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Characterization of the Stages of Soil Resilience to Degradative Stresses: Erosion

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ABSTRACT

Although soil variants are globally recognized, characterization of their resilience/degradation factor controls is not well documented. In this study, three variants of a Miamian fine mixed mesic Typic Hapludalf at Ohio (USA) and of a Sandy clay loam Kandiudult at Makerere (Uganda) cropped to corn (*Zea mays*) were identified on the basis of crop vigor. For each soil variant, selected soil properties, and corn grain yields (CGY) were measured. Based on the results, the Miamian soil of relatively high resilience was characterized by significantly ($p=0.05$) better structure than that of low resilience (e.g. bulk density of 1.43 Mg m^{-3} vis-a-vis 1.57 Mg m^{-3}; water stable aggregates of 58.7% vis-a-vis 47.3%; geometric mean diameter of 0.62 mm visa-a-vis 0.56 mm). Similarly, water transport characteristics were more favorable in relatively high resilience variants than in variants of low resilience (e.g. saturated hydraulic conductivity of 2.4 cm hr^{-1} vis-a-vis 1.1 cm hr^{-1} in USA) ($p=0.05$). Interestingly, cumulative soil loss was high ($p=0.05$) for variants of high resilience compared to that of low resilience probably due to subjection to unusually high rainfall intensity. For MUARIK soils, despite the quasi-homogeneity of soils in terms of measured physical and chemical properties, lower segments of land presented, relatively high resilience ($p=0.05$) suggesting in light of Ohio experiment that available water for plant was the key factor in the observed resilience differences.

INTRODUCTION

Soil is a dynamic and living entity used to produce goods and services of value to humans but not necessarily with perpetual ability to withstand the degradative processes (e.g. soil erosion, nutrient depletion, compaction, pollution, salinization) unless appropriately managed. As soon as land is newly put into production, the soil degradative processes are set in motion triggering deterioration of soil structure and disruption of cycles of carbon, depletion of soil nutrient reserves, and weakening of nutrient recycling mechanisms (Kannegiester, 1968; Lal, 1974; Lal, 1976; Lal, 1994a). However, soils have an inherent ability to restore their life-support processes, provided that the disturbance created especially by human activities is not too drastic, and sufficient time is allowed for the life-support processes to restore themselves (Lal, 1994a). This intrinsic soil productivity regeneration ability is called resilience (Szabolcs, 1994).

Unless some interventions are made, all soils exhibit a similar pattern of degradation (Wolman, 1967; Lee, 1990). However, the amplitude of degradation and duration it takes for a given soil to undergo the full cycle of degradation varies depending on the permutations of the magnitude, intensity and duration of the stress and the inherent soil characteristics (Wolman, 1967; Rozanov, 1990; Lal, 1994b). Examination of a given landscape reveals a wide range of soil associations (aggregations of infinitesimal soil pedons), with unique soil properties and thus differing degrees of degradation. These soil variants have historically been given different names: erosion phases for example the Minnesota erosion series (Foster, 1988), partial contribution areas (source-areas) (Bernard, 1937; Beston, 1964; Amerman, 1965; Ben-Asher, and Humborg, 1992), *Lunnyu* in Uganda (Zake, 1993), low fertility patches in Kenya (Woomer et al., 1998). In essence, these variants exhibit different degrees of resilience.

Though there is growing acceptance of resilience as a valuable attribute of soil, it is not well expressed and documented (Szabolcs, 1994). The objective of this study was to characterize the different stages of soil resilience for two representative soils in Ohio (USA) and Makerere (Uganda) under contrasting ecoregions and land use history.

