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Identification and Interpretation of Regional Soil Quality Factors for the Central High Plains of the Midwestern USA

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ABSTRACT

Appropriate indicators and indices for assessing soil quality on a regional scale are needed to accurately assess the impact of different land-uses and soil conservation practices on soil quality over broad geographic areas. Our objectives were to: 1) identify soil quality factors present at a regional scale, and 2) interpret these factors using an index of the attributes that comprise them. An Ascalon (Fine-loamy, mixed, superactive, mesic Aridic Argiustoll) soil was sampled from a statistically representative subset of National Resource Inventory (NRI) points in the Central High Plains Major Land Resource Area (MLRA 67) and analyzed for 18 soil attributes. Factor analysis was used to group correlated soil attributes and identify underlying soil quality factors. The frequency distributions of soil attributes comprising each factor were used to construct an index of soil quality for each factor. Four soil quality factors, termed the texture, organic matter, acidity, and phosphorus factors, were identified. Index scores for the organic matter and acidity factors varied significantly with land-use, but index scores for the texture factor did not vary significantly with land-use. Organic matter factor index scores were highest for native rangeland and perennial pasture, intermediate for land in CRP and wheat-row crop rotations, and lowest for wheat-fallow rotations. Wheat-fallow rotations also had significantly lower acidity factor index scores than native rangeland, perennial pastures, and land in CRP. Wheat-fallow rotations appear to be particularly detrimental to soil quality in the Central High Plains. The use of this soil quality index may enable both researchers and policy makers to evaluate the effects of different land-uses and soil conservation practices on soil quality over a broad geographic area.

INTRODUCTION

Soil quality is 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). Specific functions represented by soil quality include the ability to: (1) accept, hold, and release nutrients and other chemical constituents, (2) accept, hold, and release water to plants and surface and groundwater recharge, (3) promote and sustain root growth, (4) maintain suitable soil biotic habitat, and (5) respond to management and resist degradation (Karlen and Stott, 1994). Maintaining or improving soil quality can provide economic benefits in the form of increased productivity, more efficient use of nutrients and pesticides, improvements in water and air quality, and amelioration of greenhouse gases. The National Research Council (1993) recommended that monitoring and protection of soil quality should be a fundamental goal of a national environmental program.

Soil quality cannot be measured directly however, but must be inferred by measuring soil attributes or properties that serve as soil quality indicators. Changes in these indicators are used to determine whether soil quality is improving, stable, or declining with changes in management, land-use, or conservation practices. Although many of soil quality indicators have been proposed for use 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. In addition, many of the soil attributes that contribute to soil quality are highly correlated, interacting with other soil attributes to influence the many functions soil provides (Larson and Pierce, 1991; Seybold et al., 1997). A soil quality index comprised of indicators sensitive to regional scale changes in land-use and soil conservation practices could be useful to researchers and policy makers for evaluating the effects of different practices on soil quality over broad geographic areas. Our objectives were to: (1) identify soil attributes most useful for assessing soil quality at a regional scale and (2) construct a soil quality index that is sensitive to land management. These objectives were addressed using data for an Ascalon soil under different land-uses in the Central High Plains Major Land Resource Area, which comprises portions of Colorado, Wyoming, and Nebraska in the US.

MATERIALS AND METHODS

The Central High Plains Major Land Resource Area (MLRA) covers 74,410 km^2 in eastern Colorado, southeastern Wyoming, and western Nebraska. Elevation ranges from 1,100 to 1,800 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^{0}C. About 25% of the land is farmed to wheat (*Triticum aestivium* L.) and other small grains, and 50% is native rangeland supporting intensive livestock production enterprises. The remainder of the area is irrigated and used for corn (Zea mays L.), alfalfa (*Medicago sativa* L.), sugar beet (*Beta vulgaris* L.), and vegetable production (USDA-SCS, 1981).

