Identification of Regional Soil Quality Factors and Indicators: I. Central and Southern High Plains

John J. Brejda,* Thomas B. Moorman, Douglas L. Karlen, and Thanh H. Dao

ABSTRACT

Appropriate indicators for assessing soil quality on a regional scale using the National Resource Inventory (NRI) are unknown. Our objectives were to (i) identify soil quality factors present at a regional scale, (ii) determine which factors vary significantly with land use, and (iii) select soil attributes within these factors that can be used as soil quality indicators for regional-scale assessment. Ascalon (fine-loamy, mixed, superactive, mesic Aridic Argiustoll) and Amarillo (fine-loamy, mixed, thermic Aridic Paleustalf) soils were sampled from a statistically representative subset of NRI sample points within the Central and Southern High Plains Major Land Resource Areas (MLRA) and analyzed for 20 soil attributes. Factor analysis was used to identify soil quality factors, and discriminant analysis was used to identify the factors and indicators most sensitive to land use within each MLRA. In the Central High Plains, five soil quality factors were identified, with the organic matter and color factors varying significantly with land use. Discriminant analysis selected total organic C (TOC) and total N as the most sensitive indicators of soil quality at a regional scale. In the Southern High Plains, six factors were identified, with water stable aggregate (WSA) content, TOC, and soil salinity varying significantly with land use. Discriminant analysis selected TOC and WSA content as the most sensitive indicators of soil quality in the Southern High Plains. Total organic C was the only indicator that consistently showed significant differences between land uses in both regions.

Soil conservation on private lands in the USA is monitored by the USDA-NRCS using the NRI. However, with the NRI no soil samples are collected and in most cases field sites are not visited. The NRI calculates an estimated rate of soil erosion using the Universal Soil Loss Equation to determine whether the nation's soils are improving, stable, or degrading (U.S. Congress, Office of Technology Assessment, 1995). However, soil can be degraded by means other than soil erosion. Degradation can result from declines in organic matter content, compaction, salinization, acidification, alkalinization, nutrient depletion, chemical or heavy metal contamination, or reduced diversity and activity of soil organisms. Thus, a complete assessment of soil conservation must go beyond estimating soil erosion and should consider other soil qualities that may be degraded.

Soil quality has been defined as "the capacity of a soil to function within ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran and Parkin, 1994). Soil functions that soil quality influences include the ability (i) to accept, hold, and release nutrients and other chemical constituents; (ii) to accept, hold, and release water to plants and surface and groundwater recharge; (iii) to promote and sustain root growth; (iv) to maintain suitable soil biotic habitat; and (iv) to respond to management and resist degradation (Larson and Pierce, 1991). Because of its importance, the National Research Council (1993) recommended that protecting soil quality should be a fundamental goal of a national environmental program.

The diversity of soils across the USA could hinder our ability to detect significant change in soil quality at a national scale. An assessment of soil quality at a regional scale may be more feasible if each region contains similar soil and land use patterns. Major Land Resource Areas are geographic units of several thousand hectares in extent that contain similar patterns of soils, climate, water resources, and land uses (USDA-SCS, 1981). They are important in agricultural planning at the state, regional, and national levels (USDA-SCS, 1981). Thus, the MLRA offers a regional-scale unit for assessing soil quality.

However, two problems hinder a regional-scale assessment of soil quality. First, soil quality cannot be measured directly, but must be inferred by measuring soil attributes or properties that serve as indicators. Changes in these indicators can be used to determine whether soil quality is improving, stable, or declining with changes in management, land use, or conservation practices. Although several minimum data sets of soil attributes have been proposed for use as soil quality indicators at the plot and field scale (Arshad and Coen, 1992; Doran and Parkin, 1994; Kennedy and Papendick, 1995; Larson and Pierce, 1991, 1994), none have been evaluated at a regional scale.

Second, many of the soil attributes that contribute to soil quality are highly correlated, functioning in concert with other soil attributes (Larson and Pierce, 1991; Seybold et al., 1997). Because of the correlation, a stronger assessment of soil quality may be achieved by evaluating several soil attributes simultaneously using statistical procedures that account for correlations among soil attributes. Multivariate statistical analyses provide techniques for simultaneously analyzing correlated variables. Because several variables are considered together, multivariate analyses can reveal relationships not previously sus-

J.J. Brejda, USDA-ARS, Wheat, Sorghum, and Forage Res. Unit, 344 Keim Hall, Univ. of Nebraska, Lincoln, NE 68583; T.B. Moorman and D.L. Karlen, USDA-ARS, Natl. Soil Tilth Lab., 2150 Pammel Drive, Ames, IA 50011; and T.H. Dao, USDA-ARS, Conserv. and Prod. Res. Lab., P.O. Box Drawer 10, Bushland, TX 79012. Received 21 Apr. 1999. *Corresponding author (jbrejda@unlserve.unl.edu).

Published in Soil Sci. Soc. Am. J. 64:2115–2124 (2000).

Abbreviations: CEC, cation-exchange capacity; CRP, Conservation Reserve Program; MBC, microbial biomass C; MEP, Mehlich III extractable P; MLRA, Major Land Resource Area; NRI, National Resource Inventory; PMC, potentially mineralizable C; PMN, potentially mineralizable N; PSU, primary sampling unit; TOC, total organic C; WSA, water stable aggregate.

*, ** Significant at the 0.05 and 0.01 levels of probability, respectively.

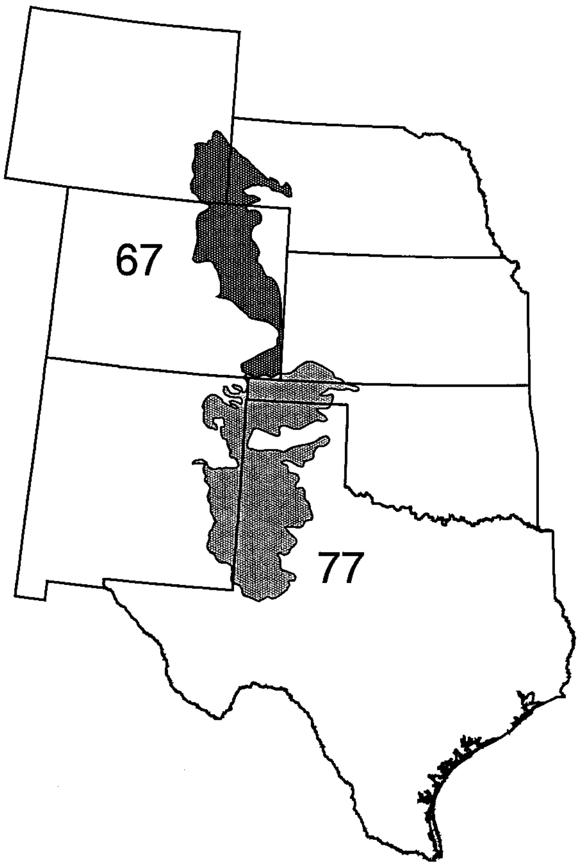

Fig. 1. Geographic distribution (shaded areas) of the Central (67) and Southern High Plains (77) Major Land Resource Areas.

pected when variables are analyzed individually (James and McCulloch, 1990).