MATERIALS AND METHODS

Variants of a Miamian soil series (fine mixed mesic Typic Hapludalf) and a Sandy clay loam Kandiudult (Rhodic Nitisol) cropped to corn (*Zea mays*) were identified and characterized at Columbus, Ohio-USA (Tenywa, 1993) and Makerere University Agricultural Research Institute, MUARIK-Uganda (Majaliwa, 1998), respectively. The Agronomy Farm of the Ohio State University, Columbus lies approximately at latitude 40^{o} and longitude 83^{o} 02'. The experimental site consisted of four instrumented overland flow plots measuring 21 by 18 m, with an average slope of 5 % and north-facing aspect. All plots were managed with a plow-till method of seedbed preparation and were planted to “Pioneer 3394” corn (*Zea mays*) hybrid each year. Before planting, NPK was uniformly applied at the rate of 150-91-122 Kg ha^{-1}. Weeds were controlled by spraying glyphosate (N-phosphonomenthyl) glycine ($C_3 H_8 NO_5 P$) of 41% active ingredient at a rate of 2.3 l ha^{-1}. Corn height measured 56 days after planting was used as an index of soil relative productivity/ degradation (Lal, 1985; Andraski and Lowery, 1992; Pesant and Vigneux, 1990, 1992; Belay, 1992;

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Agnihorti et al., 1994; Uehara et al., 1995; Giller et al., 1997; Rutunga et al., 1998) to identify and delimit soil variants in each of the four runoff plots. Soils bearing corn plant height ranging between 0-15 cm, 15-35 cm and above 35 cm were categorized as relatively low-, moderate- and high-resilience, respectively. A total of 8, 8, and 9 subplots of 4 m^2 were then delimited for variants; relatively high-, moderate- and low-resilience, respectively and were considered as replicates. After harvesting corn, micro-plots of dimensions 0.75 x 0.7 m were selected in each variant and subjected to simulated rainfall intensity of 210 mm hr^{-1} to determine runoff and soil loss for a period of 30 minutes. Soil characterization of each variant was done by conducting field and laboratory measurements. Soil cores measuring 76 cm in both diameter and length were taken to determine soil bulk density (Blake and Hartge, 1986), saturated hydraulic conductivity (Klute and Dirksen, 1986) and to evaluate water retention characteristics (Childs, 1940). Bulk soil samples were collected from 0 to 50 mm for determination of water stable aggregation (WSA), aggregate size distribution and stability using the wet sieving technique (Kemper and Roseneau, 1986) and expressed as % WSA, mean weight diameter (MWD) and geometric mean diameter (GMD), respectively. Infiltration tests were done using double ring infiltrometers (Bouwer, 1986).

The second experiment was established at Makerere University Agriculture Research Institute, Kabanyolo (MUARIK) lying at 0º 28 N and 32º 37 E at an average altitude of 1200 m ab.s.l and located about 20 km north of Kampala. Climatic conditions are those of tropical wet and dry region. The mean annual rainfall is 1160 mm distributed bi-modally (March to June, September to November) with a monthly mean temperature of 24.5 ºC (Yost and Eswaran, 1990). Nine plots each of 2 m width and 9 m length each were demarcated on the experimental site of 450 m^2 on the west facing Kyetume ridge. Average slope angle on the experimental terrain was 21%. Of the nine plots, three were allocated to each of three treatments; sole maize, maize-beans inter-crop and bare following a completely randomized design (CRD). But only maize inter-cropped with beans data are presented in this paper. Two consecutive plots were separated by 1m path. The land was tilled using the traditional method (hand hoe). Corn (*Zea mays* variety L1) and common beans (*Phaseolus vulgaris* cultivar K131) were planted manually during the long rains (March to July, 1997) and the short rains (October, 1997 - January, 1998). As at Ohio, soil variants were identified and delimited on basis of plant height at the MUARIK site. Each soil variant was characterized in terms of organic matter and infiltration rate during the long and short (El-nino linked) rainy seasons of 1997. The short rainy season had unusually high amount and intensities of rainfall linked to the El-Nino phenomena. Analysis of variance was done using Genstat, and as for MUARIK experiment the design in Ohio was considered as a CRD, and LSDs were obtained to determine treatment effects.

