Soil Change, Soil Survey, and Natural Resources Decision Making: A Blueprint for Action

A. J. Tugel,* J. E. Herrick, J. R. Brown, M. J. Mausbach, W. Puckett, and K. Hipple

ABSTRACT

Land managers and policymakers need information about soil change caused by anthropogenic and non-anthropogenic factors to predict the effects of management on soil function, compare alternatives, and make decisions. Current knowledge of how soils change is not well synthesized and existing soil surveys include only limited information on the dynamic nature of soils. Providing information about causes and attributes of soil change and the effects of soil change on soil function over the human time scale (centuries, decades, or less) should be a primary objective of 21st century soil survey. Soil change is temporal variation in soil across various time scales at a specific location. Attributes of change include state variables (dynamic soil properties), reversibility, drivers, trends, rates, and pathways and functional interpretations include resistance, resilience, and early warning indicators. Iterative elements of the blueprint for action described in this article are: (i) identify user needs; (ii) conduct interdisciplinary research and long-term studies; (iii) develop an organizing framework that relates data, processes, and soil function; (iv) select and prioritize soil change data and information requirements; (v) develop procedures for data collection and interpretation; and (vi) design an integrated soil–ecosystem–management information system. Selection of dynamic soil properties, soil change attributes, and functional interpretations to be included in future soil surveys should be based on analyses comparing the benefits of meeting user needs to the costs of data acquisition and delivery. Implementation of the blueprint requires increased collaboration among National Cooperative Soil Survey partners and other research disciplines.

We believe one of the most critical natural resource management needs of the 21st century is information about the dynamic nature of soil, or simply, soil change. This concern is prompted by the increasing evidence and awareness about human impacts on the condition of the nation's resources and the tacit demand for sustained use of soil. To meet this need, information about how soils change as a result of natural factors and human activities should be added to surveys of the National Cooperative Soil Survey (NCSS). The objectives of this paper are to present the soil change concept and to propose a strategy for meeting information needs related to soil change.

What are the needs of soil survey users? Soil surveys have effectively supported agricultural and natural resource management for more than 100 years (Indorante et al., 1996). While these surveys have been invaluable in guiding development of natural resources through the disciplines of agronomy, animal husbandry, forestry, and land use planning (Durana and Helms, 2002), the focus in the 20th century has been classification of relatively static soil properties to facilitate inventory, define limitations, and provide soil property data for input-based production system design. Since the passage of the National Environmental Protection Act in 1969, standard soil survey information has required reinterpretation to address questions of environmental quality and sustainability (Muhn, 2002). The increasing emphasis on quantitative resource assessment and monitoring to meet legal mandates on both public and private land (i.e., Resources Planning Act of 1974, Soil and Water Resources Conservation Act of 1977, Public Rangeland Improvement Act of 1978, Department of Interior and Related Agencies Appropriations Act of 2002), accountability in the administration of publicly funded programs (e.g., Government Performance Results Act of 1993), and combating land degradation threats to soil productivity (Johnston and Crossley, 2002) and global food security (Anecksamphant et al., 1999) will, however, require not just a reinterpretation of existing information, but a new approach to gathering, analyzing, and interpreting soil information.

Today's land managers and policymakers require information about how soils change to compare alternatives and make decisions that balance goals for production, economics, sustainability, and the environment. Soil change data are needed to (i) establish quality criteria and measures of performance; (ii) interpret assessment and monitoring results; (iii) predict management effects on resource condition; (iv) support management of sustainable production systems; (v) prevent soil and land degradation; and (vi) support restoration and remediation activities (Table 1).

THE SOIL CHANGE CONCEPT

We define soil change as temporal variation in soil properties at a specific location. The temporal variation may be determined for a variety of time scales and is driven by natural factors, human use and management, or their combined impacts. Soil changes through time, although change is not caused by time (Fig. 1). Soil properties emerge as a result of pedogenesis, are affected by historical land use, and are currently changing in modern ecosystems that have increasing human influence (Richter and Markewitz, 2001). This follows from Jenny's (1941) factorial model which states that soil is a

A.J. Tugel, USDA-NRCS, Box 30003, 3JER, Las Cruces, NM 88003; J.E. Herrick, USDA-ARS, Jornada Experimental Range, Las Cruces, NM 88003; J.R. Brown, USDA-NRCS, Las Cruces, NM 88003; M.J. Mausbach, USDA-NRCS, Washington, DC 20250; W. Puckett, USDA-NRCS, Washington, DC 20250; K. Hipple, USDA-NRCS, Lincoln, NE 68508. Received 7 May 2004. Pedology. *Corresponding author (atugel@nmsu.edu).

Published in Soil Sci. Soc. Am. J. 69:738–747 (2005).
doi:10.2136/sssaj2004.0163
© Soil Science Society of America
677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: NASIS, National Soil Survey Information System; NCSS, National Cooperative Soil Survey; SOC, soil organic carbon; SOM, soil organic matter; USFS, United States Forest Service.

Table 1. Users, scale of use, and probable uses of soil change information for land management and policy development.

User	Scale of use	Probable uses
Agricultural producers	field, farm or ranch, watershed	support short- and long-term soil productivity minimize negative environmental impacts manage for short-term economic profit and long-term sustainability (cost–benefit analysis)
Land managers (federal, state, local, nongovernmental organizations), program managers, policymakers	field, watershed, state, regional, national, global	interpret results of resource assessment and monitoring predict effects of management and climate change on soil function plan for food security support planning and site selection for restoration and remediation prevent land degradation
Homeowners, developers, engineers, urban planners	garden, public works project, city, county	assess risks to human and animal health support decontamination, restoration, and remediation control erosion manage storm water

result of climate, organisms, topography, and parent material acting through time. The increasing human influence, however, has dramatically altered the type, intensity, and rate of change for many soils (Robarge and Johnson, 1992).

Change results from variation in physical force or energy (Smeck et al., 1983), whether the force is climate change on a geologic time scale, absence of fire on a centurial time scale, or use of a plow on the seasonal time scale. We use the term "disturbance" to represent relatively discreet events in time that can modify soil morphology, composition, or processes, and the capacity of the soil to function.