Factor analysis is a multivariate procedure used to describe the interrelationships among many correlated variables in terms of a few underlying factors (Johnson and Wichern, 1992). However, the reader must keep in mind that the factors generated by factor analysis are a statistical construct (Johnson and Wichern, 1992) and should not be confused with the factors of soil formation proposed by Jenny (1980), which are pedological concepts. Using factor analysis, a large number (p) of correlated variables are reduced to $m < p$ uncorrelated factors that are linear functions of the original variables. Each factor is responsible for the correlation among the group of soil attributes that comprise it (Johnson and Wichern, 1992). If these factors can be related to soil functions, they could represent soil quality factors. Changes in the soil attributes that comprise each soil quality factor could be used to assess whether soil quality is aggrading, degrading, or remaining stable under different land uses or soil conservation practices. Our objectives were (i) to identify regional-scale soil quality factors present from a set of 20 soil attributes, (ii) to determine which soil quality factors vary significantly with land use, and (iii) to select soil attributes within these factors that can be used as indicators with the NRI to assess effects of land use or soil conservation programs on soil quality at a regional scale.

MATERIALS AND METHODS

Two MLRAs, designated the Central and Southern High Plains, were selected for this study. The Central High Plains covers 74 160 km^2 in eastern Colorado, southeastern Wyoming, and western Nebraska (Fig. 1). Elevation ranges from 1100 to 1800 m, increasing from east to west. Average annual precipitation ranges from 325 to 425 mm with maximum precipitation falling in late spring and early autumn. Average annual temperature ranges from 7 to 10°C. Results from the 1992 NRI, the most recent year for which data have been summarized, indicate 49% of the land area is covered by native range supporting intensive livestock production enterprises, 31% is crop land used for wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), alfalfa (*Medicago sativa* L.), sugar beet (*Beta vulgaris* L.), and vegetable production, 10% is in miscellaneous and minor land uses including land enrolled in the Conservation Reserve Program (CRP), and 4% is covered by urban and rural development and transportation structures.

The Southern High Plains covers 126 470 km^2 in eastern New Mexico and northwestern Texas and Oklahoma (Fig. 1). Elevation ranges from 800 to 2000 m, increasing from southeast to northwest. Average annual precipitation ranges from 375 to 550 mm but fluctuates widely from year to year. Average annual temperature ranges from 13 to 17°C. Results from the 1992 NRI indicate that 43% of the land area is covered by native rangeland supporting intensive livestock production enterprises, 40% is dryland farmed to winter wheat, grain sorghum [*Sorghum bicolor* (L.) Moench], and cotton (*Gossypium hirsutum* L.), 12% is in miscellaneous and minor land uses including CRP, and the remainder is covered by urban and rural development and transportation structures.

Experimental Design

The NRI sampling design was used to select statistically representative sample points within each MLRA. The design of the NRI is a stratified two-stage area sample (Nusser and Goebel, 1997; Nusser et al., 1998). The 36 sections (259 ha = 1 section) within each township are placed into three groups of 12 sections each. The groups are called strata, and each stratum is 3.22 by 9.66 km in size. The first stratum is comprised of Sections 1 through 12, the second stratum of Sections 13 through 24, and the third stratum of Sections 25 through 36. The purpose of stratification is to ensure the sample points are well distributed across each county and MLRA. In the first stage of sampling, two primary sampling units (PSU) were randomly selected within each strata. Each PSU represents a 64.8-ha (quarter-section) area, 0.8 km on each side. In the second stage of sampling, two sample points were selected within each PSU according to a restricted randomization procedure. Detailed description on sample point selection within a PSU is found in Goebel and Baker (1982).

A sample of 100 points was selected within each MLRA, with the restriction that points were confined to a single soil series. In the Central High Plains, sampling was confined to the Ascalon series. This series was chosen because Ustolls cover >47% of the land area in the Central High Plains. The Ascalon series is representative of Ustolls in this MLRA and has a wide geographic distribution. In the Southern High Plains, sampling was confined to the Amarillo series. The Amarillo series is widely distributed throughout the Southern High Plains, covering >10% of the land area within this MLRA. Field crews located each sample point using aerial photographs taken during previous NRI sampling periods. The correct location of each point was verified in the field using global positioning system technology. If the soil present at the sampling site was not the designated series, the point was not sampled. As a result, only 64 points were sampled in the Central High Plains and 47 points were sampled in the Southern High Plains.

Soil Sampling and Analysis

At each sample point a soil pit was dug to determine the depth of the A horizon. The hue, value, and chroma of the A horizon were determined using a Munsell color chart and duplicate 1000-cm^3 soil samples were collected. If the soil had been recently cultivated, samples were taken from the 0- to 10-cm depth. If the soil had not been cultivated, samples were taken from the 0- to 2.5- and 2.5- to 10-cm depths. However, for this study all data were analyzed for the 0- to 10-cm depth using weighted average values for samples taken from the 0- to 2.5- and 2.5- to 10-cm depths. One of the soil samples was collected for biological analysis and was placed in a cooler with ice packs for transport to the lab. The other sample was collected for physical and chemical analysis and was sent to the lab without refrigeration.

Samples collected for biological analysis were analyzed for microbial biomass C (MBC), potentially mineralizable C (PMC), and potentially mineralizable N (PMN). Microbial biomass C was determined on 50-g samples by chloroform fumigation and direct extraction with 0.5 M K_2SO_4 using duplicate 4-mm sieved field-moist soil samples (Tate et al., 1988). Total organic C in the fumigated and nonfumigated extracts was measured using a Dohrmann DC-180 carbon analyzer (Rosemount Analytical Services, Santa Clara, CA) calibrated with potassium phthalate standards. Microbial biomass C was calculated using the correction factor ($k = 0.33$) of Sparling and West (1988). Potentially mineralizable C and PMN were measured on the <2-mm fraction using procedures outlined by Drinkwater et al. (1996) with the following modifications. Forty grams of soil were used in the analysis instead of 10 g, and the samples were incubated for 35 d at 25°C instead of 30°C.

