THE STATE AND FUTURE OF U.S. SOILS

Framework for a Federal Strategic Plan for Soil Science

PRODUCT OF THE
Subcommittee on Ecological Systems,
Committee on Environment, Natural Resources, and Sustainability
OF THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

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About the Soil Science Interagency Working Group (SSIWG)

The purpose of the SSIWG is to develop a Federal Strategic Plan to establish soil research priorities, ensure availability of tools and information for improved soil management and stewardship, deliver key information to help land managers implement soil conserving systems, and inform related policy coordination and development. The SSIWG also strives to enhance the Federal R&D enterprise by embracing diversity, recognizing that the inclusion of a broad range of backgrounds and perspectives is critical to achieving robust intellectual dialogue.

About this Document

This Framework provides recommendations for improving the coordination of soil science research and the development, implementation, and evaluation of soil conservation and management practices among Federal agencies and between Federal agencies and non-Federal domestic and international soil science efforts. The document identifies the current needs and gaps in soil science and in protecting soil ecosystem services, and recommends priorities for future research initiatives.

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Executive Summary

Soil is essential to human life. Not only is it vital for providing most of the world's food, it plays a critical role in ensuring water quality and availability; supports a vast array of non-food products and benefits, including mitigation of climate change; and affects biodiversity important for ecological resilience. These roles make soil essential to modern life. Thus, it is imperative that everyone—city dwellers, farmers and ranchers, land owners, and rural citizens alike—take responsibility for caring for and investing in our soils. Given their importance, soil must be protected from degradation, as the alternative is the loss of an array of important ecosystem services. The Soil Science Interagency Working Group (SSIWG) was established to support interagency coordination of research activities and ensure the long-term sustainable use of soil resources.

VISION

A future in which the Nation manages its soils to support healthy ecosystems, vibrant communities, and a secure world.

MISSION

The establishment of a whole-of-government approach for interagency coordination and collaboration on soil research, conservation, and restoration priorities.

Enhanced coordination will ensure tools and information for improved soil management and stewardship are made available, and help land managers implement soil-conservation practices to maintain, enhance, or restore this nonrenewable resource. A collaborative, whole-of-government approach will help inform related policy development and coordination related to soil research and conservation.

This Framework organizes the key threats to U.S. soil resources into three broad categories:

- **Land-Use and Land-Cover Change**, including expansion of urban and industrial land and infrastructure at the expense of productive lands; management of resource extraction sites; expansion of cropland into vulnerable areas such as wetlands; and inappropriate land-use intensification.
- **Unsustainable Land Management Practices**, including insufficient soil surface cover, excessive application or poor management of nutrients and pesticide, poor water management, agricultural and forestry practices that excessively disturb the soil, and other practices that may degrade soil.
- **Climate and Environmental Change**, including potential effects of changes in temperature and precipitation patterns on erosion rates and degradation of soil organic matter, potential feedback mechanisms from release of greenhouse gases caused by different forms of soil degradation (such as the drainage of wetland soils), opportunities for terrestrial carbon

sequestration, effects of atmospheric deposition on forest soils, and changes in invasive species distribution.

To address these challenges, the SSIWG makes five recommendations for future cross-agency science and technology priorities:

1. **Support applied social-science research in soil sciences and enhance public awareness of soils**, including developing incentives for implementing sustainable soil-management strategies, growing citizen-science networks, educating potential scientists on the role and importance of soils in human society, and engaging academics in a wide range of disciplines.
2. **Advance the national research infrastructure for soil-data storage, analysis, and sharing**, including standardizing methods for obtaining data, storing large volumes of data, developing more sophisticated predictive models, and working with land managers to expand research opportunities.
3. **Support a coordinated research effort on the interactions between soils and the global climate**, including better understanding soil-atmosphere carbon exchanges, improving the resolution of climate models in their interpretation of soils, and studying the effects of temperature and precipitation changes on soil properties.
4. **Support the expansion of, and increased investment in, long-term research programs and collaborations to better understand, document, and manage the effects of land-use and land-cover change on soils**, including expanding existing Federal research networks and long-term studies to include more soil properties and a wider diversity of land use and land cover types, strengthening long-term research partnerships with land managers, and exploring opportunities for developing landscape-scale resilience to environmental change.
5. **Prioritize programs and technical assistance designed to promote sustainable land-management practices and to minimize unsustainable land-management practices**, including supporting and enhancing Federal, State, and local conservation programs that provide financial and technical assistance to land managers for adoption of sustainable practices, implementing routine review of technical methodologies used by Federal agencies in assessing soil function and the effectiveness of conservation practices, developing more-precise and less-expensive sensors for deployment by land managers, and developing a consistent set of benchmarks and targets against which to measure progress in protecting U.S. soils.

Soils: The Foundation for Civilization

> The Soil Science Glossary published by the Soil Society of America (SSSA) defines soil as:
>
> "The unconsolidated mineral or organic matter on the surface of the Earth that has been subjected to and shows effects of genetic and environmental factors of: climate (including water and temperature effects), and macro- and microorganisms, conditioned by relief, acting on parent material over a period of time."[1]
>
> Under natural conditions, one inch of topsoil can take 500 years or more to form.[2]

Soil scientists categorize soils into 12 broad classifications called soil orders (Map 1: Soil Orders of the United States.[3]) The soil characteristics that define these orders are fundamental to each soil's ability to provide ecosystem services and govern responses to different management practices. A wide range of land-use and land-cover conditions occur across the United States (Map 2: Land Uses and Land Cover in the United States). The U.S. Department of Agriculture's (USDA) National Resources Inventory (NRI) groups the U.S. land-use and land-cover classes into six broad categories: crop land, pasture, rangeland, forest land, developed land, and other rural land. Federal lands are treated as a separate category in the NRI, as is land enrolled in the Conservation Reserve Program (CRP), a USDA conservation program that retires agricultural land to protect its natural resources (Figure 1: Land-Use Distribution in the United States). This document focuses on land *use* and *management* rather than land *ownership*, so Federal land and CRP land are not treated separately. The interaction of inherent and dynamic soil properties with existing and potential land-management practices across the Nation are the basis for this document.

The ecosystem services provided by a soil vary among land uses. There is a common need for the development and implementation of management strategies that maximize the ability of a specific soil to provide the desired services for the future and to reduce the risks of irreversible negative effects on that soil. In working lands (crop land, pastures, rangeland and much of the Nation's forest lands), the primary management objective is to provide food and fiber for a growing world population. The most significant challenge is to minimize negative effects such as soil erosion and loss of organic matter as well as unintended on- and off-site environmental risks resulting from inappropriate application of agricultural inputs (such as fertilizer and pesticides).

A Brief History of Soil Management in the United States

The Dust Bowl period of the 1930s, which devastated agriculture throughout the Great Plains, resulted from a severe drought, the effects of which were magnified by poor land management in the region. The event caused a severe loss of ecosystem services and agricultural productivity. In response to this crisis, the U.S. Congress established the Soil Conservation Service in 1935 (which later became the Natural Resources Conservation Service) through the Soil Conservation and Domestic Allotment Act.[4] The Act authorized USDA to administer conservation programs and acquire lands to conserve their soil, to encourage "…the protection of land resources against soil erosion.[5]" With these actions, the Federal Government began what would become a long-standing policy of encouraging and supporting the use of conservation practices on agricultural land.

New pressures on soil resources have emerged as a result of changing societal needs and norms. For example, the co-development of new crop varieties and more efficient irrigation equipment has facilitated the expansion of high-yield and high-input agriculture into more arid and cooler areas, creating new threats to soils that formerly had been managed less intensively for livestock production or lower-input agricultural systems. The pursuit of additional acreage for crop production has led land managers to drain wetland soils to expand agricultural activity, often causing significant soil loss and carbon release to the atmosphere.[6] The growth of bioenergy and bio-product markets and the rise of industrial-scale confined livestock operations have also contributed to the spread of monocrop agriculture (primarily corn) through wide swaths of the central United States.[7] These changes in cropping systems have decreased species diversity, which can lead to accelerated soil degradation.[8] Furthermore, as urban populations continue to expand, demand for more housing and urban development has increased pressure on agricultural or forested lands; the associated increase in impervious land cover in these areas creates challenges for both soil and water management. Industrial activities, including mining and resource extraction, also continue to present soil-management challenges.

Many Federal agencies have conducted research and developed programs to address these issues. A few examples include:

1) **Agricultural soils**: Within USDA, NRCS, the National Institute of Food and Agriculture (NIFA), and Agricultural Research Service (ARS)) have implemented—and continue to implement—coordinated programs of field and laboratory research, demonstrations, outreach, and financial assistance to quantify and control soil erosion processes better. Programs have focused on designing appropriate management practices (such as terraces, waterways, and reduced- and no-tillage systems) and working with landowners to support implementation of these practices. Although erosion continues to be an important resource issue, significant improvements were made in the late 20th century (Maps 3a and 3b: Sheet and Rill Erosion in the United States). Even though erosion management has been a primary focus for USDA agencies, most are now trying to develop a better understanding of biological and physical processes in soil.
2) **Urban and industrial soils**: Brownfields are sites that may contain hazardous substances, pollutants, or contaminants due to prior human use. To remediate soils at these sites, the U.S. Environmental Protection Agency (EPA) developed the Brownfields Program to provide grants and technical assistance to communities, states, tribes, and others to assess, safely clean-up, and sustainably reuse previously contaminated sites. Cleaning up and reinvesting in Brownfields protects human health and the environment and takes development pressures off greenspaces and working lands. EPA estimates 450,000 to 1,000,000 Brownfield sites exist nationwide[9]—but only about 17,000 sites have applied for and received grants for assessing or cleaning up the contamination (Map 4: Brownfield Sites across the United States). These investments have been successful;

every dollar invested in the Brownfields program has leveraged $17.79 in additional investment,[10] and as of 2014, Brownfield investments have led to the creation of over 97,000 jobs.[11] Other Federal agencies also work to protect urban soils; for example, NRCS has expanded its work on soil mapping into urban areas to further characterize soils that exist in close interaction with human populations. The Forest Service's Forest Inventory and Analysis (FIA) program also surveys urban sites.

3) **Contaminated sites**: The Department of Energy (DOE) operates dozens of research facilities across the country that manage large quantities of contaminants, including radionuclides, toxic metals, organics, and dense liquids such as mercury.[12] DOE's inventory of degraded soil and debris is 40 million cubic meters.[13] The Department invests hundreds of millions of dollars each year to ensure the appropriate cleanup of contaminated soils, and the Office of Soil and Groundwater Remediation operates research programs to develop improved technologies for solving specific technical challenges associated with contamination. For example, DOE's proposed Fiscal Year 2017 budget includes an additional $3 million to help develop and test technologies to stabilize mercury pollution in soil from activities at Oak Ridge National Laboratory.[14]

Public Perception of the Importance of Soil

Soil is one of the least recognized national resources. No mascot along the lines of "Smokey the Bear" has widely popularized the importance of soil. The benefits of soil are more likely to be recognized only after they have been degraded or eroded, or after extreme events—such as landslides or land subsidence—have occurred.

Soil is often viewed as "just dirt," and the general public rarely hears of the importance of healthy soil or soil ecosystem services, but in fact, it is one of three pillars—along with water and air—of the Earth's capacity to support human life. That this precious resource is underappreciated is due in part to an increasingly urbanized society that separates people from soils and the services they provide. Raising awareness and engaging the public on the complexity and importance of soil ecosystem services could lead to better soil management decisions at the local level, more support at all levels of government for efforts to protect soil, and opportunities for scientific workforce development. Educating the public on the different roles soil plays beyond agriculture in, for example, filtering drinking water, storing water, supporting the plants that provide oxygen, and mitigating climate change, is also important.

In addition to increasing overall public awareness of the importance of soils to human society, addressing the needs and concerns of farmers and other land managers and increasing their knowledge of practices that protect and improve soils remains a significant challenge. While every grower knows the importance of soil, there can be considerable resistance to changing soil-degrading practices.

The State of the Nation's Soils

The United States features diverse soil types, formed over time by site-specific factors including local climate and hydrology, biological activity, topography, and geologic parent material (referred to collectively as soil forming factors). Different soil types vary in their sensitivity to degrading practices, the rate at which ecosystem services can be regenerated, the management practices that will enable restoration, and the level of soil function that can be restored.

Soil Degradation

Soil degradation is a general term often applied to the process of rendering a soil incapable of providing its expected level of ecosystem services. Originally, the term was applied to agricultural productivity, but the concept has expanded to cover the broader range of services that soils provide. Degradation reduces the availability of soils for food and fiber production, water filtration and storage, carbon sequestration, and other important ecosystem services upon which society depends. In many instances, degraded soils can be remediated by implementing improved management practices or soil amendments, such as organic matter, that ameliorate physical or chemical limitations. Degraded soils can take hundreds or even thousands of years to recover naturally.[15] For example, organic matter depletion is a common type of degradation in agricultural soils, commonly due to intensive tillage that is often accompanied by leaving the land uncovered in the non-growing season. Changes in management can halt and often reverse soil organic matter losses.