Soil disturbances are an integral component of natural systems, promoting diversity and renewal processes (Holand Meffe, 1996; Evans et al., 2000), and include essential operations in managed systems. Examples of natural phenomena (Raup, 1957; White, 1979) and human actions include drought, fire, floods, windstorms, cultivation, fertilization, irrigation, fire suppression, grazing, and weed establishment. In addition to the type of disturbance, its spatial scale, intensity, frequency, and predictability all determine the severity of impact (Sousa, 1984). Episodic, stochastic events such as hurricanes and drought are difficult to predict or control and are often the events that trigger a detrimental state shift in systems that have experienced gradual change resulting from long-term management (Scheffer et al., 2001).

In any discussion of change over time, the immediate question is "what is the relevant temporal scale"? Time scales important for studying management effects on soil (Fig. 2) are decadal and centurial (Richter and Markewitz, 2001). An understanding of temporal variability over time frames of years, seasons, days, and possibly

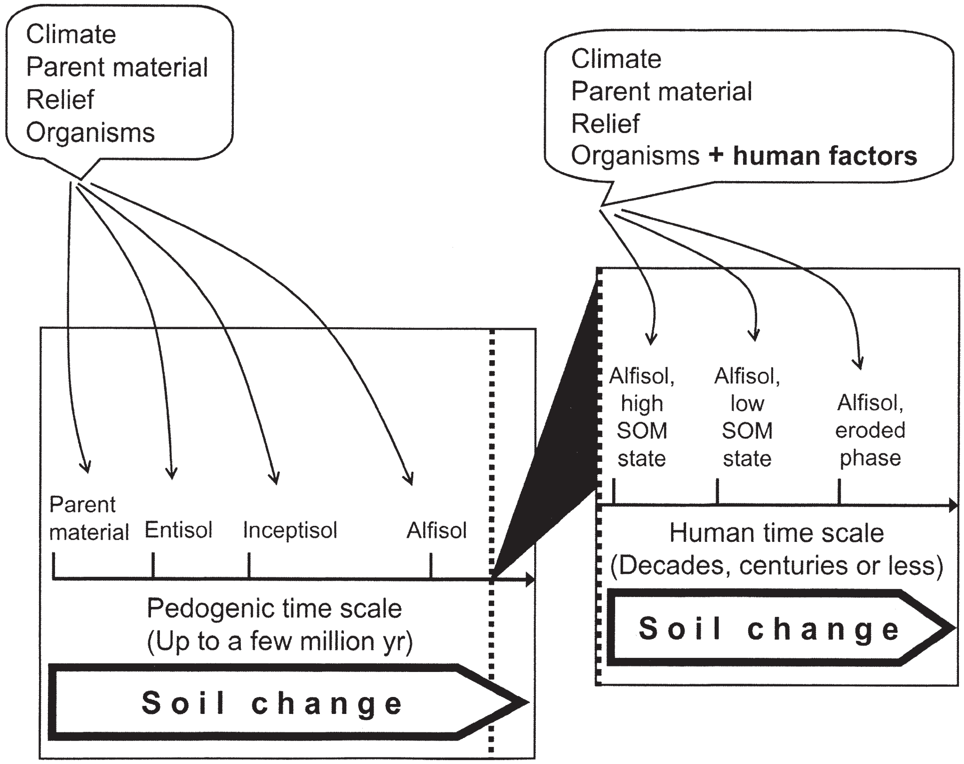

Fig. 1. Relative time scales of change. Soil change, a function of soil-forming factors, occurs over the pedogenic time scale (periods up to a few million years) and its subset, the human time scale (periods of centuries, decades, or less). Human factors can drive the degradation of an Alfisol from a state high in soil organic matter (SOM) to a state low in SOM, and eventually to an eroded soil phase of the Alfisol.

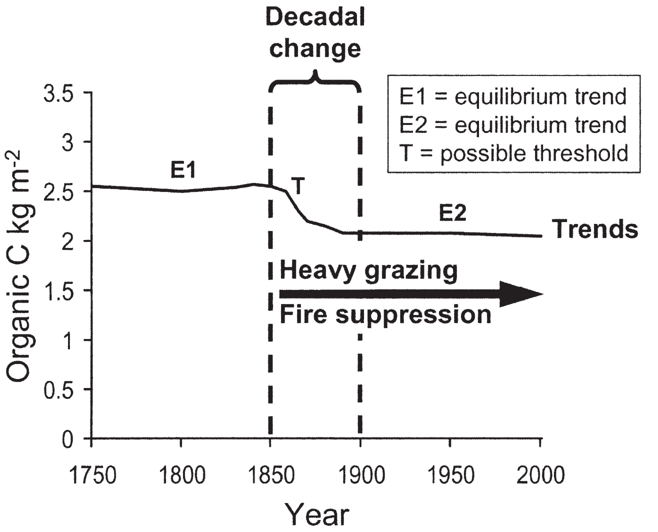

Fig. 2. Centurial trends and decadal soil changes in response to management. Simulated soil organic carbon (SOC) of a sandy loam grassland soil (0–20 cm), La Copita Experimental Range, TX, for the period 1750 to 2000 (Hibbard, 1995; redrawn from Archer, 1989; Archer et al., 2001) illustrates two levels of equilibrium trend (Arnold et al., 1990) over periods of centuries. Attributes of change reflected in the decadal changes between 1850 and 1900 include pathways and rates of change and a possible threshold value. Historical levels of SOC decreased as the plant community shifted from tall- and mid-height perennial grasses to short perennial grasses and annuals in response to the onset of heavy grazing (1850s) followed by absence of fire. The historical range of variability is not fully depicted and depends on the frequency of observations. The SOC levels (0–20 cm) are higher in areas where woody plants encroach this grassland creating an even greater potential range of soil variability.

hours, however, is also necessary to ensure appropriate sampling and context for interpretation of soil properties that change. Understanding historic ranges of anthropogenic and non-anthropogenic variability is essential for interpreting modern changes in soil although it does not provide all information necessary for predicting future change (Millar and Woolfenden, 1999; Parsons et al., 1999). The time scale of change that will most likely relate to both the time frame of recovery (Stringham et al., 2003) and impacts of human management includes decades and centuries. Consequently, we suggest that change-related soil survey products should address the human time scale (i.e., centuries, decades, or less) with an emphasis on centuries and decades (Fig. 1).