A 100-g subsample (air dried) of soil collected for physical and chemical analysis was analyzed for WSAs using screens with 4-, 2-, 1-, 0.5-, and 0.25-mm openings (Kemper and Rosenau, 1986). Aggregate weights were summed from each sieve and divided by the sample weight to calculate total WSA content.

A duplicate soil sample was sieved through a 2-mm screen and analyzed for sand, silt, and clay content (pipette method), pH (1:1 soil/water), TOC by dry combustion measured with a Leco SC-444 analyzer (Leco Corp., St. Joseph, MI), total N by dry combustion measured with a Leco FP-438 analyzer, cation-exchange capacity (CEC) at pH 7 by ammonium acetate extraction measured with a Kjeltec Auto 1035 Analyzer (Tecator, Perstorp Analytical Inc., Florence, MA), and exchangeable Ca, Mg, K, and Na at pH 7, by ammonium acetate extraction measured with a Perkin-Elmer AA 5000 (Perkin-Elmer Corp., Norwalk, CT), and exchangeable acidity by $BaCl_2$-triethanolamine solution buffered at pH 8.2 and back-titrated with HCl. Standard soil survey lab methods (USDA-NRCS, 1996) were used for these analyses. The soil samples were also analyzed for Mehlich III extractable P (MEP) (Mehlich, 1984) measured using inductively coupled plasma emission spectroscopy.

Statistical Analysis

Factor Analysis

Factor analysis was used to group the 20 soil attributes into statistical factors based on their correlation structure using PROC FACTOR in SAS (SAS Institute, 1989). Several methods are available for factor extraction (SAS Institute, 1989). Principal component analysis was used as the method of factor extraction for this study because it requires no prior estimates of the amount of variation in each soil attribute explained by the factors. Factor analysis was performed on standardized variables using the correlation matrix (Tables 1 and 4), to eliminate the effect of different measurement units on the determination of factor loadings (James and McCulloch, 1990; Johnson and Wichern, 1992). Factor loadings are the simple correlations between the soil attributes and each factor (Sharma, 1996). The soil variables analyzed were A horizon value, chroma, and depth; percentage sand, silt, and clay; WSA content; TOC, MBC, and PMC; total N and PMN; MEP; pH; CEC; exchangeable Ca, Mg, K, Na, and acidity.

Eigenvalues are the amount of variance explained by each factor (Sharma, 1996). Because factor analysis was performed on standardized values of soil attributes, each attribute had a variance of one with a total variance of 20 for the entire data set. Factors with eigenvalues >1 explained more total variation in the data than individual soil attributes, and factors with eigenvalues <1 explained less total variation than individual soil attributes. Therefore, only factors with eigenvalues >1 were retained for interpretation. Retained factors were subjected to a varimax rotation. A varimax rotation redistributes the variance of each factor to maximize the relationship between the interdependent soil variables (SAS Institute, 1989).

Communalities estimate the portion of variance in each soil attribute explained by the factors. A high communality for a soil attribute indicates a high proportion of its variance is explained by the factors. In contrast, a low communality for a soil attribute indicates much of that attribute's variance remains unexplained. Less importance should be ascribed to soil attributes with low communalities when interpreting the factors.

The sample points used in this study are sampled every 5 yr as part of the NRI. As a result, information on land use practices for 1989 through 1996 was available for each point. This information was used to place each sample point in the Central High Plains into one of four land use categories: (i) continuous crop land, (ii) CRP, (iii) perennial forages comprised of introduced grasses and legumes used for pasture and hay production, or (iv) native rangeland. In the Southern High Plains each sample point was assigned to one of three land use categories: (i) continuous crop land, (ii) CRP, or (iii) native rangeland. Factor scores for each sample point were computed by SAS using the regression method (SAS Institute, 1989; Johnson and Wichern, 1992) and analyzed by analysis of variance using the GLM procedure with land use as the independent variable, to determine which factors varied significantly with land use.

Discriminant Analysis

Discriminant analysis was used to select the statistical factor(s) that were most discriminating between the different land use categories. The analysis was done using PROC DISCRIM in SAS (SAS Institute, 1989). Covariance matrices for the land use groups were tested for equality at the $\alpha = 0.01$ significance level with the POOL = TEST option. The matrices were unequal in both regions, so the pooled within group covariance matrices and a quadratic discriminant function were used in the analysis (SAS Institute, 1989). Following selection of the most discriminating factor(s), soil attributes that comprised these factors were also subjected to discriminant analysis to select soil quality indicators. Prior to analysis, all soil attributes were tested for normality using the procedure of D'Agostino et al. (1990), and non-normally distributed soil attributes were $\log_e$ transformed.

Table 1. Correlations among physical, chemical, and biological attributes in the 0- to 10-cm depth of Ascalon soils in the Central High Plains Major Land Resource Area (n = 64).

	A horizon														Exchangeable				
Soil attributes	Value	Chroma	Depth	Sand	Silt	Clay	WSA†	TOC‡	MBC§	PMC¶	Total N	PMN#	Mehlich P	pH	CEC††	Ca	Mg	K	Na
A horizon chroma	0.44**																		
A horizon depth	−0.09	−0.13																	
Sand	0.11	0.17	0.10																
Silt	−0.17	−0.21	−0.10	−0.91**															
Clay	0.01	−0.07	−0.06	−0.82**	0.51**														
WSA†	0.08	−0.07	−0.37**	0.27*	−0.26*	−0.22													
TOC‡	−0.08	−0.30*	−0.45**	−0.25*	0.15	0.32**	0.37**												
MBC§	−0.14	−0.10	−0.28*	−0.19	0.12	0.22	0.21	0.66**											
PMC¶	0.18	0.04	−0.34**	0.22	−0.28*	−0.07	0.51*	0.37**	0.17										
Total N	−0.32*	−0.30*	−0.37**	−0.31*	0.19	0.38**	0.26*	0.91**	0.68**	0.27*									
PMN#	−0.18	−0.28*	−0.39**	−0.06	0.05	0.05	0.19	0.76**	0.66**	0.35**	0.77**								
Mehlich P	−0.23	−0.11	0.06	−0.11	0.22	−0.07	−0.07	0.17	0.27	−0.10	0.28*	0.40**							
pH	0.24	0.05	0.00	−0.26*	0.08	0.42**	−0.05	0.10	0.14	0.08	0.04	0.08	−0.06						
CEC††	−0.12	−0.20	−0.28*	−0.77**	0.52**	0.88**	−0.09	0.57**	0.41**	0.01	0.62**	0.35**	−0.02	0.45**					
Exchangeable Ca	0.40**	0.18	−0.18	−0.37**	0.19	0.51**	0.03	0.28*	0.09	0.08	0.12	0.03	−0.14	0.67**	0.50**				
Exchangeable Mg	0.15	0.05	−0.11	−0.62**	0.35**	0.81**	−0.24	0.19	0.18	−0.10	0.28*	0.12	0.00	0.51**	0.73**	0.42**			
Exchangeable K	−0.28*	−0.35**	−0.20	−0.50**	0.54**	0.29**	−0.16	0.36**	0.25*	−0.13	0.37**	0.37**	0.28*	0.04	0.46**	0.06	0.22		
Exchangeable Na	0.01	0.01	0.06	−0.18	0.09	0.25*	−0.01	−0.08	0.07	−0.14	0.04	0.02	0.35**	0.49**	0.23	0.20	0.48**	0.03	
Exchange. Acidity	−0.38**	−0.25*	−0.26*	−0.24	0.28*	0.10	0.01	0.47**	0.37**	0.07	0.53**	0.39**	0.30*	−0.62**	0.22	−0.40**	−0.05	0.37**	−0.33**

