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Soil quality: an indicator of sustainable land management?

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Abstract

Soil quality appears to be an ideal indicator of sustainable land management. Soil is the foundation for nearly all land uses. Soil quality, by definition, reflects the capacity to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. By reflecting the basic capacity of the soil to function, it integrates across many potential uses. Nonetheless, few land managers have adopted soil quality as an indicator of sustainable land management. There are a number of constraints to adoption. Most could be overcome through a concerted effort by the research community. Specifically, we need to address the following issues: (1) demonstrate causal relationships between soil quality and ecosystem functions, including biodiversity conservation, biomass production and conservation of soil and water resources. True calibration of soil quality requires more than merely comparing values across management systems; (2) increase the power of soil quality indicators to predict response to disturbance. Although there are many indicators that reflect the current capacity of a soil to function, there are few that can predict the capacity of the soil to continue to function under a range of disturbance regimes. Both resistance and resilience need to be considered; (3) Increase accessibility of monitoring systems to land managers. Many existing systems are too complex, too expensive, or both; (4) Integrate soil quality with other biophysical and socio-economic indicators. Effective early-warning monitoring systems will require not just the inclusion of both biophysical and socio-economic indicators, but also the development of models that incorporate feedbacks between soil quality and socio-economic conditions and trends and (5) Place soil quality in a landscape context. Most ecosystem functions depend on connections through time across different parts of the landscape. In conclusion, soil quality is a necessary but not sufficient indicator of sustainable land management. Its value will continue to increase as limitations are diminished through collaboration between scientists, land managers and policymakers. Published by Elsevier Science B.V.

Keywords: Soil quality; Sustainability; Indicators; Landscape; Ecosystem functions

1. Introduction

Soil quality is increasingly proposed as an integrative indicator of environmental quality (National Research Council, 1993; Monreal et al., 1998), food security (Lal, 1999) and economic viability (Hillel, 1991). Therefore, it would appear to be an ideal indicator of sustainable land management. Soil is the foundation for nearly all land uses. It is no coincidence that definitions of soil quality and sustainable agriculture are parallel. The Soil Science Society of America (1997) defined soil quality as, “The capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health”. Another organization has suggested that, “sustainable agriculture should involve the successful management of resources to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources” (Technical Advisory Committee to the CGIAR, 1988).

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By reflecting the basic capacity of the soil to function, soil quality integrates across many potential uses.

Despite its clear utility, soil quality has not been widely adopted as an indicator of sustainable land management. In a recent review of the contribution of soil quality to policy, Jaenicke (1998) concludes that "... Despite these increasingly important potential benefits, soil quality continues to receive surprisingly little attention in policy circles ... Significant gaps still exist in our ability to quantify the soil's physical, chemical and ecological relationships to environmental quality... We need a stronger scientific base before we can design reasonable soil-quality goals and recommend viable farming practices to achieve these goals". Furthermore, soils are almost never directly included in the balance sheets of modern farm operations: they are both figuratively and literally 'below the bottom line'. Although soils are the foundation for production and profit, returns on investment in soil management (except for short-term fertilizer responses) are difficult to quantify and the effects of today's management practices may not appear for decades.

Measurements of soil quality have the potential to reflect the status of soil as an essential resource (Doran and Zeiss, in press). There are at least five limitations which, if addressed, could bridge the gap between this potential and the current reality described by Jaenicke (1998). (1) Causal relationships between soil quality and ecosystem functions, including biodiversity conservation, biomass production, and conservation of soil and water resources are rarely defined or quantified. True calibration of soil quality requires more than merely comparing values across management systems. (2) Most soil quality indicators have limited power to predict soil responses to disturbance. Although there are many indicators that reflect the current capacity of the soil to function, there are few that can predict the capacity of the soil to support a range of disturbance regimes. (3) Land managers frequently find soil quality monitoring to be inaccessible because the measurement systems are too complex, too expensive, or both. (4) Soil quality measurements are generally presented as 'stand-alone' tools. However, in order to be effective, they need to be integrated with other biophysical and socio-economic indicators. (5) Most current soil quality assessments are point-based, yet ecosystems are generally managed at the landscape level.

