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SOIL RESILIENCE: A FUNDAMENTAL COMPONENT OF SOIL QUALITY

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Soil resilience has recently been introduced into soil science to address sustainability of the soil resource and to combat soil degradation. The concept of soil resilience and its relationship to soil quality have not been well defined or well developed. The main objectives of this paper are to clarify the concept of soil resilience and its relationship to soil quality and to present a framework for its assessment. A review of the literature on the assessment and quantification of soil resilience is presented and discussed. The concept of soil resilience in combination with resistance is presented as an important component of soil quality, a key element of sustainability. Factors that affect soil resilience and resistance are soil type and vegetation, climate, land use, scale, and disturbance regime. Maintenance of recovery mechanisms after a disturbance is critical for system recovery. Three approaches for assessing soil resilience are presented: (i) directly measuring recovery after a disturbance, (ii) quantifying the integrity of recovery mechanisms after a disturbance, and (iii) measuring properties that serve as indicators of those recovery mechanisms. Research is needed in the development of indicators or quantitative measures of the ability of soils to recover from specific disturbances. (Soil Science 1999;164:224–234)

Key words: Soil resilience, soil resistance, soil quality, assessment, definition, soil function, indicators.

THE term "resilience" has been used in the ecological literature since the late 1960s and early 1970s. Ecologists have regarded it as a subjective term because it has not been well defined, and its meaning varies with the scientist using it (Blum 1994). Resilience has been defined in two ways in the ecological literature (Holling and Meffe 1996). The first definition, referred to as "equilibrium resilience," concentrates on stability near an equilibrium steady-state. Speed or rate of return to an equilibrium after a disturbance are used to measure resilience. The second definition, referred to as "ecosystem resilience," is the magnitude of disturbance that can be absorbed or accommodated before the system changes its structure. Much of the ecological literature uses the equilibrium definition of resilience (Holling and Meffe 1996).

The term "soil resilience" has been introduced into soil science only recently, mainly to address soil ecology and sustainable land use issues (Blum 1994). It was introduced to create a common theory that describes the reaction of soil to a range of impacts or disturbances. Because of the complexity of soil systems and the many ways in which soil can react to an external disturbance, it has not been defined operationally (Blum 1994). A precise definition of soil resilience, methods for measuring it, a description of processes that contribute to it, and its significance and development are lacking (Szabolcs 1994a). There is a need to develop a comprehensive concept of soil resilience that can be used operationally to combat soil degradation (Blum 1998).

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Soil degradation refers to the decline in a soil's inherent capacity to produce economic goods and perform ecologic functions (Lal 1993a). Causes of degradation include deforestation, overgrazing, agricultural practices, overexploitation of the vegetative cover, and bioindustrial and industrial activities. Information about the ability of a soil to recover from degradation is essential for the maintenance and sustainability of the soil resource base (Szabolcs 1994a). Sustainability deals with performance at certain acceptable levels over a given time frame (Eswaran 1994) and refers to the productivity and economic, social, and environmental aspects of a land use system, i.e., agriculture (Smyth and Dumanski 1995). Soil quality is a key component of sustainability (Warkentin 1995; Doran et al. 1996). The direction in soil quality with time is a primary indicator of sustainable management (Doran et al. 1996).

The objectives of this paper are to (i) clarify the concept of resilience as it pertains to soils, (ii) define its relationship to soil quality, (iii) review the literature on its measurement and quantification, and (iv) present a framework for the assessment of soil resilience.

DEFINITION AND CONCEPT

Soil resilience has been defined as the capacity of a soil to recover its functional and structural integrity after a disturbance (Herrick and Wander 1998; see also Lal 1993b; Szabolcs 1994a; Eswaran 1994; Sombroek 1994; Blum and Santelises 1994; Pimm 1984; Lal 1997). This definition is consistent with the broader use of resilience as defined by Webster, which is "the capability of a strained body to recover its size and shape after deformation caused especially by compressive stress." However, others have defined soil resilience as the capacity of a soil to resist change caused by a disturbance (Rozanov 1994; Lang 1994). This concept of "resistance to change," which differs from resilience, is an important component of ecosystem stability (Tilman and Downing 1994) and will be defined as a separate concept in this paper.