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† WSA = water stable aggregates.
‡ TOC = total organic C.
§ MBC = microbial biomass C.
¶ PMC = potentially mineralizable C.
# PMN = potentially mineralizable N.
†† CEC = cation-exchange capacity.

Table 2. Rotated factor loadings and communalities of a five-factor model of physical, chemical, and biological soil attributes in the Central High Plains Hills Major Land Resource Area.

	Factor					
Soil attributes	1	2	3	4	5	Communalities
A horizon value	−0.09	−0.04	0.28	0.71	−0.21	0.64
A horizon chroma	−0.10	−0.16	0.02	0.87	0.07	0.80
A horizon depth	−0.13	−0.61	0.16	−0.39	0.12	0.59
Sand	−0.95	−0.02	−0.06	0.06	−0.03	0.91
Silt	0.82	−0.05	−0.15	−0.09	0.13	0.72
Clay	0.85	0.12	0.33	0.00	−0.12	0.86
WSA†	−0.41	0.56	0.07	0.01	−0.24	0.55
Total organic C	0.25	0.90	−0.02	−0.14	−0.03	0.89
Microbial biomass C	0.17	0.71	0.01	−0.04	0.29	0.62
Potentially mineral. C	−0.32	0.60	0.14	0.11	−0.31	0.59
Total N	0.31	0.84	−0.05	−0.25	0.14	0.88
Potentially mineral. N	0.05	0.82	−0.03	−0.17	0.31	0.80
Mehlich P	0.02	0.17	−0.08	−0.10	0.87	0.81
pH	0.23	0.08	0.88	0.06	0.00	0.84
CEC‡	0.81	0.41	0.28	−0.11	−0.08	0.92
Exchangeable Ca	0.38	0.17	0.61	0.31	−0.23	0.70
Exchangeable Mg	0.69	0.09	0.47	0.15	0.11	0.73
Exchangeable K	0.55	0.23	−0.18	−0.28	0.22	0.52
Exchangeable Na	0.11	−0.06	0.65	−0.02	0.55	0.75
Exchangeable acidity	0.30	0.38	−0.76	−0.16	0.18	0.87
Eigenvalues	4.54	4.22	2.76	1.80	1.68	

† WSA = water stable aggregates.
‡ CEC = cation-exchange capacity.

RESULTS

Central High Plains

If there were no correlation between soil attributes, identification of underlying factor patterns would not be possible (Johnson and Wichern, 1992). However, in the Central High Plains, significant correlation ($P < 0.05$) was present among 87 of 190 soil attribute pairs (Table 1). The high frequency of correlation indicates that soil attributes can be grouped into factors based on their correlation patterns. In general, percentage clay, TOC, MBC, total N, and PMN concentrations were positively correlated with most soil attributes (Table 1). In contrast, A horizon value, chroma, and depth, and percentage sand were negatively correlated with most soil attributes. The strongest negative correlations were between percentage sand and percentage silt ($r = -0.91$**), clay ($r = -0.82$**), and CEC ($r = -0.77$**). A horizon value was positively correlated with exchangeable Ca ($r = 0.40$**), but not with TOC ($r = -0.08$). This suggests that lightness of soil color was more related to soil Ca content than soil organic matter content.

Each of the first five factors had eigenvalues greater than one (Table 2) and were retained for interpretation. Communalities for the soil attributes indicate the five factors explained >90% of the variance in percentage sand and CEC, and 80% of the variance in A horizon chroma, percentage clay, TOC, total N, PMN, MEP, pH, and exchangeable acidity (Table 2). However, the five factors explained <60% of the variance in A horizon depth, WSA concentration, PMC, and exchangeable K.

The order in which factors were interpreted was determined by the magnitude of their eigenvalues. The first factor was termed the *soil texture factor* because it had high positive loadings (>0.80) for percentage silt and clay, and CEC, and a high negative loading for percentage sand (Table 2). The soil texture factor also had moderate positive loadings for exchangeable Mg and K (Table 2), resulting from the significant correlation between exchangeable Mg and K and CEC (Table 1). Grouping of CEC with soil texture resulted from the large positive correlation between CEC and percentage clay ($r = 0.88$**), which was greater than the correlation between CEC and TOC ($r = 0.57$**).

The second factor was termed the *soil organic matter factor* because it had high positive loadings (>0.80) on TOC, total N, and PMN, and moderate positive loadings on WSA (0.56), MBC (0.71), and PMC (0.60) (Table 2). A horizon depth had a moderate negative loading on the soil organic matter factor. This factor was termed the soil organic matter factor because most of the attributes comprising it are important components of soil organic matter quality (Gregorich et al., 1994).

The third factor was termed the *soil acidity factor* because it had a high positive loading for pH, moderate positive loadings for exchangeable Ca and Na, and a moderate negative loading for exchangeable acidity (Table 2). These soil attributes were grouped together because all four were significantly correlated ($P < 0.05$) with each other (Table 1).

The fourth factor was termed the *soil color factor* because it had high positive loadings on A horizon value and chroma (Table 2). These two soil attributes had their largest correlation with each other (Table 1). The fifth factor was termed the *soil P factor* because it had high a positive loading on MEP (Table 2).

Factor scores for only the organic matter and color factors varied significantly with land use (Table 3). Average organic matter factor scores were negative for crop land and positive for land in perennial forages and native rangeland. Organic matter factor scores were also negative for land in CRP, but the magnitude of the scores were not as large as for crop land. This pattern is consistent with the effects of management on soil organic matter quality (Gregorich et al., 1994).

Native rangeland had large, negative soil color factor

Table 3. Soil attribute means and factor scores with different land uses in the Central High Plains Major Land Resource Area.