Almost all soil properties change eventually. We propose the term dynamic soil properties for those soil properties that change over the human time scale. Grossman et al. (2001) define use-dependent properties as properties that change with land use; these are included within the concept of dynamic soil properties (e.g., soil organic carbon [SOC], bulk density, pH, salinity, and aggregate stability).

Dynamic soil properties vary across space as well as through time. In this paper, we do not refer to the "changes" in soil properties across a soil boundary line or through the gradient of an ecotone. For that context, we use the terms "differences" or spatial variability. Dynamic soil properties such as water and organic matter content or salinity generally have greater spatial variability than more stable properties such as soil texture and mineralogy (Wilding et al., 1994). Changes in the spatial distribution of dynamic soil properties, such as the increased concentration of SOC in the surface layer under shrubs and its corresponding depletion in intershrub spaces following shrub invasion of semiarid grasslands, result in increased spatial variability at the map unit scale and are important indicators of changes in ecological processes (Bird et al., 2002). Some types of spatial patterns resulting from human impacts are currently addressed in soil survey through naming conventions and classification. Phase (e.g., erosion, deposition) and soil taxon names (e.g., Arents), however, only reflect the results of past management and do not provide information related to the dynamics of soil behavior.

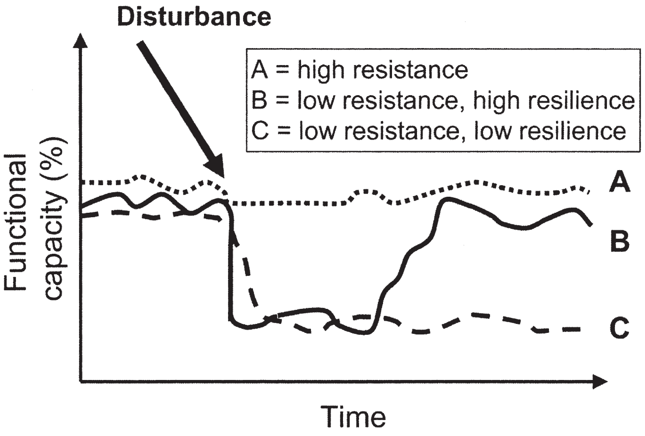

Fig. 3. Function, disturbances, resistance, and resilience. Each soil can have unique resistance to disturbances and resilience to recover from the disturbances. Soil A resists the disturbance. Soil functional capacity declines for Soils B and C after the disturbance. Soil B recovers its functional capacity; Soil C does not. Redrawn from Herrick and Wander (1998) and Seybold et al. (1999).

The ability of a soil to resist disturbances (resistance) and to recover functionally (resilience) (Blum, 1997; Herrick and Wander, 1998; Seybold et al., 1999) is an important ecological concept for managed and unmanaged ecosystems and agricultural systems (Scheffer et al., 2001; Pyke et al., 2002). The resistance and resilience of a specific soil to a disturbance depend on relationships between processes and relatively static and dynamic properties (Fig. 3). Thus, the development of interpretations for soil change requires the integration of pedological and ecological studies (Brown and MacLeod, 1996). We generally study pedogenic and geomorphic processes (Simonson, 1959; Daniels and Hammer, 1992) to explain the formation, composition, morphology, and distribution of soils and landscapes. Studies of primary ecological processes including energy flow, the hydrologic cycle, and nutrient cycling are also needed to determine dynamics, fluxes, and functional capacities of soil systems. For example, the depletion of soil organic matter (SOM) in response to a vegetation shift (Fig. 2) limits mineralization and changes the soil's capacity to provide nutrients for plant growth (Archer et al., 2001).

The importance of soil change is that it affects soil function. The ultimate consequences of change depend

Table 2. Soil survey user inquiries that address soil condition or level of function (functional capacity) and the corresponding soil change attribute necessary for response. Soil change attributes and their occurrences in a state and transition model (Stringham et al., 2003) are listed. State variables are dynamic soil properties and include use-dependent soil properties. Arnold et al. (1990) describe trend of change, reversibility, and pathways of change.

Inquiry	Soil change attribute within a state†	Soil change attribute within a transition†
What is the condition of the soil or level of function?	state variable (actual and potential)	–
Is it degrading, improving, or maintaining?	–	trend of change
What should it be for the intended or sustained use?	state variable (potential or standard)	–
What can be used to detect soil degradation before it occurs?	–	early warning indictors
If degraded, can it be restored or improved?	–	reversibility
What will it take to restore or improve it?	–	drivers of change
How long will it take?	–	rate of change
	–	pathways of change (feedbacks)
How will soil changes affect future management options?	soil resilience	–

† Soil resilience and early warning indicators may be quantifiable in the future but currently should be viewed as interpretations.

on its reversibility (Arnold et al., 1990). With knowledge of cause and effect relationships regarding detrimental soil change, land managers can choose practices and policymakers can establish programs that promote positive changes in the soil resource and the environment. Through improved understanding of soil resistance and resilience, decision makers will also be able to develop management strategies to protect soil functions that may be important in the future.

THE SOIL SURVEY OF THE FUTURE

Documenting and describing the nature and effects of soil change should be a primary objective of soil survey. Soil surveys should include information about soil and ecosystem change on human time scales resulting from natural and human factors. A process-based relational framework should be used to organize and disseminate soil change hypotheses, data, and interpretations pertaining to the human time scale. We suggest state and transition models (Westoby et al., 1989; Stringham et al., 2001, 2003; Herrick et al., 2002; Bestelmeyer et al., 2003, 2004). Standard protocols should be followed to collect dynamic soil property data and quantify attributes of soil change (Table 2). Qualitative descriptions of the changes in soil behavior should be provided until quantitative technologies become available. The soil survey enhancements we suggest are not about delineating dynamic soil properties on maps. The enhancements comprise additional information about soil behavior for resource decision making.

Changes in dynamic soil properties can be measured over time through long-term studies or monitoring. They can also be estimated by the careful substitution of space-for-time by comparing locations (having the same soil but different current conditions) where (i) the past conditions are known or can be inferred with sufficient precision and (ii) an operational model that hypothesizes causes and effects of change is available (Pickett, 1989). Space-for-time sampling strategies are similar to comparison and chronosequence studies (Richter and Markewitz, 2001) and are suited to soil survey operations. Although of limited availability, long-term study data is helpful for interpreting results and quantifying attributes.