Functional and structural integrity are defined as a soil's capacity to perform vital soil functions such as those proposed by Karlen et al. (1997): (i) sustaining biological activity, diversity, and productivity; (ii) regulating and partitioning water and solute flow; (iii) filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials, including industrial and municipal by-products and atmospheric deposition; (iv) storing and cycling nutrients and other elements within the Earth's biosphere; and (v) providing support of socioeconomic structures and protection for archeological treasures associated with human habitation. Structural integrity is linked to soil function and deals with the physical arrangement of primary soil particles and their aggregation.

A disturbance is broadly defined as any event that causes a significant change from the normal pattern or functioning of an ecosystem (Forman and Godron 1986). Whether an event is considered to "cause a significant change from the normal pattern or functioning" depends on the temporal and spatial scale of interest. At geologic time scales, nearly every event can be considered to contribute to normal functioning. Many types of perturbations are actually necessary for ecosystem function. For example, formation of a single earthworm burrow is clearly a disturbance at the scale of the root system of a grass tussock when considered in terms of the lifespan of the plant. But, it may be considered part of the "normal pattern" at the field scale. A wide variety of disturbances are included in this broad definition, including those that are primarily natural in origin and others that are largely or wholly anthropogenic. Natural disturbances and causes of disturbance include fires, earthquakes, floods, landslides, and high-intensity storms. Nearly all human activities associated with land management and use can be classified as "disturbances," including logging, grazing, urban and industrial development, recreation, and annual cropping. Agriculture itself is one of the greatest sources of stress and disturbance to the environment (Brussaard 1994). Common disturbances or stresses associated with agriculture include heavy load as a result of vehicular traffic; tillage; application of fertilizers and pesticides; and removal or exclusion of competing plant species, e.g., monoculture (Bezdicek et al. 1996).

The soil's capacity to recover has two components, the rate of recovery and the degree of recovery (Fig. 1a) (Herrick and Wander 1998). The rate of recovery is the amount of time it takes soil to recover to its original potential or to some stabilized lower potential after a disturbance (Fig. 1a). The magnitude of recovery to some stabilized potential relative to its predisturbance state defines the degree of recovery. If the disturbance is too drastic or if the soil is inherently fragile, the soil can undergo irreversible degradation in which its capacity to function will not recover within any reasonable time frame (e.g., human life span). In this case, the soil's resilience capacity has been exceeded, resulting in permanent damage or the need for very costly restoration. The greater the rate and/or degree of recovery, the more resilient the soil system is to a specific disturbance.

Soil Resistance

Soil resistance, which is distinguished from soil resilience, has been defined as the capacity of a soil to continue to function without change throughout a disturbance (Herrick and Wander 1998; Pimm 1984). The magnitude of decline in the capacity to function defines the degree of resistance to change (Fig. 1a). A small decline indicates a high resistance, whereas a relatively large decline indicates a low resistance to change throughout a disturbance. Williams and Chartres (1991) distinguish the difference between the resilience and resistance concepts with respect to soils: "The magnitude of the decline [in the capacity of the soil to function] (resistance) and the rate of recovery or the elasticity (resilience) are two key measures of sustainability."

The distinction between resistance and resilience can be illustrated further in an example using soil functions related to soil physical properties on an annual time scale (Fig. 1b). In temperate regions, many surface soils are resilient with respect to porosity changes following compaction. Frost action may serve as a recovery process. However, some soils are inherently resistant to porosity changes following compaction. These resistant soils can maintain their functioning capacity (e.g., hydrologic functions) at a higher level throughout the year than those that have a lower resistance but are resilient on an annual time scale (Fig. 1b).