2. Demonstrate causal relationships to ecosystem functions

Pierce and Lal (1991) state that, "Soil management practices in the 21st century must be formulated based on an understanding of the ecosystem concept". This means that they must also be based on an understanding of how ecosystems function, and how various management practices affect function. This is a serious challenge given the complexity of both natural and managed ecosystems and the fact that our understanding of even the simplest systems is rudimentary at best. Ecosystem functions include but are not limited to primary and secondary production, nutrient recycling, and conservation of soil and water resources. The ecosystem services, on which human life depends, are based on these functions (Daily, 1997).

Although management decisions will always be based on incomplete information, substantial opportunities exist to improve the quality of the information which is used. The challenge for monitoring (evaluation of trend) and assessment (evaluation at a point in time) is more limited in scope, but still quite important. Relationships between some abiotic soil properties and ecosystem functions are reasonably well-established for those functions that are directly related to crop production and soil erosion (e.g. Evans and Loch, 1996; Laflen et al., 1997). For example, infiltration capacity is positively related to the capacity of the soil to supply water to plants and negatively correlated with erosion. More recently, relationships between abiotic properties have been quantified for nutrient and pesticide fate and transport (e.g. Trojan and Linden, 1994).

Most of these relationships, however, are indirect because they are based on laboratory measurements, which leaves the simple field measurements commonly used in soil quality evaluations with little support. This problem is compounded by the fact that many coarse-scale efforts to validate indicators, such as EPA's Environmental Monitoring and Assessment Project (EMAP) (Hunsaker and Carpenter, 1990), have attempted to calibrate indicators by comparing the values of the indicators for land under different

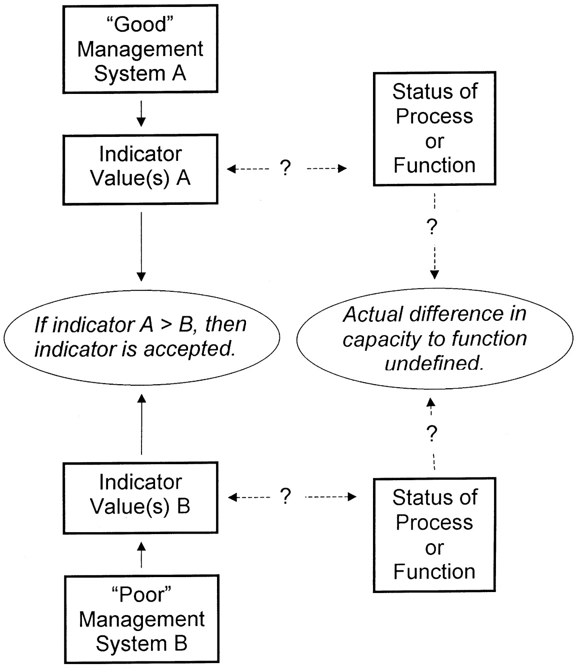

Fig. 1. Common approach to calibration of soil quality indicators in which the traditional use of measurements to compare management systems is simply reversed, which leaves the relationship of the indicators to actual functions unquantified.

types of management (Fig. 1). If the indicators are significantly different among management systems, then they are often accepted. If the indicators are not significantly different, then they are rejected. This is a rather circular approach, particularly as the ultimate objective is often to determine how various management systems are affecting soil quality. If we rely only on this criteria, we will simply codify existing beliefs about which management systems are superior. The comparison between no-till and cultivated systems provides a good illustration of this risk: although no-till is generally accepted as superior overall because it increases the capacity of the land to resist erosion, it may actually increase groundwater contamination due to increased use of herbicides and increased macropore continuity and stability (Trojan and Linden, 1994). We also risk losing the potential to identify those properties that could serve as early warning indicators of change in the capacity of a system to function because these properties, by definition, tend to vary in patterns unlike those of more standard indicators and are therefore at risk of being discarded as outliers. For example, an increase in carbon inputs generally results in important increases in soil microbial biomass and some of the more labile soil organic matter fractions (Herrick and Wander, 1998). These changes are eventually followed by an increase in soil organic matter, infiltration capacity and nutrient availability (Monreal et al., 1998). Initially, however, changes in these early warning indicators are not well correlated with differences in the standard indicators due to the time lag involved. Another problem is that soil quality researchers often completely ignore relationships to many ecosystem functions, including biodiversity conservation. Although the environmental community generally recognizes that water quality frequently depends on soil quality, few people concerned with the environment are aware of the role that soils play in maintaining diverse, resilient plant and animal communities (Hillel, 1991).