Soil Loss across the United States

Soil loss, primarily through wind and water erosion, can be thought of as the most extreme type of soil degradation, as its effects cannot be alleviated by simply replacing lost soil with soil from another location. An inch of soil can take more than 500 years to form,[16] and since soil is also a living community and the microbial community structure needed for healthy and functional soil varies by location and use, physically replacing lost soil with soil from another location is not enough to restore its function. The average rate of soil erosion from cropland decreased by over 30 percent from 1982 to 2012,[17] the last year for which NRI data are available (Figure 3), largely due to the adoption of reduced tillage management by a growing number of farmers. Despite this improvement, the current estimated rate of erosion (an average of 4.6 tons per acre per year[18]) results in significant soil losses. These estimated losses are not evenly distributed, with some areas of the country still experiencing average losses of nearly twice that amount[19] (Maps 3a and 3b).

Soil formation rates cannot on their own offset the current rates of soil losses due to erosion. Despite numerous attempts to quantify the rate of soil formation under a wide range of conditions, the only consensus from these efforts is that soil formation rates are highly variable. Recent estimates suggest that average soil formation rates are close to 0.5 tons per acre per year.[20,21] Therefore, it is not possible to rely on natural soil formation alone to make up for the high rates of soil loss in agricultural and other soils.

Current Availability and Quality of Federal Data on Soils

Considerable data document the state of soil resources in the United States. The primary source for soil information is the Soil Survey Geographic (SSURGO) database, which is accessible through the USDA's Web Soil Survey.[22] This database, maintained by NRCS, contains hundreds of estimated properties for soil landscapes and components that cover over 90 percent of the continental United States mapped at a 1:24,000 spatial scale. The State Soil Geographic (STATSGO) database, also distributed through Web Soil Survey, provides a smaller set of estimated properties for the entire country at a 1:250,000 scale. The spatial resolution of the chemical data in SSURGO is sufficient for large, homogeneous landscapes, but in variable terrain with multiple soil parent materials, such as those found in much of the East and Mountain West, this dataset is limited. Therefore, SSURGO data usually do not provide detailed information on surface waters or forest conditions, nor provide useful estimates of soil-carbon storage; however, NRCS continues to invest in improved soil resource mapping programs that are expected to help resolve current limitations.

The National Cooperative Soil Survey (NCSS) Soil Characterization database contains measured data on over 1,000 soil properties obtained from over 63,000 sites throughout the United States and the world, though measurement is limited by low spatial resolution in many parts of the country.[23] The NCSS also contains calculated data on many other soil properties. All of these datasets are based on consistent, well-documented standards and specifications. NRCS is able to leverage significant information on global soil resources through international collaborations, including with the United Nations Food and Agriculture Organization's (FAO) Global Soil Partnership and international organizations such as ISRIC—World Soil Information.

NRCS also maintains the NRI, a longitudinal sample survey of the Nation's land-use characteristics based upon statistical principles and procedures. The NRI is conducted in cooperation with Iowa State University's Center for Survey Statistics and Methodology. Current estimates cover the contiguous 48 States, Hawaii, and parts of the Caribbean. Separate estimates also cover Alaska. The NRI approach to conducting inventories facilitates examination of trends in rural and developed land characteristics and uses over time, because:

- the same sample sites have been studied since 1982;
- the same data have been collected since 1982;
- the inventory accounts for 100 percent of the surface area;
- quality assurance and statistical procedures are designed and developed to ensure that trend data are scientifically legitimate and unambiguous; and
- it is easy to track lands as they change in their characteristics and uses.

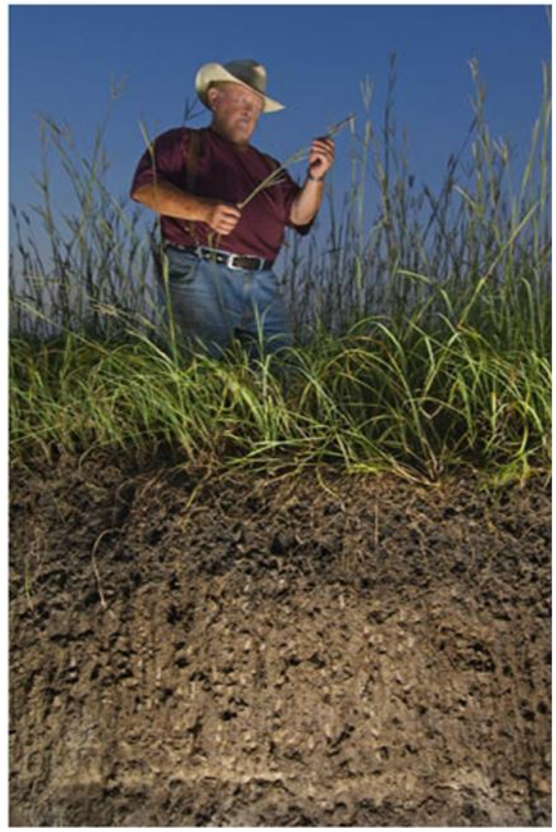
Key information collected over time includes land cover and use, water and wind erosion, and wetland characteristics, paired with soil properties. The NRI's applicability, however, to developing responses to threats to soil ecosystem services is limited, because it is principally a land-use database, not a soil-property database, and therefore lacks detailed information about soil characteristics.

Another USDA agency, the Forest Service, leads the FIA, which produces an annual survey of the state of U.S. forests, including forest soils, and reports on issues such as land-cover change, carbon sequestration, and effects of pollutants and fires. The survey includes approximately 125,000 plots for core data collection, of which approximately 7,800 are sampled intensively and include forest-health and soil characteristics.

Several public-private collaborations aggregate and analyze large quantities of soil data. For example, scientists have created the International Soil Carbon Network (ISCN), a platform working to develop a globally integrated database of soil carbon measurements.[24] ISCN partners with several Federal programs, including the interagency U.S. Global Change Research Program (USGCRP) and the NSF-funded National Ecological Observatory Network (NEON)[25,26] (NEON's scientific steering group includes several U.S. and foreign government agencies as well as universities and research institutions.) Federal agencies including EPA, DOE, and others host numerous other datasets. Despite all of these efforts, however, many existing datasets lack the requisite resolution for effective policy and soil-management decisions, and many higher-resolution datasets are regional and lack integration into national databases.[27] The United States lacks a single clearinghouse for soil data or infrastructure for intercomparison of heterogeneous datasets, especially those containing data collected via different methods and with different goals (for example, when two researchers measure the same properties at different depths). Aggregation and intercomparison are inherently difficult due to the wide range of soil properties, the varying degree of importance of each property depending on the location and land-use or land-cover type, scale, and the different research needs for different soil-management goals. For example, the Soil Moisture Active-Passive (SMAP) satellite is designed to measure soil moisture to a depth of 5 centimeters, while a hydrologist might study groundwater flows down to 10 meters. Ensuring data are discoverable (searchable through metadata formatting and the use of Digital Object Identifiers to tag datasets) and accessible (allowing for consistent data formats and methods of installation and synthesis) is also challenging. An important component of a planned interagency approach to managing soil resources will be the coordination of these types of datasets across Federal agencies to maximize the discoverability, accessibility, and usability of information and analytical tools on which to base important policy decisions.

A Global Perspective on the Importance of Soils

The historical success of American agricultural, livestock, and forestry production rests largely on the Nation's highly fertile soils. Mollisols, which are among most productive soils in the world,[28] are also the most common soils in the United States, comprising approximately 22 percent of the Nation's land area but less than 7 percent of global land area.[29] Generally formed under grassland vegetation, Mollisols contain high levels of organic matter that store large amounts of carbon and nutrients important for plant health. The especially rich soils of the United States provide American farmers, ranchers, and foresters a considerable competitive advantage over producers in other regions of the world.



The United States has a higher percentage of highly fertile soils, such as the dark-colored Kansas prairie soil show here, than any other country in the world, resulting in abundant and reliable harvests. Poor soils can impede a nation's progress to improve incomes and nutrition by increasing the likelihood of crop and livestock failures. (Photo: Jim Richardson, Small World Gallery, by permission)

Many parts of Africa, for example, struggle to produce adequate food from the continent's widespread highly-weathered and nutrient-depleted soils.[30] Only about 16 percent of Africa's soils are optimal for crop and livestock production[31,32] (see Map 5, Global Soil Orders), while the rest present one or more major challenges to successful agriculture, such as low levels of organic matter or high acidity. Farmers managing such soils are vulnerable to crop and livestock losses during droughts and extreme weather events. These losses can lead to famines or severe food shortages that are less likely in the United States. Through Federal agencies such as the U.S. Agency for International Development, the Federal Government helps countries around the world avoid such tragedies by supporting agricultural development projects, many of which focus on helping smallholder farmers conserve and improve their soils.

Due to the global nature of both the threats to soils and their diverse roles in society, a range of international entities exist to address soil sustainability issues directly or indirectly. Among them are the FAO, which operates the Global Soil Partnership and the Intergovernmental Technical Panel on Soils (ITPS); the United Nations Convention to Combat Desertification (UNCCD), which combats land degradation around the world; and the United Nations Environment Programme (UNEP)'s International Resource Panel (IRP). These entities work with countries around the world to produce data and databases for use in addressing important soil-related research questions.

Challenges and Opportunities

Land-Use and Land-Cover Change

Overview

Land-use changes in the United States during the last 50 years have contributed to reduced ecosystem services. These changes have been driven by factors including population growth and movement; an increasing urban footprint (e.g., roadway development and energy infrastructure); changing demands on water and land, including through increased biofuel feedstock production; changing public and consumer preferences; and economic pressures on land managers. The amount of developed land increased by more than 42 million acres between 1982 and 2012; between 2007 and 2012, while cropland increased by nearly 4 million acres, the amount of agricultural land enrolled in the Conservation Reserve Program decreased by more than 8 million acres (Figures 3 and 4).[33] The changes in land management practices that accompany land use and land cover shifts can lead to degraded hydrologic function, contamination, salinization, and compaction of soils. The issues identified in this section may also change nutrient and carbon levels and affect the microbial and invertebrate communities in soil. The scope of these threats vary from local to global scales. The data and information needed to inform land use decisions are not always available or incorporated into policy or management decision at all scales (local, State, regional, and national).

Challenges

(1) *Cropland Conversion*

Economic and policy pressures have led to the conversion of forests, wetlands, grasslands and rangelands to cropland.[34] In addition, technological development has led to an increased movement towards larger farms with lower crop diversity and less integration of croplands with other uses such as grazing lands, woodlots, wildlands, and recreational lands.[35] While much cropland is managed well for conservation of soil resources, initial conversion often causes extreme soil and landscape cover disturbance that causes rapid loss of soil carbon, physical compaction, and other changes that disrupt hydrologic functioning (infiltration, aeration, and drainage), soil nutrient cycles, and soil ecosystems, particularly the soil microbial community. An extreme example of a conversion that leads to large-scale losses of carbon to the atmosphere is cropland developed on organic soil wetlands that are drained to allow for crop production.[36]

(2) Urban Development

Over 80 percent of the U.S. population resides in urban or peri-urban areas, and although these areas account for only about 3 percent of the total land area of the country,[37] urban development can significantly disrupt natural ecosystems, causing soil, water, and air pollution, and depleting natural resources. Urban and industrial land uses place great demands on soils, especially in providing a medium for infrastructure and buildings, and soils degraded by urban development are usually unable to recover naturally due to the impervious surface cover that is imposed by engineering projects. Some soils have limitations for certain urban land uses, such as buildings, roads, and underground pipelines, where soils with certain properties, such as shrink-swell clays, water-saturated soils, and soil with inappropriate pH levels, can lead to structural failures in these projects.[38] Toxic heavy metals (including lead and arsenic), excessive pesticide usage, and asbestos are common urban pollutants that can adversely affect soil animal and microbial communities and on human health, especially for children.

> **Success Stories: EPA Brownfields**
>
> EPA's brownfield regeneration program has allowed sites to be redeveloped into thriving new centers of commerce and industry, created jobs through cleanup and reuse, formed innovative partnerships between government and private-sector stakeholders, and trained residents of brownfields communities for high-wage environmental careers. As of 2014, Brownfields investments had led to the creation of over 97,500 jobs, according to EPA.

(3) Mining and Resource Extraction and Processing

Resource extraction refers to the industries, processes, procedures, and techniques related to extraction of natural or other resources, such as metal-based ores, coal, or natural gas. Unlike urban development, resource extraction often occurs in remote but ecologically important areas. Natural resource extraction processes conducted in remote areas bring roads, power transmission infrastructure, residential sites, and waste rock piles, which can all affect soil function. In addition, many operations rely on hazardous chemicals such as cyanide to separate small quantities of valuable ore from large quantities of waste rock, and large volumes of water are used and contaminated in this process, and later stored in large ponds that can reach the size of small lakes.[39] Coal mining and other resource extraction activities can cause considerable loss of land due to chemical contamination, destruction of productive layers of soil, and permanent scarring of the land surface.[40] Significant radiological pollution challenges are also associated with mining and processing uranium, plutonium, and other radionuclides that are used in nuclear energy.[41] Similar contamination can result from the disposal of remnants associated with the production of early atomic weapon stockpiles.

