Soils: A Contemporary Perspective

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Abstract

Soils are viewed in the context of ecosystem services, soil processes and properties, and key attributes and constraints. The framework used is based on the premise that the natural capital of soils that underlies ecosystem services is primarily determined by three core soil properties: texture, mineralogy, and soil organic matter. Up-to-date descriptions and geographical distribution of soil orders as well as soil attributes and constraints are given, along with the relationships between soil orders, properties, and biomes. We then relate ecosystem services to specific soil processes, soil properties, and soil constraints and attributes. Soil degradation at present is not adequately assessed and quantified. The use of an approach combining digital soil maps, pedotransfer functions, remote sensing, spectral analysis, and soil inference systems is suggested for simultaneous characterization of various chemical, physical, and biological properties to overcome the great limitations and costs of conventional methods of soil assessments.

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INTRODUCTION

Soils are a key resource in the production of food, feed, fiber, and fuels, and they also play a central role in determining the quality of our environment. Soil nutrients and water, solar energy, and carbon dioxide (CO_2) are converted through plant uptake and photosynthesis into plant products that feed animals and humans and provide them with fiber and fuels. Soils store water [so-called "green water" (1)] from rainfall and irrigation and hold nutrients added from organic or mineral sources, releasing them at rates that sustain plant growth. Soil biota decomposes organic materials, cycles nutrients, and regulates gas fluxes to and from the atmosphere. Soils filter nonhazardous as well as toxic substances through clay surface adsorption and precipitation reactions that determine the quality of surface waters. These soil functions that benefit humankind are referred to as ecosystems services (2).

Ecosystem services: as related to soil, are those soil processes that benefit humankind

Soils deliver provisioning, regulatory, cultural, and supporting ecosystem services. The provisioning of food from crops and livestock grown on soils has increased by 170% in the past four decades (1961–2003), the production of timber by 60%, and the production of fuels (mainly for firewood) and fibers (cotton, wool, flax, hemp, sisal, and jute) has probably increased by similar magnitudes (3). These large increases in production, however, have come with trade-offs that include the degradation of soils and many of the regulatory and supporting services they provide (3), such as the regulation of hydrological and nutrient cycles. These trade-offs between provisioning and regulation services will ultimately undermine the ability of the ecosystems to provide food, fuel, fiber, and water.

At the same time, the world is committed to meeting the Millennium Development Goals (MDGs) (4). Achieving many of the MDGs depends directly or indirectly on the ecosystem services of soils. Examples include (*a*) reducing hunger (MDG 1), which depends directly on the provisioning services of soils that in turn depend on nutrient cycling, a supporting ecosystem service; and (*b*) increasing access to clean water and sanitation (MDG 7), particularly for people living in rural areas, which depends directly on the soil's regulatory services of filtering and detoxifying water. Many of the health-related MDGs are indirectly related to the services of soils (5); malnutrition, related to insufficient food, reduces the immune system making people more susceptible to infectious diseases such as malaria and the earlier onset of HIV/AIDS. The ability of soils to deliver the ecosystem services required to meet the MDGs depends on meeting MDG 7: to integrate the principles of sustainable development into country policies and programs and reverse the loss of environmental resources. This will require substantial efforts in better management, as well as the rehabilitation, of soils to continue to provide these essential ecosystem services for an increasing population.

The purpose of this review is to put key aspects of our knowledge of soils into a contemporary context relevant to the concept of ecosystem services, the Millennium Ecosystems Assessment (2, 3), and the challenge to meet the MDGs (4, 6, 7).

Soils differ in their properties—their resource endowment or natural capital, the rate of soil processes, and the ecosystem services they provide as well as in their vulnerability and resilience to degradation. We present a review of (*a*) the different soils and the key properties that distinguish them and (*b*) their distribution by broad geographical regions and by biomes. Then we describe the links between soil properties, soil processes, and ecosystem services, and how these relationships differ among soils. We finish the chapter with soil degradation, its causes, and the processes involved and also include the past problems and recent approaches of estimating soil degradation and its impacts on ecosystem services.

FRAMEWORK AND BACKGROUND DEFINITIONS

The framework for discussing and comparing soils is based on our premise that the natural capital of soils that underlies ecosystem services is primarily determined by three core soil properties: texture, mineralogy, and soil organic matter. These key soil properties are in turn determined by the variety of conditions under which they are formed, the state factors of soil formation: climate, organisms, topography, parent material, and time (8–11). Soil texture and mineralogy are inherent properties of the soil that do not generally change with changes in land use and management, although topsoil texture can be altered by erosion. Soil organic matter levels in well-drained conditions are determined by soil texture and mineralogy but change dramatically with land use and management. Secondary soil properties, such as aggregation, bulk density, nutrient ions, and pH are determined by the combination of these core soil properties, and they

can be modified by management and thus impact ecosystem services.

This overarching framework we propose does not ignore the facts that soils are an integral part of ecosystems, natural and managed, and that many soil processes occur as part of larger ecosystem processes. These linkages are essential and explicit in the soil forming factors. For thorough discussions on the links and feedbacks between soils, vegetation, and ecosystem processes, we refer the reader to References 9, 11–15. Nor are we downplaying the role of soil biota as a determinant of many soil processes. We do not, however, discuss soil biota explicitly or the larger issue of soil biodiversity and ecosystem function; for this we refer the reader to References 16–21.

Soil texture determines the surface area and, to a large extent, the pore space of soils. It thus directly influences many other soil properties and can be considered an indicator of many ecosystem processes (22). Texture determines soil bulk density, total soil porosity, and pore size distribution, which in turn affect the total and available water-holding capacity, hydraulic conductivity, and the oxidation-reduction status. These combined properties affect the movement of water in the soil, chemical and biological transformations, and the exchange of gases with the atmosphere. Texture is a primary determinant of soil organic matter content, except in waterlogged soils.

Mineralogy includes both primary minerals in the sand and silt fractions and secondary minerals in the clay fraction (23). Mineralogy determines inherent soil fertility through the type of weatherable minerals present in the sand and silt fractions of the soil and the number of ion exchange sites on the clay minerals (24, 25). Primary minerals in the soil are determined by the parent material (geology). The weatherable primary minerals (feldspars, micas, volcanic glass, olivine, apatite, and others) provide the reservoir of all nutrients, except nitrogen (N), that are made available to plants in time. Other primary minerals such as quartz contain no weatherable nutrients. Secondary

Soil processes: relate to inputs, losses, and transfers of material and energy within the soil or dependent on the soil

minerals are those formed in the soil through weathering processes and occur in the clay fraction. They can be classified in two groups: those with permanent charge, whose ECEC (effective cation exchange capacity) does not change with pH, and those with variable charge, where ECEC increases with increasing soil pH. The main permanent charge clay minerals in order of descending ECEC are smectites, chlorites, vermiculites, hydroxy-interlayered minerals, and hydrous micas. The main variable charge clay minerals, again in descending order of ECEC are allophane, imogolite, halloysite, gibbsite, goethite, ferrihydrite, kaolinite, and amorphous iron and aluminum oxides and hydroxides (26, 27). The predominant cations in soils are determined by the release of weatherable minerals and clay mineralogy. The basic cations calcium (Ca^{2+}), magnesium ion (Mg^{2+}), and potassium (K^+) are essential for plant growth, whereas the main acidic cation (Al^{3+}) is toxic to plants. Clay mineralogy also influences the soil structure, porosity, and stability through formation of microaggregates (28).

Soil organic matter is an integrator of many soil properties and can serve as an index of the capacity of the soil to provide certain processes (29, 30). The type and distribution of soil organic matter are biologically determined by the type of vegetation, climate, and soil biota. Soil organic matter content is the balance between the addition of organic inputs to the soil and decomposition by soil biota. It provides the carbon and energy for soil organisms and thus also supports the biological functions of soil. Soil organic matter is physically determined first by soil texture, which affects the surface area of the soil, and second by mineralogy, which affects the nature of organo-mineral complexes (31). Clayey soils have higher soil organic matter content than sandy soils because of higher surface area for the formation of organo-mineral complexes, and they also form more micropores where organic particles can be physically protected from decomposition. Soil organic matter is a major binding agent in the formation

of macroaggregates in 2:1 clay-dominated soils because polyvalent metal-organic matter complexes form bridges between the negatively charged 2:1 clay platelets. However, in oxide and 1:1 clay mineral-dominated soils, soil organic matter is not the only major binding agent (32); part of the soil stability in these types of soils is induced by the binding capacity of oxides and 1:1 minerals (28, 33).

Soil organic matter affects the soil's capacity to retain and release nutrients for plant growth by contributing to its ECEC and through the mineralization of organic N, phosphorus, and sulfur. Soil organic matter, along with texture, affects the soil's capacity to store and release water and affects the exchange of gases with the atmosphere by influencing the aggregation of soil particles, soil pore size distribution, and bulk density. Soil organic matter also serves in detoxification through chelation of toxic elements.