The alternative to traditional approaches to calibration and testing does not necessarily involve spending more research dollars to set up new experiments. There are numerous existing long-term experiments on which soil processes and functions are already being monitored (Rasmussen et al., 1998). These experiments, including instrumented watersheds, rainfall simulator trials and chemical fate and transport studies, could be exploited by simply adding soil quality measurements to the protocols, yielding causal relationships between, for example, soil quality indicators and the ecosystem functions of conservation of soil and water resources.

3. Increase power to predict response to disturbance

Although there are many indicators that reflect the current capacity of the soil to function, there are few that can predict whether or not the soil will maintain this capacity following disturbance. The capacity of a soil to continue to support the same potential range of uses in the future that it supports today depends on both its resistance to degradation and on its resilience, or potential to recover following degradation (Fig. 2). Resistance is defined as the capacity of a system to continue to function without change through a disturbance (Pimm, 1984). Resistance is generally a

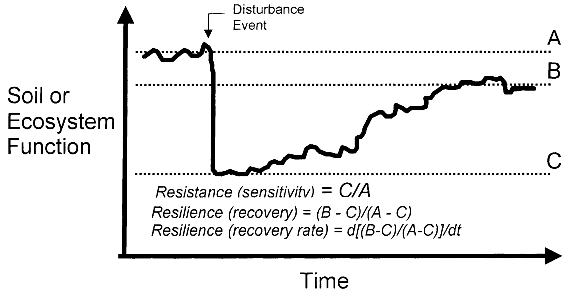

Fig. 2. Graphical and mathematical description of resistance and resilience (modified from Herrick and Wander, 1998).

function of soil properties. These properties can often be measured directly. An example of an indicator of resistance to compaction is soil bulk density, which is related to soil strength which, in turn, is inversely related to susceptibility to compaction. Resilience is the recovery of the functional integrity of a system following a disturbance (Pimm, 1984) or catastrophic disturbance (Holling and Meffe, 1996) relative to its original state. Although resistance can be defined in terms of soil properties, resilience is more often a function of soil processes, including processes that may not be detectable or even present until after degradation has occurred. Soil processes, such as decomposition, mineralization, and macropore formation are difficult and costly to measure. However, the properties on which these processes depend can often be quantified more cheaply and easily. For example, in many systems, recovery following compaction is related to earthworm density and species composition (Edwards and Bohlen, 1996).

There is a large body of literature linking soil properties to processes (e.g. Edwards and Bohlen, 1996 and papers in Lal et al., 1998). Studies in soil biology and soil ecology, in particular, are frequently designed to better understand the role of one or more organisms in a particular soil. These studies represent a highly useful resource, but few can be applied directly to evaluations of soil quality. The question of which organism most consistently reflects the long-term potential of the soil to resist or recover from disturbance is rarely addressed as a primary objective. Studies are needed that clearly define the linkages between organisms, processes, ecosystem properties and ecosystem functions. Unfortunately, even these types of studies would not be sufficient to support monitoring programs based on soil biota. Few soil-dwelling organisms, with the exception of macroinvertebrates such as earthworms (Edwards and Bohlen, 1996) and termites (Taylor et al., 1998), can be even approximately quantified in the field, and sample transport and processing costs exceed most monitoring budgets (see Section 4). In order to make studies in soil ecology relevant to monitoring for management, the strength and consistency of the linkages illustrated in Fig. 3 need to be clearly defined so that more accessible indicators can be related to ecological processes.