The negative impacts on soil that accompany resource extraction are usually not apparent to the public due to the remoteness of such sites, but these activities will have long-lasting effects on ecosystems and human populations over the long term.

(4) Threats to Soil Capacity to Support Forests

Forest soils are a critical component of American landscapes. Although they only occupy about one-third of the Nation's land area, they are responsible for 80 percent of the Nation's surface freshwater.[42] While not considered as impacted as agricultural and urban soils, forest soils were degraded across the United States at an alarming rate in the early- to mid-1900s, primarily due to unsustainable intensive forestry practices.[43] With threats to forests mirroring those facing agricultural soils, conservationists developed best management practices to minimize effects on forest soils, but like with agriculture, better adherence to these practices is needed. Today, many large urban areas have upstream watershed protection measures in place that protect related forest soils. Yet forest soils continue to be threatened by development. An estimated 1 million acres of forest per year are being converted to developed or urban land.[44]

Several additional threats make forest soils vulnerable to land cover change. In the northeastern United States, acidification of soils (through acid rain) is still an important issue. Even though policies have dramatically decreased acid deposition, soil recovery has been slow.[45] In addition, the effects of climate change on forest soils remain uncertain and will depend on the magnitude of temperature and precipitation changes, the frequency of extreme events, and the response of floral and faunal communities. All of these challenges are likely to make soils less able to support forests as a land cover in the long term.

(5) Non-Anthropogenic Land Cover Changes

Extreme events such as droughts, floods, hurricanes, and tornadoes cause disruptions to soil function. Regardless of potential increases in frequency due to climate change, the impact on soil caused by extreme weather may continue to increase due to land use changes. For example, when levees and barriers designed to protect lands from flooding suffer structural failures, the result can be particularly damaging to local soils. Some land management practices may cause channeling of surface water that increases risk of catastrophic damage from events such as landslides.[46,47] Population growth and suburban encroachment into rural lands may push crop production into areas with even more vulnerable soils, resulting in further degradation of those soils.

Opportunities and Needs

(1) Research

Additional research is needed to improve fundamental understanding of soil ecosystem services and to develop metrics or indicators to evaluate and track soil function under changing land-use scenarios. The lack of a full understanding of soil ecosystem services makes it difficult to establish targets and metrics for the severity of the effects of changes in land use, mostly due to the absence of benchmarks. Analysis is currently limited to trends in individual characteristics with minimal capability for sophisticated intercomparison, and comparisons of these characteristics across sites. Long-term effects of land-use and land-cover change are better understood through more robust data and modeling, and the development of appropriate benchmarks.

One possible mechanisms for achieving these goals includes integration and expansion of, and increased investment in, long-term research programs that include soil observations (such as the National Science Foundation's Long-Term Ecological Research Network (LTER) program and National Ecological Observatory Network, and ARS' Long-term Agroecosystem Research (LTAR) program). Goals should include covering a wider diversity of land-use and land-cover types, collecting data at higher resolution, and developing public-private collaborations among academic institutions, city governments, State agencies, financial institutions, rural land owners and managers, and others. These types of intensive research sites can be most effective when linked with spatially distributed soil monitoring programs (including remote sensing programs) to enable research to be directly applied over entire regions and leveraged alongside relevant work from the international community. Long-term research and monitoring efforts are also necessary to evaluate how soils are being changed through land use practices and environmental drivers such as climate change and acidic deposition. For example, while soil erosion can be greatly reduced within 1-2 years under certain changes in agricultural practices, the recovery of forests from acid deposition requires decades of ongoing monitoring and analysis. Pollution and chemical contamination can also have long-term effects on urban, rangeland, and other ecosystems (both managed and unmanaged), suggesting the need for additional support for long-term studies of soil function.

Further multidisciplinary efforts, as related to soil ecosystem services, are needed in Federal funding for soil science. Soil science sits at the intersection of the broad disciplines of earth and life sciences, and overlaps with many other fields, and the emerging research questions have created a need for broader technical experience. For example, understanding the role of soil microbiomes in carbon exchanges with the atmosphere is neither the job of a strict geologist nor that of a pure biologist. An applied example might be the need for further research at the intersection between urban agriculture, urban planning, and forest management, which results in programs that bring significant improvements to urban quality of life and sustainable management of natural resources that includes protection of fragile soils. Research that integrates insights at all scales—from microorganisms to landscape-wide processes—can enhance knowledge in ways that individual research programs cannot accomplish on their own.

(2) Land Management

Research questions and conservation programs related to the impact of changes in land use and land cover can be further complicated by land tenure issues such as changes in land ownership and management rights. Such changes nonetheless provide opportunities to embed sustainable practices as they take place. There is an ongoing need to develop and implement knowledge, technologies, and strategies to improve the application of sustainable agroforestry in protecting water and soil resources; build landscape-level resilience to the impacts of climate change; reconnect ecological services across rural-urban boundary lands and communities; support bioenergy production systems that are both innovative and sustainable; and more broadly develop multi-purpose landscapes that can produce food, feed, fiber, bioenergy, and bioproducts, while protecting natural resources. Four agencies in USDA—ARS, NRCS, the National Institute of Food and Agriculture (NIFA), and the Forest Service—have already begun developing these priorities further. It is important to develop tools and approaches that will enhance monitoring to increase understanding of how atmospheric pollution affects water, air, and soil resources in Federally designated wilderness areas.

These needs and opportunities should be addressed through cross-agency (and cross-sector) collaboration in landscape-scale soil-conservation planning that takes into account the dynamic nature of land use and land cover in the United States. Existing models include USDA's Climate Change Hubs and the Department of the Interior's Landscape Conservation Cooperatives (LCCs), which are Departmental collaborations focused on land management at regional and landscape scales.

(3) Social Science

An improved understanding of the social drivers behind changes that might threaten soil function is needed; in particular, further research in the behavioral sciences, psychology, economics, and other fields would inform efforts to design more effective public policy and incentives for land managers in the future. This would be especially useful in assessing the effectiveness of existing incentives on lands managed under different ownership and tenure arrangements.

For management of urban soils, integrating soil sustainability considerations into urban growth planning would also contribute to improved quality of life and public health enabling cities to take advantage of the numerous ecosystem services provided by soils. Additional interdisciplinary research is needed to quantify the public health risks posed by toxins and metals in urban soils, and to identify the most effective public policy mechanisms and industry-led efforts to address those risks.

Unsustainable Land-Management Practices

Overview

Degradation of soils due to poor land-management practices is a significant anthropogenic threat to soils. Unsustainable practices affect soil ecosystem services across all soil uses and types. Conversely, many practices can improve soil function, including enhanced crop rotation, the use of cover crops, conservation tillage, improved grazing management, and more. Less sustainable land management may be driven by short-term economic incentives over management practices that enhance the long-term sustainability of the soil.[48] Many of these practices can help land managers balance and optimize business objectives with risk management and other conservation goals for their operations. Improving outreach and access to technical assistance for landowners remains a priority to reduce threats and deploy wider use of sustainable soil-management practices. Since poor soil management affects the long-term food, biofuel, and fiber production system, the threat of soil degradation from poor management practices spans local, national, and global interests.

Challenges

Many of the threats posed by unsustainable land-management practices primarily concern agricultural soils, but there also exist threats to urban, rangeland, wetland, and forest soils. The impact of those challenges can be broadly classified into the following categories.

(1) Changes to Soil Biodiversity Relevant to Soil Ecosystem Services

Soil biota provide key agronomic and environmental services at local, regional, and global scales. They are involved in all major nutrient and biogeochemical cycles including carbon, nitrogen, and phosphorus cycles, thus influencing plant nutrients, the flux of atmospheric gases, carbon sequestration, and water quality.[49,50,51] Soil biota assist plants in their nutrient uptake through nitrogen-fixing bacteria, increasing plant nutrient use efficiency; they also assist in the biodegradation and bioremediation of wastes, pollutants, and agrochemicals, helping to reduce negative impacts from pesticide use.[52] Soil biota also build soil organic matter and stable soil aggregates that positively affect aeration, reduce compaction, improve water infiltration, and increase water-holding capacity.[53] These combined services reduce erosion risks, mitigate adverse effects of flood and drought, and enhance carbon storage. Through plant-microbe-faunal signaling, some soil biota also help suppress many plant diseases, as well as the germination, growth, and persistence of weeds.[54]

Soil organisms interact within complex food webs. Consequently, alterations in abundance and diversity in one trophic or functional group may change the diversity and functioning of another. Multiple studies have shown that intensive agricultural practices, land-use change, soil contamination, and other anthropogenic effects can reduce microbial and faunal abundance and the overall diversity of soil organisms.[55] This loss of (or even alterations to) soil community structure can impair multiple ecosystem functions, including plant diversity, decomposition, and nutrient retention and cycling.[56]

(2) Biomass Management

Biomass is defined as the quantity of living organisms, or amount of plant and animal matter within a particular environment. It is generally measured or estimated in terms of dry weight per unit of area or volume. Within soil ecosystems, the food web is predicated on sufficient biomass for primary consumers to provide energy for respiration and reproduction. Biomass must be properly managed for the soil biological community to survive. Within agricultural production systems, poor biomass management practices include (1) harvesting too much of the available plant residues, which are also needed to protect soil from wind and water erosion (and as a primary source of fixed carbon to support ecological processes and the organismal diversity that supports them)[57] and (2) employing excessive tillage, which accelerates the decomposition of those materials.[58]

Another influence on biomass is the effect of fire. In some ecosystems, fire is a natural component, and a burn of appropriate temperature may reinvigorate many range and forest lands.[59] Poor fire and biomass management, on the other hand, can negatively affect soil carbon, water retention, structure, and biological communities, generally leading to lower productivity in soils and an increase in overland flow and water erosion.[60]

(3) Resource Pressure, Competition, and Efficiency

One threat to soil resources derives from the desire to optimize and enhance outputs from the land without a holistic understanding of all ecological functions and interactions that occur within those resources. Returning waste products such as animal manure, industrial by-products, or municipal solid waste to soils to balance the loss of carbon and other elements can increase resource-use efficiency; however, these practices can result in unintended consequences, such as excess nutrient contamination of soils and waterways.[61]

(4) Water Management

Poor water management can threaten soil function due to both saturated (excessively wet) and dry conditions. Developing irrigation systems to alleviate drought and increase productivity is feasible, but such systems must be managed to prevent accumulation of sodium or other salts in the soil (*i.e.*, salinization and sodification), which can cause plant stress, decrease productivity, and result in other environmental problems.[62] Installing artificial drainage is one method for alleviating excessive soil water (which can affect soil productivity), but without careful nutrient management or landscape practices that include buffers, wetlands, and/or cover crops, drainage can also short-circuit natural flow and transfer nutrients, pesticides, and even pathogens into streams and rivers that often are used downstream as sources of drinking water.[63]

Water use efficiency is also important. Soils that have been degraded through poor management generally infiltrate and store water less effectively, such that more water is needed for each unit of agricultural output. Irrigated agriculture, as well as dryland or rain-fed operations, may greatly benefit from soil-conservation systems. One solution to alleviate pressure on water resources is to use wastewater for irrigation, but this practice requires extra care to avoid contamination and salinization of lands, particularly in arid or semi-arid areas, since wastewater is often of lower quality than freshwater.[64,65]

(5) Managing Agricultural Systems

Proper management of agricultural land is needed to ensure the Nation's long-term soil, food, and water security. Often, multiple factors contribute to soil degradation on agricultural lands. The lack of either residue or living ground cover on cropland leaves the soil more vulnerable to the effects of extreme events (especially intense rainfall) and reduces infiltration, water-holding capacity, plant productivity, soil biodiversity, and capacity to maintain soil organic matter.[66,67] Lack of cover also decreases nutrient use efficiency; increases proliferation of weeds and other plant pests; increases sheet, rill, and wind erosion (sheet and rill erosion are forms of water erosion); and reduces water quality.[68,69] The inappropriate use of fertilizer can affect soil organisms negatively, and severely reduce both water and air quality.[70] Applying fertilizer at the wrong time of year (particularly for nitrogen), using too much or too little, or applying with the incorrect method, source, or placement contribute to reduced nutrient use efficiency and plant productivity.[71,72] Excessive tillage and traffic often result in chronic compaction of soil.[73] Compaction reduces the infiltration, water holding capacity, biodiversity, and the soil's ability to maintain soil organic matter; it also decreases nutrient cycling and use efficiency, increases water and wind erosion, aggravates water quality problems, and represents an unnecessary use of energy and other input in the agricultural system.[74,75,76,77] In the long run, tillage and compaction can reduce productivity.[78]

(6) Unsustainable Livestock and Grazing Practices

Overgrazing of pastures, grasslands, and rangelands can lead to soil and land degradation. Even if stocking rates are optimal for most years, a prolonged drought or reduced precipitation can lead to overgrazing in normally well-managed systems.[79] There are many systems of grazing management; targeted optimization of grazing systems for the particular land use and climate can also help restore degraded soils.