The characteristic mineralogy, texture, and soil organic matter of any specific soil begins with composition of the parent material and involves a series of biogeochemical processes including energy and water exchange as well as biocycling, which depend on the climate, vegetation type, and soil biota. Details on soil formation and the relationship of the state factors and resulting soil characteristics can be found in References 8 and 9. These three core soil characteristics are so central in defining the nature of the soil that they are also used to differentiate and classify soils.

SOIL CLASSIFICATION AND GEOGRAPHY

Soils are classified and mapped according to natural or technical classification systems. Natural systems characterize and classify soils as they exist, and technical systems classify soils according to their suitability for specific uses. Details of two commonly used natural and technical classification systems and the geographic distribution and extent of the classes from these different systems are provided below.

Soil Classification

There are two international soil classification systems: Soil Taxonomy developed by the United States Department of Agriculture (34) and the World Reference Base for soil resources that succeeds the Food and Agriculture Organization (FAO)-UN Educational, Scientific and Cultural Organization (UNESCO) classification system (35). Both systems are widely used throughout the world and are freely downloadable from the Internet. Relationships and translations between the two and other natural soil classification systems can be found in Reference 9.

Soil Taxonomy is a hierarchical system with six categories: order, suborder, great group, subgroup, family, and series. The system is based on quantitatively defined diagnostic soil horizons and measured properties that define the different classes. For the precise, highly quantitative descriptions of the soil classes readers are referred to References 9, 34, and 36. The data embedded in the taxonomic name is a useful code that defines the soil in quantitative terms. Its use, however, is often hampered by the seeming complexity of the nomenclature. An example of the information conveyed by the name is illustrated by the classification of a typical, highly weathered red soil of the humid tropics as a clayey, kaolinitic, isohyperthermic Rhodic Acrudox. This name contains the following information:

- ox = Oxisol order: The soil contains an oxic horizon with low activity clays and a low ECEC.
- ud = Udox suborder: The soil has a udic soil moisture regime, meaning the subsoil is moist for 9–12 consecutive months.
- Acr = Acrudox great group: The soil has very low ECEC and $pH_{KCl} > 5.0$.
- Rhodic = Rhodic subgroup: The soil has a deep red color (2.5YR or redder), denoting high iron oxide content.
- The three family terms are *isohyperthermic*, which indicates a hot, aseasonal soil temperature regime (>22°C mean

annual with <6°C seasonal variation); *kaolinitic*, which indicates the dominant clay mineral; and *clayey*, which indicates the soil has more than 35% clay.

Once this classification system is understood, the name imparts much about the characteristics of the soil.

FAO: UN Food and Agriculture Organization

Soil Orders and Geographical Distribution

The extent of the 12 soil orders of Soil Taxonomy and their geographical distribution were determined using the U.S. Department of Agriculture's (USDA's) Global Soil Regions data set (37), which is based on a reclassification of the FAO-UNESCO Digital Soil Map of the World combined with a soil climate map (**Table 1** and **Figure 1**) (38). The tropics, temperate, and boreal zones account for 38%, 50%, and 12% of the world's land area, respectively; however, the distribution of soils does not follow that geographic breakdown in distribution: 97%, 71%, and 65% of Oxisols, Ultisols, and Vertisols, respectively, are in the tropics, but less than 1% of Spodosols or Gelisols are in the tropics; 95% of Mollisols and 76% of Aridisols are in the temperate region; and 76% of Gelisols are in the boreal region. The distribution of other soil orders is similar in proportion to the areal coverage of those zones globally.

The distribution of soils by natural biomes (**Tables 2a** and **2b**) was obtained by overlays of the soil map with that of the world's biomes (39). Biomes are large geographic areas with similar climates and distinct groups of plants and animals. Soils and climate also interact to determine the vegetation structure and composition, and as such, relationships between soils and biomes emerge (40). In the discussion that follows, a soil order is considered prevalent in a biome if it encompasses more than 20% of the area, and highly prevalent is more than 35%. Of the 156 combinations of the 12 soil orders × 13 biomes, only two cells have prevalence higher

Table 1 Distribution of 12 Soil Taxonomy orders by major geographical region[a]

Order[b]	Tropical[c]		Temperate[c]		Boreal[c]		World	
	10^6 ha	%	10^6 ha	%	10^6 ha	%	10^6 ha	%
Entisols	1267	26.8	1055	17.1	31	2.0	2353	19.0
Inceptisols	470	9.9	1154	18.7	362	24.0	1986	16.0
Aridisols	376	8.0	1187	19.3	3	0.2	1565	12.6
Alfisols	561	11.9	736	12.0	22	1.4	1319	10.6
Gelisols	1	0.0	281	4.6	900	59.6	1181	9.5
Ultisols	757	16.0	303	4.9	0	0.0	1061	8.6
Oxisols	956	20.2	31	0.5	0	0.0	987	8.0
Mollisols	48	1.0	866	14.1	0	0.0	913	7.4
Spodosols	5	0.1	286	4.6	168	11.1	458	3.7
Vertisols	206	4.4	110	1.8	1	0.1	318	2.6
Histosols	31	0.7	100	1.6	21	1.4	152	1.2
Andisols	48	1.0	47	0.8	2	0.2	98	0.8
Total	4726	100.0	6155	100.0	1510	100.0	12392	100.0

[a]Estimates exclude areas not covered by soils (e.g., rocks, water bodies, shifting sands, ice) (38).
[b]Arranged in descending order of areal extent.
[c]Definitions: tropical, <23.5°; temperate zone, 23.6°–60°; boreal, >60°.

than 50%, underscoring the high spatial variability of soils. A short description of the soil orders in decreasing order of area coverage follows.

Entisols are the most extensive soils worldwide. They are young because of only slight horizon development and generally have high nutrient capital, being high in weatherable minerals. Exceptions are sandy Entisols with very low nutrient capital. Entisols are highly prevalent only in the desert biome and prevalent in the tropical savannas and Mediterranean biomes.

Inceptisols, the second most extensive soils, are also considered young soils with some soil horizonation and high nutrient capital, except for sandy infertile ones. Inceptisols are prevalent in boreal forests, temperate coniferous forests, temperate mixed forests, montane grasslands, Mediterranean and tropical/subtropical coniferous forests.

It is interesting to note that the two "youngest" soil orders are the most extensive, covering 35% of the world's land area; this is due in part to the natural erosion and sedimentation processes occurring, both of which counteract the formation of soil horizons and

aging. Many are alluvial, in fertile river valleys, and are the best agricultural soils as well as where much of the Green Revolution in Asia, Latin America, and the Middle East took place. Texture, soil organic matter, and clay mineralogy in Entisols and Inceptisols vary considerably. With climatic change-induced rainfall variability and intensity, many Entisols and Inceptisols located on alluvial plains may be more susceptible to droughts, floods, and river erosion, which may have broad implications for food production.

Aridisols, the third most extensive soil order, are the soils of deserts with some horizon differentiation. They are usually high in weatherable minerals, but low in soil organic matter, and variable in texture and clay mineralogy. They are highly prevalent only in desert biomes, are not prevalent elsewhere, but include many saline and alkali soils of nondesert regions. Many Aridisols are irrigated and thus vulnerable to increasing salinity as the good aquifers become depleted and saline waters replace them.

Alfisols are deep, have high nutrient capital, are not acid and are therefore of generally high fertility. Topsoil texture varies, and clay

Nutrient capital:
the stocks of N, P, K, Ca, Mg, S, Fe, Mn, Zn, B, Mo in the topsoil and subsoil. Nutrient capital is found in the weatherable minerals and in soil organic matter

mineralogy is mixed with both permanent and variable charged clays. Alfisols cover much of the farmlands in previously forested parts of midwestern North America, Europe, and Russia, as well as much of subhumid and semi-arid tropical Africa and India. Alfisols are not highly prevalent in any biome but are prevalent in 5 of the 13 biomes: flooded grasslands and savannas, temperate broad-leaved and mixed forests, tropical/subtropical dry broad-leaved forests, tropical/subtropical coniferous forests, and Mediterranean biomes. Alfisols in tropical Africa are increasingly threatened by nutrient depletion (5, 41, 42), more frequent droughts in Southern Africa, and more intense erosion caused by increasingly erratic rainfall variability.

Gelisols are soils with permafrost found in boreal regions and near glaciers in high mountains, even in the tropics. Gelisols are highly prevalent in the tundra and montane grassland/shrubland biomes and prevalent in the boreal forests/taiga. They vary in texture and mineralogy but have high soil organic matter contents. These soils are severely threatened by global warming. The combination of high soil organic matter content and the extensive coverage of these soils will result in the release of large amounts of CO_2 as the soils warm and decomposition rates increase (9).