Soil attributes	Cropland	CRP	Perennial forages	Native rangeland	SE	ANOVA $P > F$
Number of points sampled	28	11	17	8		
A horizon value	3.14	3.27	3.35	3.00	0.13	NS
A horizon chroma	2.93	2.73	2.88	2.25	0.13	0.05
A horizon depth, cm	18.7	19.5	14.4	16.3	1.5	0.10
Sand, %	61.4	63.2	65.2	66.9	3.4	NS
Silt, %	23.5	22.4	17.8	20.2	2.2	NS
Clay, %	15.1	14.5	17.0	12.9	1.6	NS
WSA†, g kg^{-1}	380	480	470	510	40	0.10
TOC‡, g kg^{-1}	6.5	10.1	14.1	17.7	1.2	0.01
MBC§, mg kg^{-1}	310	420	560	740	61	0.01
PMC¶, mg kg^{-1} d^{-1}	9.6	14.9	21.3	18.5	2.8	0.01
Total N, g kg^{-1}	0.82	0.90	1.37	1.59	0.11	0.01
PMN#, mg N kg^{-1}	19.8	24.5	42.6	49.2	3.2	0.01
Mehlich P, mg kg^{-1}	39	33	39	51	6.5	NS
pH (1:1 soil/H_2O)	6.48	6.82	7.16	6.44	0.19	0.05
CEC††, cmol kg^{-1}	11.3	11.0	13.8	12.4	1.1	NS
Exchangeable Ca, cmol kg^{-1}	9.2	11.4	13.0	8.7	2.2	NS
Exchangeable Mg, cmol kg^{-1}	2.4	2.1	3.2	1.9	0.2	0.10
Exchangeable K, cmol kg^{-1}	0.95	1.04	0.97	0.95	0.09	NS
Exchangeable Na, cmol kg^{-1}	0.17	0.07	0.13	0.08	0.04	NS
Exchangeable acid., cmol kg^{-1}	2.4	2.2	2.2	3.6	0.34	0.10
			Factor scores			
Factor 1 (texture)	0.15	−0.07	−0.05	−0.32	0.25	NS
Factor 2 (organic matter)	−0.67	−0.18	0.73	1.05	0.18	0.01
Factor 3 (acidity)	−0.18	0.00	0.45	−0.34	0.25	NS
Factor 4 (color)	0.13	−0.17	0.25	−0.74	0.24	0.10
Factor 5 (phosphorus)	0.16	−0.42	−0.07	0.17	0.25	NS

† WSA = water stable aggregates.
‡ TOC = total organic C.
§ MBC = microbial biomass C.
¶ PMC = potentially mineralizable C.
# PMN = potentially mineralizable N.
†† CEC = cation-exchange capacity.

scores (Table 3). Native rangeland had the lowest A horizon value and chroma, indicating darker soil colors, resulting in the large negative scores. In contrast, soil color factor scores were positive under crop land and perennial forages. These two land uses had the highest A horizon value and chroma, indicating lighter soil colors. Land under CRP had intermediate soil color factor scores (Table 3).

Discriminant analysis of the five statistical factors indicated the soil organic matter factor was the most powerful in discriminating among the four land use categories (Eq. [1]).

$$Y_1 = 1.00(\text{organic matter}) - 0.28(\text{texture}) + 0.26(\text{acidity}) - 0.24(\text{color}) - 0.09(\text{soil P}) \quad [1]$$

The discriminant coefficient for the soil organic matter factor was about fourfold larger than coefficients for soil texture, acidity, and color factors, and more than tenfold larger than the coefficient for the soil P factor (Eq. [1]). Results from the discriminant analysis are consistent with results from the analysis of variance, in which the soil texture, acidity, and soil P factors did not vary significantly with land use. These results indicate that the soil texture, acidity, and soil P factors were not useful indicators for monitoring changes in soil quality under different land uses or conservation programs on a regional scale within the Central High Plains.

Discriminant analysis of soil attributes that comprise the soil organic matter factor indicated that TOC and total N were the most powerful soil attributes in discriminating among different land uses (Eq. [2]).

$$Y_2 = 0.98(\text{TOC}) - 0.73(\text{total N}) + 0.39(\text{PMC}) + 0.39(\text{PMN}) + 0.26(\text{MBC}) + 0.16(\text{A horizon depth}) + 0.11(\text{WSA}) \quad [2]$$

Both TOC and total N varied significantly with land use (Table 3), with values decreasing in the order: native rangeland > perennial forages > CRP > crop land (Table 3). Thus, TOC and total N appear to offer the greatest potential for monitoring changes in soil quality with changes in land use and soil conservation practices at a regional scale in the Central High Plains.

Southern High Plains

For the Southern High Plains significant correlation ($P < 0.05$) occurred among 65 of 190 soil attribute pairs, indicating the soil attributes can be grouped into factors on the basis of their correlation patterns (Table 4). Soil attributes with the largest number of significant correlations were exchangeable K and percentage clay (11), percentage sand and exchangeable acidity (10), and percentage silt and exchangeable Ca and Mg (9) (Table 4). Biological soil attributes, including MBC (2), PMC (2), and PMN (3), were correlated with the fewest number of soil attributes. Percentage sand and A horizon depth were negatively correlated with most soil attributes.

Each of the first six factors had eigenvalues greater than one (Table 5). The first six factors explained >90% of the variance in percentage sand and clay, and CEC, and 80% of the variance in percentage silt, TOC, total N, pH, and exchangeable Ca, Mg, K, and Na (Table 5).

Table 4. Correlations among physical, chemical, and biological attributes in the 0- to 10-cm depth of Amarillo soils in the Southern High Plains Major Land Resource Area ($n = 47$).