Poor manure management practices can also impair soil function. For example, applying manure in the winter can lead to excessive nutrients, particularly with nitrogen and phosphorus, which can lead to nutrient runoff and contamination of surface waters.[80] Excessive manure applications in soils can also lead to additional salinization in regions with insufficient precipitation.

Opportunities and Needs

The science and technology needs for improving the sustainability of land-management practices are highly interlinked. Basic and applied research needs, data acquisition and management issues, collaborations with producers and communities, and broader implementation of sustainable practices should be addressed. Some specific opportunities include:

(1) Research

There continues to be a need for research in the biological, chemical, and computational sciences on the effects of different land-management practices on soil ecosystem services. In addition, research partnerships with public and private landowners need to be strengthened across the Nation. Research should be coordinated and standardized while leaving room for scientific innovation. Nationally applicable metrics for understanding and quantifying the effects of—and solutions to—poor land management would enable land managers to properly manage soils for a wide variety of land uses.

Methodologies and models used by Federal agencies for collecting, measuring, storing, interpreting, and disseminating the wide range of soil information needed to track and understand soil ecosystems should undergo a periodic technical review. Many of the methodologies used to measure and respond to threats to soil function date back to the 1970s or earlier. Implementing routine reviews would also enable the use of modern technologies and computational tools for assessing the status of the Nation's soils. Such tools are not only useful for data analysis but also for data acquisition, including the use of new remote and on-site sensing technologies to increase the precision and range of available data.

Expanded data collection would contribute to the development, assessment, and validation of prediction models used by Federal agencies for measuring components of soil conditions. Given the scale of the data requirements for rigorous analysis, a national, cooperative, focused coalition is needed to gather the research community, public-private partnerships, and Federal agencies in building a data infrastructure that incorporates critical information about rangeland, agricultural, forest, wetland, urban, and other soils. While existing platforms, such as the NCSS, are large and important sources of information, they could be expanded and further standardized to incorporate new data, introduce ever more sophisticated analytical methods, and monitor nationwide changes to soil conditions. There are also opportunities for expanding access to essential data through mutually beneficial collaborations with international organizations, such as the ITPS and other international scientific consortiums.

(2) Technology

The most pressing technological need is the development of low-cost, highly precise sensors that can be easily obtained, used, and deployed to detect critical soil properties. These include sensors for soil moisture, soil carbon, nutrients, trace gas fluxes, and more, including techniques to assess microbial community structure and function. These technologies are not only important for building a higher-resolution, nationwide stream of data; they would also enable agencies, land managers, and decision-makers to make responsible soil-management decisions in a more efficient, effective, and timely manner. Continued collaboration between U.S. researchers and the international community using databases and knowledge developed by the international community can help reduce the burden on U.S. institutions for developing these efforts and improve the applicability of outcomes. Outcomes could include the development of mobile applications supported by advances in cloud computing through international mechanisms such as UNCCD, CGIAR (a global agricultural research partnership), and other organizations, which would increasingly allow U.S. farmers to access global knowledge and information sources.

(3) Land Management

Broader public-private collaboration is needed to leverage existing networks and implement appropriate soil-management strategies across the Nation. This might include developing research or data collaborations among Federal agencies, scientific non-government organizations, universities or extension services, and industry. These collaborations could also involve stronger collaboration with, or leadership of, international working groups (for instance, through the ITPS or UNCCD's Knowledge Hub), including organizations that focus on marginal or vulnerable lands, such as the Arctic Council, whose work is relevant to tundra and permafrost regions. Such collaborations would expand the impact of investments in Federal programs and engage landowners and decision makers more deeply in achieving the goal of long-term sustainability.

Another need is the improved documentation of land management practices, a goal that also can be advanced through innovative public-private collaborations. Each land use type faces a unique set of needs and will require different documenting efforts. For instance, rangeland soils require improved baseline monitoring capabilities across large areas, as well as further research to incorporate the collected data into comprehensive models of threats and degradation scenarios. Meanwhile, forest soils require less uniformly distributed monitoring but need closer documentation of practices that affect forest boundaries, including the effects of urban encroachment or fire risk management. Opportunities to incorporate the use of existing technologies and platforms (such as Landsat and other Federally maintained remote sensing tools), as well as to build new partnerships within and outside of the Federal Government to achieve these goals, should be explored.

In urban areas, there is an increasing need for interdisciplinary specialists in urban soil management to develop recommended best practices for cities not only to manage their soils and other natural resources responsibly, but also to harness them to improve the quality of life of residents and advance broader sustainability efforts in the built environment. This would build on any progress made in addressing the aforementioned needs for expansion of long-term research efforts to monitor urban soils.

(4) Social Science

Integrating scientific advances with implementation mechanisms will be critical to ensuring the long-term sustainability of soils. The key challenges include designing incentive structures that will increase the adoption of sustainable practices, developing mechanisms for communicating the best science to decision makers, and designing policies that ensure fair and equal representation of all communities across the Nation.

The most urgent social science needs, or those at the nexus of natural and social sciences, include:

- determining how to best use incentive policies to improve rates of adoption of sustainable practices;
- undertaking economic studies to quantify the costs and benefits of implementing sustainable soil-management strategies;
- incorporating soil data into Integrated Assessment Models (IAMs) that seek to map scientific principles to economic risks associated with a changing climate;
- understanding the economic effects of changing or revising the technical components of soil-science methodologies and models; and
- developing improved decision-support tools that can help inform revised policies on an ongoing basis and help reframe land-management goals to foster long-term improvements in soil ecosystem services.

Climate and Environmental Change

Overview

Soil ecosystems are vulnerable to the effects of climate and other forms of environmental change. Climate-driven perturbations to temperature and precipitation are having significant impacts on soil processes, function, and loss, including the potential for carbon sequestration. The National Climate Assessment notes that most parts of the United States are projected to experience temperature increases of between 2°F and 4°F,[81] depending on the path of anthropogenic greenhouse gas emissions. Atmospheric warming will lead to higher soil temperatures and changes in soil moisture regimes, which could result in higher carbon and greenhouse gas release through soil organic-matter decay.[82] Climate change may also lead to droughts of increasing duration and intensity,[83] which in turn would limit plant productivity and therefore carbon inputs into soil. Drought-affected areas will also experience increased wind erosion.[84] By contrast, in some regions, climate change will drive extreme storm and precipitation events that result in creased water erosion from runoff.[85]

In addition, changes in the distribution of invasive species can have adverse effects on soil ecosystems. Potential effects include changes in pH, soil structure, biotic diversity, moisture levels, water retention capacity, and nutrient cycling.[86,87,88,89] The interactions between climate change and invasive species can exacerbate the effects of both.[90]

Challenges

(1) Changes in Hydrology and Precipitation Patterns

Shifts in global precipitation patterns are likely to include both more frequent and more intense rainfall and increased severity and frequency of drought in parts of the United States.[91] Changes in precipitation are expected to increase the erosivity (the ability of rainfall to erode soil[92]) of rainfall events—a key multiplicative factor in water erosion models, such as the Revised Universal Soil Loss Equations (RUSLE and RUSLE2) and the Water Erosion Prediction Project model (WEPP)—by up to 58 percent. [93,94] Significant uncertainties remain in projections for changes in erosivity, partly because erosivity models inherit the uncertainties of climate change models in addition to the uncertainty in translating intensified precipitation to a change in erosivity.[95] Current estimates by the Coupled Model Intercomparison Project Phase 5 (CMIP5), an internationally adopted framework for coupled ocean-atmosphere General Circulation Models (GCMs) [of the climate system], show an overall increase in erosivity across the country.[96]

In the United States, the Southwest and other regions are likely to experience more severe drought conditions[97] due to the combination of reduced precipitation, reduced frequency of precipitation, and increasing temperatures during longer periods of the growing season. Reduced snowpack may also severely limit water storage and availability during the growing season for much of the western United States.[98,99] These shifts can cause previously sustainable soil-management practices and production systems to become unsustainable. As a result, hydrologic changes could significantly increase the rates of soil degradation and erosion, and could lead to other negative impacts, including reduced water holding capacity and increased bulk density, resulting in reduced infiltration rates and greater risk of flooding.

(2) Effect of Increasing Global Temperatures on Soils

Soils store about 1,300–1,600 petagrams (Pg) organic carbon in the top meter and at least 900 Pg more below that,[100,101] representing more than half the global terrestrial carbon sink. The Arctic's permafrost regions are estimated to contain 1672 Pg of additional organic carbon,[102] and peatlands a further 180 to 455 Pg of fixed carbon.[103] Warming air temperatures, along with increased solar radiation, will raise soil temperatures globally. As a result of this (and of longer growing seasons and longer intervals of non-frozen soils in temperate regions), soil microbial communities will become more active and are expected to increase the rate of decomposition of the large quantities of soil organic matter and potentially accelerate limitations in soil nutrients.[104, 105] This accelerated decomposition will lead to higher soil respiration rates, resulting in a positive carbon dioxide (CO_2) feedback to the atmosphere, and potentially higher nitrogen mineralization rates,[106] which may result in limitations in soil nutrient availability. This may lead to reduced soil fertility, which is already a food security issue in some parts of the world and can contribute both to lower yields and nutrient-poor crops.[107] In regions with higher soil moisture (for example, wetlands and agricultural lands), droughts and heatwaves caused by increasing temperatures will increase plant demands on soil water and soil evaporation, resulting in a transition from methane (CH_4) production to CO_2 emission.[108,109] Rising temperatures and longer growing seasons associated with climate change will also result in shifts in plant distributions (both in elevation and latitude) towards zones that often feature different soil properties, thereby adding new pressures onto soil nutrient dynamics and moisture.

(3) Carbon Sequestration

Soils have the ability to store a significant portion of Earth's biologically active carbon through the interplay between organic inputs by primary producers, soil organic matter stabilization, and assimilation and mineralization by soil organisms. In fact, soil represents the largest pool of carbon in the terrestrial biosphere.[110] Carbon enters the soil via plants (photosynthesis-derived carbon through root systems or detritus from dead leaf, stem, and woody materials). But anthropogenic processes, such as fossil fuel use, have increased atmospheric CO_2 concentrations to over 400 parts per million.[111,112] This increased CO_2 has enhanced primary production in terrestrial ecosystems, enhancing terrestrial sequestration of carbon dioxide.[113,114,115] Climate change manipulation experiments such as the Free-Air Carbon Dioxide Enrichment (FACE) studies found this carbon fertilization effect was lessened in forests due to limitations of nutrients and water in soils.[116,117] Changes in microbial communities and their carbon use efficiency will also affect the source-sink balance of carbon in soils.

A number of land-management strategies (such as incorporating rapid-growing plant species or the use of perennial feedstocks for biofuel production) have shown promise in abating carbon emissions. These may help reduce carbon-driven climate change feedbacks, but could present other risks, such as the introduction of invasive species. As a result, there is a need to quantify carbon pools and fluxes adequately at various temporal and spatial scales and to develop a robust predictive modeling framework, including high-resolution models of below-ground processes, to better elucidate uncertainties with soil sequestration strategies and policies for all land uses.

Overall, even though soil ecosystems are profoundly resilient and adaptive, increased stresses and projected effects from climate change will likely decrease soil ecosystem services.

(4) Atmospheric Deposition

Soils in forested landscapes have traditionally been viewed as a static component of the environment that change over centuries, as opposed to air and water quality (which can change hourly), but increasingly sophisticated soil monitoring has identified more rapid ecologically important changes in soils caused by air pollution.

Acidic deposition (acid rain) was discovered in North America in the early 1970's, and was determined to be caused primarily by emissions of sulfur and nitrogen pollutants from fossil fuel combustion and some agricultural activities.[118] Because a large proportion of precipitation typically infiltrates the soil surface before reaching surface waters, soils play a critical role in determining the extent of harm caused by acidic deposition to both terrestrial and aquatic ecosystems.