Ultisols look similar to Alfisols but are acid and have low nutrient capital, and clay mineralogy is dominated by variable charge, 1:1 clays. Ultisols are common throughout the humid and subhumid tropics as well as nonglaciated temperate regions, such as the southeastern United States and southeastern China. They are only prevalent in the tropical/subtropical moist broad-leaved forest biome. Over half of the Ultisols are found in the tropical/subtropical moist broad-leaved forest biome and another 20% in tropical savanna biome.

Oxisols, the stereotypic tropical soils, without contrasting horizons, are similar to Ultisols in that they are acid, have low nutrient capital and have 1:1 clays, iron, and aluminum oxides. Oxisols have similar soil organic matter content to temperate Mollisols (43). They occupy 20% of the tropics, virtually all in the humid and subhumid tropics. Oxisols are prevalent only in the tropical/subtropical moist broad-leaved forest biome and the tropical/subtropical savanna biome, including the Brazilian Cerrado (44). Sixty-five percent of the Oxisols are located in the tropical/subtropical moist broad-leaved forest and another 33% in tropical savanna biome. Many of the Ultisols and Oxisols in the tropics are under natural forest; once the land is cleared for cultivation, they quickly lose soil organic matter and soil fertility; and unless they are put under tree-based cropping systems, they require intensive fertilization and often liming. Oxisols are less vulnerable to erosion than Alfisols and Ultisols owing to their stable aggregate structure (26). Extensive areas under Oxisols and Ultisols in the Amazon Basin are predicted to become drier with changing climate.

Mollisols are the stereotypic black soils of the temperate zone grasslands of the U.S. Midwest, Russian heartland, and Pampas of Argentina. They are high in topsoil organic matter and high in nutrient capital and have permanent-charge clay minerals. They are excellent soils both in terms of fertility and physical properties. They are highly prevalent in the temperate grassland/shrubland biome, but they are not prevalent in the other biomes. This stereotypic temperate soil accounts for only 14% of the temperate region, but 58% of Mollisols are located in temperate grasslands and another 14% in temperate broad-leaved forests. Mollisols are being degraded through severe erosion losses in the intensively farmed areas of the U.S. Midwest.

Spodosols, also known as podzols, are the typical sandy soils of northern temperate regions such as northeastern North America and Scandinavia, usually developed under coniferous forests. Spodosols are both acid and infertile and have low nutrient capital. They are prevalent in the boreal forest/taiga biome. Although Spodosols cover only 0.2%

Table 2a Distribution of 12 Soil Taxonomy orders by 13 major biomes[a]

Order	Tropical/ subtropical moist broadleaf forest[b,c]		Tropical/ subtropical dry broadleaf forest		Tropical and subtropical coniferous forest		Temperate broadleaf and mixed forest		Temperate coniferous forest		Boreal forest/taiga		Tropical and subtropical grassland, savanna, shrubland	
	10^6 ha	%	10^6 ha	%	10^6 ha	%	10^6 ha	%	10^6 ha	%	10^6 ha	%	10^6 ha	%
Entisols	179	9	55	15.3	10	14	157	12.4	32	8.2	33	2.3	598	32
Inceptisols	341	17.1	58	16.1	17	24.9	385	30.4	131	33.4	531	36.2	90	4.8
Aridisols	7	0.3	18	4.8	1	2.1	17	1.3	29	7.3	13	0.9	169	9
Alfisols	131	6.6	88	24.3	15	21.3	309	24.4	47	12	130	8.9	324	17.3
Gelisols	0	0	0	0	0	0	1	0.1	16	4	359	24.5	0	0
Ultisols	599	30	49	13.6	6	8.3	114	9	47	12.1	0	0	215	11.5
Oxisols	638	32	11	3.1	0	0.2	2	0.2	0	0	0	0	322	17.2
Mollisols	23	1.2	30	8.2	10	15	126	10	39	10	14	1	22	1.2
Spodosols	5	0.2	0	0	0	0	104	8.2	34	8.8	284	19.3	0	0
Vertisols	26	1.3	44	12.2	1	1.5	14	1.1	0	0.1	1	0.1	129	6.9
Histosols	25	1.3	1	0.2	0	0.4	17	1.3	5	1.2	88	6	2	0.1
Andisols	20	1	8	2.3	9	12.3	18	1.4	12	3	12	0.8	1	0.1
Total	1995	100	362	100	69	100	1264	100	392	100	1466	100	1870	100

[a]Estimates exclude areas not covered by soils (e.g., rocks, water bodies, shifting sands, ice) (38, 39).

[b]Definitions: tropical, <23.5°; temperate zone, 23.6°–60°; boreal, >60°.

[c]The mangrove biome is not included because its resolution was not good enough to separate actual mangroves from adjacent areas.

Table 2b   Distribution of 12 Soil Taxonomy orders by 13 major biomes[a]

Order	Temperate grassland, savanna, and shrubland		Flooded grassland and savanna		Montane grassland and shrubland		Tundra		Mediterranean forest, woodland, and shrub		Deserts and xeric shrubland		World	
	10^6 ha	%	10^6 ha	%	10^6 ha	%	10^6 ha	%	10^6 ha	%	10^6 ha	%	10^6 ha	%
Entisols	115	12	21	19.3	57	12.8	9	1.2	75	23.4	999	43.4	2353	19
Inceptisols	63	6.6	14	13	117	26.5	128	16.1	81	25.1	23	1	1985	16
Aridisols	169	17.6	11	10.3	40	9.1	0	0	53	16.5	1036	45	1564	12.6
Alfisols	67	6.9	35	32	31	6.9	0	0	76	23.5	64	2.8	1319	10.7
Gelisols	3	0.3	0	0	155	35	630	79.1	0	0.1	11	0.5	1175	9.5
Ultisols	2	0.2	1	1.3	11	2.5	0	0	1	0.3	13	0.6	1061	8.6
Oxisols	0	0	2	1.6	7	1.5	0	0	0	0	4	0.2	987	8
Mollisols	512	53.3	6	5.8	9	2.1	0	0	20	6.1	102	4.4	913	7.4
Spodosols	0	0	0	0.1	0	0	26	3.3	5	1.5	0	0	458	3.7
Vertisols	25	2.6	15	13.9	7	1.6	0	0	9	2.7	45	1.9	318	2.6
Histosols	4	0.4	3	2.7	2	0.5	0	0	0	0	2	0.1	152	1.2
Andisols	1	0.1	0	0	7	1.5	3	0.4	3	0.8	3	0.1	97	0.8
Total	961	100	109	100	442	100	796	100	323	100	2303	100	12,382	100

[a]See the footnotes in Table 2a for details.

of the tropical/subtropical moist broadleaf forest biome, they received disproportionate attention in early nutrient cycling studies (45), leading to several misconceptions about soils of the humid tropical forests (46).

Vertisols are the clayey, black soils that crack when dry and swell when wet. They have difficult physical properties but high nutrient capital and permanent-charge clay minerals. Soil organic matter contents are not high in spite of their clayey textures. They cover large areas of Texas and Mexico, much of central India, tropical Australia, and the Ethiopian highlands. They are not prevalent in any biome but are associated with tropical/subtropical dry broad-leaved forests and flooded grasslands and savannas, systems that have distinct wetting and drying cycles.
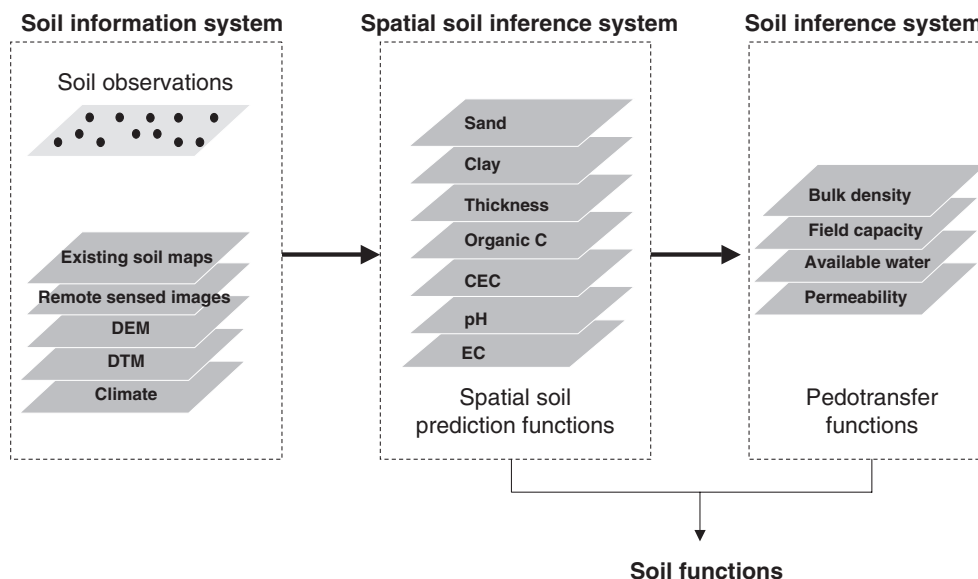
Histosols are organic or peat soils, with more than 12% organic carbon in the topsoil. They are wet, have low bulk density, subside when drained and because of their high organic content usually have low nutrient capital reserves and exhibit pronounced N and copper deficiencies. The concept of texture is not relevant in Histosols. They are found in boreal regions of Canada, Finland, and Russia, and they also occur in Florida, North Carolina, and Indonesia. Histosols are currently threatened by expansion of agriculture in Indonesia, which contains large expanse of peatlands. With prolonged droughts caused by El Niño, these peats are also drying and catching fire from land-clearing activities; both the expansion of agriculture and burning of peat release of large amounts of CO_2 to the atmosphere (47).

