# ENVIRONMENTAL SOIL MANAGEMENT

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## Contents

## Summary

Environmental soil management is fundamental to the sustainability of diverse rangeland ecosystems. Key concepts necessary for rangeland soil management include dynamic and static soil properties, resilience to both anthropogenic and natural (including climate change and extreme events) stressors, soil-plant-animal feedbacks and management at multiple scales, many of which are not correlated with existing management units. Rangeland soils can be managed to support a broad range of

ecosystem services, including forage production, wildlife habitat, biodiversity conservation, water quantity and quality, air quality and carbon sequestration. In some cases, managing for one service can be used to simultaneously enhance other services. Environmental soil degradation is caused by both mismanagement associated with overgrazing, and by land conversion to other uses, including crop production, urbanization and energy development. Rangeland remediation usually focuses on the plant community and few resources are usually available to directly improve soil quality, but integrated approaches to soil and vegetation management can be successful. Soil management is more likely to be addressed if soils are included in assessment and monitoring programs. Finally, a system is introduced to help determine when environmental soil management should be the focus of sustainable development projects, and when resources are better allocated to address other issues.

Rangeland soil management is both challenging and fascinating in large part because of the complex and frequently unpredictable nature of soil-plant animal feedbacks. A change in one of the three components invariably has effects on the other two. Where these effects trigger positive feedbacks, dramatic changes in soils, vegetation and the capacity to support ecosystem services can occur. These feedbacks may be exacerbated or disrupted by extreme and unpredictable climatic events, particularly those associated with spatial and temporal rainfall patterns. The result is to make the feedbacks more sporadic or discontinuous.

The objective of this chapter is to provide an overview of environmental soil management, emphasizing aspects that are unique to rangeland management. The chapter begins with a review of key concepts and includes provides a brief overview of ecosystem services supported by rangeland soils. The causes and consequences of rangeland degradation, and potential remediation strategies are addressed throughout the chapter, and more specifically in separate sections. Because soils are frequently omitted from discussions of rangeland monitoring and assessment, the chapter includes a discussion of these issues, and concludes with a brief discussion of how an integrated analysis can be used to determine when a focus on rangeland soil management is justified in the context of other potentially critical factors limiting the sustainability of rangeland ecosystems.

## 1. Introduction

Rangeland soils are the foundation for plant production, which serves as livestock forage, wildlife habitat and a reservoir of biodiversity. Soils capture, store and filter water. They recycle nutrients, have the potential to sequester large amounts of atmospheric carbon, and wind erosion can affect air quality in regions thousands of kilometers downwind. Because rangelands cover such a large proportion of the earth's surface, changes in rangeland soil management can have dramatic effects on these and other ecosystem services.

Rangeland soil management is based on the same fundamental principles of soil science as cropland management because the same basic processes govern the movement and availability of water, air and nutrients in the soil. The general causes and consequences of rangeland soil degradation are also quite similar. For example, increased soil compaction and soil structure degradation by both livestock trampling and tillage increases runoff and erosion.

While the basic processes are similar, environmental soil management on rangelands is much more diverse than on croplands for three reasons. The first is that rangeland soils themselves are much more diverse. Rangelands occur on virtually all types of soil because nearly all plant communities can be converted to rangelands, while croplands can only occur where soils, climate and topography are suitable for crop production. This usually limits crop production to relatively flat, well-drained soils in tropical and temperate regions with a reasonably long growing season. In contrast, rangelands can occur north of the Arctic Circle, and on soils that are too steep or rocky to operate machinery. Because of the wide adaptation of rangeland vegetation, rangelands can also occur on soils that are too poorly drained, arid, acidic, or saline to support crops. While most rangeland plants cannot be used directly by humans, animal production (from both livestock and wildlife) is possible. Animals convert plants that are indigestible by humans into fats and protein.

The second reason that environmental soil management is more diverse on rangelands than croplands is that the economic value of ecosystem services (including food production) supported by rangelands is extremely variable. Economic production ranges from nearly zero in hyper-arid rangeland ecosystems like the Atacama Desert to levels similar to those supported by croplands in areas where intensive livestock production systems are used, and where multiple ecosystem services can be marketed from the same piece of land. Where economic production on a per area basis is very low, soils can only be managed indirectly through manipulation of plant and animal populations. Where it is high, more traditional agronomic practices, such as tillage, liming and fertilization can often be applied.

The third reason is the diversity of the production system itself on many rangelands. While rangeland managers often lack the financial resources necessary for mechanized approaches to soil management, they frequently have diverse plant communities including species with unique soil-building, and soil-protecting attributes. These include dense foliage near the soil surface, deep taproots that can ‘mine’ nutrients and water from depths of over ten meters and fibrous, shallow root systems

Where it is too dry or soils are too shallow for 100% coverage of the soil surface by vascular plants, microbiotic crusts consisting of mosses, lichens and cyanobacteria protect the soil surface, improve soil structure, and can even increase plant nutrient availability by trapping dust and fixing atmospheric nitrogen, converting it into a form that can be used by plants.