Example

Management effects on a dynamic soil property (SOC) and the capacity of a soil to function are described in this example. Carbon sequestration amounts based on standard soil survey data and long-term study data are compared. Soil organic C associated with different land uses and management systems is used to estimate total SOC stored in a region, changes in C sequestration resulting from a change in management practices, rate of change, and resilience of a soil disturbed by cultivation. Data for SOC were obtained from long-term studies in Pendleton, OR (Rasmussen and Albrecht, 1998). Similar data could be obtained by soil survey staff through comparative sampling where location is substituted for time. The soil at the study area, Walla Walla soil (coarse-silty, mixed, superactive, mesic Typic Haploxeroll), is extensive in the Palouse region of Oregon and Washington. The study area historically supported grassland. It was farmed beginning about 1880 and was converted to various cropping systems in 1931 (Table 3). Soil organic C was determined in the year of initiation of the management system change and in 1990.

Using values from the National Soil Survey Informa-

Table 3. Soil organic carbon change in the 0- to 20-cm zone of the Walla Walla soil under various cropping systems (Rasmussen and Albrecht, 1998).

Cropping system	Date started	Soil organic carbon		
		Initiation	1990	Change per year
		Mg ha^{-1}		
Virgin grassland	–	56.83		
Grass pasture	1931	35.40	45.09	+0.162
Wheat–summer fallow†	1931	35.40	28.49	−0.115
Annual wheat†	1931	36.16	35.48	−0.011
Annual wheat, no-till	1981	31.45	32.29	+0.093
Walla Walla soil, NASIS	–	–	30.16–38.28‡	–

† Moldboard-plowed to a 20-cm depth.

‡ Amount calculated from estimated values in the soil survey database (National Soil Survey Information System, NASIS) and does not represent 1990 data.

tion System (NASIS), the estimate of total SOC storage for the 334 920 ha of the Walla Walla soils (0–20 cm) is 10.4 to 13.2 Tg. If future soil survey products include management-related dynamic soil property information, sequestration predictions (indicative of the capacity to function) could be made for specific systems. Based on virgin grassland data, the historical soil C stock in all Walla Walla soils would have been 19.6 Tg (Table 3). Using 1990 data which does not reconcile possible C losses from soil erosion, the C pool for grass pasture, wheat–summer fallow, and annual wheat is 15.6, 9.8, and 12.2 Tg, respectively. The potential range of variability (i.e., 9.8–19.6 Tg) can be used by scientists and policymakers to (i) improve global C budgets through the use of potential, nearly 20 Tg, rather than the undefined NASIS estimate of 10 to 13 Tg, and (ii) establish incentives for cropping systems that increase C storage and maintain commodity productivity.

In addition to the amount of C that could be restored, producers need to know how long it will take to reach that amount. Rate, such as the annual increase in SOC after the 1981 initiation of a no-till cropping system (Table 3), is one attribute of change (Table 2) that will add value to soil survey products, although such information would be obtained from long-term studies or process models such as CENTURY (Parton et al., 1987). Long-term study data is available for only a few soils and ecosystems (Richter and Markewitz, 2001) and its use should be limited to inferences about similar soils.

From the data in Table 3, the resistance and resilience of the Walla Walla soil to cultivation, with respect to C sequestration, can be estimated (Seybold et al., 1999). Resistance is expressed as the SOC ratio of cultivated systems to virgin grassland. The recovery of SOC can be used to interpret the soil's resilience. Formerly cultivated land planted to grass pasture regained much of its SOC by 1990, recovering 45% of the lost amount and attaining a level 79% of the native state. From this response, we infer that the other treatments, if returned to grass pasture, would also recover. Qualitative soil survey interpretations for resilience would be developed from space-for-time sample data combined with estimates of rate of change. A relative term (e.g., high or moderate resilience) would be assigned to these soils. Appropriate interpretive criteria are uncertain at this time, but classes could be based on relative recovery over time, as estimated from properties such as SOC that reflect the processes important to sequestration. If rate of recovery is obtained from long-term studies, chronosequences, or process models, resilience can be expressed quantitatively based on the potential recovery rate.

Attributes of soil change and resistance and resilience interpretations would be presented for individual map unit components or benchmark soils in the soil survey report and databases. Attributes in this example include rate of change and the state variable, SOC, for virgin grassland, grass pasture, annually cultivated, and no-till states.

STRATEGY FOR MEETING THE TWENTY-FIRST CENTURY CHALLENGE

Following a strategic approach, or blueprint, is essential for the efficient development of relevant, scientifically credible soil survey procedures, data, and an integrated information system that will have utility well into the 21st century. Implementation of this blueprint will require the participation of a large number of scientists and technical personnel. Increased collaboration among the NCSS partnership and other research disciplines is needed. The existing NCSS has the expertise and organizational structure necessary to identify priorities and facilitate this process. Additionally, each member organization can participate through research, technology development, testing, or data collection according to their existing mission and responsibilities.

Blueprint for Action

Integrating soil change in soil survey requires advances in the science of soil change. Furthermore, advancing the science, understanding user needs, and developing technologies of soil change for soil survey is an iterative process. Six elements, which can also be considered benchmarks of progress, are included in the blueprint (Fig. 4):

1. Identify user needs.
2. Conduct interdisciplinary research and long-term studies.
3. Develop an organizing framework that relates data, processes, and soil function.
4. Select and prioritize soil change data and information requirements.
5. Develop procedures for data collection and interpretation.
6. Design an integrated soil–ecosystem–management information system.

Element 1: Identify User Needs

The desired outcome of this element is to define data elements and soil information requirements for different types of needs (Table 1). Users are generally seeking answers to one or more questions (Table 2) about the potential impacts of use and management on the capacity of the soil to function. The answers to these inquiries relate to soil change and the dynamic nature of soil. Specific applications such as the example presented in this paper must be identified so that the appropriate data and information can be collected. Currently, both open-ended and direct questions posed to users will likely prompt responses of limited value because the use of soil change data is a new paradigm. Workshops (Kolb, 1984; Pretty et al., 1995) for users, technical specialists, and scientists are useful tools for educating different groups and identifying their needs.