Andisols, the least extensive soil order, develop from volcanic materials. They usually have excellent physical properties and high nutrient capital. The high phosphorus retention of the noncrystalline minerals results in phosphorus deficiencies, although they support intensive agriculture. These young, fertile soils support some of the highest rural population densities. Andisols are not prevalent in any biome but occupy 12% of the tropical/subtropical coniferous forests along volcanic mountain chains around the Pacific Basin "ring of fire."

Limitations of soil maps. Maps and tabular data of soil taxonomic groups are useful for making broad distinctions among soil types and provide general trends at the global and regional scales but have limitations when applied at higher levels of resolution. Soils mapped at the 1:5 million scale are based on the dominant soil unit, even though the area is comprised of many soil types, thus overestimating the extent and importance of the dominant soil. Many of these polygon maps are also quite old and are based on very few soil profiles. The South America sheet of the world soil map was published in 1970, with very limited observations of remote areas in the western Amazon in Brazil and Peru. These areas were mapped as Oxisols, whereas recent maps at much higher resolution show that there are essentially no Oxisols in the Amazon of Peru. There are large areas of many countries, particularly in the tropics, where soil units are not based on even a single soil profile. Legacy data sets can be found throughout the tropics and elsewhere, but the amount of effort needed to find, evaluate, and digitize this information must be balanced against the quality and age of the data (48). The most useful maps for management are at resolutions of 1:50000 or 1: 25000 and exist for only a few countries such as the United States and Cuba.

Within the past decade, there has been considerable progress in assessing soil properties by data generated from remote and on-ground sensors and in prediction of soil types and properties by combining geospatial soil information with digital elevation models, remote sensing images, and existing soil maps (**Figure 2**) (49, 50). Soil properties for large areas can thus be predicted and mapped using regression, kriging, or a combination of both. The spatially inferred soil properties can then be used to predict soil properties, such as field capacity and available water capacity, using pedotransfer functions. Such products could be useful for modeling individual and

Soil information system

Soil observations

Existing soil maps
Remote sensed images
DEM
DTM
Climate

Spatial soil inference system

Sand
Clay
Thickness
Organic C
CEC
pH
EC

Spatial soil
prediction functions

Soil inference system

Bulk density
Field capacity
Available water
Permeability

Pedotransfer
functions

Soil functions

Figure 2

Information and processes for digital soil mapping. Adapted from Reference 50. Abbreviations: CEC, cation exchange capacity; DEM, digital elevation model; DTM, digital terrain model; EC, electrical conductivity.

integrated soil functions over broader areas. Examples of these digital soil maps and the methods used to construct them can be found in References 51 and 52. Such digital soil maps are pixel based, in comparison with digitized soil maps, which remain polygon based. Efforts to produce a digital soil map at sufficient resolution are essential to increase our capacity to use information on the distribution of soil properties and processes at landscape and larger levels for modeling ecosystem processes.

Soil Attributes and Constraints

Soil Taxonomy is based on more permanent soil properties mostly located in the subsoil; therefore, it does not capture the dynamic soil parameters or features of the topsoil that are crucial to plant productivity and so has limited use for land use and management considerations. The fertility capability classification (FCC) system was developed 30 years ago to interpret the soil profile descriptions used in soil taxonomy in terms of

soil constraints for crop production (53), and although it is also based on the more permanent soil properties, it does focus on the topsoil. It is now widely used (54, 55).

A digitized soil FCC map and database was constructed (38) with the ISRIC-WISE-2 soil attribute database (56), the FAO soil map, and the latest version of the FCC system (57). The extent of the FCC soil attributes or constraints is shown by regions in **Table 3** and by biomes in **Tables 4a** and **4b**. Although originally designed for constraints to crop production, its use in assessing other soil processes and ecosystem services is explored. Soil attributes and constraints can be divided into physical and chemical groupings; however, the only biological attribute included in FCC is soil organic carbon saturation. The top category for classification in FCC is topsoil texture, indicating the overriding importance of this property to soil functions.

The FCC attributes are described in descending order of areal extent by region and biome. Detailed descriptions including quantitative definitions can be found in

FCC: fertility capability classification system

Soil attributes and constraints: properties of soils that effect soil processes and ecosystem services

Table 3 Distribution of soil attributes by latitudinal belt[a,b]

Attributes and constraints[c]	Tropical[d]		Temperate[d]		Boreal[d]		Total area under each attribute[e]	
	%	10^6 ha	%	10^6 ha	%	10^6 ha	%	10^6 ha
Soil moisture stress d	43.6	2154.9	20.9	1381.4	0.3	4.8	27.1	3541.1
Aridic d+	25.8	1272.7	38.4	2535.6	0.2	3.6	29.2	3811.9
High erosion risk y	15.4	758.1	18.1	1194.0	17.3	264.0	17.0	2216.1
Low nutrient capital reserves k	36.5	1803.5	9.9	652.6	7.7	116.9	19.7	2573.0
Calcareous b	6.9	342.4	22.2	1464.1	2.7	40.6	14.1	1847.0
Permafrost t+	0.3	12.7	12.2	805.1	84.7	1289.4	16.1	2107.2
Aluminum toxic a	27.8	1374.6	7.7	507.4	5.9	90.4	15.1	1972.3
Cold t	0.4	20.9	17.7	1168.4	11.2	170.4	10.4	1359.7
Waterlogged g	8.5	419.0	9.6	634.7	34.3	522.2	12.1	1576.0
High P fixation i	10.5	519.8	1.7	112.6	0.0	0.0	4.8	632.4
High leaching potential e	9.0	443.2	1.8	117.7	0.0	0.1	4.3	561.0
High organic content O	0.9	44.6	2.4	160.9	12.7	194.2	3.1	399.7
Cracking clays v	4.5	220.2	1.6	104.2	0.0	0.7	2.5	325.1
Sodic n	1.6	81.3	3.0	197.0	0.3	4.4	2.2	282.7
Saline s	0.7	35.3	2.4	157.5	0.0	0.0	1.5	192.8
Volcanic x	0.5	24.2	0.5	33.1	0.0	0.3	0.4	57.6
Sulfidic c	0.3	12.5	0.0	0.5	0.0	0.0	0.1	13.1

[a]Arranged in descending order of world total.

[b]Estimates exclude areas not covered by soils (e.g., rocks, water bodies, shifting sands, ice).

[c]Letters are the FCC modifier symbols (33).

[d]Definitions: tropical, <23.5°; temperate zone, 23.6°–60°; and boreal, >60°.

[e]The sum of percentages exceeds 100 because a single soil usually has more than one attribute.

Reference 57. Only attributes covering 10% or more of one of the regions are described in detail below. Maps indicating the global distribution of the soil constraints are available at **http://sedac.ciesin.columbia.edu/soils/fcc**.

Soil Physical Attributes

Soil physical attributes, in addition to texture, are related to climate (specifically temperature and moisture regimes) and topography. One additional physical constraint, soil cracking, is related to the soil mineralogy.

Seasonal soil moisture stress (d modifier) and aridity (d+ modifier). Lack of available water in the soil during parts of the year is the most extensive soil constraint for plant growth, encompassing about 57% of the world's soils; some of these soils have enough water for one annual rain-fed crop (seasonal soil moisture stress), and others require irrigation to grow any crop (aridity). Dryness is influenced by soil texture, depth of the moisture control section, and related soil water-holding capacity, meaning that some soils are dry while others are not under the same rainfall (34).

The presence of dry seasons longer than three months characterizes subhumid and semiarid climates and is a constraint to crop production in about 44% of soils in the tropics and 21% in the temperate region. Biomes with high prevalence (>35%) of seasonal soil moisture stress are: tropical/subtropical dry broadleaf forest, including most of unimodal subhumid tropical Africa in

the Miombo woodlands, Mediterranean, tropical/subtropical savannas, flooded grasslands/savannas, and tropical/subtropical coniferous forests. More than a quarter of the tropical/subtropical moist broadleaf forest biome even has the soil dry for more than three months. The soils of the eastern and southern Amazon Basin have seasonal moisture stress, whereas the western Amazon does not (58).