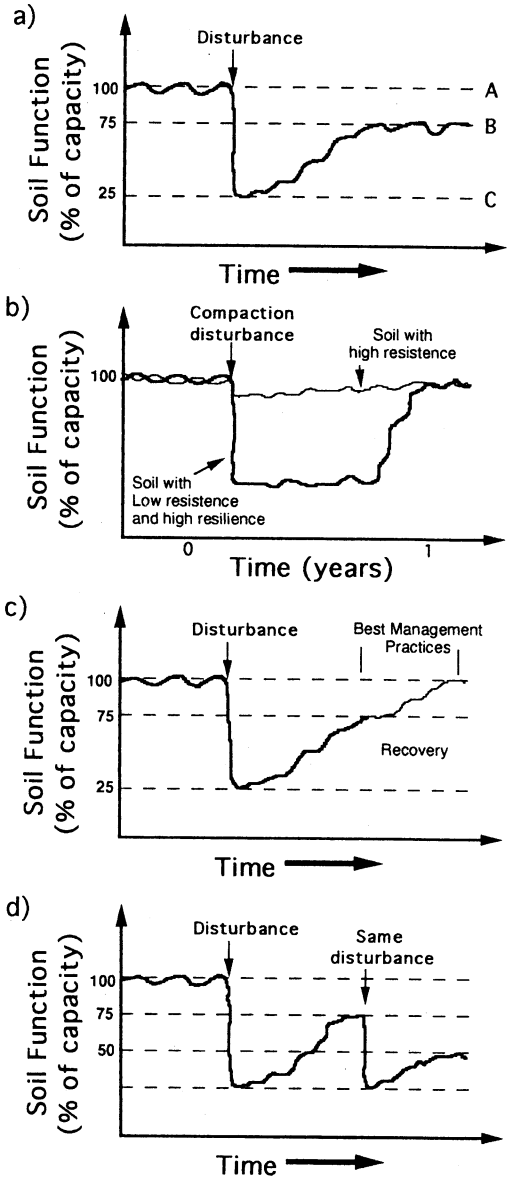

Fig. 1. Graphs illustrating the affects of disturbance, resistance, and resilience on soil functions: (a) general concept; (b) two soils with differences in resistance and resilience to compaction disturbance; (c) positive management impacts on soil resilience; and (d) repeat disturbances without sufficient recovery.

The distinction between soil resistance and soil resilience also depends on the temporal scale of interest. For example, the capacity of soil to supply nutrients to plants (a soil function) can be degraded by nutrient removal through plant uptake into biomass. For short periods of time, the soil solution near the root surface can be replenished from supplies on exchange surfaces and through diffusion. Temporary reductions in nutrient availability may result. However, because these reductions are generally undetectable in plant growth measurements, the soil is perceived to be resistant from a functional perspective. As exchangeable nutrients decline and diffusion distances increase, resistance to nutrient depletion processes decline and the importance of mineralization (recovery mechanism) increases. If mineralization rates are high, measurements made on an annual basis may indicate little or no change in nutrient availability, again suggesting high resistance, even though nutrients were limiting at one or more times during the year. The proportion of the year during which nutrients are limiting, then, depends on the rate of recovery or resilience.

The importance of soil resistance in sustainable management was demonstrated by Davenport et al. (1998) for pinyon-juniper (*Pinus edulis, P. monophylla, P. cembroides-Juniperus monosperma, J. osterosperma, J. Occidentialis, J. scopulorum, J. deppeana*) ecosystems in the western U.S. They found dramatic variation in the capacity of pinyon-juniper ecosystems to resist soil erosion as a result of reductions in ground cover. In sites that exhibited low resistance, a small reduction in ground cover was needed before a threshold was reached and soil erosion increased dramatically. In sites with high resistance, thresholds sometimes did not exist, and if one existed, a large reduction in ground cover was needed before the threshold was reached.

RELATIONSHIP TO SOIL QUALITY

Soil quality has been defined as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen et al. 1997). Quality can be viewed in two ways: (i) as inherent soil quality, which is defined by the soil's inherent properties as determined by the five factors of soil formation (Jenny 1980); or (ii) as dynamic soil quality, which is the change in soil function as influenced by human use and management of the soil. In the second case, quality is measured by the change in the capacity of soil to function relative to some reference or baseline condition (Larson and Pierce 1991; Pierce and Larson 1993). Historically, civilizations tended to focus first on inherent soil quality. However, as they began to run out of arable land, the focus changed to practices that would maintain dynamic soil quality (e.g., sustainable agriculture) or the civilizations perished (Hillel 1991). In the U.S., it was not until the Dust Bowl era and the formation of the U.S. Department of Agriculture's Soil Conservation Service that dynamic soil quality began to be valued on a national scale. The recent emphasis on dynamic soil quality (Seybold et al. 1998) represents a deepening and broadening of this recognition of its importance to our environment and economic survival (National Research Council 1993; Acton and Gregorich 1995; Doran et al. 1996; Karlen et al. 1997).