The NRI sampling design was used to select statistically

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representative sample points within this MLRA, with the restriction that sampling was confined to the Ascalon soil series (Fine-loamy, mixed, superactive, mesic Aridic Argiustoll). This restriction was imposed in order to clearly assess the effects of land use on soil quality without the confounding effects of sampling multiple soil series. Detailed descriptions on the design of the NRI and on sample point selection are presented elsewhere (Nusser and Goebel, 1997; Nusser et al., 1998). The Ascalon series was chosen because it is a benchmark soil and has a wide geographic distribution within this region.

A set of 64 points were sampled within this MLRA using the NRI sampling framework. At each sample point the depth of the A-horizon was determined. 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. For this preliminary study, a 10-cm sampling depth was chosen because changes in soil quality will be most evident at the soil surface. However, additional soil depths could be used on future studies if the objectives of the study warrant it. Soil collected for biological analysis was kept on ice during transport to the lab, while soil for physical and chemical analysis was sent to the lab without refrigeration.

Samples collected for biological analysis were analyzed for microbial biomass carbon (MBC), potentially mineralizable carbon (PMC), and potentially mineralizable nitrogen (PMN). The MBC was determined by chloroform fumigation-extraction on 4-mm sieved field-moist soil samples (Sparling and West, 1988). Potentially mineralizable C and N 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 days at 25^0C instead of 30^0C. Total organic C (TOC) (Leco SC-444 analyzer; Leco Corp., St. Joseph, MI) and total N (Leco FP-438 analyzer; Leco Corp., St. Joseph, MI) were measured by dry combustion. A 100 g subsample (air dried) was analyzed for water stable aggregates (WSA) 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. Sand, silt, and clay content (pipette method) and pH (1:1 soil:water) were also determined. Cation exchange capacity (CEC) was measured at pH 7 by ammonium acetate extraction, with exchangeable Ca, Mg, K, and Na determined by atomic absorbance spectroscopy. Exchangeable acidity was determined by extraction with by $BaCl_2$-triethanolamine solution buffered at pH 8.2 and back-titration. Standard soil survey lab methods (USDA-NRCS, 1996) were used for these analyses. The soil samples were also analyzed for Mehlich extractable phosphorus (MEP) (Mehlich, 1984) measured using ICP spectroscopy.

An initial correlation matrix showed that many of the soil attributes in the data set were highly correlated. Factor analysis was used to reduce the large number of correlated variables to a smaller number of uncorrelated factors that are linear functions of the original variables (Johnson and Wichern, 1992). 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. Analysis was performed using PROC FACTOR in SAS (SAS Institute Inc., 1989) on standardized variables using the correlation matrix to eliminate the effect of different measurement units on the determination of factor loadings (Johnson and Wichern, 1992). Factor loadings are the simple correlations between the soil attributes and each factor (Sharma, 1996).

Eigenvalues are the amount of variance explained by each factor (Sharma, 1996). Because factor analysis was performed on standardized soil attributes, each attribute had a variance of one with a total variance of 18 for the entire data set. Factors with eigenvalues >1 were retained for interpretation because factors with eigenvalues less than one explained less variance than individual soil attributes. Retained factors were subjected to a varimax rotation, which redistributes the variance of each factor to maximize the relationship between the interdependent soil variables (SAS Institute Inc., 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

Frequency distributions for the soil attributes that comprised each factor were used to calculate factor index scores for each point. If the measured value for a soil attribute at each sample point was ≥ 75th percentile of the distribution, it was given a soil quality index score of 5. If the value was ≤ 25th percentile, it was assigned a score of 1. Values between the 25th and 75th percentiles were divided into three equally spaced intervals and assigned scores of 2, 3, or 4 as the intervals increased. The 25th, 75th, and middle 50th percentiles were chosen because many statistical packages readily provide them. This pattern was used for all attributes except sand content and exchangeable Na and acidity, for which soil quality scores were reversed. Epstein et al. (1997) reported negative correlations between sand content and annual primary productivity in this area of the Great Plains. With soil pH, values ≥ 6.8 and ≤ 7.2 were assigned a score of 5. Soil pH values ≥ 6.4 and < 6.8, or ≥ 7.2 and < 7.6 were assigned a score of 4. Soil pH values ≥ 6.0 and < 6.4, or ≥ 7.6 and < 8.0 were assigned a score of 3. Soil pH values ≥ 5.6 and < 6.0, or ≥ 8.0 and < 8.4 were assigned a score of 2. Soil pH value <5.6 or > 8.4 were assigned a score of 1.