Rangeland managers can exploit this diversity to indirectly improve soil quality by carefully managing livestock numbers and distribution at different times of the year. This increases some types of plants at the expense of others. Different breeds of livestock can also be used independently or in combination to affect plant community composition. Where financial resources permit, additional soil-building plant species can be introduced to degraded plant communities by ground or aerial seeding, and undesirable species can be removed through herbicides, mechanical control and biological control agents, such as the saltcedar leaf beetle, (*Diorhabda elongata* (Coleoptera: Chrysomelidae)), which is being used to control saltcedar in rangeland riparian ecosystems. Ironically, it is exactly the diversity of rangeland vegetation that progressive agronomists are attempting to artificially introduce into croplands in order to improve soil quality at low cost.

Another important distinction between many cropland and rangeland soils is the frequency with which the soils are mixed or inverted by tillage. Most soils supporting crop production are tilled at least occasionally to temporarily increase aeration, improve seed contact, kill weeds, or incorporate crop residues. Even many crop production systems that are described as ‘minimum tillage’ or ‘no-tillage’ do include some disturbance to the soil surface during planting and harvest. Consequently, measurements of soil samples from the top 5-20 cm of soil are usually used to reflect soil surface conditions. In contrast, the surface of most rangeland soils is relatively stable over time, allowing strongly developed horizons of just a few millimeters to develop (Figure 1). The properties of these horizons can be extremely different, requiring these thin surface horizons to be carefully sampled, or near-surface properties to be measured directly measured in the field. Methods that require disturbance of the soil surface, such as some infiltrometers, are generally inappropriate for rangeland soils for this reason.

Figure 1. Soil horizonation in the surface of a sandy rangeland soil showing large differences in soil structure and organic matter content in the top several millimeters associated with microbiotic crust development.

The objective of this chapter is to provide an overview of environmental soil management, emphasizing aspects that are unique to rangeland management. For additional information on soil management, please see EOLSS chapters in the “Land Use, Land Cover and Soil Sciences” section. The chapter begins with a review of key concepts and includes provides a brief overview of ecosystem services supported by rangeland soils. The causes and consequences of rangeland degradation, and potential remediation strategies are addressed throughout the chapter, and more specifically in separate sections. Because soils are frequently omitted from discussions of rangeland monitoring and assessment, the chapter includes a discussion of these issues, and concludes with a brief discussion of how an integrated analysis can be used to determine when a focus on rangeland soil management is justified in the context of other potentially critical factors limiting the sustainability of rangeland ecosystems.

## 2. Key Concepts

This section provides a brief introduction to key concepts necessary to understand rangeland environmental soil management.

### 2.1. Relatively Static vs. Dynamic Soil Properties

Some soil properties are relatively stable, while others can change quickly in response to weather, natural disturbances or management. Relatively stable or static properties include mineralogy (including degree of weathering of clay minerals), depth, texture and rock content. Relatively dynamic properties include organic carbon content, bulk density, aggregate stability and nutrient availability. Even relatively static properties change over time, and all can change rapidly in response to particular disturbances. Soil surface texture normally changes very slowly. Weathering of soil minerals tends to increase the clay content of soils over long periods of time, and many clay particles in the topsoil move slowly to the subsoil, creating increases in clay content with depth. A fire on rangelands can expose soils to catastrophic erosion events, exposing a finer (or coarser) textured soil horizon below, and dramatically changing a number of other relatively ‘static’ soil properties at the soil surface, in addition to texture. Similarly, a livestock track cutting through a relatively stable surface can expose a sub-surface soil horizon that is more dispersive, leading to gully formation.

Where a particular property falls along the static-dynamic continuum varies depending on the soil, the disturbance regime, and how the property is defined. Soil carbon is one of the most commonly measured dynamic soil properties. Total soil carbon includes both inorganic (carbonates) and organic carbon. Inorganic carbon content is itself a relatively static property. It is much higher than organic carbon content in many rangeland soils, and particularly those derived from limestone. Consequently, large changes in organic carbon have little effect on total carbon. Even total organic carbon changes relatively slowly (on the order of centuries), except when a significant land use change occurs, such as the conversion of rangeland to cropland, when it can decline by over 50% in just 10 years. Instead, many scientists prefer to use components or fractions of the total carbon pool that are the most dynamic. This includes recently decomposed plant litter and roots, root exudates, and the living and decomposed bodies of soil organisms including bacteria and fungi. Eventually, a small part of each of these fractions is converted to a more recalcitrant soil organic matter component, such as the humic acids. Humic acids can have turnover rates of hundreds of years or more, changing more slowly than even some properties that are considered to be relatively ‘static’. Soil water content and the amount of the soil water that is available to plants are two of the most dynamic, and important, soil properties.