Soil resilience is related to soil quality in terms of the recovery of soil functions (Fig. 2). Soil resistance is related to soil quality in terms of the degree of change in soil functions as a result of a disturbance (Fig. 2). During a disturbance, soil quality becomes a function of soil resistance. After a disturbance, soil quality becomes a function of soil resilience. Resilient and resistant systems will maintain soil quality, which is key to sustainability. Over time, the capacity to resist or recover soil functions after a disturbance can be degraded or lost as a result of improper and poor soil management, resulting in concomitant reductions in soil quality. Because disturbances are ubiquitous in nature, soil resilience and resistance characteristics become fundamental components of soil quality.

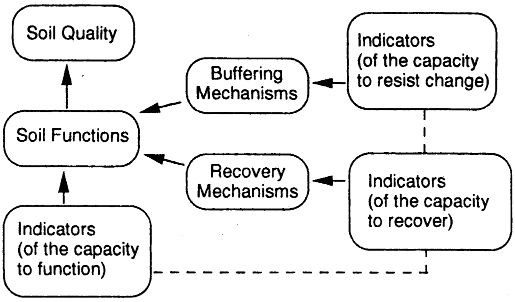

Fig. 2. The concept of how soil resilience and resistance relate to soil quality through soil functions.

FACTORS AFFECTING SOIL RESILIENCE AND RESISTANCE

Soil resilience and resistance depend on soil type (including soil biota) and vegetation, climate, land use, disturbance regime, and temporal as well as spatial scales (Lal 1994b; Herrick et al. 1997). The concept that numerous factors can affect soil resistance was demonstrated by Willen (1964), who found the potential erodibility (resistance) of three soils was related to the parent material, vegetative cover type, aspect, slope, and elevation.

Soil Type and Vegetation

Soil resilience and resistance are affected by both inherent and dynamic soil characteristics and, thus, will vary substantially from one area to the next and will change over time (MacEwan 1997). For example, among soil physical properties, texture has a strong influence on soil resilience and resistance. Greater rates of interrill erosion and splash losses with raindrop impact have been observed in soils with greater amounts of fine sand and silt (Miller and Baharuddin

1987; Wilcox and Wood 1989). The type of clay is also important. Soils with montmorillonite and other 2:1 layer silicates, which exhibit considerable shrinking and swelling with wetting and drying cycles, are more resilient to compaction than soils with nonswelling clays.

Biological communities, both above and below ground, are among the most significant factors affecting soil resilience. Most soil recovery mechanisms are biologically mediated, including cycling of nutrients, detoxification of pollutants, and suppression of pathogenic organisms. Biological activity influences weathering and solubilization of minerals and contributes to the formation and stabilization of soil structure (Sims 1990; Oades 1993). The inability of certain microorganisms, such as mycorrhizal fungi, to recover within a reasonable time frame can lead to long-term degradation of the soil and the ecosystem it supports (Perry et al. 1989; Perry and Amaranthus 1990). For example, crops grown on soils subjected to prolonged fallow periods or flooding may exhibit reduced P uptake, stunted growth, and reduced yields. This condition has been attributed to low colonization of crop plants by mycorrhizal fungi after the fallow or flooding period (Wetterauer and Killorn 1996).

The type and amount of vegetation and its recovery (when lost) are important to soil resilience and resistance (Castillo et al. 1997), largely because high levels of biological activity are frequently associated with plants and plant roots. For example, after 18 years of protection from grazing in Arizona chaparral, several soil properties showed significant recoveries, including increased concentrations of nutrients, greater cation exchange capacity, and lower bulk density (Brejda 1997). Recovery was greater under mountain mahogany (*Cercocarpus betuloides*) than under live shrub oak (*Quercus turbinella* Greene). In California chaparral, the rate and degree of system recovery after a fire often depends on the dominance of several N-fixing shrubs and subshrubs for the first few years after the burn (Gray and Schlesinger 1981; DeBano et al. 1989). These shrubs replace much of the lost N in the system.