Land-use practices for 1989 through 1996 from the NRI database were used to classify each sample point as: (1) wheat-fallow rotation, (2) wheat-row crop rotation, (3) Conservation Reserve Program (CRP) land, (4) grasses and legumes used for pasture and hay production, or (5) native rangeland. Index scores were analyzed by analysis of variance with land-use as the independent variable. Soil quality was considered "excellent" if the index score was ≥ 4 but <5 , "good" if the score was ≥ 3 but <4, "at risk" if the score was ≥ 2 but <3, and seriously degraded if the score was <2.

Table 1. Soil attribute concentrations and soil quality factor scores under different land-uses in the Central High Plains Major Land Resource Area, USA.

Soil Attributes	Wheat-fallow	Wheat-row crop	CRP	Tame pasture	Native rangeland	SE	ANOVA P > F
Sample size (n)	21	7	11	17	8		
A horizon depth (cm)	18.4	19.6	19.5	14.4	16.3	3.6	NS
Sand (%)	61.3	61.7	63.2	65.2	66.9	3.8	NS
Silt (%)	23.3	24.1	22.4	17.8	20.2	2.5	NS
Clay (%)	15.4	14.1	14.5	17.0	12.9	1.8	NS
WSA (g kg^{-1})	370	400	480	470	510	45	NS
TOC (g kg^{-1})	6.0	7.9	10.1	14.1	17.7	1.3	0.01
MBC (mg kg^{-1})	270	420	420	560	740	68	0.01
PMC (mg kg^{-1} d^{-1})	9.9	8.6	14.9	21.3	18.5	3.2	0.05
Total N (g kg^{-1})	0.78	0.92	0.90	1.37	1.59	0.12	0.01
PMN (g kg^{-1} d^{-1})	16.7	28.9	24.5	42.6	49.2	3.5	0.01
Mehlich P (mg kg^{-1})	31	64	33	39	51	6.8	0.05
pH (1:1 soil:water)	6.27	7.10	6.82	7.16	6.44	0.20	0.01
CEC (cmol kg^{-1})	11.2	11.5	11.0	13.8	12.4	1.2	NS
Exch. Ca (cmol kg^{-1})	9.3	8.8	11.4	13.0	8.7	2.5	NS
Exch. Mg (cmol kg^{-1})	2.5	2.4	2.1	3.2	1.9	0.4	NS
Table 1. Continued.							
Exch. K (cmol kg^{-1})	0.84	1.26	1.04	0.97	0.95	0.10	0.10
Exch. Na (cmol kg^{-1})	0.13	0.29	0.07	0.13	0.08	0.04	0.05
Exch. Acid. (cmol kg^{-1})	2.4	2.2	2.2	2.2	3.6	0.38	NS

Table 2. Factor loadings and communalities of four soil quality factors in the Central High Plains Major Land Resource Area, USA.

	Factor				
Soil variables	Soil Texture	Organic matter	Acidity	Mehlich P	Communalities
A horizon depth	-0.07	-0.61	0.02	0.27	0.45
Sand	-0.94	-0.05	-0.16	0.00	0.91
Silt	0.84	-0.02	-0.07	0.09	0.72
Clay	0.80	0.14	0.43	-0.13	0.86
WSA	-0.44	0.55	0.05	-0.21	0.55
TOC	0.24	0.91	0.01	0.02	0.89
MBC	0.16	0.71	0.04	0.29	0.62
PMC	-0.38	0.58	0.14	-0.29	0.59
Total N	0.31	0.85	-0.03	0.19	0.86
PMN	0.06	0.82	-0.04	0.36	0.81
Mehlich P	0.07	0.16	-0.11	0.86	0.79
pH	0.13	0.05	0.90	0.05	0.83
CEC	0.77	0.43	0.38	-0.07	0.92
Exch. Ca	0.27	0.16	0.71	-0.27	0.67
Exch. Mg	0.62	0.09	0.57	0.06	0.72
Exch. K	0.60	0.25	-0.17	0.25	0.51
Exch. Na	0.06	-0.08	0.64	0.56	0.74
Exch. Acid.	0.38	0.42	-0.72	0.14	0.87