It is important to distinguish between relatively static versus dynamic properties because each affects management decisions in different ways. The static properties determine the long-term potential of the soil, and ultimately determine the limits of a soil to support different types and amounts of plant production, to capture water from intense storms, and to serve as wildlife habitat. A shallow, coarse-textured soil cannot store as much water as a fine-textured soil, nor can it be used by ground-dwelling animals, such as prairie dogs and many reptiles, that must create deep, stable burrows to escape predators and temperature extremes on the soil surface. The potential range of infiltration rates for most fine-textured soils is very wide. When degraded, water moves into these soils at a rate of less than 1mm per hour, while infiltration rates of over 100 mm per hour are possible on well-structured sandy clay loam rangeland soils. Some static soil properties, such as the quantities of minerals that shrink and swell in response to changes in moisture content, can also change the potential temporal dynamics of soils. High shrink-swell soils, such as Vertisols have very high infiltration rates only when dry due to the development of large cracks that close when the soils are saturated.

Soil maps are based primarily on relatively static properties. Because static soil properties often vary in consistent patterns across rangeland landscapes, they can often be predicted based on easily observable geomorphic features, even where a soil map is not available. These properties repeat in consistent patterns because they depend on soil parent material (geology), landscape position, climate and the amount of time that the soil has been exposed at the land surface.

Dynamic soil properties are used to assess the current status of soil relative to its potential, and to monitor changes over time. Static and dynamic soil properties, together with topography, climate and current plant community composition, are used to determine the current suitability of a soil for particular land uses, and its potential responsiveness to particular management actions.

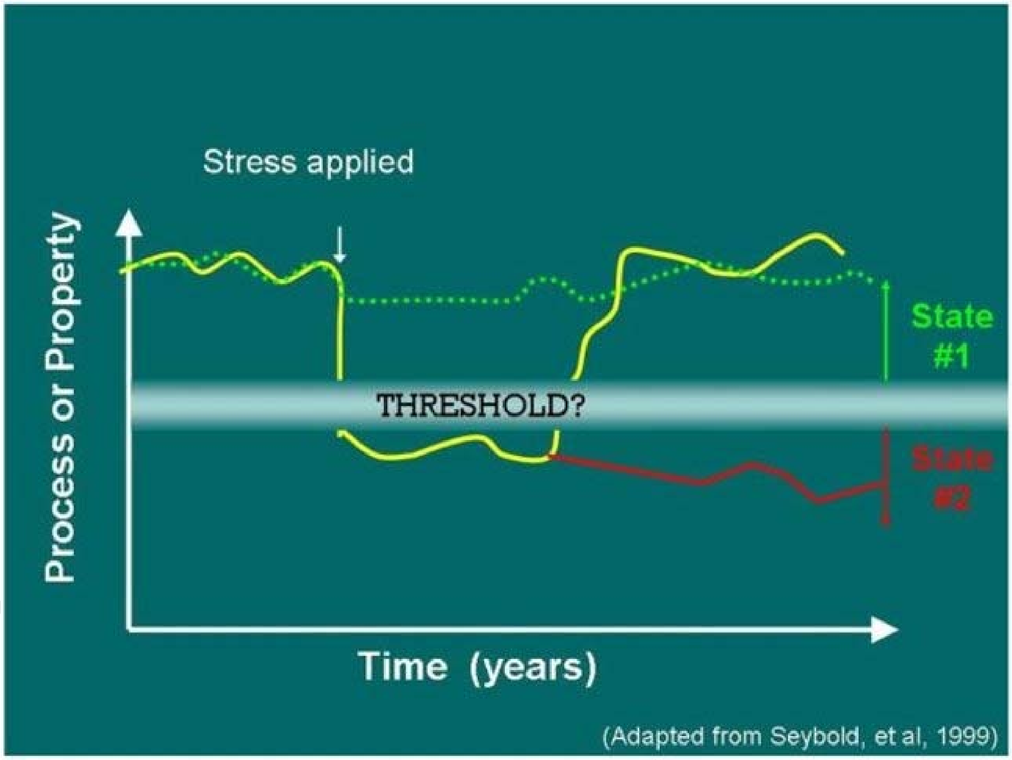
## 2.2. Resilience

Resilience is possibly the most important concept associated with environmental soil management in rangelands because it defines the capacity of the soil to remain in its current state. In other words, resilience is the soil’s capacity to resist degradation, or to rapidly recover without external inputs. While resilience is important for cropland soils, it is even more important for rangeland soils because sufficient external inputs to promote recovery of a non-resilient soil are rarely available.