Climate

A close relationship exists between climate and soil resilience. The drier the climate, the less resilient soil systems are following various disturbances (Lal 1994a). Climatic factors that should be considered include precipitation amount and distribution, radiation, temperature, seasonal fluctuations in these factors, and length of growing season. In ecosystems in which precipitation comes in low-intensity events throughout the growing season, soils will be less vulnerable to rill erosion than if the soil is subjected to high-intensity, low-frequency precipitation events. Furthermore, the kinetics of many recovery mechanisms are climate dependent. In semiarid ecosystems, the frequency and duration of precipitation events strongly influences many recovery mechanisms. Many years may pass before optimum climatic conditions occur.

Land Use

Land use and management affects soil resilience, which is directly related to sustainability (Szabolcs 1994b). Sustainability is based on the long-term maintenance of soil functions or soil quality. The capacity of a soil to resist and recover from minor stresses and disturbances can be enhanced through management (Fig. 1c). Managing for soil quality will enhance soil resilience, and resilient soils respond to management (Lal 1998). For example, management practices that increase soil organic matter levels will improve most soil functions. Soil resilience can indicate the degree to which a soil will recover from a particular cropping or management system.

Scale

Soil resilience depends on the spatial scale of the disturbance(s). If the disturbance occurred on a square meter, the rate and degree of recovery would be greater than if it occurred across a watershed. In areas where large-scale disturbance results in destruction of part or all of the soil biological community, recovery may be more rapid if relatively undisturbed patches are retained.

Whether or not a soil is defined as being resilient to a particular disturbance also depends on the time frame of the evaluation. Soils are not static. They are dynamic systems that are developing continually and changing over time. The rate of change may be very slow. Some changes may only be noticed on a geologic time scale, in which case resiliency may not be relevant. When dealing with sustainability, however, a human life span is more relevant; for economic planning, 5 to 10 years, or less, would be considered relevant (Lal 1993b).

Disturbance Regime

Soil resilience, without knowing the type and degree of disturbance, has no absolute meaning in terms of soil value (Szabolcs 1994b). Resilience needs to be described with respect to the type of disturbance, which becomes important when comparing resiliency among soils. For example, a soil's capacity to recover its functions after a fire may be different than recovering function after tillage. The two disturbances have different effects on soil functions and on the factors and processes that contribute to recovery of those functions. The disturbance regime can be characterized in terms of type, frequency, intensity, and predictability (or regularity) of each event (Sousa 1984; Herrick et al., 1997). Each disturbance regime may affect soil functions in a different way.

Frequency and timing of the disturbance will affect the recovery of the system. For example, the ability of a soil to recover from frequent compactive disturbances, such as livestock trampling, is lower than if the disturbance was occasional. The impact will also be greater when soil is wet than when it is dry. In general, recovery from compaction is faster if it occurs immediately before a period of intense soil biological activity. Metz and Farrier (1971) showed that the abundance of mites (Acari) and springtails (Collembola), which are important for nutrient cycling, was significantly decreased by annual burning. It was shown, however, that these mesofauna were essentially unaffected by fires at 5-year intervals. This demonstrated the need for a longer than 1-year recovery period.

In an annual cropping system, soil may recover in a hysteretic manner in which it does not fully recover before the next cropping cycle is imposed (Fig. 1d). Each year the same hysteretic effect occurs until, eventually, the soil's capacity to restore itself and its quality are significantly degraded. This concept explains the decline in organic matter levels of tilled soils from the time they are brought into agricultural production. Cultivation tends to increase the rate of organic matter loss in soils primarily by accelerated microbial decomposition.

MECHANISMS OF SOIL RECOVERY

Recovery mechanisms for different soil functions vary widely, depending on the factors discussed above. Often multiple mechanisms are occurring simultaneously, and each may affect one or more soil functions. A multitude of soil and plant community processes, including physical, chemical, and biological mechanisms, contribute to recovery (Table 1).