Element 2: Conduct Interdisciplinary Research and Long-Term Studies

This element advances the science of soil change through the study of soil as a part of dynamic, interre-

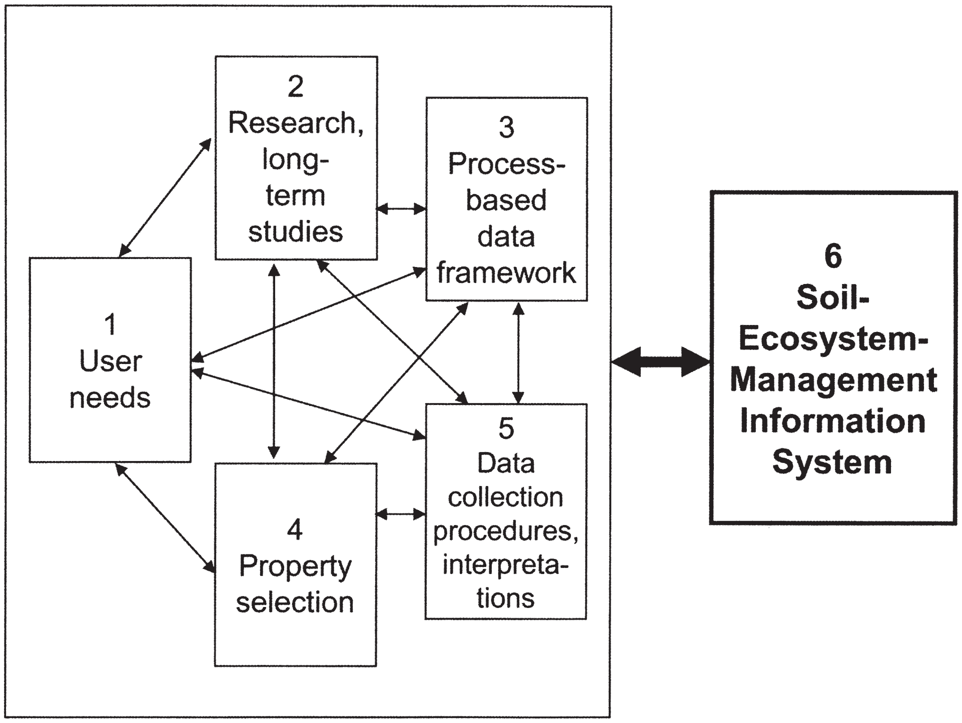

Fig. 4. A multicomponent blueprint for action. The strategy for including soil change information in agency soil survey programs is an iterative process.

lated systems. Integrated research at the systems level is essential to understand decadal and centurial soil change and pattern–process relationships, and to predict the effects of natural and anthropogenic disturbances. Research is needed to support the development of relational frameworks, sampling protocols, and functional interpretations for dynamic soil behavior (Elements 3, 4, and 5). Long-term studies (Magnuson, 1990; Tinker, 1994) are needed to answer questions about historical and current natural disturbance and management effects on soil, to differentiate those effects, and to explain their functional significance. The NCSS should formally encourage soil change research and monitoring of benchmark soils in the Long Term Ecological Research Program (Hobbie et al., 2003), the proposed National Ecological Observatory Network (National Research Council, 2003), the Agricultural Experiment Stations, ARS, United States Forest Service (USFS), and USGS research, and similar programs with mandates for increasing an understanding of soil function and management impacts.

Soil change as a field of study should strive to identify and quantify functionally important characteristics, called attributes of soil change (Table 2), to describe and predict soil change on the human time scale. Arnold et al. (1990) describe many of these attributes (Fig. 2).

This element is designed to bridge the gap between disciplines (e.g., pedology, soil sciences, hydrology, geomorphology, biogeochemistry, soil ecology, microbiology, forest sciences, range sciences, terrestrial and plant community ecology, agronomy, sociology), many of which address the same system but from different perspectives (Hedin et al., 2002; Lin, 2003). Traditional pedology research should be conducted collaboratively with disciplines that address the ecology and management of natural and agricultural resources. Interdisciplinary analysis (Dent et al., 1996) at multiple scales should be followed by reductionistic basic research in relevant areas (Bouma, 1997).

Element 3: Develop an Organizing Framework that Relates Data, Processes, and Soil Function

A relational framework to organize, interpret, and apply soil change information is needed. We suggest the state and transition model structure in Stringham et al. (2003) and Bestelmeyer et al. (2003) (Table 2). State and transition models are conceptual models of the causes and effects of change. The models are based on primary ecological processes; provide a relational framework for open, dynamic systems; and incorporate state variables, thresholds (Fig. 2), resistance, resilience, and drivers of change (Table 2). Other potential frameworks should be identified and evaluated. Information on the dynamic and relatively static properties of a soil should be considered together (Grossman et al., 2001) to determine functional capacity.

Element 4: Select and Prioritize Soil Change Data and Information Requirements

This element helps ensure that limited resources are focused on generating high value data and information (identified in Element 1). The first step is to select the soil and landscape properties and disturbances to be included. The second involves defining the types of information (soil change attributes) that will be documented about each dynamic soil property. The criteria for soil property selection (MacEwan, 1997; Herrick and Tugel, 2002) should meet three requirements. First, the relationships between the properties and the processes or functions they reflect should be clearly defined. Second, the properties should be easy to repeatedly measure accurately and precisely by different people. Third, the benefit–cost ratio of including the property should be relatively high. High benefit–cost ratios are generally associated with properties that are extremely important and/or are relevant to a large number of different functions. Ratios may also be high when a small amount of time is involved in completing the number of measurements required to detect a functionally significant difference in the property at a specified level of statistical significance. Benefit–cost analyses should also be developed for soil change attributes. Clearly, not all needs of users can be included in soil surveys because of limited operational resources or scientific knowledge.

Element 5: Develop Procedures for Data Collection and Interpretation

Describing and quantifying the temporal dynamics of soil systems will require new soil survey procedures. For field data collection, we suggest space-for-time sampling procedures applied to state and transition models (Bestelmeyer et al., 2003). Relevant soil change attributes should be characterized for soil map unit components (Foussereau et al., 1993). The spatial and temporal variability resulting from disturbances to soil–plant interactions needs to be addressed with statistically based sampling methods. Sampling designs should provide data that meets user requirements for precision and accuracy. Sampling strategies and data stratification should be appropriate for the on-site heterogeneity in space, time, or depth (Lepretre and Martin, 1994). Specific sampling depths should be based on functionally important zones in the soil (e.g., zones of biological activity, rooting, compaction). Reliability standards should be defined.