Soils vary in their ability to neutralize acidic deposition depending on the amount of reactive calcium in the soil. Soils developed from limestone and other similar minerals are effective at neutralizing inputs of acidic deposition (since the soil tend to be rich in calcium), thereby preventing harmful effects.[119,120,121] There are, however, large areas across the eastern United States that still have soils with naturally low amounts of reactive calcium. In these landscapes, the calcium is leached out of the soil into surface and ground water, eventually depleting the pool of available calcium, and causing the acidity to increase in surface waters.[122] Aluminum released by acidic deposition is harmful to forests and most forms of aquatic life.[123] The aluminum has been shown to reduce fish populations to the point of rendering lakes and streams fishless, and to kill sensitive species of trees, such as the sugar maple, that have a high demand for calcium and sensitivity to aluminum. In mountain forests, previous high levels of acidic deposition killed up to 50 percent of the trees.[124]

In low-calcium soils, particularly in the eastern United States, atmospheric deposition of nitrogen tends to contribute, along with sulfur, to soil acidification. Increases in reactive nitrogen from livestock and fertilizer use further increase the amount of atmospheric nitrogen deposition which can potentially affect sensitive ecosystems.[125] Potential atmospheric sources of reactive nitrogen include nitrogen oxides, nitric acid vapor, gaseous ammonia, particulate nitrate, and ammonia. In the United States, some of these anthropogenic nitrogen contributions rival or exceed contributions from natural sources.[126,127]

Wet deposition of reactive nitrogen (along with atmospheric nitrate, NO_3^-) could be viewed as another source of fertilizer for agricultural crops, but since their deposition is random, these substances can also be an unwanted addition to sensitive ecosystems. Overall, precipitation throughout the Midwest contributes 1.2 to 2.8 kilograms per acre of inorganic nitrogen to the soil each year.[128] This generally represents less than 5 percent of the inorganic nitrogen needs for corn and up to 15 percent of the total nitrogen needs for wheat (depending on the condition of the soil).[129] Major non-nitrogen-fixing crops could derive at least 10 percent of their nitrogen needs from atmospheric deposition.[130] This added input should be taken into account to avoid application of excess fertilizer, which can result in unnecessary costs and unintended environmental effects.

(5) Invasive Species

Invasive species are non-native organisms whose introduction causes harm or is likely to cause harm. The adverse impacts of invasive species on soil ecosystem services are multiple and they may have long legacies that ultimately lead to significant changes in biological diversity and ecosystem structure and function. These impacts may originate above or below ground.[131,132]

Invasive plants and their associated symbionts (e.g., Japanese stiltgrass, *Microstegium vimineum*; Cheatgrass, *Bromus tectorum*) can drive changes in soil chemistry, moisture levels, and soil-microbial associations that inhibit the growth of native plants and, indirectly, native animals[133] [134]. Invasive species that inhabit the soil can also have impacts on human health (e.g., fire ant stings[135]) and safety (e.g., fire frequency and scale[136]), and the economy (e.g., through declines in agricultural productivity[137]). Invasive earthworms and microorganisms can affect soil nutrient availability, as well as nutrient and energy flows, which in turn affect above-ground biota. Animals can also alter soil chemistry and community composition (above and below ground), changing plant communities through herbivory (e.g., root-feeding weevils), seed dispersal (especially birds, but also mammals and reptiles), and ecosystem engineering (e.g., earthworms and burrowing rodents).[138,139]

Alteration of soils by invasive species has the potential to hinder the restoration of native communities long after the invasive species have been removed.[140] Due to their long history of isolation and the resultant uniqueness of their flora and fauna, island ecosystems are particularly susceptible to the impacts of invasive species.[141] Arctic ecosystems are also of particular concern as permafrost melt exposes soil over large areas, leaving it vulnerable to invasion by a diversity of soil-altering organisms.[142] Islands and Arctic regions thus warrant special consideration for addressing the ecological and socio-economic impacts of invasive species on soil ecosystem services.

Climate change will have direct and indirect impacts that facilitate the introduction, establishment, and spread of invasive species. Similarly, invasive species can increase the vulnerability of ecosystems to other climate-related stressors and reduce their potential to sequester greenhouse gases.[143]

Opportunities and Needs

A robust and predictive understanding of soil-plant-atmosphere processes and feedbacks is necessary to maintain soil ecosystem services and enhance soil carbon sequestration potential. The challenges outlined above can be addressed partly through focused investment in the following areas.

(1) Research

Better characterization of the threats that climate and environmental changes present to soils is needed, including higher-resolution, down-scaled climate models. For example, there is a need to adequately quantify and monitor soil carbon pools and fluxes at various temporal and spatial scales, as well as develop a robust predictive modeling framework, including high resolution belowground processes to elucidate uncertainties with soil carbon sequestration strategies and policies. Support for additional manipulative experiments could allow researchers to explore important thresholds or tipping points for soil ecosystems in response to temperature and soil moisture changes. Further research is also needed to constrain uncertainty in the effects of climate change on erosivity of rainfall across the United States.

Coupling experimental and modeling research can accelerate advances in process-level predictive understanding of soil ecosystems, and support scaling from plot-level data to ecosystem- and global-scale insight. Models will need to better incorporate the various adoption scenarios for potential technologies and land-management strategies that enhance carbon sequestration or the recovery of soils from nutrient losses.

Coordinated baseline studies, one example being NEON, are also important for providing long-term datasets on soil ecosystem services, especially in the context of a changing climate. Continued and expanded support for long-term studies of soil characteristics and trends, including studies that capture the broad spatial and temporal heterogeneity of soil systems, would help ensure the long-term sustainable use of soil resources across the Nation. This includes the need for further research in the role of microbial communities in mediating biosphere-atmosphere exchanges of carbon on all lands.

Expanded research support could also include studies on the effects of climate and environmental change on invasive species. Examples of important research questions include how ranges shift under different future climate scenarios, how ecosystem composition and vulnerability to stresses such as fire might change, and any connections between extreme weather patterns and the spread of invasive species.

(2) Technology

Advances in information technology, robotics, chemical and biological sensing, and other areas provide an opportunity for high-resolution monitoring of environmental change, including precise sensing of soil characteristics and large-scale data management. This also includes the potentially transformative impact of investing in high-risk, early-stage technologies for targeted solutions to the threats to soil posed by climate and environmental changes. An example is the Advanced Research Projects Agency – Energy's Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS) program, which seeks to enhance sequestration by changing root mass architecture and other plant features, using technologies enabling high-throughput phenotyping.

New technological advances for remote sensing now include technologies for measuring spectral properties of soils at high resolution using unmanned aerial systems. This creates opportunities for further research to develop more sophisticated tools for measuring key properties—such as moisture, carbon content, nutrient availability, water properties, root architecture, and other factors. Collaborations between U.S. and international researchers should be encouraged to enable a global perspective on the use of these tools.

Existing tools and frameworks provide a basis for such collaborative research, one example being the Ecoinformatics-based Open Resources and Machine Accessibility

(EcoINFORMA) where environmental data layers are compatible, easily formatted, and well documented.

There are additional opportunities to leverage existing and funded satellite technologies to study the effects of environmental change on soils. Hyperspectral imaging could provide data to remotely infer properties of soils. Improving mid-infrared spectroscopy and integration with CubeSat technology would also be significant steps forward in remote sensing of soil properties.

(3) Land Management

The concept of "climate-smart agriculture," defined by the FAO as "an approach [to agriculture] to help the people who manage agricultural systems respond effectively to climate change,"[144] has gained traction in recent years. It focuses on three primary objectives: (1) sustainably increasing agricultural productivity and incomes; (2) adapting and building resilience to climate change; and (3) reducing and/or removing greenhouse gas emissions where possible. In May 2016, USDA announced the "Building Blocks for Climate Smart Agriculture & Forestry," which aims to help farmers and land managers respond to climate change through ten focus areas including and conserving soils and sensitive lands,[145] Further efforts are needed to research and develop best management practices for different land uses, land cover types, and climate-oriented goals (e.g.., carbon sequestration, resilience to extreme weather, or a different goal or combination of goals). This will require strong research collaborations with land managers across the Nation.

(4) Social Science

An improved understanding of the social drivers of resistance to adopting climate-smart agricultural and forestry practices is needed. Integrated economic and scientific analysis would increase understanding of the social impacts of the effects of climate change on soils, and further support for public policy research would help improve incentive structures for land managers to adopt more climate-resilient and carbon-sequestering practices, and to leverage the authority of existing rules and regulations.

Citizen science can also present an opportunity for public engagement and education, as well as provide better spatial coverage and ground-truth data. An example is the recent effort to strengthen soil monitoring networks to assist in the verification of satellite soil moisture measurements, such as SMAP. Efforts to develop educational and outreach materials for "crowdsourced" science, as well as standardizing methodologies taught to members of the public and land managers, should be supported. Stronger integration of research and outreach, and education of extension specialists, would advance these efforts.

Priorities for the Future: Objectives for Federal Soil Science

The opportunities and needs outlined for each category of challenges described in the previous section demonstrate numerous soil research and management priorities that apply almost universally across soil use types and threats. This section outlines a set of five Federal science and technology priority areas that, if acted upon, could significantly support government-wide efforts to ensure the long-term sustainable use of soils in the United States. Each objective is critical to the vision and mission of this document, and is drawn from the needs identified in the previous sections.

***Objective 1**: Support applied social science research in soil sciences and enhance public awareness of soil science and the importance of soils.*

Although many methods to protect soil are well known, they are not always implemented at a sufficient scale to adequately protect soils resources. It is therefore important to support further interdisciplinary research in behavioral sciences, economics, and public policy analysis as needed to protect the long-term viability of soil resources. The public, decision-makers, and land managers should be engaged in efforts that communicate the importance of sustainable practices and incentives to implement improved, science-based practices across all land-uses. Agencies should build on the strong foundation of social science research to foster and develop stronger, longer relationships with stakeholders. Engagement of the public through citizen science programs such as the Community Collaborative Rain, Hail, and Snow network (CoCoRaHS), the Global Learning and Observation to Benefit the Environment (GLOBE) program, and others can foster an understanding and appreciation of soil as one of the Nation's most important, yet most vulnerable non-renewable natural resources.

Increasing public awareness of the importance of soils and ecosystems services should be as much a priority in advancing science and technology as the other objectives listed in this document. In addition to rigorously justifying taxpayer dollars to support soil research and conservation programs, two critical needs addressed by supporting public engagement in this topic are workforce development and cross-disciplinary research. Without a substantial effort to increase public awareness, potential future soil researchers and professionals might never enter the field. Equally importantly, researchers in other disciplines whose work would benefit from deep intellectual engagement with soil science and vice-versa—including climate scientists, applied statisticians, computational scientists, engineers, and others—often lack awareness of the field of soil science, one that can be quite insulated despite requiring a high level of interdisciplinary collaboration. Fostering increased public awareness will help deliver the talent required to continue to solve critical natural resource concerns in the future. A coordinated interagency educational and public awareness effort might include the creation of a government-wide public awareness campaign and educational partnerships with school districts and local communities.

***Objective 2**: Advance the national research infrastructure for soil-data storage, analysis, and sharing.*

A consistent theme identified during preparation of this document is the insufficiency of data storage and analytical tools needed to advance understanding of the state of U.S. soils. Significant challenges remain in acquiring high-quality data, standardizing methods for obtaining it, storing large volumes of high-resolution data in four dimensions (across the Nation in location, soil depth, and time), analyzing this information with modern tools, easily sharing data and insights across institutions and networks, and other challenges. All of these must be addressed and integrated to monitor properly nationwide environmental change and trends in soil ecosystem services.

A coordinated effort for developing computational tools and systems is required. Such tools and systems should not only include basic storage, analysis, and sharing technologies, but also extend to support for artificial intelligence and machine learning tools to improve the sophistication of predictive models and more efficiently analyze data. An important component of this endeavor will include finding the right balance between intellectual rigor and respect for landowners' privacy rights. Another is the balance between open access to data and methodological transparency—a high degree of which is required to work with outside parties to identify research gaps—and to protect researchers' right to claim credit for their original work.

***Objective 3**: Support a coordinated research effort on the interactions between soils and the global climate.*

One of three critical challenge categories outlined in this document is devoted to the interaction between soils and ongoing climate change. The role of soils in mediating global environmental change is complex, but with support for the appropriate research programs, soils could play a transformative role in abating greenhouse-gas emissions. Conversely, failing to address important research questions could leave the Nation vulnerable to more severe soil degradation and erosion and to reduced resilience against the effects of a changing climate.

An integrated interagency effort, combining the substantial existing Federal research initiatives on these issues (many of which are currently housed in DOE and USDA), would help the Nation take a significant step toward answering critical questions on this topic. This might include efforts to constrain estimates for current soil carbon content in the United States and around the world; develop technologies for accelerated soil carbon sequestration; quantify the effects of temperature increases on soil carbon decomposition and feedback mechanisms; develop more sophisticated models in projecting changes in rainfall erosivity; monitor drought and changes in soil moisture; re-evaluate nutrient management plans for a changing climate; and better understand carbon and nutrient cycling in carbon-heaving soils, especially wetland and peatland soils. An example of the latter is Oak Ridge National Laboratory's Spruce-Peatland Response Under Climate and Environmental Change (SPRUCE) experiment, that seeks to understand wetland/peatland-atmosphere exchanges of carbon in response to a changing climate.

Objective 4*: Support the expansion of, and increased investment in, long-term research programs and collaborations to better understand, document, and manage the effects of land-use and land-cover change on soils.*

Long-term research programs should include a wider diversity of land use and land cover types, and data collection at higher spatial and temporal resolution. The recovery of lost soil ecosystem services can take years, decades, or even centuries. NEON can serve as a model for coordinated baseline studies on soil, which are needed across all land-use types. Federal agencies can provide the framework and guidance for these efforts through interagency collaboration. Existing long-term studies, such as the LTER program, ARS' Long-Term Agroecosystem Research (LTAR) program, and the Forest Service's Experimental Forest and Rangeland sites, could coordinate their soil data collection.