Seasonal moisture stress affects not only crop growth but also rates of primary production, soil microbial activity, and soil pest and disease life cycles. When dry seasons fail to occur, pest attacks can be stronger in the following planting season. Long dry seasons in the tropics slow down N mineralization and leaching. When the rains come, there is a flush of N mineralization, producing ammonium and nitrate ions that young plants can readily utilize (59).

About 29% of the world's soils are arid, with higher prevalence in the temperate zone (38%) than in the tropics (28%). Biomes with high prevalence of aridity are deserts and temperate grasslands; aridity is prevalent in the Mediterranean and the tropical/subtropical savannas.

High soil erosion risk (y modifier).

Whereas all soils, even flat ones are susceptible to wind and water erosion, only 20% are at a high risk of erosion that can result in loss of fertile topsoil, affecting watershed stability, sedimentation, and subsequent eutrophication of rivers and lakes. Erosion can continue in these high risk soils even under natural vegetative cover. Once the vegetation is removed, erosion is excessive, and soils on less steep slopes also become susceptible. It is also important to realize that erosion is a natural process that produces fertile alluvial soils with high productivity, which is where most civilizations first settled (60).

Over half the biomes have soils with a prevalence of high erosion risk: tropical/subtropical coniferous forest, temperate coniferous forest, temperate broadleaf and mixed forest, tropical/subtropical moist broadleaf forest, montane grassland and shrubland, tropical/subtropical dry broadleaf forest, and Mediterranean biomes.

Permafrost (t+ modifier) and cold soils (t modifier).

Soils that are frozen throughout the year occupy 16% of the land area (2.1 billion hectares), the bulk of them are in the boreal region, but they also occur at high altitudes in the temperate region and even in 12 million hectares in the tropics. They dominate the tundra and the boreal forest/taiga biomes.

Cold soils cover 10% of the world, are highly prevalent in the temperate coniferous forest biome (49%), and are prevalent in the boreal forest/taiga, temperate grasslands, montane grasslands, and temperate broadleaved/mixed forest biomes. These soils support slow plant growth, microbial activity, and nutrient cycling in spite of favorable soil moisture or fertility but, as with permafrost soils, are susceptible to global warming.

Waterlogged soils (g modifier).

Poorly drained soils cover 10% of the world's land area and are more prevalent in the boreal zone (34%) than in the temperate and tropical zones (9% and 6%, respectively). Waterlogged soils are highly prevalent in mangroves and prevalent in the tundra, boreal forests/taiga, and flooded grassland savannas. These soils are chemically reduced and have many different biogeochemical processes compared to soils in the oxidized state (61); they are also a primary source of methane. In Asia, many of these soils have been converted to rice paddies and to aquaculture, supporting intensive agriculture. Others remain as natural wetlands but are threatened by urbanization, eutrophication, and large-scale engineering projects.

Soil Chemical Attributes

Soil chemical attributes are related to mineralogy and soil texture as well as to the degree

Table 4a Distribution of soil by biomes[a,b]

Attributes and constraints[c]	Tropical/ subtropical moist broadleaf forest[d] %[e]	Tropical/ subtropical moist broadleaf forest[d] 10⁶ ha	Tropical/subtropical dry broadleaf forest %	Tropical/subtropical dry broadleaf forest 10⁶ ha	Tropical and subtropical coniferous forest %	Tropical and subtropical coniferous forest 10⁶ ha	Temperate broadleaf and mixed forest %	Temperate broadleaf and mixed forest 10⁶ ha	Temperate coniferous forest %	Temperate coniferous forest 10⁶ ha	Boreal forest/taiga %	Boreal forest/taiga 10⁶ ha	Tropical and subtropical grassland, savanna, shrubland %	Tropical and subtropical grassland, savanna, shrubland 10⁶ ha
Seasonal soil moisture stress d	26	519	79.5	288	50.1	35	23.9	304	25.2	101	7	103	63.6	1244
Aridic d+	0.7	15	12.1	44	7.3	5	3.3	42	14.1	56	1.8	26	24.4	477
High soil erosion risk y	18.7	374	16.9	61	41.1	28	17.9	228	31.6	127	15	222	12.1	236
Low nutrient capital reserves k	53	1057	14.6	53	6.9	5	15.8	201	19.5	78	14.8	219	37.1	726
Calcareous b	2.1	41	16.1	58	5.9	4	12.2	156	8.5	34	3.8	56	7	137
Permafrost t+	0	1	0	0	0	0	1.2	15	18.6	75	68.8	1019	0	0
Aluminum toxic a	50.1	999	12.2	44	6.9	5	14.3	182	16.9	68	13	193	21.6	423
Cold t	0.1	1	0	0	0.2	0	20.3	259	39.8	160	29.2	432	0	0
Waterlogged g	12.2	243	8.6	31	2.8	2	18.2	231	8.9	36	31.6	468	7.2	141
High P fixation i	21.1	421	4.3	16	2.3	2	1.5	19	0.3	1	0	0	8	157
High leaching potential e	3.4	68	2	7	0	0	0.4	5	0	0	0	0	15.8	310
High organic content O	1.6	32	0.2	1	0.5	0	2.1	26	2.1	8	15.6	231	0.4	8
Cracking clays v	1.6	33	13.5	49	2.4	2	0.9	12	0.3	1	0	1	6.3	123
Sodic n	0.2	4	3.9	14	0.1	0	1.5	19	0.1	0	0.3	5	3	59
Saline s	0.4	7	0.8	3	0	0	0.6	8	0.3	1	0	0	0.7	14
Volcanic x	0.8	17	0.5	2	2.1	1	1.5	19	0.5	2	0.4	7	0.1	2
Sulfidic c	0.4	8	0.2	1	0.1	0	0	0	0	0	0	0	0	1

[a]Estimates exclude areas not covered by soils (e.g., rocks, water bodies, shifting sands, ice) (38, 39).

[b]The mangrove biome is not included because its resolution was not good enough to separate actual mangroves from adjacent areas.

[c]The letters in the first column are the FCC modifier symbols (57).

[d]Definitions: tropical, <23.5°; temperate zone, 23.6°–60°; boreal, >60°.

[e]The sum of percentages of all attributes exceeds 100 because a single soil usually has more than one attribute.

Table 4b   Distribution of soil by biomes[a,b]

Attributes and constraints[c]	Temperate grassland, savanna, and shrubland[d] %[e]	Temperate grassland, savanna, and shrubland[d] 10^6 ha	Flooded grassland and savanna %	Flooded grassland and savanna 10^6 ha	Montane grassland and shrubland %	Montane grassland and shrubland 10^6 ha	Tundra %	Tundra 10^6 ha	Mediterranean forest and scrub %	Mediterranean forest and scrub 10^6 ha	Deserts and xeric shrubland %	Deserts and xeric shrubland 10^6 ha	Total area under each attribute[f] %	Total area under each attribute[f] 10^6 ha
Seasonal soil moisture stress d	32.3	323	50.7	54	18.3	92	0	0	73.7	239	8.1	223	27.1	3541
Aridic d+	48.5	486	13.2	14	16.2	81	0	0	21.5	70	90.3	2493	29.2	3811
High soil erosion risk y	9.6	96	12.6	13	29.9	150	24.6	199	27.8	90	14.1	389	17	2215
Low nutrient capital reserves k	0.7	7	9.4	10	3.2	16	2.1	17	4.9	16	6	166	19.7	2573
Calcareous b	42.8	428	24.2	26	9.4	47	2.2	18	28.9	94	26.9	742	14.1	1847
Permafrost t+	5.7	57	0.5	1	38.4	193	88.5	715	0.2	1	1.1	31	16.1	2106
Aluminum toxic a	0.3	3	2.5	3	2.2	11	1.8	15	1.8	6	0.7	19	15.1	1972
Cold t	26.4	264	10	11	22.6	114	4.9	39	1.1	4	2.7	76	10.4	1359
Waterlogged g	6.7	67	32.7	35	3.5	18	30.5	247	2.5	8	1.3	35	12.1	1576
High P fixation i	0	0	1.1	1	1.5	8	0	0	0.2	1	0.2	7	4.8	632
High leaching potential e	0.3	3	6.5	7	1	5	0	0	2.9	9	5.3	146	4.3	561
High organic content O	0.7	7	5.3	6	1.5	7	8.6	70	0	0	0.1	2	3.1	400
Cracking clays v	1.8	19	12.1	13	1.8	9	0	0	3.4	11	1.9	54	2.5	325
Sodic n	6.5	66	5	5	0.8	4	0	0	6.8	22	3	84	2.2	283
Saline s	2.7	27	5.9	6	1.6	8	0	0	1.8	6	3.9	109	1.5	193
Volcanic x	0	0	0	0	0.5	2	0.5	4	0.6	2	0	0	0.4	58
Sulfidic c	0	0	0.2	0	0	0	0	0	0	0	0	0	0.1	13

[a]Estimates exclude areas not covered by soils (e.g., rocks, water bodies, shifting sands, ice) (38, 39).