The form in which information on soil change is to be reported will help determine data collection and analysis procedures. Reportable parameters may include mean, median, minimum, maximum, indices, ratios, variance, confidence interval, or statistical significance in differences. Alternatively, soil survey information could be provided through a textual description of temporal variability, spatial distribution, and soil behavior. Another possibility is to provide mathematical or pedotransfer functions that allow users to calculate results from their own measurements. Appropriate reporting options should be determined through an analysis of user needs.

Models, pedotransfer functions, and inference systems (McBratney et al., 2002) for deriving dynamic soil property data should be tested to supplement field data acquisition. Pedometrics incorporates uncertainty and is primarily applied to studies of the spatial distribution and genesis of soil (McBratney et al., 2000). Specific statistical and geostatistical tools of pedometrics may be helpful, however, for determining pattern–property–process relationships when combined with knowledge of the causes of soil change on the human time scale. Soil function interpretations and simple predictive models should be developed to help users evaluate management-impacted conditions.

Relationships between dynamic soil properties and soil behavior resulting from impacts of human use and management are not, and most likely should not, be addressed by *Soil Taxonomy* (Soil Survey Staff, 1999) except in the case of extreme soil alteration such as Arents or physically transported soil material (Galbraith, 2003). Because feedback relationships are important to the stability and functioning of ecosystems (Scheffer et al., 2001), process and pattern information about the feedbacks between soils, plants, animals, and climate, as well as anthropogenic impacts, should be included in soil survey products such as reports, databases, and interpretations. State and transition models provide a framework to integrate and present the feedback information.

Element 6: Design an Integrated Soil Information System

Knowledge gained from Elements 1 to 5 should be used to modify an existing soil information system, or if necessary, design a new one. The information system should integrate soil and its interactions with plants, animals, and the environment with management. It is premature to design a database before user needs are clearly understood, practical approaches for applying or acquiring soil change information are developed, and primary research needs are addressed. The obvious alternative of expanding existing soil survey databases to include state variables (use-dependent values) for each land use may or may not be the best way to meet user needs or be the most cost effective. Required data may include: (i) reference values that specify the desired level; (ii) drivers of change that can be managed to reach the desired condition; and (iii) information on thresholds of change, resistance, resilience, pathways, and rates of change that can be used to estimate the probability and time frame for degradation or recovery. The organizing framework selected in Element 3 can provide important relationships for database design. Sampling strategies for data collection (Elements 4 and 5) will also dictate database structure and content. Before information system design, interim data storage systems that will ensure future access to the data should be developed.

Implementation

This paper presents new concepts for soil survey and suggestions in the form of a blueprint. It is not, however, an implementation plan. It is the authors' intention that the blueprint provide a starting point for an NCSS-facilitated discussion that leads to the identification of common goals and collaborative implementation. Relevant new information about soil change and its acceptance by decision makers will most likely be attained from close and continual interactions among researchers, the NCSS boundary organizations such as NRCS, USFS, Bureau of Land Management, National Park Service, and Bureau of Indian Affairs, and users (Cash et al., 2003). Boundary organizations are those that convey research needs to researchers and interpret results for decision makers (Guston, 1999; Cash, 2001).

Interdisciplinary involvement is required for the completion of most of the tasks in the blueprint. Synthesizing agronomic and ecological principles with pedology will be the greatest challenge and departure from existing soil survey paradigms. The synthesis will also strengthen the field of pedology and likely leverage additional research funds. Tasks will be performed by researchers and agency specialists, with input from soil surveyors. Soil survey update projects provide field situations and staff resources that could be used to assist researchers and specialists in the development of standardized protocols, data storage resources, interpretations, and user-friendly products related to soil change.

Implementation should build on existing strengths and resources. The past success of the NCSS can be attributed to the identification of common goals and commitments of staff and funds by individual member organizations to achieve those goals. Federal agencies of the NCSS (i.e., the boundary organizations) have personnel supported by existing budgets with experience in soil inventory, technology development, and research as well as the infrastructure to apply new technologies and train personnel in new skills required to address soil change. The authors do not recommend that the soil survey program become a research program, but rather, the link between the state experiment stations (NCSS members), the broader research community, and the soil survey program be strengthened to accomplish the goals of this paper. As dialog evolves and user and research needs are clearly defined, funding priorities should be adjusted accordingly within existing agency research and soil survey programs, competitive grant programs, and state experiment stations.

Many soil surveys are complete and the program of the future will focus on soil survey maintenance and upgrading activities. These activities should include data collection for soil change. Where funding is limited, efforts should focus on benchmark soils and other extensive soils. Soil surveyors will need additional sampling skills and a broader ecological background to successfully apply new soil survey protocols. The skills can be developed through training and by following standard soil survey protocols for soil change data collection and interpretation. The relative proportions of soil survey employees with specific skills may need revision with slight increases in individuals with data analysis and ecological expertise. Academic departments routinely adjust curricula to include new knowledge and technologies and should continue to make revisions corresponding to new soil survey needs.

CONCLUSIONS

Soil surveys should include information about causes of soil change over the human time scale and the resulting effects on soil function to meet user needs for decision making. The traditional application of use-neutral concepts in soil classification, mapping, and interpretations is necessary to make a consistent national inventory of the soil resource. Soils are a part of open, dynamic systems, however, and the effectiveness of managing these systems depends on the integration of information about how soils change in their environment through time. The concepts of soil change in soil survey are currently based on the pedogenic time scale. Increasing evidence shows that natural disturbances, land use, and management practices can change soil properties over periods of centuries, decades, or less. Providing information about the human impacts on soil is not enough to meet resource management needs. Land managers and other decision makers also need information about naturally driven changes that occur on the human time scale. Making new advances in soil survey through the addition of information about soil change on the human time scale is a profound and unique opportunity that will benefit generations to come. Increased availability of soil change information will expand the application of soil information in agriculture and natural resource management. It may take a generation to complete the task, but in so doing, soil scientists will develop skills and knowledge about systems and the ecological processes that comprise soil behavior. Increased understanding of soil change on the human time scale is critical to local and global issues of sustainability and the environment, both now and in the future.

ACKNOWLEDGMENTS

We thank Lynn Loomis, USDA-NRCS, and an anonymous reviewer for their valuable comments.