Long-term projects should not only collect data but also provide much-needed knowledge, develop technologies, and implement strategies to improve the application of sustainable agroforestry in protecting water and soil resources. Other long-term opportunities include building landscape-level resilience to climate change impacts; reconnecting ecological services across rural-urban boundary lands and communities; enabling bioenergy production systems that are both innovative and sustainable; and more broadly developing multi-purpose landscapes that can produce food, feed, fiber, and energy, while protecting natural resources.

Many of the research objectives listed in this document can be achieved only if the Federal Government continues to strengthen research collaborations with those that own or manage private lands. A continued effort to incentivize public-private collaborations between rural landowners and managers, city governments, State agencies, and academic institutions is required to increase access to high-quality data. Such collaborations can enhance the role of land managers in helping to shape national priorities and provide an ongoing avenue by which individuals who are most affected by government policies can provide their input and be heard, empowering communities in the grant- and policy-making processes.

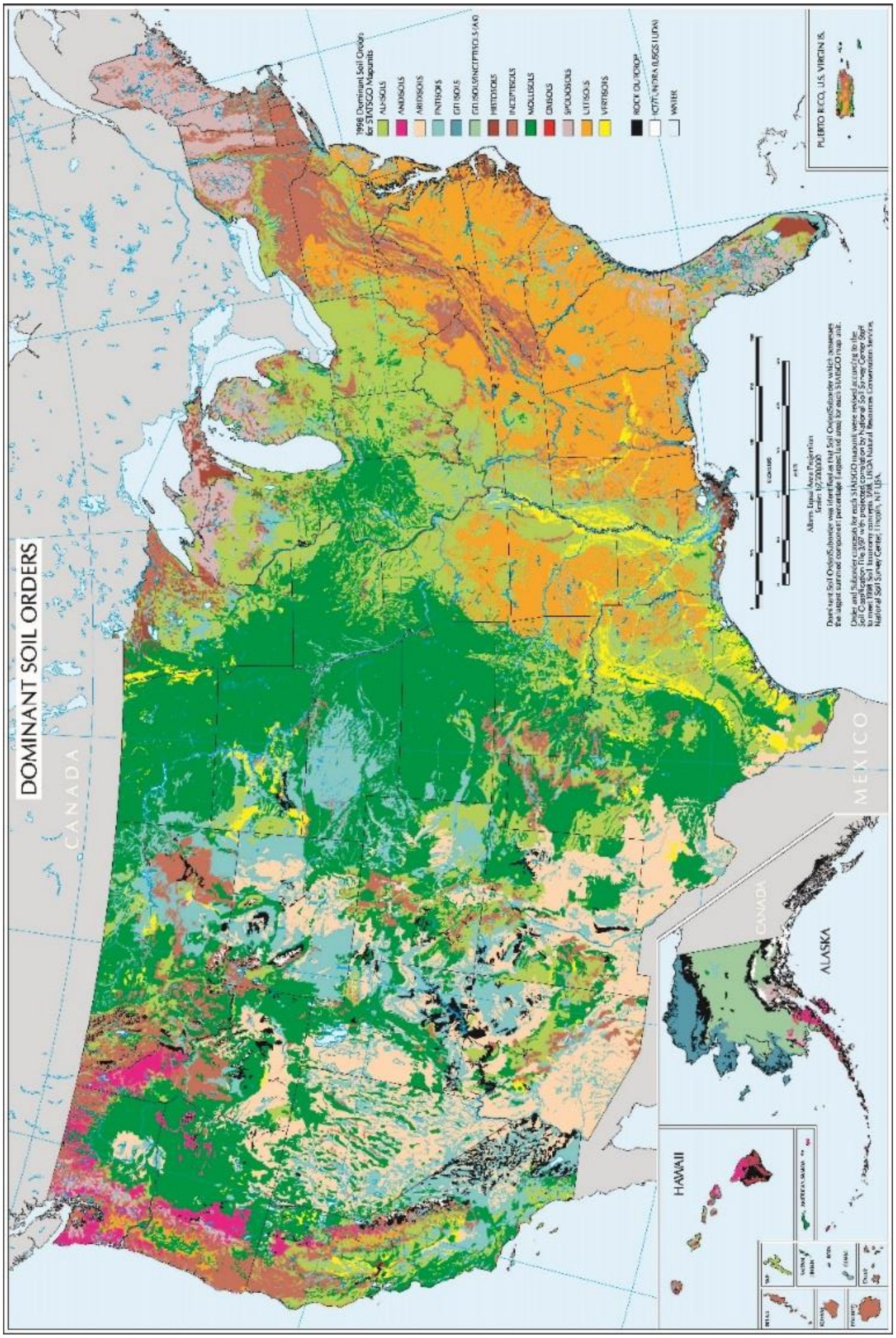
Objective 5*: Prioritize programs and technical assistance designed to promote sustainable land-management practices and to minimize unsustainable land-management practices.*

Expanded research and data collection should contribute to the development, assessment, and validation of models and practices Federal agencies use to measure, predict and manage soil ecosystem services. Regular technical evaluation of the wide range of land-use and land-management practices including soil conservation, reclamation, and urban development practices would ensure that up-to-date science is consistently being applied. This is especially important in the case of agricultural conservation practices, given that nearly 450 million acres of land are enrolled in Federal conservation programs and evaluated against agency criteria, with incentives and program administration expected to cost the Federal Government $6.7 billion in FY2017. Regular review of metrics is one way to prevent Federal dollars from being spent on outdated practices, while continuing to validate the use of methods that are deemed rigorous. Review should be conducted for expectations or standards for soil properties such as biodiversity, moisture, organic carbon, and other characteristics and processes as required by the most recent science. It should also include processes governing sediment and contaminant transport from all land uses.

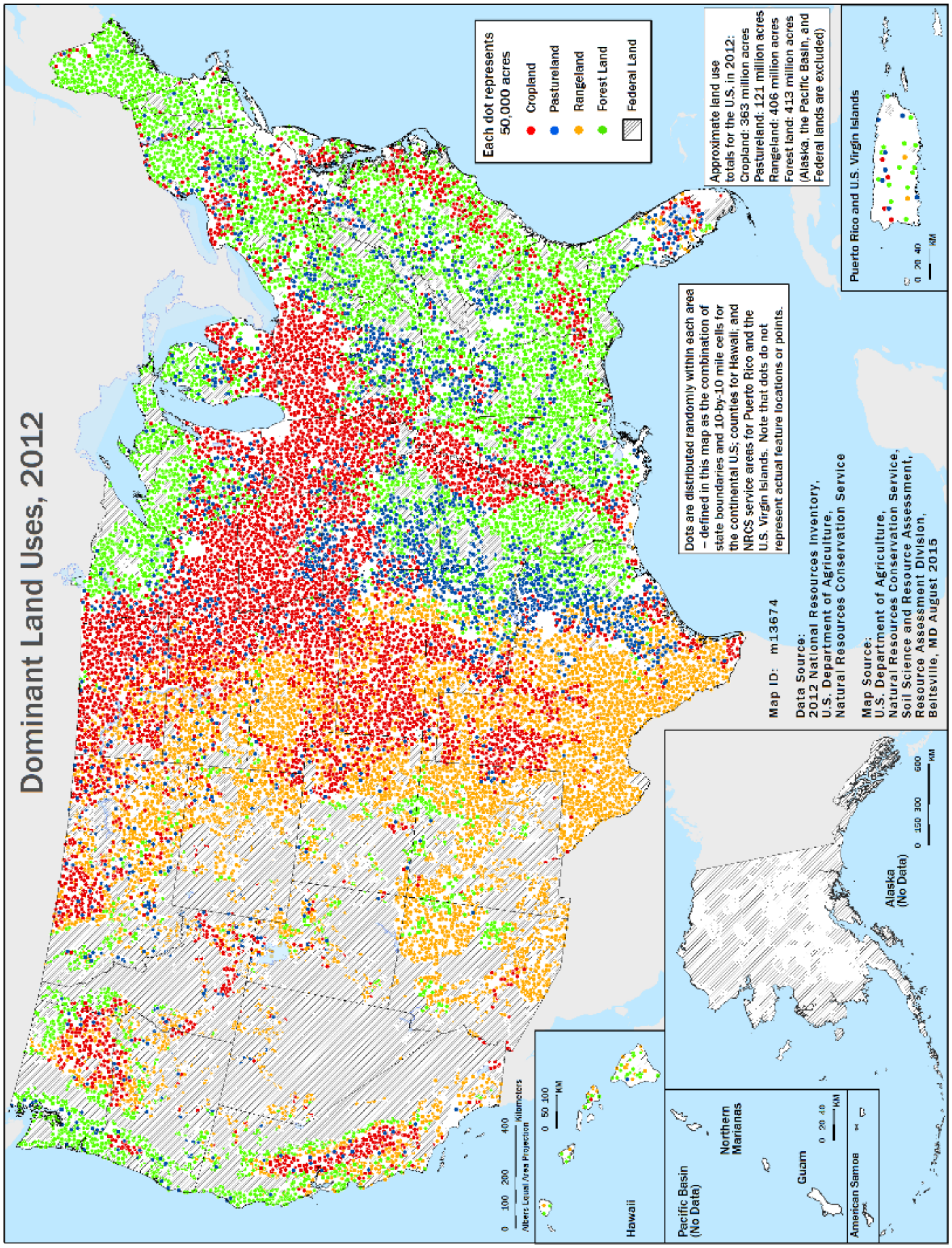
In order to attain adequate information for critical soil properties, there also needs to be a concerted effort to develop low-cost, highly precise sensors for critical soil properties that can be easily obtained, used, and deployed. These include sensors for soil carbon, soil moisture, microbial structure, and more. Additional benefit could be drawn from further collaboration between agencies with remote sensing tools that may supplement field data.

Finally, there is a need for a concerted Federal effort to work toward a consistent set of metrics, benchmarks, and targets by which to measure progress in protecting and improving soil function. This key research priority is necessary to enable the proper evaluation of soil ecosystem services and the effects of different land-management practices.