[b]The mangrove biome is not included because its resolution was not good enough to separate actual mangroves from adjacent areas.

[c]The letters in the first column are the FCC modifier symbols (57).

[d]Definition: temperate zone, 23.6°–60°.

[e]The sum of percentages of all attributes exceeds 100 because a single soil usually has more than one attribute.

[f]The total area under each attribute column does include the area under the mangrove biome as mapped.

of weathering, which affects loss or accumulation of exchangeable ions.

Low nutrient capital reserves (k modifier).

About 36% of tropical soils have less than 10% reserves of weatherable minerals in their sand and silt fractions; in contrast, most soils in the temperate (90%) and boreal (92%) zones still have high nutrient capital reserves (**Figure 3**). Although highly prevalent in the tropics, these soils show highest prevalence in the tropical/subtropical moist broadleaf forest (53%), tropical/subtropical grasslands, savannas, and shrubland (37%); but they show low prevalence in the tropical/subtropical dry broadleaved forests and the tropical/subtropical coniferous forest. As such, this modifier is useful for indicating highly weathered soils in the humid and subhumid tropical regions and is often associated with kaolinitic and oxidic clay mineralogy.

The other source of nutrient capital reserve is soil organic matter, which contains all the N and much of the phosphorus and sulfur capital of soils. There is currently no quantitative definition for organic N capital, although soils with high nutrient capital often have high quantities of soil organic N.

Calcareous reaction (b modifier).

These young soils are high in nutrient capital but are often deficient in micronutrients, particularly iron and zinc, and have imbalances between potassium, calcium (Ca), and magnesium, which can affect plant production. Calcareous soils are highly prevalent in temperate grasslands and prevalent in the Mediterranean, desert, and flooded grasslands.

Aluminum toxicity (a modifier).

High levels of aluminum on cation exchange sites and in the soil solution is the main component of soil acidity. Generally associated with highly weathered soils with small amounts of basic cations, the result is aluminum levels that are toxic for most crop species (62). This constraint is usually identified with a soil pH value less than 5.5 and is highly correlated with soils having low nutrient capital reserves.

About 27% of soils in the tropics, but less then 10% of the temperate and boreal soils, exhibit this constraint. Aluminum toxicity is highly prevalent in the tropical/subtropical moist broad-leaved forest biome and prevalent in the tropical/subtropical savanna biome. Aluminum toxicity is usually the overwhelming constraint to crop agriculture in these soils.

High phosphorus fixation (i modifier).

High phosphorus fixation by iron and aluminum oxide is found in only 5% of the world's soils and is usually considered typical of tropical soils, even though only 10% of the tropical soils have the constraint. These soils are usually red or yellowish. Most sandy red soils do not fix significant quantities of phosphorus. Crop production in such soils is usually constrained by phosphorus because its of limited bioavailability. Large "investment" applications of phosphorus fertilizers in P-fixing soils can, however, become a phosphorus capital reserve (63), with subsequent phosphorus release for several years for crop production (44). Soils with this type of phoshorus fixation are most extensive in the humid tropics and tropical savannas but are also important in subhumid East Africa. This modifier is only prevalent (21%) in the tropical/subtropical moist broadleaf forest biome.

There is also phosphorus fixation by the amorphous allophanic minerals of volcanic soils, but the mechanism is different and is described by the "x" modifier and covers only 0.4% of the world's soils.

High organic content (O type).

This constraint relates directly to the Histosol soil order. Organic soils are characterized by wetness, low bulk density, low fertility (particularly in N and micronutrients). Those organic soils with pH below 4.2 can actually trigger hydrogen (H_3O^+) toxicity. They cover only about 3% of the world's soils, mostly in the boreal region (12.7%). They are

not prevalent in any biome but occupy 16% of the boreal forest/taiga and 9% of both the tundra and mangrove biomes. When drained, soil organic C oxidizes to CO_2 causing subsidence of the soil surface and releasing large amounts of carbon to the atmosphere. These soils are difficult to manage.

Although we have listed soil constraints individually, it is as or more important to look at the soils that have no soil constraints or at the suite of constraints of individual soils, such as the acid soils complex of low nutrient reserves, Al toxicity, and P-fixation. Such suites of soil attributes can be obtained through map overlays in the digital FCC. Use of such overlay maps could provide an indication of the soil type and the suite of soil processes that might be predicted. The following section explores further the use of FCC for characterizing soil processes.

SOIL PROPERTIES, PROCESSES, AND ECOSYSTEM SERVICES

The previous sections of the review have dealt primarily with soil properties. Here, we will relate specific soil properties to soil processes and ecosystem services and compare them among different soil types. Processes relate to inputs, losses, transformations, and transfers of material and energy within the soil or are dependent on the soil. The Millennium Ecosystem Assessment (2, 3) divides ecosystem services into provisioning services, products/goods obtained from ecosystems; regulating services, such as greenhouse gas emissions and associated climate regulation, as well as erosion control and associated effects on regulation of water flows and availability; cultural services, which are nonmaterial benefits; and supporting services, which are those services necessary for the production of all other services. Provisioning services depend on regulating services, and both provisioning and regulating services depend on supporting services. Indeed, many of the supporting services such as soil formation, nutrient cycling, and primary production are all dependent on soil processes and indicate the centrality of soils in the provision of ecosystem goods and services.

Ecosystem processes and services provided by soils and the biota within them have been discussed in detail (13, 16–18, 55, 64). These include provision of nutrients, provision of water, regulation of biogeochemical cycles (nutrient cycling), regulation of the water cycle (runoff and erosion), bioremediation of pollutants, suppression of soilborne pests and diseases, and physical support for plants. Many of these services are interrelated (64).

The degree to which soils exert different ecosystem services depends on a suite of soil properties (13, 29). Currently, there are few explicit connections made between specific soil properties and the resulting soil and ecosystem processes that depend on them. Predictive relationships between soil properties and soil processes (pedotransfer functions) are needed in order to understand natural systems but also to manage systems to favor and not degrade ecosystem services. To develop these relationships, there must be specific information about the key soil properties, such as the percent of clay and mineralogy, which together determine secondary soil properties, e.g., aggregation and nutrient capital, which result in specific rates of infiltration or nutrient supply. The next step is to look at the combined soil processes that together result in a quantitatively defined ecosystem service.

In **Table 5**, we attempt to make these relationships more explicit: provisioning ecosystem services (column 1) are linked to soil/ecosystem processes (column 2), which are in turn related to a hierarchy of measurable soil properties, secondary and key soil properties (column 3), and determinants (column 4). Column 5 identifies the relevant FCC types and modifiers that can be used to signal the magnitude of the soil constraints to soil processes related to ecosystem services. Parts of this framework are perhaps implicit in the equations underlying many agricultural, ecosystem, trace gas, or hydrological models

Table 5 Relationships between provisioning ecosystem services, soil processes, soil properties, and core soil determinants

Provisioning ecosystem service	Ecosystem/ soil process	Soil property	Core soil determinants	Relevant FCC type or modifier[a]
1. Physical support for plants	Soil formation	Depth	State factors of soil formation, clay mineralogy	R[b], y, v
2. Provision of nutrients	Mineral weathering	Type/amount of minerals in silt/coarse sand fraction	Primary mineral type: volcanic ash >olivine>micas)	k
	Soil organic matter mineralization	Soil organic matter quantity and quality	Texture: soil organic matter decomposes faster in sandy, fertile, and warmer soils	S>L>C[c]g, t
	Decomposition of organic additions	Soil biota	Same as above	Same as above
	Ion retention and exchange	Effective cation exchange capacity (ECEC), anion exchange capacity	Texture: ECEC increases with clay content. Mineralogy: ECEC in permanent charge clays> variable charge clays. Soil organic matter: ECEC increases with soil organic matter content	C>L>S
	Toxicities	Percent Al saturation, electrical conductivity, percent exchangeable Na, toxic levels of Fe, Mn, B	Clay mineralogy pH	a, s, n
3. Provision of water	Infiltration	Surface macroporosity, hydraulic conductivity	Macroporosity- aggregation, texture, bulk density, soil organic matter, soil biota	S>L>C Ci>Cv
	Storage in soil	Aggregation, bulk density, depth	Texture, mineralogy, soil organic matter	C>L>S Ci, x
	Drainage	Macroporosity hydraulic conductivity	Texture, mineralogy, soil organic matter	S>L>C Ci>Cv

[a]FCC modifiers that can distinguish soils with possible constraints to providing the desired ecosystem service are noted.
[b]R indicates rock or other hard root-restricting layer within 50 cm of the soil surface.
[c]S, L, and C indicate topsoil texture, other FCC modifers are in lower case letters.