RESULTS

Variation in soil properties between the different land uses are presented in Table 1. Nine of the 18 soil properties varied significantly with land-use. Most of the soil properties that varied with land-use were correlated ($P<0.05$) with each other. In total, significant correlation was present in 77 out of 153 pairs of soil attributes (data not shown). Factor analysis yielded four factors with eigenvalues greater than one and these were retained for interpretation (Table 2). Communalities for the soil attributes indicate the four factors explained more than 90% of the variance in sand content and CEC, and 80% of the variance in clay content, TOC, total N, PMN, pH, and exchangeable acidity (Table 2). However, the four factors explained less than 60% of the variance in A-horizon depth, WSA concentration, PMC, and exchangeable K.

The first factor was termed the "soil texture" factor because it had high positive loadings (>0.80) for silt and clay content and a high negative loading for sand (Table 2). The soil texture

Table 3. Mean soil quality index scores for land-uses and the percentage of NRI points falling in each scoring class.

Land-use	Mean	Degraded ≤2	At Risk 2<x≤3	Good 3<x≤4	Excellent 4<x≤5
		- - - - - -	- - - - - - %	- - - - - -	- - - - - -
			Soil Texture Factor†		
Wheat-fallow	2.89	33	19	19	29
Wheat-row crop	3.09	14	29	43	14
CRP	2.89	36	18	18	27
Tame pasture & hayland	3.21	12	29	29	29
Native rangeland	2.65	25	25	50	0
P > F	NS				
			Soil Organic Matter Factor‡		
Wheat-fallow	2.06a§	43	52	5	0
Wheat-row crop	2.65b	14	86	0	0
CRP	2.88b	18	45	36	0
Tame pasture & hayland	3.48c	12	6	53	29
Native rangeland	3.98c	0	13	25	62
P > F	0.01	(lsd=0.56)			
			Acidity Factor¶		
Wheat-fallow	2.80a	24	48	24	4
Wheat-row crop	3.46b	0	0	0	0
CRP	3.57b	0	27	55	18
Tame pasture & hayland	3.66b	0	0	88	12
Native rangeland	3.28ab	0	63	25	12
P > F	0.01	(lsd=0.51)			

†Soil texture factor index was computed using percent sand and clay, CEC, and exchangeable Mg and K. Although percent silt also had a high loading on the texture factor, it was not included in the texture factor index because percent sand and clay adequately captured the particle size properties of the soil.
‡Organic matter factor index was computed using and A-horizon depth water stable aggregates, total organic C, microbial biomass C, potentially mineralizable C, total N, and potentially mineralizable N.
¶Acidity factor index was computed using soil pH, and exchangeable Ca, Na, and acidity.
§Means followed by the same letter are not significantly different by LSD at the α=0.05 probability level.

factor also had moderate (>0.60) positive loadings for CEC and exchangeable Mg and K resulting from the significant correlation between exchangeable Mg and K, and CEC (data not and CEC (data not shown). Soil texture scores did not vary significantly between land-uses, and the distribution of sample points among the index classes were uniform for all land-uses, with the exception of native rangeland which had no points with a score above four (Table 3).

The second factor was termed the "organic matter" factor, because most of the attributes comprising it are important components of organic matter quality (Gregorich et al., 1994). The organic matter factor had high positive loadings (>0.80) for TOC, total N, and PMN, and moderate positive loadings (>0.50) for WSA, MBC and PMC (Table 2). A-horizon depth had a moderate negative loading on the organic matter factor, indicating that it is negatively correlated with the other attributes in this factor. Mean index scores for the organic matter factor and the attributes contributing to this factor varied significantly between land-uses (Table 1, Table 3). Based on our sampling, over 80% of tame pasture and hayland and native rangeland had index scores ≥3, indicating good or excellent organic matter levels. In contrast, only 5% of the wheat-fallow rotations and none of the wheat-row crop rotations had good or excellent organic matter levels (Table 3). Forty-three percent of the wheat-fallow rotations had index scores <2, indicating seriously degraded organic matter levels. In contrast, none of the points from native rangeland had an index score <2.