Many resilience mechanisms can also be viewed as contributing directly to various soil functions (Table 1). An example is the soil function of supplying contaminant-free food. In order for the soil to provide contaminant-free food, biodegradation of xenobiotics (e.g., pesticides) assimilated into the plant must occur. By degrading the xenobiotic compounds, the soil is recovering its function of providing contaminant-free food. When certain xenobiotic compounds are applied to the soil, the soil loses its capacity to provide contaminant-free food until it degrades or attenuates the compound (recovery process).

Nearly all processes associated with soil formation also contribute to resilience. Soil formation is a result of the interaction of environmental conditions and biological activity. It is dependant on five factors—climate, biology, topography, parent material, and time (Jenny 1980)—and four processes—additions, removals, translocations, and transformations (Simonson 1968). The interaction of these factors and processes naturally forms soils and develops horizons in a soil profile. Soil resilience depends on these same interacting factors and processes, all of which can be influenced by management. The most important factors controlling the recovery of degraded soils are floral and faunal activity, including microbial activity, and climate. At longer (often geologic) time scales, the relative importance of weathering in-

TABLE 1

Soil functions and associated recovery processes or mechanisms

Soil function	Recovery processes or mechanisms
Nutrient cycling	Biological activity, biological diversity, plant growth
Partitioning of water	Soil fauna activity (earthworms, termites, etc.), shrink-swell cycles, freeze-thaw cycles, and plant growth, aggregation processes, vegetation establishment.
Productivity	C sequestration, aggregation processes, nutrient cycling, biological diversity.
Water storage	C sequestration, aggregation processes, biological activity
Decomposition	Biological activity
Absorbing and detoxifying pollutants	Biological activity, C sequestration, biological diversity, mineral weathering, clay formation
Nutrient supplying capacity	Biological activity, mineral weathering, nutrient cycling

creases, and the terms soil formation and resilience become virtually synonymous.

QUANTIFICATION AND ASSESSMENT

Soil resilience can be quantified experimentally by measuring the rate, Eq. (1), or extent, Eq. (2), of recovery after a disturbance. Resistance can be expressed simply as the ratio of the capacity of the soil to function after a disturbance to its predisturbance capacity, Eq. (3) (Herrick and Wander 1998):

$$\text{recovery rate} = d[(B - C) \div (A - C)] \div dt \quad (1)$$

$$\text{recovery} = (B - C) \div (A - C) \quad (2)$$

$$\text{resistance} = C \div A \quad (3)$$

Where A is the predisturbance functioning capacity of the soil, B is the level of recovery to a stabilized equilibrium level of soil functioning, and C is the level of soil function immediately after the disturbance (Fig. 1a).

The capacity of the soil to function (soil quality) cannot be measured directly, but it can be measured indirectly through indicators of those functions (Fig. 2) (Karlen et al., 1997; Seybold et al., 1998). Herrick and Wander (1998) emphasized that the time scale of interest, nature of the disturbance, level of recovery expected, and the type and amount of inputs needed to support recovery must be known for assessment of soil resilience. Soil resilience is a dynamic property that is very dependent on a soil's status at the time of assessment.

Several published approaches attempt to quantify or assess the concept of soil resilience or resistance. However, none provide an independent estimate of resilience as defined in this paper. One approach evaluates the change in soil function based on the balance between the soil regenerative and degradative processes over a given time period (Lal 1993b, 1994a, 1997). Included in Lal's model are initial soil conditions and effects of management inputs on soil processes: $S_r = S_a + \int(S_n - S_d + I_m)dt$, where S_r indicates change in soil function and can give information about the integrated effect of soil resilience or resistance, S_a is antecedent soil condition, S_n is soil renewal rate, S_d is soil degradation rate, and I_m is management inputs. If the rate of change in soil function is evaluated during the disturbance period, information can be obtained about soil resistance. If the rate of change is evaluated after the disturbance, information can be obtained about soil resilience (Refer to Eq. (1).