REFERENCES

Anecksamphant, C., C. Charoenchamratcheep, T. Vearaslip, and H. Eswaran (ed.) 1999. Recommendations of the 2nd International Conference on Land Degradation. *In* Meeting the challenges of land degradation in the 21st century. Conf. Rep., Int. Conf. on Land Degradation, 2nd, Khon Kaen, Thailand. 25–29 Jan. 1999. Dep. of Land Development, Bangkok, Thailand. Also available online at http://soils.usda.gov/use/worldsoils/landdeg/ld99.html (verified 27 Jan. 2005).

Archer, S. 1989. Have southern Texas savannas been converted to woodlands in recent history? Am. Nat. 134:545–561.

Archer, S., T.W. Boutton, and K.A. Hibbard. 2001. Trees in grasslands: Biogeochemical consequences of woody plant expansion. p. 115–137. *In* E.D. Schulze, S.P. Harrison, M. Heimann, E.A. Holland, J. Lloyd, I.C. Prentice, and D. Schimel (ed.) Global biogeochemical cycles in the climate system. Academic Press, San Diego, CA.

Arnold, R.W., I. Szabolcs, and V.O. Targulian (ed.) 1990. Global soil change. Report of an IIASA-ISSS-UNEP task force on the role of soil in global change. Int. Inst. for Appl. System Analysis, Laxenburg, Austria.

Bestelmeyer, B.T., J.R. Brown, K.M. Havstad, R. Alexander, G. Chavez, and J.E. Herrick. 2003. Development and use of state-and-transition models for rangelands. J. Range Manage. 56(2):114–126.

Bestelmeyer, B.T., J.E. Herrick, J.R. Brown, D.A. Trujillo, and K.M. Havstad. 2004. Land management in the American Southwest: A state and transition approach to ecosystem management. Environ. Manage. 34(1):38–51.

Bird, S.B., J.E. Herrick, M.M. Wander, and S.F. Wright. 2002. Spatial heterogeneity of aggregate stability and soil carbon in semi-arid rangeland. Environ. Pollut. 116:445–455.

Blum, W.E.H. 1997. Basic concepts: Degradation, resilience, and rehabilitation. p. 1–17. *In* R. Lal, W.H. Blum, C. Valentine, and B.A.

Stewart (ed.) Methods for assessment of soil degradation. Advances in Soil Science. CRC Press, Boca Raton, FL.

Bouma, J. 1997. Soil environmental quality: A European perspective. J. Environ. Qual. 26:26–31.

Brown, J.R., and N.D. MacLeod. 1996. Integrating ecology into natural resource management policy. Environ. Manage. 20:289–296.

Cash, D.W. 2001. "In order to aid in diffusing useful and practical information": Agricultural extension and boundary organizations. Sci. Technol. Human Values 26(4):431–453.

Cash, D.W., W.C. Clark, F. Alcock, N.M. Dickson, N. Eckley, D.H. Guston, J. Jager, and R.B. Mitchell. 2003. Knowledge systems for sustainable development. Proc. Natl. Acad. Sci. USA 100(14):8086–8091.

Daniels, R.B., and R.D. Hammer. 1992. Soil geomorphology. John Wiley & Sons, New York.

Dent, J.B., M.J. McGregor, and G. Edward-Jones. 1996. The interaction between soil and social scientists in rural land use planning. p. 113–122. *In* R.J. Wagenet and J. Bouma (ed.) The role of soil science in interdisciplinary research. SSSA Spec. Publ. 45. ASA and SSSA, Madison, WI.

Durana, P.J., and D. Helms. 2002. Soil survey interpretations: Past, present, and looking to the future. p. 275–302. *In* D. Helms, A.B.W. Effland, and P.J. Durana (ed.) Profiles in the history of the U.S. soil survey. Iowa State Press, Ames, IA.

Evans, C.V., D.S. Fanning, and J.R. Short. 2000. Human-influenced soils. p. 33–67. *In* R.B. Brown et al. (ed.) Managing soils in an urban environment. Agron. Monogr. 39. ASA, Madison, WI.

Foussereau, X., A.G. Hornsby, and R.B. Brown. 1993. Accounting for variability within map units when linking a pesticide fate model to soil survey. Geoderma 60:257–276.

Galbraith, J.M. 2003. ICOMANTH Circular Letter No. 4 [Online]. Available at http://clic.cses.vt.edu/icomanth/circlet4.pdf (verified 20 Jan. 2005). Virginia Tech Univ., Blacksburg.

Grossman, R.B., D.S. Harms, C.A. Seybold, and J.E. Herrick. 2001. Coupling use-dependent and use-invariant data for soil quality evaluation in the United States. J. Soil Water Conserv. 56:63–68.

Guston, D.H. 1999. Stabilizing the boundary between US politics and science: The role of the Office of Technology Transfer as a boundary organization. Social Stud. Sci. 29(1):87–111.

Hedin, L., O. Chadwick, J. Schimel, and M. Torn. 2002. Linking ecological biology and geoscience: Challenges for terrestrial environmental science [Online]. Available at www.agu.org/sections/biogeo/BioGeoFuture.html (verified 20 Jan. 2005). AGU, Washington, DC.

Herrick, J.E., J.R. Brown, A.J. Tugel, P.L. Shaver, and K.M. Havstad. 2002. Application of soil quality to monitoring and management: Paradigms from rangeland ecology. Agron. J. 94:3–11.

Herrick, J.E., and A.J. Tugel. 2002. Criteria for dynamic soil property selection for soil survey. *In* 2002 Annual meeting abstracts [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

Herrick, J.E., and M.M. Wander. 1998. Relationships between soil organic carbon and soil quality in cropped and rangeland soils: The importance of distribution, composition and soil biological activity. p. 405–425. *In* R. Lal, J.M. Kimble, R.F. Follet, and B.A. Stewart (ed.) Soil processes and the carbon cycle. Advances in Soil Science. CRC Press, Boca Raton, FL.

Hibbard, K.A. 1995. Landscape patterns of carbon and nitrogen dynamics in a subtropical savanna: Observations and models. Ph.D. diss. Texas A&M Univ., College Station.

Hobbie, J.E., S.R. Carpenter, N.B. Grimm, J.R. Gosz, and T.R. Seastedt. 2003. The US Long-Term Ecological Research program. Bioscience 53(1):21–32.