The third factor was termed the "soil acidity" factor because it had a high positive loading for pH (0.90), moderate positive loadings for exchangeable Ca and Na, and a moderate negative loading for exchangeable acidity (-0.72) (Table 2). The soil acidity factor varied significantly with land-use (P<0.01). Mean acidity index score for land in wheat-fallow rotation was significantly lower than the mean scores for land in wheat-row crop rotation, CRP, or tame pasture and hayland (Table 3). Twenty-four percent of the points from wheat-fallow rotations had scores <2, indicating seriously degraded soil quality for the acidity factor. All land in wheat-row crop rotations and tame pasture, and 73% of CRP land had index scores ≥3, indicating good to excellent quality for the acidity factor. However, 63% of the native rangeland scored between 2 and 3, indicating that quality was at risk for the acidity factor under this land-use.

The fourth factor was termed the "phosphorus" factor because it had high a positive loading (0.86) on MEP (Table 2). An index score was not calculated for the phosphorus factor because only a single attribute (MEP) comprised this factor. However, MEP varied significantly with land-use (P=0.05), and concentrations were highest in soil under wheat-row crop rotations and native rangeland (Table 1). Wheat-fallow rotations and soil under CRP had the lowest MEP concentrations.

DISCUSSION

Factor analysis identified four uncorrelated soil quality factors related to soil texture, organic matter, pH and acidity, and extractable-P. These factors relate to certain soil functions, which are important to agricultural production in this MLRA. The index rating system used here relies on a statistical approach, which yields a relative assessment of soil quality in the region under study. Our index combines the quality control approach described by Larson and Pierce (1994) with the scoring function approach of Karlen and Stott (1994).

The soil texture factor was invariant with respect to land-use, and thus probably represents an inherent soil quality (Seybold et al., 1997). The texture factor is related to plant available water (Epstein et al. 1997) and soil fertility. The organic matter factor is composed of both labile and stable organic matter fractions and includes an index of biologically available N. The sensitivity of the organic matter factor to land-use indicates this factor can reflect long-term changes in soil resulting from different land uses. Including microbial biomass and activity measurements may also allow this factor to respond to short-term changes in management. The organic matter factor also contains the A-horizon depth and aggregate diameter, two physical soil properties that may relate to resistance to erosion and conservation of organic matter.

Rangeland had the lowest texture-related soil quality, which may have resulted from landowners choosing to use land with higher inherent soil quality for crop production. Rangeland had the highest index scores for the organic matter factor, with wheat-fallow and wheat-row crop rotations having the lowest index scores for the organic matter factor. Assuming native rangeland represents the status of the soil prior to intensive crop production, mean index scores for wheat-fallow rotations, wheat-row crop rotations, and CRP indicate significant degradation of the soil organic matter under these land-uses. Organic C losses, relative to rangeland, were 66% in wheat-fallow soils and 55% in wheat-row crop soil, which are comparable to results from controlled experiments on an Ascalon soil (Bowman et al., 1990). Other studies have shown the benefit of organic matter in improving yield (Bowman et al., 1999). The acidity factor (and direct pH measurements) in the wheat-fallow system appear to indicate decreasing pH. We cannot demonstrate that acidification is an ongoing process, but long-term ammonia fertilizer use has reduced pH in other soils (Bouman et al., 1995).

The presentation of soil quality as component factor scores allows for some interpretation of the underlying causal factors for changes in soil quality. Soil quality can be assessed using the mean scores for the factors in order to evaluate a practice such as CRP. The sampling design also allows the variation of soil quality within land uses to be evaluated. Our interpretations of soil quality, such as the scores delineating "degraded' versus other classes may require further modification based upon additional information quantitatively relating endpoints, such as productivity or erosion to soil attributes or index factors. The use of this soil quality index may enable both researchers and policy makers in the Central High Plains to evaluate the effects of different land-uses and soil conservation practices on soil quality over a broad geographic area. Similar indices could be developed for other regions of the country.

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