Rozanov (1994) attempted to quantify the change in soil function after a disturbance based on the general laws of physics. This approach quantifies the force (work) that would be required to return soil to its initial state after a disturbance. This force is proportional to the induced change (resistance): $dA \div dx = -kx$; where "A" is an amount of work required for moving the soil between states, "k" is the soil resistance coefficient, "x" is the variable (soil function), and the minus sign shows that work is required against an impact of the acting force. However, the ability of soil to do work and recover (resilience) to its initial state was not quantified.

To assess soil resilience, Rozanov (1994) suggested developing soil resilience classes using the degrees of a specific degradation process most characteristic for a type or class of land use. For example, degrees of soil salinization (degradation process) for irrigated cropland in drylands (land use) could be used. The theory for assessment is based on the fact that inherent soil resilience characteristics cannot be measured directly and that the results of degradation would constitute a reliable base for evaluation against a particular degradation process. General soil resilience groups that can be modified based on various soil degradation processes in different land use systems were developed (Table 2).

Szabolcs (1994b) presented a concept that models the potential of soil function to change as a result of a disturbance. The model has both resilience and resistance components: $SR = BC_{ph} + BC_{ch} + BC_b + \int dPSF \div dt + \int dAF \div dt$, where SR indicates the potential of the soil to resist change and recover soil functions, BC_{ph} is the physical buffering capacity, BC_{ch} is the chemical buffering capacity, BC_b is biological buffering capacity, PSF is pedological soil fluxes, and AF is for anthropological soil fluxes. The buffer capacities indicate the ability of the soil to counteract stress or disturbance (resistance). The last two components evaluate renewability of the soil over time as a function of the natural and anthropogenic soil-forming processes in operation.

Another approach for assessment of resilience is development of threshold values for soil properties. The threshold values indicate the level beyond which soil becomes sensitive to degradative processes and loses its capacity to resist and/or recover after a disturbance (Lal 1994a). Delineation of threshold values can be identified by evaluating soil dynamics under a

TABLE 2

Examples of general and specific soil resilience classes (after Rozanov 1994)

General soil resilience classes	
Nonresilient	soils are very severely affected after continuous use
Slightly resilient	soils are severely affected after continuous use
Moderately resilient	soils are moderately affected after continuous use
Highly resilient	soils are non- or slightly affected after continuous use
Specific soil resilience classes	
Soils resilient to salinization	none, slightly, moderately, highly
Soils resilient to sodification	none, slightly, moderately, highly
Soils resilient to acidification	none, slightly, moderately, highly

range of land uses and farming systems for principal soils in major ecoregions. In most cases, determination of threshold values for soil properties can only be evaluated in long-term experiments (Elliott and Lynch 1994). This concept of applying thresholds is further described and applied to desertification by Puigdefabregas (1995) and by Schlesinger et al. (1990).

Grossman et al. (1995) have developed near-surface indices of fragility, which relate to soil resistance. Fragility pertains to the magnitude of loss in soil function that would result from deterioration of near-surface conditions. The index assumes that if the initial near-surface conditions are favorable, the fragility would be low or resistance would be high. Soils are ranked for susceptibility to deterioration because of (i) truncation, i.e., erosion; (ii) near-surface compaction and/or crust formation; and (iii) "O" horizon obliteration. Indicators of each are placed in classes from 1 to 5, with 5 having the lowest fragility or highest resistance. The index is used to rank soil survey information with respect to fragility.

FRAMEWORK FOR ASSESSMENT

Three primary approaches for determining soil resilience are: (i) measuring the recovery of the soil after degradation directly, (ii) identifying and quantifying the integrity of the mechanisms that contribute to resilience after a disturbance, or (iii) measuring specific properties that serve as indicators of recovery mechanisms. The first approach requires monitoring of the rate and mode of recovery of a soil after it is degraded. Long-term studies may be required if the soil has low resilience to a particular disturbance. Eq. (1) and Eq. (2) can then be used to measure rates of recovery. Kay et al. (1994) used this method to assess resilience with respect to the structural component of soils. Resilience was described as the ability of a soil to recover its structural form after an applied stress. Recovery mechanisms included freezing/thawing, wetting/drying, and biological activity (e.g., root development and soil fauna). Resilience was characterized by maximum recovery in soil structural form and the rate at which recovery occurred. Maximum recovery in a given state was defined as resilience potential.