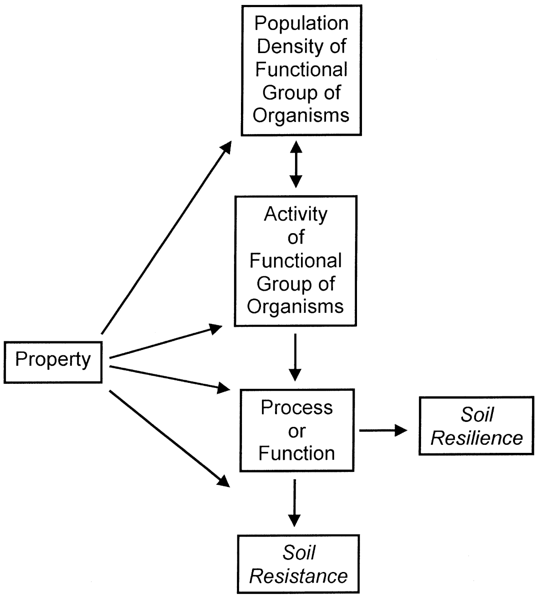

Fig. 3. Possible relationships between measurable soil properties, soil processes or functions, and soil resistance and resilience. In order to be effective, the full set of linkages needs to be described and quantified for each indicator.

4. Increase accessibility to land managers

The adoption of soil quality as an indicator of sustainable land management by land managers themselves has been hindered by a number of factors including the inherent complexity of the relationships between measurements, indicators and functions, the tendency of scientists to emphasize that complexity, and the costs of measurement and interpretation. There are at least four constraints that must be overcome to facilitate adoption: (1) make relationships between soil

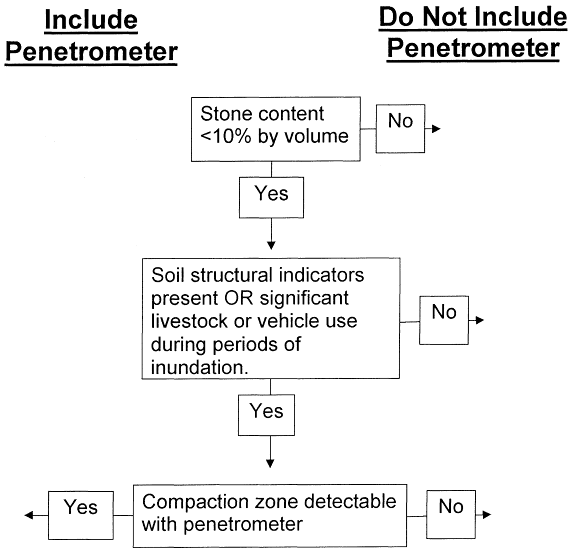

Fig. 4. Example of a decision tree for inclusion of an impact penetrometer in a rangeland monitoring program based on site conditions. This decision tree is used together with others that incorporate information on objectives, accuracy and precision requirements and resource availability.

quality and ecosystem functions (especially short- and long-term productivity) explicit; (2) reduce measurement cost; (3) increase measurement simplicity, and (4) minimize time delay between sampling or measurement and receipt of results. The first issue was discussed above. Measurement cost can often be reduced and simplicity increased through the use of decision trees of two types: those that help identify parameters that are important to measure for a particular system (Fig. 4), and those that help select the measurement tools based on assessment or monitoring objectives, accuracy and precision requirements for the data, and availability of financial resources and technical expertise.

The time delay between sampling and reporting results can be reduced from weeks or months for laboratory analyses to minutes or hours through the use of a combination of field-based qualitative observations and quantitative or semi-quantitative measurements, for example. Substantial progress has been made in the development and application of qualitative indicators in the United States Department of Agriculture Natural Resource Conservation Service (USDA–NRCS) soil health scorecard program (NRCS, 1999, based on Romig et al., 1996). The scorecard is a rapid, flexible system designed with farmer input that generates easily interpretable results in the time that it takes to walk through a field and dig a few holes. The NRCS and Bureau of Land Management (BLM), working in collaboration with the USDA-ARS (Agricultural Research Service) and other organizations, have developed a similar qualitative system which can be used to evaluate rangeland health (Shaver et al., 2000). This system includes a combination of soil surface and vegetation indicators. More quantitative, but still field-based, systems are being developed for both soil quality (USDA, 1998) and rangeland health (de Soyza et al., 1997).