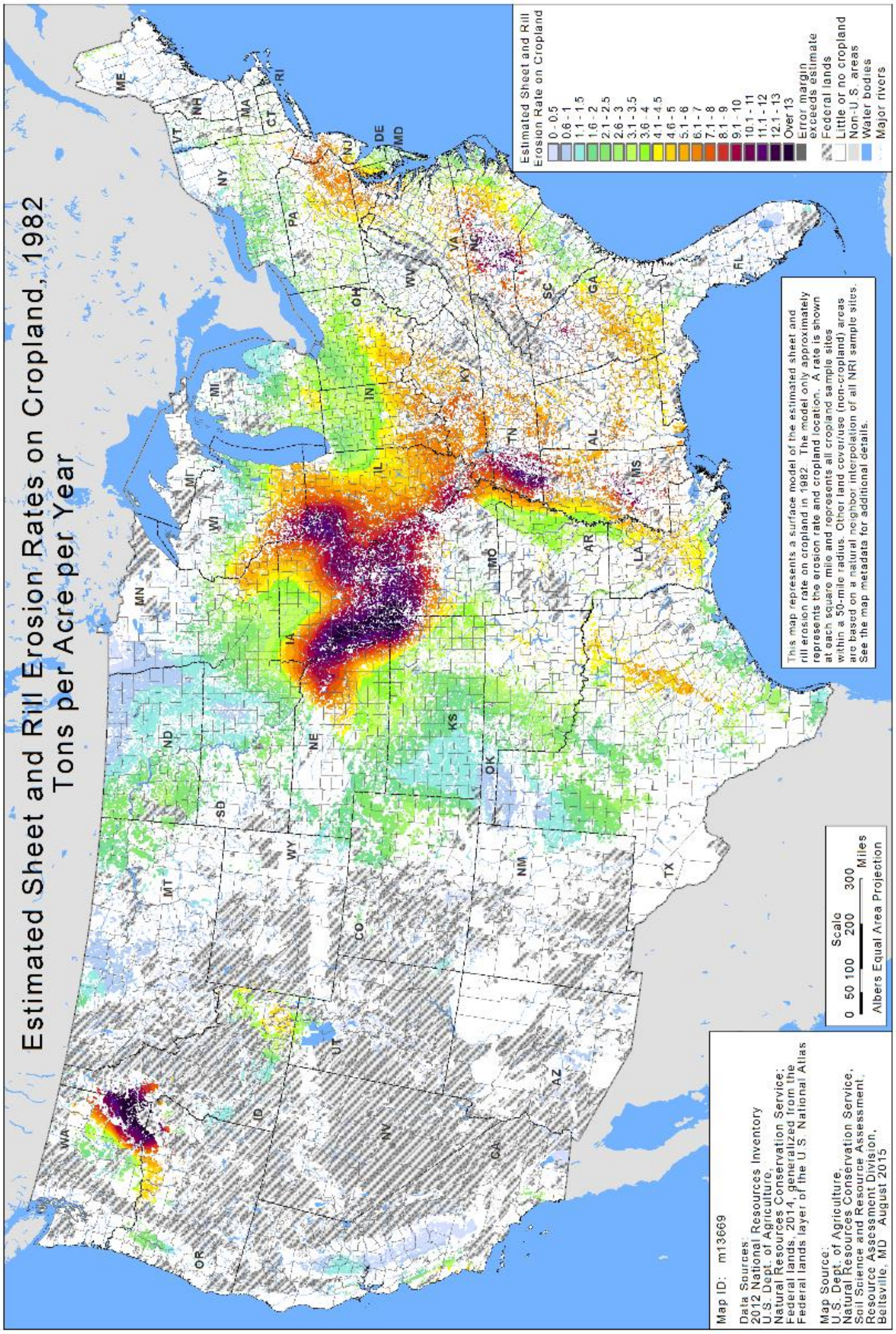
Maps and Figures



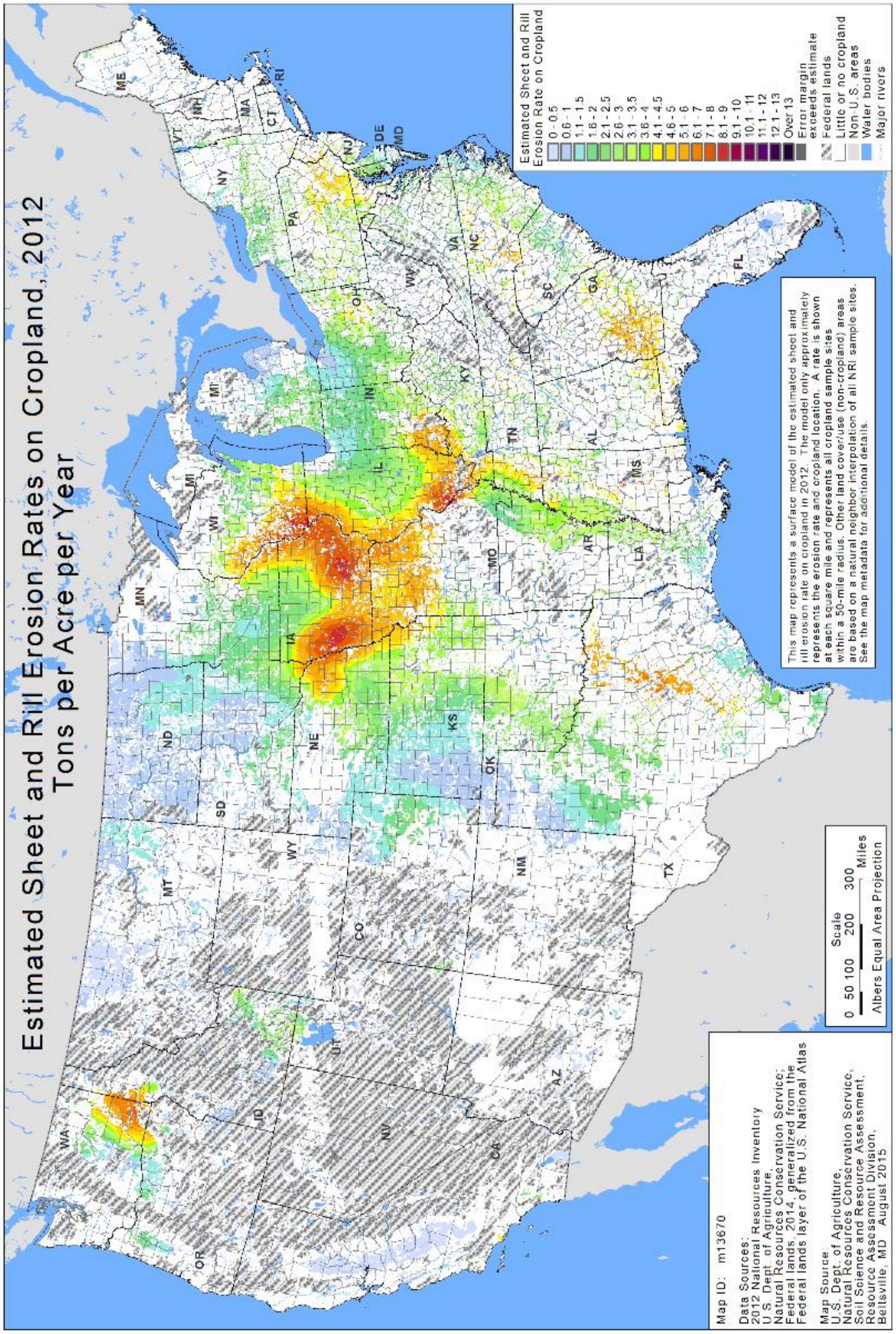
Map 1: Soil Orders of the United States. Source: USDA NRCS.



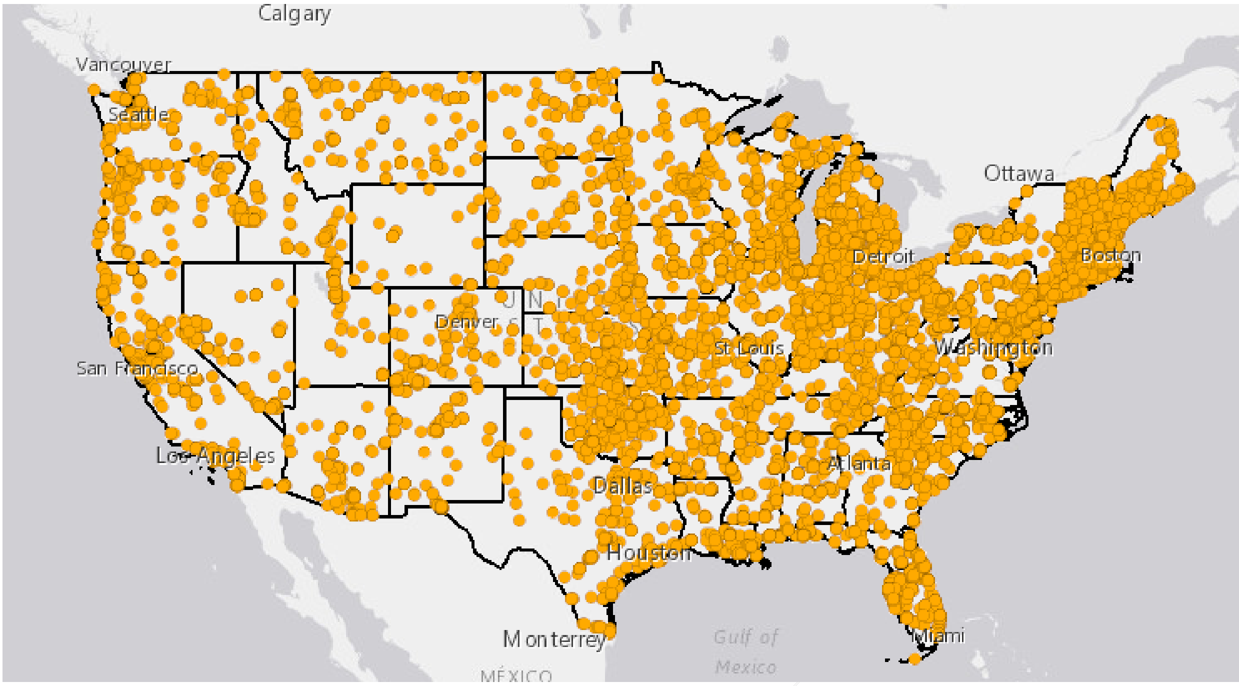
Map 2: Land Uses and Land Cover in the United States, 2012. Source: 2012 National Resources Inventory, USDA NRCS.



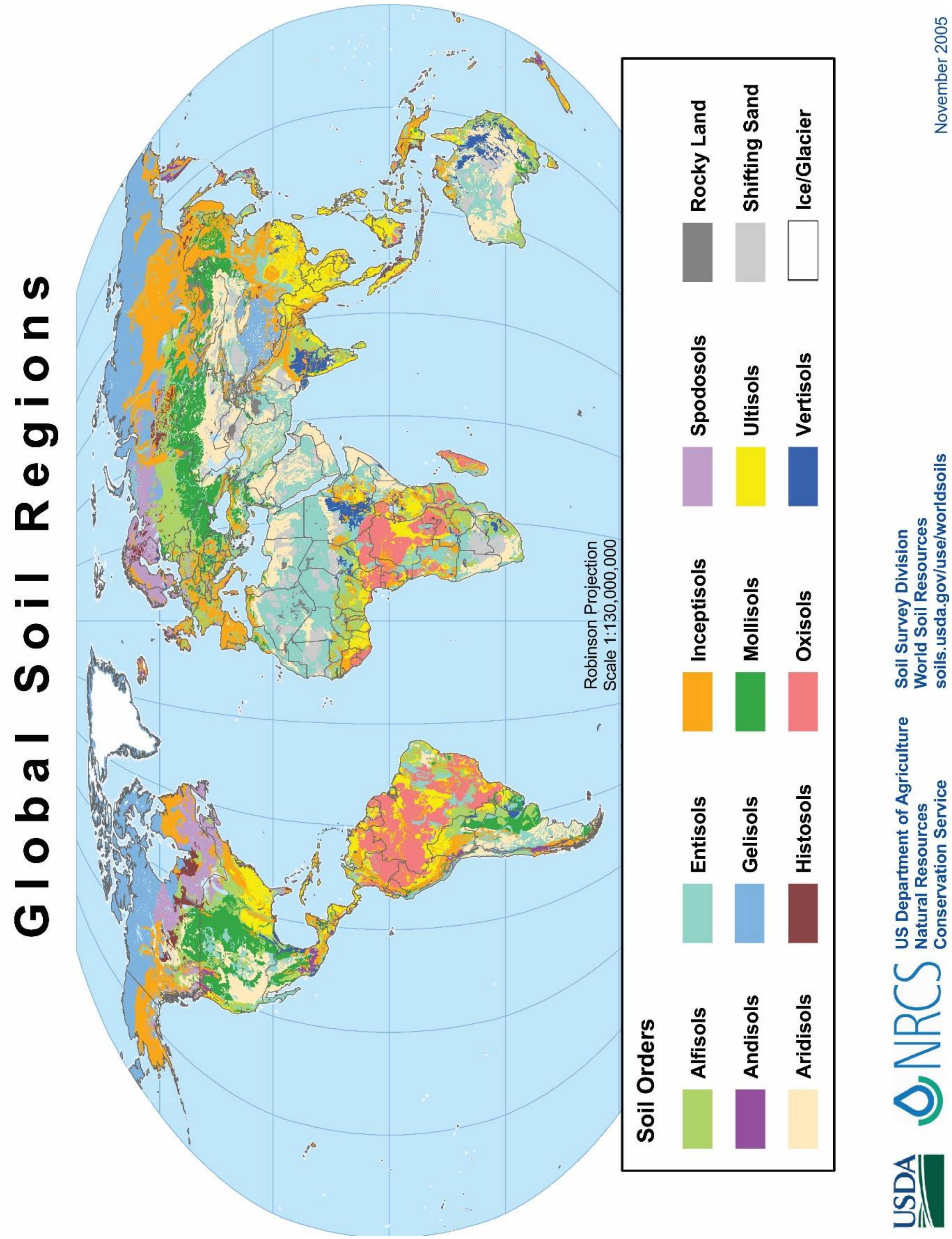
Map 3a: Sheet and Rill Erosion in the United States, 1982. Source: 2012 National Resources Inventory, USDA NRCS.



Map 3b: Sheet and Rill Erosion in the United States, 2012. Source: 2012 National Resources Inventory, USDA NRCS.



Map 4: Brownfield Sites across the Contiguous United States. Source: U.S. EPA.[146]



Map 5: Global Soil Orders. Source: USDA NRCS.[147]

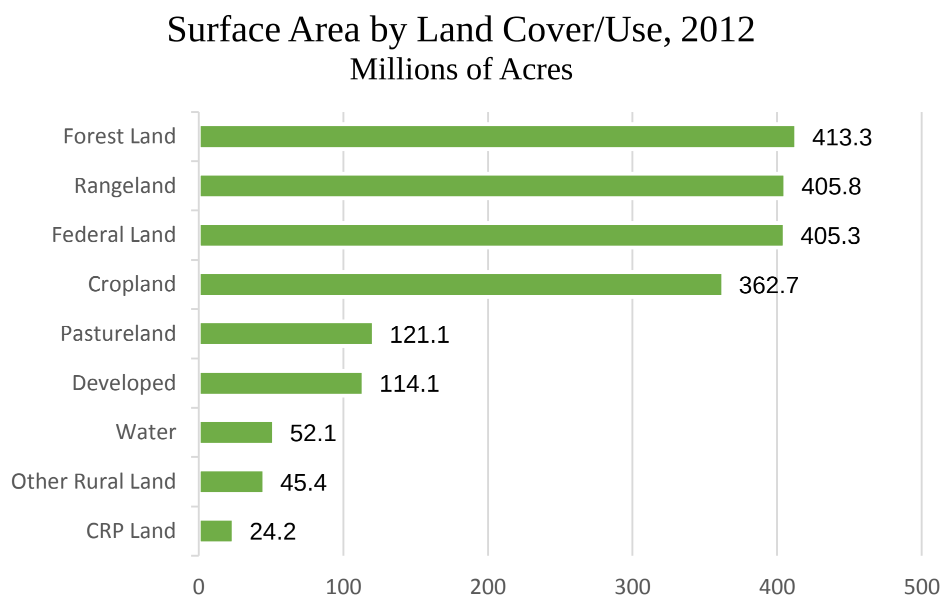


Figure 1: Land-Use Distribution in the United States. Includes both cultivated and non-cultivated cropland. Total surface area: 1,944 million acres. Source: 2012 National Resources Inventory, USDA NRCS.