	A horizon														Exchangeable				
Soil attributes	Value	Chroma	Depth	Sand	Silt	Clay	WSA†	TOC‡	MBC§	PMC¶	Total N	PMN#	Mehlich P	pH	CEC††	Ca	Mg	K	Na
A horizon chroma	0.00																		
A horizon depth	−0.02	0.23																	
Sand	0.19	0.26	0.32*																
Silt	−0.15	−0.32	−0.28	−0.94**															
Clay	−0.21	−0.15	−0.31*	−0.89**	0.68**														
WSA†	0.33*	−0.05	−0.29*	−0.03	0.16	−0.15													
TOC‡	−0.15	−0.35*	−0.28	−0.57**	0.67**	0.32*	0.19												
MBC§	−0.08	−0.19	−0.10	−0.13	0.16	0.07	0.16	0.07											
PMC¶	0.03	−0.02	0.01	−0.20	0.25	0.08	0.03	0.45**	−0.11										
Total N	−0.02	−0.42**	−0.21	−0.70**	0.75**	0.49**	0.26	0.79**	0.22	0.42**									
PMN#	0.02	−0.01	−0.19	−0.16	0.04	0.29*	−0.18	0.19	−0.07	0.06	0.16								
Mehlich P	−0.14	−0.17	−0.17	0.08	−0.04	−0.11	−0.11	0.04	0.31*	−0.13	−0.04	0.07							
pH	0.22	0.36*	0.17	0.01	−0.12	0.14	0.01	−0.26*	−0.29*	−0.13	−0.16	0.03	−0.27						
CEC††	−0.17	−0.19	−0.28	−0.93**	0.78**	0.95**	−0.07	0.47**	0.02	0.21	0.64**	0.26	−0.12	0.20					
Exchangeable Ca	0.00	0.04	−0.10	−0.49*	0.36*	0.55**	0.10	0.34*	−0.11	0.11	0.39**	0.08	−0.29*	0.51**	0.61**				
Exchangeable Mg	−0.07	−0.05	−0.14	−0.43**	0.33*	0.48**	−0.38**	0.21	−0.11	0.17	0.27	0.37**	0.07	0.29*	0.53**	0.10			
Exchangeable K	−0.27	−0.12	−0.34*	−0.76**	0.63**	0.78**	−0.28	0.52**	−0.03	0.41**	0.57	0.41**	0.05	0.04	0.82**	0.44**	0.59**		
Exchangeable Na	0.18	0.06	−0.04	−0.10	0.07	0.12	−0.09	−0.19	−0.17	−0.02	0.05	0.06	0.00	0.31*	0.14	−0.11	0.56**	0.10	
Exchange. Acidity	−0.39**	−0.25	−0.32*	−0.51**	0.53**	0.38**	−0.16	0.44**	0.21	0.06	0.37**	0.07	0.20	−0.63**	0.35*	−0.11	0.12	0.39**	−0.17

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† WSA = water stable aggregates.
‡ TOC = total organic C.
§ MBC = microbial biomass C.
¶ PMC = potentially mineralizable C.
# PMN = potentially mineralizable N.
†† CEC = cation-exchange capacity.

Table 5. Rotated factor loadings and communalities of a six-factor model of physical, chemical, and biological soil attributes in the Southern High Plains Major Land Resource Area.

	Factor						
Soil attributes	1	2	3	4	5	6	Communalities
A horizon value	−0.23	0.19	0.70	0.07	0.25	0.08	0.65
A horizon chroma	−0.21	0.56	−0.19	−0.14	−0.06	0.03	0.42
A horizon depth	−0.31	0.37	−0.33	0.13	0.04	−0.52	0.63
Sand	−0.95	0.16	0.03	−0.10	−0.09	−0.01	0.95
Silt	0.85	−0.29	0.07	0.24	0.07	−0.12	0.89
Clay	0.91	0.03	−0.16	−0.09	−0.11	0.18	0.90
Water stable aggregates	0.05	−0.10	0.83	0.02	−0.24	−0.13	0.79
Total organic C	0.54	−0.29	0.12	0.60	−0.18	0.14	0.80
Microbial biomass C	0.13	−0.56	0.14	−0.28	−0.14	−0.12	0.46
Potentially mineral. C	0.12	0.07	0.00	0.86	0.03	0.03	0.76
Total N	0.68	−0.28	0.26	0.48	0.03	−0.01	0.85
Potentially Mineral. N	0.12	0.07	−0.10	0.12	0.08	0.84	0.75
Mehlich P	−0.16	−0.58	−0.11	−0.20	0.13	0.30	0.52
pH	0.17	0.79	0.19	−0.28	0.28	0.02	0.85
CEC†	0.95	0.06	−0.08	0.06	0.14	0.14	0.96
Exchangeable Ca	0.68	0.50	0.17	−0.02	−0.24	0.07	0.81
Exchangeable Mg	0.40	0.05	−0.24	0.12	0.72	0.30	0.85
Exchangeable K	0.74	−0.01	−0.28	0.28	0.15	0.39	0.89
Exchangeable Na	0.05	0.08	0.09	−0.07	0.91	−0.03	0.84
Exchangeable acidity	0.39	−0.64	−0.37	0.13	−0.16	0.05	0.75
Eigenvalues	5.74	2.72	1.85	1.79	1.78	1.43	

† CEC = cation-exchange capacity.

However, they explained <60% of the variance in A horizon chroma, MBC, and MEP.

The first factor had a high negative loading (−0.95) for percentage sand; high positive loadings for percentage silt and clay, and CEC (>0.80); and moderate positive loadings (0.60) for exchangeable Ca, K, and total N (Table 5). The first factor was termed the *soil texture factor* because of the high loadings on percentage sand, silt, and clay, and CEC. Five of the soil attributes that comprised the soil texture factor for the Southern High Plains data were identical to attributes that comprised this factor in the Central High Plains data.

The second factor was termed the *soil acidity factor* because it had a high positive loading for pH, and moderate negative loadings for exchangeable acidity, MEP, and MBC (Table 5). The soil acidity factor also had a moderate positive loading for A horizon chroma, but this soil attribute had a low communality, indicating that little weight should be given to this variable in interpreting variable associations.

The third factor had a high positive loading for WSA and a moderate positive loading for A horizon value (Table 5). This factor was termed the *soil aggregates factor* because the loading and communality were higher with WSA than A horizon value. The fourth factor was termed the *soil C factor* because it had a high positive loading on PMC and moderate positive factor loading on TOC (Table 5). The fifth factor was termed a *soil salinity factor* because it had a high positive loading for exchangeable Na and a moderate positive loading for exchangeable Mg (Table 6). The sixth factor had a high positive loading for PMN and a moderate negative loading for A horizon depth (Table 5). This factor was termed the *PMN factor* because of the higher loading and communality on PMN.

Factor scores for the soil texture, soil acidity, and PMN factors did not vary significantly with land use (Table 6). The lack of significant variation in the soil texture and soil acidity factors with land use is similar to the pattern observed for the Central High Plains data. A PMN factor was not identified in the Central High Plains. The soil attribute that comprised this factor in the Southern High Plains was a component of the organic matter factor in the Central High Plains.

Factor scores for the soil aggregate, soil C, and soil salinity factors varied significantly with land use (Table 6). Soil aggregate factor scores were positive for native rangeland, resulting from higher WSA content in soils under this land use, and negative for crop land and land in CRP. Soil C factor scores were highest under native rangeland, intermediate under CRP, and lowest under crop land. The two soil attributes that had the greatest loadings on the soil C factor (TOC and PMC) followed the same pattern, but differences between land use were not significant for PMC ($P = 0.25$) (Table 6). Soil salinity factor scores were highest under crop land, intermediate under CRP, and lowest under native rangeland. The two soil attributes that had the greatest loading on the soil salinity factor (exchangeable Na and Mg) followed the same pattern as soil salinity factor scores, but differences were small between crop land and CRP (Table 6).