Holling, C.S., and G.K. Meffe. 1996. Command and control and the pathology of natural resource management. Conserv. Biol. 10:328–337.

Indorante, S.J., R.L. McLeese, R.D. Hammer, B.W. Thompson, and D.L. Alexander. 1996. Positioning soil survey for the 21st century. J. Soil Water Conserv. 51:21–28.

Jenny, H. 1941. Factors of soil formation. A system of quantitative pedology. 1st ed. McGraw-Hill Book Co., New York.

Johnston, J.M., and D.A. Crossley, Jr. 2002. Forest ecosystem recovery in the southeast US: Soil ecology as an essential component of ecosystem management. For. Ecol. Manage. 155:187–203.

Kolb, D. 1984. Experiential learning: Experience as the source of learning and development. Prentice Hall, Upper Saddle River, NJ.

Lepretre, A., and S. Martin. 1994. Sampling strategy of soil quality. Analusis Magazine 22(3):40–43.

Lin, H.S. 2003. Hydropedology: Bridging disciplines, scales, and data. Vadose Zone J. 2:1–11.

MacEwan, R.J. 1997. Soil quality indicators: Pedological aspects. p. 143–166. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier, Amsterdam.

Magnuson, J.J. 1990. Long-term ecological research and the invisible present. Bioscience 40:495–501.

McBratney, A.B., B. Minasny, S.R. Cattle, and R.W. Vervoort. 2002. From pedotransfer functions to soil inference systems. Geoderma 109:41–73.

McBratney, A.B., I.O.A. Odeh, T.F.A. Bishop, M.S. Dunbar, and T.M. Shatar. 2000. An overview of pedometric techniques for use in soil survey. Geoderma 97:293–327.

Millar, C.I., and W.B. Woolfenden. 1999. The role of climate change in interpreting historical variability. Ecol. Appl. 9(4):1207–1216.

Muhn, J. 2002. Soil science in the Bureau of Land Management. p. 215–231. *In* R. Amundson et al. (ed.) Factors of soil formation: A fiftieth anniversary retrospective. SSSA Spec. Publ. 33. ASA, CSSA, and SSSA, Madison, WI.

National Research Council. 2003. Neon: Addressing the nation's environmental challenges. Natl. Academy Press, Washington, DC.

Parsons, D.J., T.W. Swetman, and N.L. Christensen. 1999. Uses and limitations of historical variability concepts in managing ecosystems. Ecol. Appl. 9(4):1177–1178.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. 51:1173–1179.

Pickett, S.T.A. 1989. Space-for-time substitution as an alternative to long-term studies. p. 110–135. *In* G.E. Likens (ed.) Long-term studies in ecology: Approaches and alternatives. Springer-Verlag, New York.

Pretty, J., I. Guijt, I. Scoones, and J. Thomson. 1995. Participatory learning and action: A trainer's guide. Int. Inst. for Environ. and Develop., London.

Pyke, D.A., J.E. Herrick, P. Shaver, and M. Pellant. 2002. Rangeland health attributes and indicators for qualitative assessment. J. Range Manage. 55:584–597.

Rasmussen, P.E., and J.L. Albrecht. 1998. Crop management effects on organic carbon in semi-arid Pacific Northwest soils. p. 209–219. *In* R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart (ed.) Management of carbon sequestration in soils. CRC Press, Boca Raton, FL.

Raup, H.M. 1957. Vegetational adjustment to the instability of the site. p. 36–48. *In* Proc. and Papers: 6th Tech. Meet. Int. Union Conserv. Nature Soc. for the Promotion of Nat. Reserves. ICUN, London.

Richter, D.D., Jr., and D. Markewitz. 2001. Understanding soil change: Soil sustainability over millennia, centuries, and decades. Cambridge Univ. Press, Cambridge.

Robarge, W.P., and D.W. Johnson. 1992. The effects of acidic deposition on forested soils. Adv. Agron. 47:2–83.

Scheffer, M., S. Carpenter, J.A. Foley, C. Folke, and B. Walker. 2001. Catastrophic shifts in ecosystems. Nature (London) 413:591–596.

Seybold, C.A., J.E. Herrick, and J.J. Brejda. 1999. Soil resilience: A fundamental component of soil quality. Soil Sci. 164:224–234.

Simonson. 1959. Outline of a generalized theory of soil genesis. Soil Sci. Soc. Am. Proc. 23:152–156.

Smeck, N.E., E.C.A. Runge, and E.E. MacKintosh. 1983. Dynamics and genetic modeling of soil systems. p. 51–81. *In* L.P. Wilding, N.E. Smeck, and G.F. Hall (ed.) Pedogenesis and soil taxonomy. I. Concepts and interactions. Elsevier Science Publ., Amsterdam.

Soil Survey Staff. 1999. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. 2nd ed. USDA Agric. Handb. 436. U.S. Gov. Print. Office, Washington, DC.

Sousa, W.P. 1984. The role of disturbance in natural communities. Annu. Rev. Ecol. Syst. 15:353–391.

Stringham, T.K., W.C. Krueger, and P.L. Shaver. 2001. States, transitions and thresholds: Further refinement for rangeland applications. Agric. Exp. Stn. Special Rep. 1024. Oregon State Univ., Corvallis. Also available online at http://www.glti.nrcs.usda.gov/technical/publications/index.html (verified 4 Mar. 2005).

Stringham, T.K., W.C. Krueger, and P.L. Shaver. 2003. State-and-transition modeling: An ecological process approach. J. Range Manage. 56(2):106–113.

Tinker, P.B. 1994. Monitoring environmental change through networks. p. 407–421. *In* R.A. Leigh and A.E. Johnston (ed.) Long-term experiments in agricultural and ecological sciences. CABI Publ., Wallingford, UK.

Westoby, M., B. Walker, and I. Noy-Meir. 1989. Opportunistic management for rangelands not at equilibrium. J. Range Manage. 42:266–274.

White, P.S. 1979. Pattern, process and natural disturbance in vegetation. Bot. Rev. 45:229–299.

Wilding, L.P., J. Bouma, and D.W. Goss. 1994. Impact of spatial variability on interpretive modeling. p. 61–75. *In* R.B. Bryant and R.W. Arnold (ed.) Quantitative modeling of soil forming processes. SSSA Spec. Publ. 39. ASA, CSSA, and SSSA, Madison, WI.