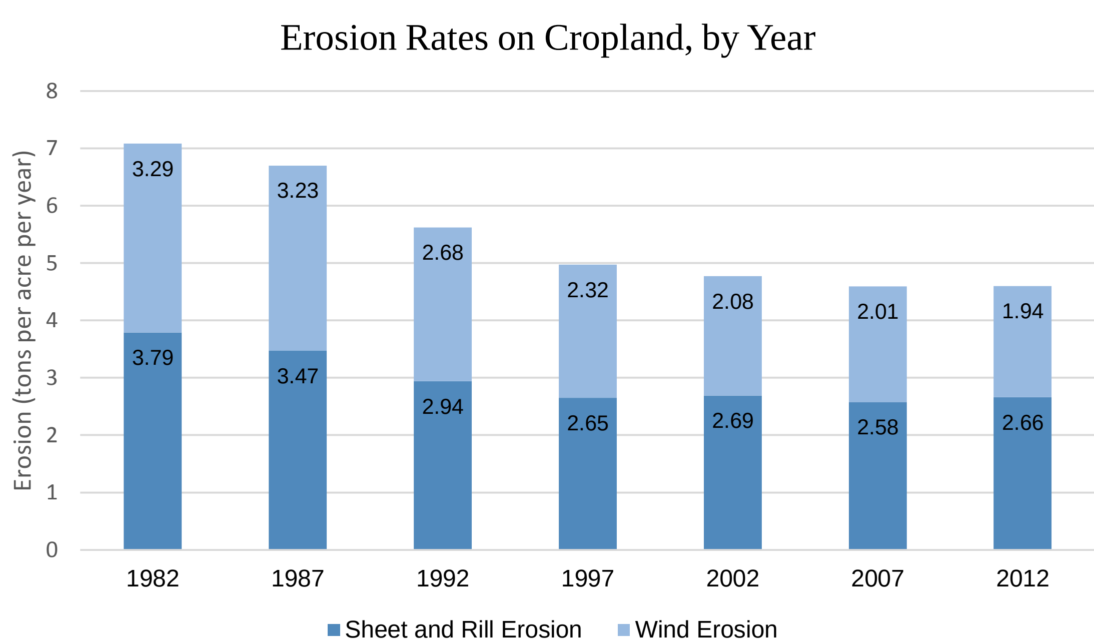


Figure 2: Change in Average Erosion Rates on Cropland in the United States. Includes both cultivated and non-cultivated cropland. (Columns totals may not exactly match due to rounding). Source: 2012 National Resources Inventory, USDA NRCS.

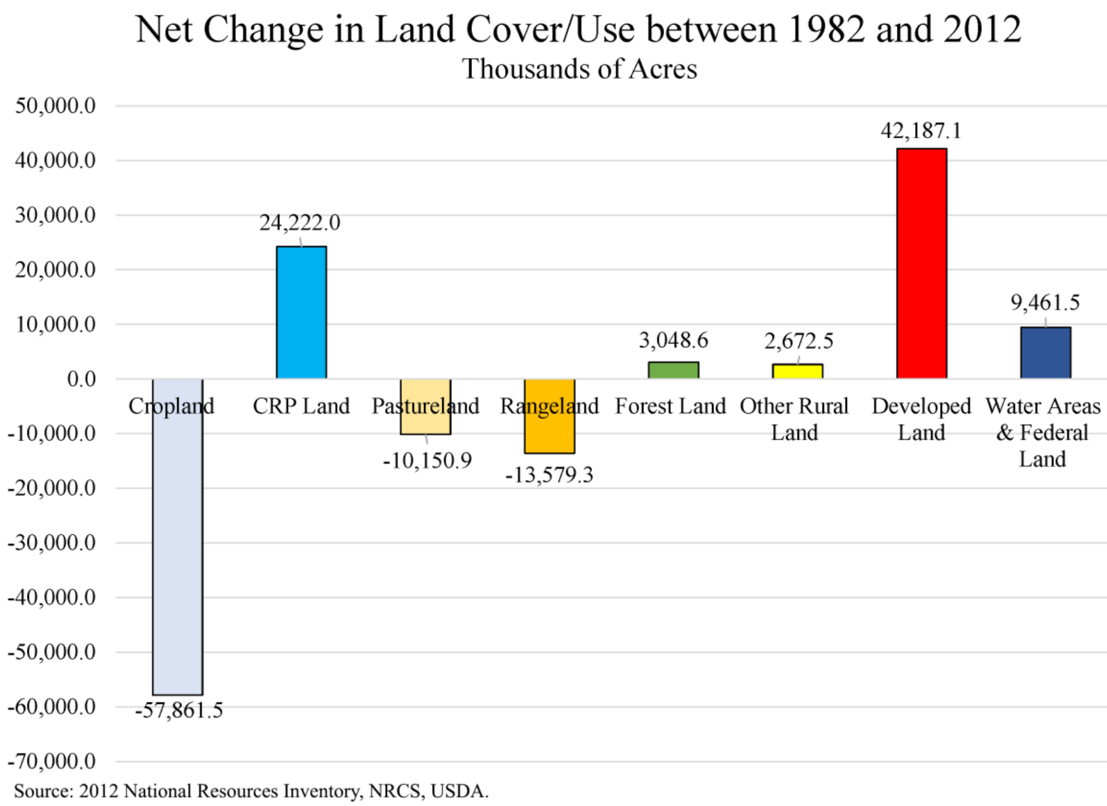


Figure 3: Net Change in Land Use/Land Cover between 1982 and 2012, in thousands of acres. Source: 2012 National Resources Inventory, USDA NRCS.

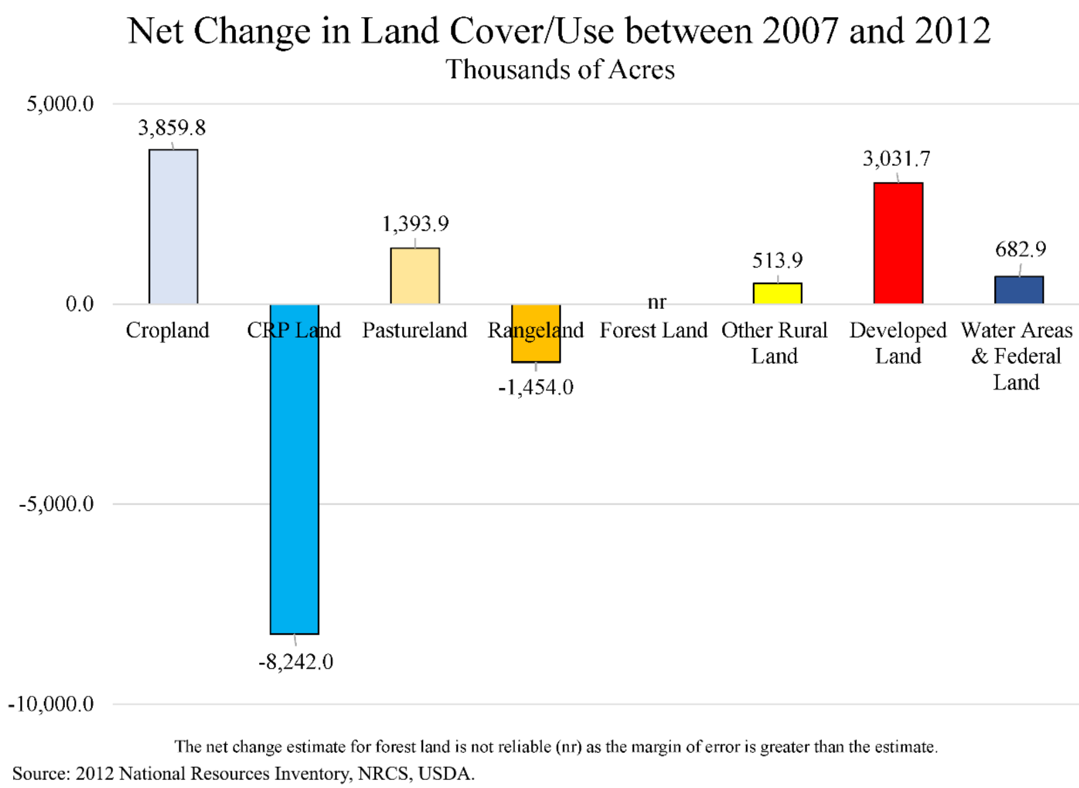


Figure 4: Net Change in Land Use/Land Cover between 2007 and 2012, in thousands of acres. Source: 2012 National Resources Inventory, USDA NRCS.

Glossary

Soil	Soil is the unconsolidated mineral or organic matter on the surface of the Earth that has been subjected to and shows effects of genetic and environmental factors of: climate (including water and temperature effects), and macro- and microorganisms, conditioned by relief, acting on parent material over a period of time.[148]
Soil Conservation	(1) Protection of the soil against physical loss by erosion or against physical or chemical deterioration; that is, excessive loss of fertility by either natural or artificial means. (2) A combination of all management and land-use methods that safeguard the soil against depletion or deterioration by natural or human-induced factors. (3) The branch of soil science that deals with (1) and (2).[149]
Soil Degradation	The breakdown of soil to the point where it is no longer able to provide one or more ecosystem services at the level that was previously possible.
Soil Ecosystem Services	Components of nature directly enjoyed, consumed or used to yield human well-being. Soils and their characteristics, such as fertility, provide important ecosystem goods and services for beneficiaries such as farmers, ranchers, gardeners and land managers.[150,151,152]
Soil Erosion	(1) The wearing away of the land surface by rain or irrigation water, wind, ice, or other natural or anthropogenic agents that abrade, detach and remove geologic parent material or soil from one point on the earth's surface and deposit it elsewhere, including such processes as gravitational creep and so-called tillage erosion.[153] (2) The detachment and movement of soil or rock by water, wind, ice, or gravity.[154]
Soil Function	The capability of soils to support agricultural, environmental, engineering, and ecosystems services, such as sustaining productivity, storing and cycling nutrients, filtering and buffering contaminants, regulating and partitioning of soil water, providing habitat for soil organisms, and supporting roads, buildings and other infrastructure.

Soil Health	The continued capacity of soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health.[155]
Soil Science	The science dealing with soils as a natural resource on the surface of the earth including soil formation, classification, and mapping; physical, chemical, biological, and fertility properties of soils; and these properties in relation to the use and management of soils and in relation to natural processes and events.[156]

List of Acronyms

ARS	Agricultural Research Service
CENRS	Committee on Environment, Natural Resources, and Sustainability
CMIP5	Coupled Model Intercomparison Project Phase 5
CoCoRaHS	Community Collaborative Rain, Hail, and Snow Network
CPP	Clean Power Plan
CRP	Conservation Reserve Program
DOE	Department of Energy
EcoINFORMA	Ecoinformatics-based Open Resources and Machine Accessibility
EPA	Environmental Protection Agency
FACE	Free-Air Carbon Dioxide Enrichment
FAO	United Nations Food and Agriculture Organization
FIA	Forest Inventory and Analysis
GCM	Global Circulation Model
GLOBE	Global Learning and Observation to Benefit the Environment
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
IRP	International Resources Panel
ISCN	International Soil Carbon Network
ITPS	Intergovernmental Technical Panel on Soils
LCC	Landscape Conservation Cooperative
LTAR	Long-Term Agrosystem Research
LTER	Long-Term Ecological Research
NASA	National Aeronautics and Space Administration
NCSS	National Cooperative Soil Survey
NEON	National Ecological Observatory Network
NIFA	National Institute of Food and Agriculture
NRCS	Natural Resources Conservation Service
NRI	National Resources Inventory
NSF	National Science Foundation

NSTC	National Science and Technology Council
ROOTS	Rhizosphere Observations to Optimize Terrestrial Sequestration
RUSLE, RUSLE2	Revised Universal Soil Loss Equation
SES	Subcommittee on Ecological Systems
SMAP	Soil Moisture Active-Passive [Satellite]
SPRUCE	Spruce-Peatland Response Under Climate and Environmental Change
SSIWG	Soil Science Interagency Working Group
SSSA	Soil Science Society of America
SSURGO	Soil Survey Geographic Database
STATSGO	State Soil Geographic Database
UNCCD	United Nations Convention on Combatting Desertification
UNEP	United Nations Environmental Program
USDA	U.S. Department of Agriculture
USGCRP	U.S. Global Change Research Program
WEPP	Water Erosion Prediction Project

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