The second approach to gauging resilience requires quantifying the functioning capacity associated with recovery mechanisms after a disturbance. If critical recovery mechanisms are still functioning, recovery can occur. However, it will depend on the rate or kinetics of the recovery processes or mechanisms. If a soil has low resilience to a particular disturbance or if it has completely lost its recovery processes, the soil and the ecosystem it supports may become permanently degraded, resulting in a new, but lower, production capacity. This new, stable, lower functioning capacity can become very resistant to change.

In the third approach, indicators of soil resilience are used to measure the capacity of a soil to restore or recover its functions (Fig. 2). This approach is similar to that proposed for the assessment of soil quality. Indicators are used to gauge the degree or capacity of a soil to function. Indicators of soil resilience are difficult to identify because knowledge about the recovery mechanisms is required. In such studies, soil functions and associated recovery mechanisms are identified, and a minimum set of indicators of those recovery mechanisms are selected. To determine recovery mechanisms and indicators, experiments can be set up to measure a suite of potential indicators and inputs into the system. The system is disturbed, and the level and rate of recovery is measured and compared with predisturbance properties or indicators. The long-term aspect is essential because many soil properties change slowly. Thus, resilience could take many years to decades to show detectable changes. Similar studies would need to be completed for each type of disturbance, soil type, and climate.

Table 3 lists soil properties that could be important indicators of recovery. Other indicators that have shown promise are the metabolic quotient for CO_2 (qCO_2), which is a useful indicator of the efficiency of nutrient and energy fluxes

TABLE 3

Potential indicators for soil resilience (modified from Bezdicek 1996)

Soil structure
Microaggregates
Soil water
Retention and transmission properties
CEC
Exchangeable cations
Soil organic matter content
Transformations
Nutrient-supplying capacity
Soil pH
Rooting depth
Soil biodiversity
Soil fauna activity
Microbial activity

through the soil; the microbial biomass C:total organic C ratio, which can indicate changes in nutrient availability (the microbial biomass responds more quickly than total C to a grading or degrading processes Anderson 1994); and the potential mycorrhizal infectivity in the soil attributable to the importance of vegetation to recovery in some ecosystems. Bezdicek et al. (1996) suggest that soil resilience and the current capacity of a soil to function are dependent on some of the same intrinsic soil properties. An example is soil organic matter content, which is a key indicator of the capacity of a soil to hold water (current function), limit water loss (resistance), and recover through its direct and indirect effects on aggregate formation (resilience) (Gregorich et al. 1994; Herrick and Wander 1998).

SUMMARY AND CONCLUSIONS

Soil resilience is an important concept in combating soil degradation and maintaining sustainability. It is defined as the capacity of a soil to recover its structural and functional integrity after a disturbance. Resilience is measured by the rate and level of recovery. Soil resistance is defined as the capacity of a system to continue to function without change throughout a disturbance. Soil resilience and resistance concepts are fundamental components of soil quality. They relate to soil quality through loss and recovery of soil functions. Factors that affect soil resilience and resistance include soil type, vegetation, climate, land use, the disturbance regime, and temporal and spatial scales. Effects of above- and below-ground biological communities are important factors in the recovery process.

Soil resilience can be quantified experimentally by measuring the rate or extent of recovery. Resistance can be quantified as a ratio of the capacity to function following a disturbance to a soil's predisturbance capacity. We have presented three approaches for assessing soil resilience: (i) direct measurement of soil recovery after a disturbance, (ii) identification and quantification of the integrity of recovery mechanisms after a disturbance, and (iii) measurement of indicators of recovery mechanisms.

Development of soil resiliency levels based on land use for specific disturbances would be useful for long-range land-use planning and management and for sustainability of the soil resource base. Further research is also needed to develop quantitative measures or indicators of soil resilience and resistance and to develop soil resiliency classes based on those indicators. For the development of indicators, long-term process studies may be required.

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