(22, 65, 66), but we felt it could be useful to explicitly frame studies on the levels of control of many ecosystem services and to encourage others to make more specific links among the properties, processes, and ecosystem services of soils. The tenet that ecosystem services are ultimately determined by soil texture, mineralogy, soil organic matter is the foundation of the table.

Table 5 can be used in various ways:

- To see how a specific ecosystem service differs among soils
- To illustrate the interconnectedness of many of the ecosystem services owing to their reliance on a few key processes and properties
- To illustrate that many soil properties can contribute to one ecosystem service

- and that the dominant contributing soil property to that service differs with soils

■ To provide a means of identifying which soil processes and properties change with different land and soil management practices and how those changes affect ecosystem services

A few examples of different ecosystem services using contrasting soils follow. The discussion focuses first on undisturbed soils, as they would be in natural ecosystems, to compare differences among soils. Then examples of changes in soil properties with land conversion and management and with their impacts on ecosystem services are compared for different soils as an introduction to soil degradation.

The provisioning ecosystem services of soils for plant production are the physical support for plants and the supply of nutrients and water. The suite of soil processes involved in nutrient supply includes mineral weathering, mineralization of soil organic matter and organic inputs, and retention and exchange of ions. In addition, soil acidification and salinization can inhibit plant growth through the excess aluminum, iron, manganese, and sodium on exchange sites. The magnitude of these soil processes is related to measurable soil properties. The simplest case in distinguishing soils is through the amount of weatherable minerals, the k modifier. Some soils with similar clay and soil organic matter contents, such as Mollisols and Oxisols, can have drastically different nutrient provisioning capacity. In addition to the presence of weatherable minerals, Mollisols have a high cation exchange capacity from the permanent charge clays, with the exchange sites dominated by basic cations. Oxisols, in contrast, have virtually no weatherable minerals and have an extremely low ECEC owing to kaolinitic and oxidic clay minerals, and their exchange sites are dominated by acidic cations. The only source of nutrient capital in Oxisols is soil organic matter. The FCC symbols of *Caek* for Oxisols

and *C* for most Mollisols adequately indicate these differences in nutrient supplying capacity.

In natural systems, soil fertility in Oxisols is maintained through nutrient cycling. With removal of vegetation for conversion to agriculture, the soil organic matter, which is the only source of nutrients, is quickly depleted, and crop yields decline dramatically in just one or two years. In contrast, when Mollisols are converted to agriculture, there is also a drop in soil organic matter, but crop yields can be maintained without external inputs for decades owing to the weatherable minerals and high nutrient-buffering capacity provided by the high ECEC (26). Both soils exhibit a degradation of soil organic matter, but the rates at which they impact on plant production are quite different.

The provision of water for crop production is related first to the soil process of infiltration and then to the storage and release of water from the soil. A comparison of Mollisols, Vertisols, and Oxisols illustrates the affect of mineralogy on these soil processes, assuming they have similar clay contents. Mollisols and Oxisols have high infiltration capacities, whereas that of Vertisols is much less. Mollisols are highly porous because of macroaggregation related to the high soil organic matter content in the topsoil. The low infiltration rates of Vertisols arise from lower soil organic matter and less aggregation but also from the smectitic clay mineralogy. When wet, these clays swell, reducing the porosity, and water infiltration essentially stops. In Oxisols, the oxidic clay mineralogy results in the strong aggregation of primary clay particles into stable sand-sized aggregates—with the macroporosity and high infiltration more similar to those of sandy soils. Although the water-holding capacity of these three soil types might be similar because of the clay and soil organic matter contents, the plants' available water differs, being higher in Mollisols and Vertisols but lower in Oxisols because more water is lost through macropores (26).

Upon conversion to agriculture, infiltration rates decrease resulting in declines in soil organic matter and macroaggregation, increases in bulk densities from compaction, and loss of soil macrofauna involved in the aggregation of soil particles and maintenance of large pores (67). The reduction in infiltration is less in Oxisols than the other soils, owing to the stable aggregation from 1:1 clays and iron and aluminum oxides. The initial low infiltration rates of Vertisols combined with management to destroy soil aggregates are exploited purposefully to puddle soils for paddy rice cultivation.

Reduction in infiltration also affects water runoff and soil erosion. High aggregate stability and the presence of low dispersivity of a kaolinitic (1:1 clay) soil have been shown to minimize soil particle detachment and sediment transport, and these limit the soil loss to 0.33 kg m^{-2}, whereas the low aggregate stability and high runoff of a smectitic soil contributes to soil losses of 1.24 kg m^{-2} in a specific example (68).

The following examples of regulatory and supporting ecosystem services that depend on soil properties also illustrate the interactions between soils and the characteristics of the ecosystem, including vegetation type and quality of litter.

Exchanges of greenhouse gas emissions between soils and the atmosphere are some of the better examples where the ecosystem service has been linked to soil processes and underlying soil properties; these relationships are even well quantified. Tropical forest soils are a major source of nitrous oxide emissions, and these are related to soil N availability and water-filled pore space (69, 70). N availability relates to the N cycling in the system and is dependent on the vegetation type and litterfall, soil organic matter levels, and texture. Water-filled pore space is related to soil aggregation and bulk density, determined in part by clay type and texture. Studies have indeed shown higher N$_2$O fluxes from clayier and more fertile soils (71–73).

Links between soil age and mineralogy to the supporting service of nutrient cycling have been detailed first through a synthesis of existing literature (74, 75) and later shown through field studies on a chronosequence of soils (15). Tropical soils with oxidic and kaolinitic mineralogy cycled low amounts of P and Ca, which are indicative of the low phosphorus availability owing to P-fixation by these clay minerals (the FCC i modifer) and the low nutrient capital of these highly weathered soils (the FCC k modifier); sandy Spodosols cycled low amounts of N.

Table 5 is a work in progress but will hopefully stimulate thinking and research that leads to a more rigorous discussion on the links between soils and ecosystem services and how these links and services differ among soil types. Although there have been considerable advances in the past 15 years, the specificity of the linkages has not been used sufficiently in recent discussions on the role of soils in ecosystem services. Much of this information exists in the literature of soil science, ecosystem science, and landscape ecology. The starting point is an integrated synthesis of existing literature focused on defining relationships between specific soil properties and associated soil properties and processes, estimating a property from other soil properties is commonly done through pedotransfer functions. There is a rapidly growing body of research using the application of pedotransfer functions for estimating difficult-to-measure soil parameters from those more easily measured (76, 77). A quantitative relationship between all the main soil properties and soil processes through pedotransfer functions is needed for modeling and prediction of thresholds in ecosystem services of soils.

SOIL DEGRADATION: AN ECOSYSTEM SERVICE PERSPECTIVE

In general, the increased provisioning of food, fuel, and fiber realized over the past four

decades (3) has resulted in the degradation of soils and several supporting and regulatory services provided by soils (3). This decline in soil properties and regulating ecosystem services will ultimately impact the ecosystem provisioning services. Understanding the factors that affect the stability and resilience of soils upon disturbance is one of the frontiers of soil science (78).

Soil degradation can be defined as the adverse changes in soil properties and processes leading to a reduction in ecosystem services. Through such changes in soil properties and processes, soil degradation undermines the sustainability of many of the ecosystem services. There are innumerable studies on soil degradation, such as loss of soil organic matter, increased erosion, and nutrient depletion (79), but there are relatively few studies that have quantified the linkages and thresholds between the change in soil properties and the associated change in soil processes. In other words, how much change in soil aggregation is required before there is a change in soil porosity and water infiltration? What level of soil organic matter, relative to the initial condition, is needed to maintain soil aggregation at sufficient levels? The studies rarely provide quantitative assessments on the impacts of soil degradation on the provisioning ecosystem services of soils. The connection to and impacts of soil degradation on the regulating services of soil have only recently begun to be considered (3, 40). Until such quantitative links are made between the magnitude of changes in soil properties and the magnitude of change in soil processes, and are ultimately integrated to ecosystem processes, it will be difficult to understand and predict soil degradation in a meaningful way.

Types and Process of Soil Degradation

Globally, the five principal anthropogenic causes of soil degradation, in order of increasing magnitude, are considered to be over-grazing, deforestation, poor land management, harvest of fuelwood, and urbanization (80). Soil degradation almost invariably begins with the removal of the natural vegetative cover through deforestation, biomass burning, nutrient depletion, and overgrazing. The soil surface is exposed to impacts of rainfall, which disrupts soil aggregates, and higher temperatures, which increase soil organic matter decomposition rates; in addition, litterfall and roots, the major sources of organic inputs that maintain soil organic matter, are removed or diminished considerably. Subsequent rates and types of soil degradation are determined by the type and intensity of land use. Soil degradation can occur quickly depending on the combination of and feedbacks between management practices, initial soil conditions, vegetation, and environmental factors such as rainfall (81–83). Soil degradation is usually categorized by physical, chemical, and biological processes; the division provides a means of establishing links between land management, degradation processes, and soil processes (**Table 6**).