Discriminant analysis of the six factors indentified in the Southern High Plains indicated that WSA content, soil salinity, soil C, and soil acidity were useful in discriminating between the different land uses (Eq. [3]).

$$Y_3 = -1.00(\text{WSA}) + 0.69(\text{salinity}) - 0.59(\text{Soil C}) + 0.54(\text{acidity}) + 0.31(\text{PMN}) + 0.30(\text{texture}) \quad [3]$$

Because no single soil quality factor clearly dominated the discriminant function, the seven soil attributes that varied significantly with land use were used in discriminant analysis for the selection of potential soil quality indicators.

Discriminant analysis of the soil attributes that varied significantly with land use indicated that TOC and WSA content were the most powerful in discriminating between different land uses (Eq. [4]).

Table 6. Soil attribute means and factor scores with different land uses in the Southern High Plains Major Land Resources Area.

Soil attributes	Cropland	CRP	Native rangeland	SE	P > F
Number of points sampled	26	8	13		
A horizon value	3.46	3.13	3.62	0.12	0.10
A horizon chroma	4.08	4.00	3.85	0.13	NS
A horizon depth, cm	24.4	23.9	22.6	2.6	NS
Sand, %	77.5	73.3	78.5	2.2	NS
Silt, %	10.5	13.4	12.2	1.4	NS
Clay, %	12.0	13.3	9.3	1.0	0.10
WSA†, g kg^{-1}	120	130	310	20	0.01
TOC‡, g kg^{-1}	3.7	4.5	5.3	0.4	0.05
MBC§, mg kg^{-1}	170	160	220	34	NS
PMC¶, mg kg^{-1} d^{-1}	6.9	8.4	8.7	0.9	NS
Total N, g kg^{-1}	0.47	0.58	0.63	0.06	NS
PMN#, mg N kg^{-1}	27.2	15.2	13.8	8.7	NS
Mehlich P, mg kg^{-1}	16	19	16	6	NS
pH (1:1 soil/H_2O)	7.31	7.30	6.98	0.14	NS
CEC††, cmol kg^{-1}	7.8	9.1	6.8	0.6	NS
Exch. Ca, cmol kg^{-1}	6.1	6.7	5.5	0.6	NS
Exch. Mg, cmol kg^{-1}	2.0	2.1	1.0	0.2	0.01
Exch. K, cmol kg^{-1}	0.70	0.98	0.56	0.06	0.01
Exch. Na, cmol kg^{-1}	0.11	0.08	0.03	0.03	0.10
Exch. acidity, cmol kg^{-1}	1.25	1.39	1.25	0.20	NS
			Factor scores		
Factor 1 (Soil texture)	−0.04	0.51	−0.23	0.25	NS
Factor 2 (Soil acidity)	0.17	0.13	−0.42	0.25	NS
Factor 3 (Soil aggregates)	−0.28	−0.59	0.93	0.21	0.01
Factor 4 (Soil C)	−0.27	0.08	0.48	0.24	0.10
Factor 5 (Soil salinity)	0.26	0.05	−0.56	0.24	0.05
Factor 6 (PMN)	0.13	−0.06	−0.24	0.25	NS

† WSA = water stable aggregates.
‡ TOC = total organic C.
§ MBC = microbial biomass C.
¶ PMC = potentially mineralizable C.
# PMN = potentially mineralizable N.
†† CEC = cation-exchange capacity.

$$Y_4 = 0.84(\text{TOC}) + 0.76(\text{WSA}) - 0.47(\text{clay}) - 0.41(\text{exch. Mg}) - 0.16(\text{exch. K}) - 0.04(\text{exch. Na}) + 0.005(\text{A horizon value}) \quad [4]$$

Thus, TOC and WSA offer the greatest potential for monitoring changes in soil quality with changes in land use and management at a regional scale in the Southern High Plains.

DISCUSSION

Factor analysis was used to group 20 correlated soil attributes into five factors for the Central High Plains and six factors for the Southern High Plains. Based on the attributes that comprised them, all of these factors contribute to one or more soil functions proposed by Larson and Pierce (1991) and therefore could be considered soil quality factors. The soil organic matter, soil C, soil aggregate, and soil texture factors contribute to the ability of the soil to accept, hold, and release nutrients and other chemical constituents; accept, hold, and release water to plants and for surface and groundwater recharge; promote and sustain root growth; maintain suitable soil biotic habitat; and resist degradation (Larson and Pierce, 1991). The soil acidity and salinity factors contribute to the ability of the soil to supply nutrients and promote and sustain root growth. The PMN and soil P factors are important in supplying N and P to the plant. The color factor influences soil temperature and thus mineralization rates.

Although some of the soil quality factors identified were similar between the two regions, several were different. This suggests that soil qualities vary between different soil and geographic regions, probably because of differences in climate, topography, parent material, vegetation, and land use practices in each region.

Not all of the soil quality factors varied significantly with land use. Soil quality factors that were insensitive to land use may represent inherent soil qualities that are controlled primarily by Jenny's factors of soil formation (Jenny, 1980; Seybold et al., 1997). Soil quality factors that did vary significantly with land use may represent dynamic soil qualities (Seybold et al., 1997), and offer the greatest potential for assessing the effects of land use or management practices on soil quality with the NRI. In the Central High Plains these were the organic matter factor and color factor, and in the Southern High Plains they were WSA, soil C, and soil salinity factors.

In general, dynamic soil qualities were significantly lower on crop land than under other land uses in both MLRAs. Thus, efforts to improve soil quality within these regions should focus on crop land. In the Great Plains, no-till in combination with cropping intensification have been shown to enhance soil water storage and water use efficiency, reducing the need for a fallow period (Peterson et al., 1996; McGee et al., 1997; Farahani et al., 1998). Widespread adoption of no-till and cropping intensification may be one approach to improving soil quality in these regions without taking land out of crop production.