5. Integrate with other biophysical and socio-economic indicators

The power of soil quality as a tool for land managers can be dramatically increased through integration with at least three other groups of indicators: use-invariant soil properties, non-soil biotic and abiotic indicators, and socio-economic indicators. Use-invariant soil properties include texture, mineralogy, soil depth and other properties that are relatively unresponsive to management. These soil properties reflect the potential of the soil to function. Dynamic indicators of soil quality that change in response to management are rarely interpretable without reference information on these more static or inherent soil properties. These inherent properties are used to establish appropriate ranges for each dynamic indicator. They can also be used to help understand why some indicators may change relatively rapidly whereas others tend to lag in some soils, but not others. For example, soil texture and mineralogy are closely related to susceptibility to crusting. In reality, there is a continuum between dynamic properties that change soil quality and inherent properties that reflect the potential of the system to function. An explicit understanding of where each property falls along this continuum is invaluable in developing cost-effective monitoring programs because use-invariant properties are only measured once, while the most dynamic properties are generally measured most frequently. Most monitoring programs ignore these relationships and, as a result, either measure relatively non-dynamic properties too frequently or measure dynamic properties (such as soil respiration) too infrequently.

The second group of complementary indicators includes non-soil biotic and abiotic processes and properties. Climate, vegetation, animal species which spend most of their lives above-ground, and micro-, meso- and macrotopography both affect and are affected by soil quality. From a soil-based perspective, many could be characterized as components of, or at least indicators of, soil quality. However, from the perspective of the general public that usually finds it easier to visualize above-ground patterns and processes than those that occur below ground, it makes more sense to incorporate most of these as complementary indicators. These attributes, like soil properties, can be placed along a continuum from those that are relatively insensitive to management practices to those that are highly sensitive. A generally parallel, but not necessarily congruent, continuum ranges in temporal scale from those attributes that change over near-geologic time, such as macrotopography, to those that change in response to events lasting only a few hours, such as cover of annual plants. These plants change in response to precipitation lasting several hours or less.

In perennial systems, including forests and many rangelands, it is essential to consider the vegetation together with the soil (Herrick and Whitford, 1995). Resistance and resilience, in particular, depend on dynamic inter-relationships between plants and soil, and on interactions between above- and below-ground vegetative structures (Seybold et al., 1999). One of the most straightforward examples is the relationship between soil erodibility, plant canopy cover, and rainfall erosivity. Soils with higher canopy cover are able to resist degradation by more erosive storms, even if soil structure is constant. Canopy cover also provides an indication of root and litter inputs of organic matter that contribute to the resilience of soil structure following degradation.

In addition to serving as a complementary indicator, vegetation measurements can be used to improve the both the precision and predictive value of soil indicators while reducing the number of samples needed by using vegetative cover to stratify soil samples. To stratify soil samples, simply group them according to the type of plant which covers the soil surface at the sampling point. Stratification by plant functional groups frequently yields increases in sampling efficiency, and the ratios of values from under and between vegetation can yield valuable insights into the functioning of the system (Herrick and Whitford, 1995). Plant functional groups may be defined relative to a number of characteristics, including above-and below-ground morphology, water use efficiency, palatability and phenology. Furthermore, in both degrading and recovering systems, the soil beneath one or more species of plants may serve as valuable internal references. At one gravelly fan site in south central New Mexico soil stability test values in bare areas were less than 60% of those measured under grass canopies (Table 1).

Table 1
Soil stability test values under grass and in bare areas (range=one to six where six is most stable) for control and plots disturbed by horse trampling[a]

Strata	Mean test value	S.E.	*N*
Control			
Bare	2.63	0.20	92
Grass	4.53	0.44	17
Bare/grass	0.58		
Disturbed			
Bare	2.34	0.21	76
Grass	4.38	0.37	29
Bare/grass	0.53		

[a] Soil is a gravelly sandy loam and samples were removed from the top 5 mm only. Bare/grass based on ratio of means.

Socio-economic indicators make up the third group of complementary parameters. This group includes both the most and least valuable indicators of changes in the capacity of the soil to function. Valuable socio-economic indicators predict changes in disturbance regimes (including inputs), whereas many others simply reflect degradation which may have occurred months, years, decades or centuries ago in the past. Increases in human immigration and road construction, changes in land ownership or increases in land values, and national or international social, political and economic turmoil can all be used to effectively predict changes in disturbance regimes. This information, together with knowledge of the relative resistance and resilience of the soils in the region likely to be affected, can be used not only to predict changes in soil quality, but also to guide decision makers in establishing policies which promote increases in utilization of those soils which have higher resistance and resilience, while limiting these increases on more fragile soils. This kind of analysis is not new:

it has been applied (with varying degrees of success) to local, regional and national land-use planning in a number of countries around the world (World Resources Institute, 1992). Traditionally, however, the emphasis has been on inherent soil properties such as texture and depth, rather than on more biological properties which often are more sensitive and better reflect recovery potential.