RESULTS AND DISCUSSIONS

Results of the Ohio experiments are presented in Table 1. Variants with relatively high resilience produced 15.3 Mg ha^{-1} CGY almost double (1.77 times) of the relatively low resilience variant (8.6 Mg ha^{-1}). Soil with relatively moderate resilience had an average grain yield production of 12 Mg/ha. Only the grain yield production of the two extreme resilience categories was significantly different ($p=0.05$).

Resilience is an index that integrates the cumulative effects of many simultaneously interacting processes within the soil system, inducing differences in bio-availables (Sposito, 1989). Many factors including chemical, biological and physical properties influence these processes. Table 1 also shows soil measured physical properties of the three variants. There is no unique (single) soil physical property explaining difference in resilience of all the three soil variants. For the case of the two extreme resilience levels, saturated hydraulic conductivity and plant available water could be pointed as the source of the observed differences. Soils belonging to relatively low resilience were characterized by significantly higher values of bulk density 1570 kg m^{-3} (1.57 Mg m^{-3}), lower saturated hydraulic conductivity (1.1 cm h^{-1}), and lower water retention values (e.g. 41.5% at 0 kPa), compared to 1.43 kg m^{-3}(143 Mg m^{-3}), 2.4 1 cm h^{-1} and 44.6% at 0 kPa; respectively for soil with relatively high resilience ($p=0.05$). Soil variant with relatively high resilience seems to have relatively better structure than the relatively low resilience variant, as illustrated to some extent by their 1-mm and 0.5 mm mean aggregate size distributions and geometric mean diameters. However, no measured physical properties could elucidate the observed differences between other resilience levels. Probably topography and erosion induced degradation could have played a significant role.

Selected soil erosion parameters are also presented in Table 1. Once again, soil erosion parameter differences could only be explained for the two extreme resilience cases, with the measured physical properties. Expectedly, when subjected to simulated rainfall, relatively high resilience soil generated low overland flow ($92\ 10^{-3}$ m of $105\ 10^{-4}$ m in 30 min) compared to the relatively low resilience soil ($62\ 10^{-3}$ m of $105\ 10^{-4}$ m in 30 min) ($p=0.05$). Though it is well known, however, that soils in a less degraded state exhibit lower erodibility (Bryan, 1968; De Ploey and Poesen, 1985; Bajracharya et al., 1992; Tenywa and Lal, 1994), it is interesting to note that soil of high resilience recorded the highest cumulative soil loss of 14.4 Mg ha^{-1} compared to 6.3 Mg ha^{-1} for low resilience (Table 1), despite its relatively better structure and water stable aggregate compared to the low resilience soils. The trend for the three soil variants seems to suggest an increasing erodibility gradient with resilience.

Table 2 shows results of the MUARIK experiment. The three soil variants were coinciding with different sections of the experimental plots. Relatively high, moderate, and low resilience was found in the lower, middle, and upper section of the plots; respectively for both cropping seasons. The landscape distribution of chemical properties shows quasi homogeneity of experimental plots, except for organic matter for the short rainy season (Majaliwa, 1998). Differential resilience observed is then largely the result of water availability for crop production (Daniels et al., 1989;

Table 1: Characterization of Miamian soil variants at Columbus, Ohio in terms of selected physical properties, soil loss (SL), overland flow (OLF), corn grain yield (CGY). (Means of eight replicates).