Because soil quality factors cannot be measured directly, the effects of land use and conservation practices on these factors must be inferred by monitoring changes in the soil attributes that comprise them. Discriminant analysis indicated the most powerful soil attributes for distinguishing differences in soil quality under different land uses in the Central High Plains were TOC and total N. In the Southern High Plains the most powerful soil attributes for distinguishing differences in soil quality under different land uses were TOC and WSA. The different sets of soil quality indicators for each region suggests there may not be a universal optimum set of indicators for use across different regions of the USA. This could hinder the ability of an agency like the USDA-NRCS to monitor soil quality nationally using the NRI, because a different set of indicators would be needed for each region. However, TOC was common to both sets of indicators. In terms of soil quality, soil C affects water retention, aggregate formation, bulk density, pH, buffer capacity, cation-exchange properties, mineralization, sorption of pesticides and other agrichemicals, color, infiltration, aeration, and the activity of soil organisms (Larson and Pierce, 1991; Seybold et al., 1997). Research at the field scale on the effects of putting land in CRP on soil properties has shown that significant increases in TOC levels can be detected 5 yr after enrollment (Gebhart et al., 1994), and significant decreases in TOC levels following cultivation of previously untilled soils can be detected in even shorter time periods (Bowman et al., 1990; Davidson and Ackerman, 1993). Five-year intervals are the time frame for NRI assessments. Thus, if only one soil attribute could be used for monitoring soil quality with the NRI, TOC appears to offer the greatest potential. However, if assessments of change are needed for shorter time periods, or at sites where TOC may change more slowly (Robles and Burke, 1998), more labile fractions of soil C may need to be evaluated (Sikora et al., 1996).

REFERENCES

Arshad, M.A., and G.M. Coen. 1992. Characterization of soil quality: Physical and chemical criteria. Am. J. Altern. Agric. 7:25–31.

Bowman, R.A., J.D. Reeder, and R.W. Lober. 1990. Changes in soil properties in a Central Plains rangeland soil after 3, 20, and 60 years of cultivation. Soil Sci. 150:851–857.

D'Agostino, R.B., A. Belanger, and R.B. D'Agostino, Jr. 1990. A suggestion for using powerful and informative tests of normality. Am. Stat. 44:316–321.

Davidson, E.A., and I.L. Ackerman. 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. Biogeochem. 20:161–193.

Doran, J.W., and T.B. Parkin. 1994. Defining and assessing soil quality. p. 3–21. *In* J.W. Doran et al. (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA and ASA, Madison, WI.

Drinkwater, L.E., C.A. Cambardella, J.D. Reeder, and C.W. Rice. 1996. Potentially mineralizable nitrogen as an indicator of biologically active soil nitrogen. p. 217–229. *In* J.W. Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI.

Farahani, H.J., G.A. Peterson, D.G. Westfall, L.A. Sherrod, and L.R. Ahuja. 1998. Soil water storage in dryland cropping systems: The significance of cropping intensification. Soil Sci. Soc. Am. J. 62:984–991.

Gebhart, D.L., H.B. Johnson, H.S. Mayeux, and H.W. Polley. 1994. The CRP increases soil organic carbon. J. Soil Water Conserv. 49:488–492.

Goebel, J.J., and H.D. Baker. 1982. The 1982 National Resources Inventory sample design and estimation procedures. Statistical Lab., Iowa State Univ., Ames.

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal, and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74:367–385.

James, F.C., and C.E. McCulloch. 1990. Multivariate analysis in ecology and systematics: panacea or pandora's box? Annu. Rev. Ecol. Syst. 21:129–166.

Jenny, H. 1980. The soil resource. Springer-Verlag, New York.

Johnson, R.A., and D.W. Wichern. 1992. Applied multivariate statistical analysis. Prentice-Hall, Englewood Cliffs, NJ.

Kemper, W.D., and R.C. Rosenau. 1986. Aggregate stability and size distribution. p. 425–442. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Kennedy, A.C., and R.I. Papendick. 1995. Microbial characteristics of soil quality. J. Soil Water Conserv. 50:243–248.

Larson, W.E., and F.J. Pierce. 1991. Conservation and enhancement of soil quality. p. 175–203. *In* Evaluation for sustainable land management in the developing world. Vol. 2. IBSRAM Proc. 12 (2). Bangkok, Thailand. Int. Board Soil Res. Manage., Bangkok, Thailand.

Larson, W.E., and F.J. Pierce. 1994. The dynamics of soil quality as a measure of sustainable management. p. 37–51. *In* J.W. Doran et al. (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA and ASA, Madison, WI.

McGee, E.A., G.A. Peterson, and D.G. Westfall. 1997. Water storage efficiency in no-till dryland cropping systems. J. Soil Water Conserv. 52:131–136.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409–1416.

National Research Council. 1993. Soil and water quality: An agenda for agriculture. Nat. Acad. Press, Washington, DC.

Nusser, S.M., F.J. Breidt, and W.A. Fuller. 1998. Design and estimation for investigating the dynamics of natural resources. Ecol. Appl. 8:234–245.

Nusser, S.M., and J.J. Goebel. 1997. The National Resource Inventory: A long-term multi-resource monitoring programme. Environ. Ecol. Stat. 4:181–204.

Peterson, G.A., A.J. Schlegel, D.L. Tanaka, and O.R. Jones. 1996. Precipitation use efficiency as affected by cropping and tillage systems. J. Prod. Agric. 9:180–186.

Robles, M.D., and I.C. Burke. 1998. Soil organic matter recovery on Conservation Reserve Program fields in southeastern Wyoming. Soil Sci. Soc. Am. J. 62:725–730.

SAS Institute. 1989. SAS/STAT user's guide. Version 6. 4th ed. Vol. 1. SAS Inst., Cary, NC.

Seybold, C.A., M.J. Mausbach, D.L. Karlen, and H.H. Rogers. 1997. Quantification of soil quality. p. 387–404. *In* R. Lal et al. (ed.) Soil processes and the carbon cycle. CRC Press, Boca Raton, FL.

Sharma, S. 1996. Applied multivariate techniques. John Wiley and Sons, New York.

Sikora, L.J., V. Yakovchenko, C.A. Cambardella, and J.W. Doran. 1996. Assessing soil quality by testing organic matter. p. 41–50. *In* F.R. Magdoff et al. (ed.) Soil organic matter: Analysis and interpretation. SSSA Spec. Publ. 46. SSSA, Madison, WI.

Sparling, G.P., and A.W. West. 1988. A direct extraction method to estimate soil microbial C: Calibration in situ using microbial respiration and ^{14}C cells. Soil Biol. Biochem. 20:337–343.

Tate, K.R., D.J. Ross, and C.W. Feltham. 1988. A direct extraction method to estimate soil microbial C: Effects of some experimental variables and some different calibration procedures. Soil Biol. Biochem. 20:329–335.

U.S. Congress, Office of Technology Assessment. 1995. Targeting environmental priorities in agriculture: Reforming program strategies. OTA-ENV-640. U.S. Gov. Print. Office, Washington, DC.

USDA-NRCS. 1996. Soil survey laboratory methods manual. Soil Survey Investigations Rep. 42, Ver. 3.0. National Soil Survey Center, Lincoln, NE.

USDA, Soil Conservation Service. 1981. Land resource regions and major land resource areas of the United States. USDA-SCS Agric. Handb. 296. U.S. Gov. Print. Office, Washington, DC.