Resilience is generally defined with respect to a particular type of disturbance that has the potential to degrade the soil. Not all disturbances are negative, of course. For example, a root growing through the soil disturbs soil particles, helping to create soil structure. The hoofprint of a sheep can simultaneously negatively affect the soil by compacting it, and positively affect it by temporarily increasing microtopography, which can help trap water and litter moving across the soil surface.

When the concept of ecological resilience is applied to soil management, it is commonly separated into two components: resistance and recoverability. Resistance is the capacity of the soil to remain in its current status. Recoverability is its capacity to recover its capacity to function at a particular level within a specified period of time, or the recovery rate (Figure 2).

Both resistance and recoverability depend on static soil properties, the status of dynamic soil properties when the disturbances occur, and the type, timing, frequency, duration and intensity of the disturbances. Rangeland soils with the greatest resistance to change tend to be those that are the most degraded because they cannot get any worse. Undegraded soils with high levels of biological activity are often the most resilient because the biological systems necessary to repair damage caused by the disturbance are already in place. Recovery from compacting disturbances also depends on the frequency of wetting and drying cycles, soil mineralogy, and the frequency and timing of freezing events. Soils with frequent wetting and drying cycles and clay minerals with high shrink-swell capacity, or that are wet during periods that the soil freezes tend to recover more quickly from compaction.



(Adapted from Seybold, et al, 1999)

Figure 2. Resilient systems are those that do not cross a threshold in response to stress. The solid, yellow line is resilient because it has high recoverability. The dotted green line is resilient because it has high resistance.

### 2.3. Soil Chemical Properties

The soil chemical properties that are most often considered in rangeland management are those that affect soil fertility. Soil acidity (pH), and salinity, or the concentration of salts in the soil solution, are two properties that tend to limit the plant species that can occur on a particular soil because they either directly or indirectly affect the availability of plant nutrients and the ability of plants to access these nutrients. Extremely saline soils can also limit water uptake by plants because they increase the osmotic potential of the water. The number of species that can be established on saline soils is generally less than those that can be established on non-saline soils. Saline soils with a high proportion of sodium in the soil, referred to as saline-sodic soils, have even more unique plant communities dominated by halophytes, or salt-loving plants.

Plant production on many soils in the tropics is limited by soil acidity. Highly acid soils reduce the availability of many plant nutrients. This problem is compounded in acid soils with high concentrations of iron and aluminum oxides. These soils occur on older land surfaces in many parts of the tropics. They ‘fix’ phosphorous, sequestering it within the amorphous mineral structure of the clays and making it virtually inaccessible to plants. Because relatively high levels of phosphorous are necessary for biological nitrogen fixation, these soils tend to have few legumes in the plant community and are therefore both nitrogen and phosphorous limited. Furthermore, the plants that do occur often survive because they need less phosphorous to survive, which means they have less phosphorous in their tissues. Supplemental phosphorous must often be provided to livestock to address mineral deficiencies resulting from consumption of forage grown on low-phosphorous soils. Similar conditions can occur on alkaline soils, where phosphorous is bound to calcium forming the mineral calcium phosphate.

Both pH and salinity are considered to be relatively static on rangelands because of the high cost of modifying them. Low pH can be modified through applications of lime, and salinity at the soil surface can be reduced by either increasing the infiltration of non-saline water, or lowering the water table if the source of the salts is saline groundwater. These options are rarely economically viable, with some significant exceptions such as parts of the southeastern United States. A more common approach in areas where livestock production is the primary economic activity is to breed palatable plant varieties that are more tolerant of these conditions.

A third property, redox potential, is important in soils that are seasonally inundated with water because it reflects the availability of oxygen to plant roots. Redox potential also affects the form of many plant nutrients, which can change their availability to plants. In intensive rangeland production systems or where runoff has the potential to negatively affect water quality, soil tests and plant tests for specific nutrients may be advisable. These tests are rarely justified in extensive systems were there is little potential to substantially modify nutrient availability.

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## Biographical Sketch

**Jeff Herrick** is soil scientist with the Jornada Experimental Range, a research unit of the USDA-ARS (United States Department of Agriculture, Agricultural Research Service) in Las Cruces, New Mexico, USA. His research program includes work on the factors controlling resilience at multiple scales in arid and semi-arid ecosystems, as well as applied work on rangeland restoration, assessment and monitoring. He is a co-principal investigator on the Jornada LTER (Long-Term Ecological Research) project and leads a number of efforts designed to increase the ability of society to predict and monitor the effects of multiple stressors on ecosystem health and services. Collaborators include scientists and land managers from throughout the United States as well as Asia, Africa, Europe and Latin America.