Resilience category	Bulk density Mg m^{-3}	Water Retention k Pa			PAW %	K_{sat} cm hr^{-1}	Mean aggregate size distribution					WSA	MWD	GMD	CGY Mg ha^{-1}	OLF cm	SL Mgh a^{-1}
		0	1	3			5	2	1	0.5	0.25						
		---------%---------					-------------------mm-------------------					--------- mm --------- --					
Relatively low resilience	**1.57**	**41.5**	**39.5**	**37.9**	**4.6**	**1.1**	**5.6**	**17.9**	**6.9**	**8.6**	**10.6**	**47.3**	**1.20**	**0.56**	**8.6**	**9.2**	**6.3**
Moderate Resilience	**1.50**	**43.6**	**42.3**	**39.2**	**10.6**	**1.2**	**5.7**	**16.5**	**7.0**	**7.5**	**10.9**	**48.2**	**1.36**	**0.59**	**12**	**4.97**	**11.6**
Relatively high resilience	**1.43**	**44.6**	**40.7**	**38.3**	**10.0**	**2.4**	**6.2**	**19.1**	**10.0**	**13.4**	**11.3**	**58.7**	**1.42**	**0.62**	**15.3**	**6.2**	**14.4**
LSD (5%)	**0.10**	**3.0**	**ns**	**ns**	**4.9**	**1.0**	**ns**	**ns**	**1.0**	**2.6**	**ns**	**5.4**	**0.24**	**0.06**	**1.3**	**2.0**	**6.2**

PAW: Plant available water, MWD: Mean weight diameter, K_{sat}: Saturated hydraulic conductivity, GMD: Geometric mean diameter, WSA: Water stable aggregation.

Table 2. Characterization of MUARIK soil variants during the long and short rainy seasons in terms of corn yield, SOM and steady-state infiltration rate. (Means of three replicates).

	Long Rainy Season			Short Rainy Season		
Landscape position	**Corn grain yield Mg ha^{-1}**	**SOM (0-15cm)**	**Steady infiltration rate cm hr^{-1}**	**Corn grain yield Mg ha^{-1}**	**SOM (0-15cm)**	**Steady state infiltration rate cm hr^{-1}**
Upper	0.9	3.2	7.8	1.5	2.3	5.4
Middle	2.1	3.5	7.2	2.0	2.7	6.6
Lower	2.6	3.7	9	2.9	3.0	7.2

Rozanov, 1994). Due to the aggressivity of rains (Zake et al., 1993) and topographic factor especially the slope steepness of MUARIK, land excessive runoff could be generated from upper section inducing a downward gradient increase in water supply to the plant.

For the two experiments soil resilience categories based on plant vigor and growth seems to be strongly related to corn yield, for the same crop variety, the same soil type, and under the same eco-region. It also appears that the two experimental sites, Ohio farm and MUARIK, exhibit two marked resiliences. Ohio soils have relatively high resilience compared to MUARIK soils. Soil resilience difference for the two soils can be attributed to the difference in agro-ecological regions, topography, land management, energy input and crop variety. The climate of the Ohio farm is classified as humid, temperate continental warm summer (Koppen, 1936), with a very good distribution of precipitation throughout the growing season falling on a nearly flat land (Tenywa, 1993), highly managed with considerable fertilizer inputs. While at MUARIK climatic fluctuation was recorded during the experimental period. The long rains ended earlier June, and short rains were characterized by unusual rains linked to El-nino phenomenon. The MUARIK soils are acidic with moderate to low nutrient levels (Majaliwa, 1998) and no fertilizer input.

In light of the fact that the pattern of soil degradation for all soils is similar (Wolman, 1967), the variants with contrasting yield characteristics are postulated to belong to different stages of degradation namely; marginal resilience (relatively low), diminishing resilience (relatively moderate) and high resilience (relatively high). These phases of resilience are also well illustrated by the three soil series in Minnesota: Port Byron, Kenyon, and Rockton (Foster, 1988).

CONCLUSION AND RESEARCH PRIORITIES

From the studies, it is evident that soils exhibit wide differences in soil properties depending on the land use history, eco-region, management, and reflecting different degrees of degradation. The range of soil properties, however, fall in three broad categories of namely; relatively low-, moderate- and relatively high-resilience. The study has highlighted the need to establish long-term experiments, to determine property critical values between two consecutive soil resilience states of soils, in different stage of their development, under different management and different eco-region, and to develop a functional relationship between the resilience, productivity, erodibility, and internal energy of these soils.

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