.9	11.9	0.44
97-120	Ck2	1.55	4.8	48.4	46.8	SiC	8.0	8.9	1.63

Depth (cm)	Horiz	% Org. C	mg kg^{-1} Tot. N	NO_3-	Tot P	Org P	Inorg P	Acid P	Resid P
0-12	Ap	1.99	2170	8.5	729	296	433	325	107
12-30	Bt1	1.30	1600	5.8	736	236	500	350	150
30-48	Bt2	1.01	1210	6.2	778	168	610	448	161
48-73	BCk	0.77	875	5.6	724	139	585	553	33
73-97	Ck1	0.66	671	5.4	752	91	661	603	88
97-120	Ck2	0.63	562	6.5	775	54	721	625	96