Socio-economic indicators that are generally less useful include rural emigration and reductions in land value. By the time human emigration due to land degradation begins to occur, soil quality has generally been reduced to a level at which management intervention is unlikely to be effective in the short-term. Notwithstanding this limitation, emigration patterns can be a good indicator of potential long-term improvements in soil quality. Case studies that illustrate this point include the evolution of Appalachian Mountain landscapes as farms and logging operations were abandoned during the last century (McKibben, 1995) and changes in the utilization of forests under the Tokugawa period (1600–1867) in Japan (Totman, 1989). In both cases, a reduction in utilization was correlated with emigration from a region. Management system surveys make up another class of socio-economic indicators. Management-based indicators, such as tillage system, can be both efficient and cost-effective. However, overreliance on these indicators comes with large risks because they simply predict changes based on empirical relationships and, by definition, do not reflect actual changes in soil properties. The effects of ‘best management practices’ (BMPs) on soil quality have been established for very few soils in only a few climates (e.g. Reeves, 1997). One risk is that these relationships will be extrapolated to conditions in which they are not applicable, yielding inaccurate predictions of soil quality. A much more serious risk is that innovation and flexible, adaptive management may be discouraged if land managers are rewarded (through government programs or special marketing) based solely on their adoption of favored technologies.

Much of the progress in incorporating diverse biophysical and socio-economic indicators into assessment and monitoring programs has been in the tropics. Gomez et al. (1996) include a suite of socio-economic indicators in their system for evaluating sustainability in the Philippines, while Lal (1994) included micro- and meso-climate indicators in his volume listing methods for assessing sustainable use of soil and water resources in the tropics. One of the key objectives of SANREM, a large multi-country research and development project funded by the US Agency for International Development, is to apply biophysical and socio-economic indicators together to guide sustainable land management. Although some attempts have been made to develop similar approaches in North America and Europe (Monreal et al., 1998), these efforts have been constrained by a research infrastructure that rarely rewards the kinds of creative approaches necessary to cross disciplinary boundaries and directly address interactions between science, management and policy (Barrett et al., 1998). These and other projects suggest that effective early-warning monitoring systems will require not just the inclusion of both biophysical and socio-economic indicators, but also the development of models that incorporate feedbacks between soil quality and socio-economic conditions and trends.

6. Place in a landscape context

Most ecosystem functions depend on connections through time across different parts of the landscape. These connections are rarely considered in soil quality evaluations which tend to focus on point measurements. Although it is generally not possible to quantify these connections directly, an understanding of them can often be used to improve the value of soil quality interpretations. Furthermore, a landscape-level approach to sampling can improve sampling efficiency through statistically stratified sampling regimes, and thereby reduce costs. The decision of where to sample is often as important as the decision of when to sample. Sampling point location depends on specific monitoring objectives. In monitoring for management, sample points might be targeted to areas that are near-threshold or highly susceptible to degradation or recovery, ignoring those areas that are unlikely to change. Where a more general evaluation of soil quality is desired, stratification by land unit can increase sampling efficiency.

Connections between different parts of the landscape can often serve as early warning indicators. For example, increased runoff from higher areas results in water supplementation at lower points. Wetting front depths and soil surface water flow patterns can serve as useful indicators of water redistribution. At larger scales, stream hydrographs can be used to evaluate the overall health of the system (Rosgen, 1996).

7. Conclusions

In spite of the clear advantages of using soil quality as an indicator of sustainable land management, it has not been widely adopted. There are a number of limitations to adoption. Most could be overcome through a concerted effort by the research community and more conscious coordination between basic process-level research, projects designed to develop and apply soil quality management systems, and the potential users of those systems. In conclusion, soil quality is a necessary but not sufficient indicator of sustainable land management.

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