Soil physical degradation. Physical degradation involves the structural breakdown of the soil through aggregate disruption, surface sealing, and compaction; these degradation processes result in reduced infiltration and increased water runoff and soil erosion.

The impact of raindrops leads to surface sealing and compaction. The formation of a structural seal results from two complementary mechanisms: (*a*) physical disintegration of surface aggregates caused by wetting raindrop impact energy; and (*b*) physicochemical dispersion of clay particles, which migrate into soil with infiltrating water and clog the pore immediately beneath the surface forming a zone of decreased porosity (84). Soils with intermediate (loamy) texture are the most susceptible to seal formation because the amount of clay is too low to stabilize aggregates but sufficient to clog pores at the surface. Cultivation further affects soil

Table 6 Types of soil degradation and causes and impacts on soil processes[a]

Type	Causes (not one to one along row)	Degradation process	Impact on soil processes
Physical	Deforestation	Breakdown of soil structure, aggregation and porosity	Reduction in infiltration capacity Changes in soil water-retention characteristics
	Biomass burning	Crusting and surface sealing	Increase in runoff rate and amount
	Tillage up and down slope, excessive animal, human, and machine traffic, overgrazing	Compaction of surface and subsoil, reduction in proportion and strength/stability of aggregates	Accelerated erosion by water and wind Increase in bulk density leading to reduction in porosity Water logging and anaerobiosis
Chemical	Irrigation with poor quality water, inadequate drainage	Salinization, alkalinization	Accumulation of base-forming cations
	Little to no use of fertilizers	Nutrient depletion	Decreased levels of macronutrients on exchange sites, soil organic matter, and in soil solution
	Excess use of fertilizers	Acidification, eutrophication	Leaching and runoff of nutrients to water sources
	Application of industrial, urban wastes	Toxification, contamination with heavy metals, pollution	Excessive build up of some elements (e.g., Al, Mn, Fe) and heavy metals (e.g., lead and mercury); increase in soilborne pathogens
Biological	Removal of or burning residues	Depletion of soil organic carbon	Reduction in N mineralization, soil aggregation, and related properties
	Little or no use of organic inputs	Decline in diversity and abundance of soil biota	Shift in species composition and diversity of favorable soil organisms
	Monoculture, excessive tillage	Loss of soil structure	Reduction in porosity and infiltration, reduction in activity of soil biota

[a]Modified from Reference 104.

structure by destroying soil aggregates that result in loss of soil organic matter (28, 85).

Soil erosion is often highlighted as the major type of soil degradation; it is also the most visible. The impacts of soil erosion ramify throughout the soil processes and ecosystem services by the loss of soil depth, soil nutrients, biota, organic matter, and water resources. These integrated changes translate into the reduced primary productivity of ecosystems. The extent of soil erosion is usually estimated from experimental Wischmeier erosion plots (86); this methodology overestimates erosion losses because of the small size of these plots and does not account for redistribution of soil in the same field, which results in no net losses at the field scale (87). These point measurements have been extrapolated to different soils, climates, and landscapes to give estimates of global soil

erosion. Erosion risk does not automatically imply productivity losses or land degradation, as commonly assumed. There are however landscape-level models that estimate erosion in an integrated manner taking into account climate, soil properties, and topography, and such models are used to look at impacts on other ecosystem services (88).

Physical degradation processes other than erosion were found to be more common in temperate region agriculture because of more intensive use of heavy machinery (89). Unfortunately, none of these estimates was related to changes in agroecosystem productivity.

Soil chemical degradation. Soil chemical degradation processes are associated with soil chemical imbalances resulting from a chemical reaction or pH; declines in availability of plant nutrients (nutrient depletion); and

excessive buildup of nutrients (eutrophication), salts (salinization in the root zone and beyond), or toxic materials.

Nutrient depletion, or soil fertility decline, is the predominant form of chemical degradation in much of the tropics, particularly Africa, where nutrient losses through crop residue removal and harvested products, erosion, and leaching are not replaced with sufficient external inputs (90). Nutrient depletion results in lower productivity of crops and biomass in general that leads to further declines of soil organic matter. Soils with low initial nutrient capital, low cation exchange capacity, low activity variable charge clays, and low soil organic matter become depleted more quickly than soils without these properties and include Ultisols, Oxisols, and sandy Inceptisols. There is a growing body of literature that will be useful in making the links between nutrient depletion and reduction in plant productivity as has been done for soil erosion and declines in productivity (91). *Soil eutrophication*, by contrast, is a degradation process that is found primarily in developed countries in temperate regions where excessive amounts of fertilizer, manures, and pesticides are applied in large-scale agriculture (92).

Soil biological degradation. Many key soil functions are underpinned by soil organic matter and soil biota, so biological degradation is often synonymous with decline in soil organic matter and loss of soil biota. The depletion of soil organic matter when natural systems are converted to agriculture and with the intensification of agriculture by tillage is the most comprehensively studied form of biological degradation (8, 26, 32, 93–100).

Rates of change in soil organic matter content and the level of change depend in part on the soil type (slower in clayey soils), land-use type, and climate (slower in colder or drier climates and waterlogged condtions). The body of literature on soil carbon changes when natural systems are converted to annual croplands is extensive and sufficient to provide the pedotransfer functions needed for relating

loss of soil properties to many ecosystem processes (22, 98). Information on changes following other land-use transitions, including natural systems to pastures or tree plantations or annual cropping systems to pastures or tree-based systems, or even changes in management of annual cropping systems is more recent. A meta-analysis of soil carbon changes with land-use change in both temperate and tropical soils shows a decline of soil carbon by 50% in the top 30 cm when forests were converted to cropland, a decline of 15% when forests were converted to coniferous plantations, no decline when forests were converted to broadleaf plantations, and an overall increase of about 10% when forests were converted to pastures (100).

Assessment of Soil Degradation

There are three significant assessments of the global extent of land degradation: the Global Assessment of Human-Induced Soil Degradation (GLASOD) (101), research work (102), and more recent assessments (103). GLASOD is the most comprehensive and widely quoted assessment. Although the initial framework set up for GLASOD was sound and based on scientific information, because of time and resource constraints, the final methodology and assessment were based on expert opinions from 250 soil and environmental scientists. The quality of the GLASOD data is extremely uneven (104) and the estimates are indicative, at best (105). Furthermore, dating from 1991, the estimate of total land area affected by soil degradation at 2 billion hectares is now out of date. This data set should no longer be used for quantifying the extent of soil degradation, and just like the FAO-UNESCO soil map of the world, there is a need for up-to-date and accurate information on soil degradation and global soil information.

One assessment was based on anecdotal accounts, research reports, travelers' descriptions, personal opinions, and local experience (102). The most recent assessment (103) has the benefit of combining multiple sources of

information, including regional data sets derived from a literature review, erosion models, field assessments, and remote sensing. However, it did not have complete spatial coverage and was limited to 62% of drylands, with some areas relying on a single data set.

These assessments of land degradation all have major weaknesses. Literature on soil degradation assessments is replete with gross extrapolations on the basis of limited data, often outside the regions from which the data were obtained (87). These data cannot be used for baseline development, assessment, and monitoring of soil degradation and are unsuitable for land-use planning and identification of conservation/restoration policies (104). A major indictment of the GLASOD land degradation assessment was delivered by its exclusion from the Pilot 2006 Environmental Performance Index for the reasons that the data are outdated and not comparable enough to permit cross-country performance assessments (106).

Conventional methods of soil assessment rely on direct laboratory measurements that are time consuming and costly. Temporal and spatial variability in soil attributes presents formidable challenges for soil survey design. There is a global surge toward developing time- and cost-efficient techniques for soil evaluation (107, 108). This demand is driven by the need for large amounts of good quality, inexpensive soil data for use in monitoring, modeling and risk assessment (109, 110).

The inherent methodological weaknesses can be removed using a combination of in situ data on soil parameters at the pedon or soilscape, and satellite information at multiple resolutions (77, 111, 112). Current advances in pedotransfer functions, reflectance spectroscopy, statistical inference, and remote sensing can overcome the limitations of conventional methods of soil analysis. Pedotransfer function research has focused on the development of functions for predicting soil physical and chemical properties for different geographical areas or soil types. Soil inference systems have been

developed (77) where pedotransfer functions are the knowledge rules for inference engines. A soil inference system takes measurements that are more-or-less known with a given level of (un)certainty, and infers data that is unknown with minimal inaccuracy, by means of properly and logically linked pedotransfer functions (113, 114). Near infrared spectroscopy is rapid and inexpensive, and a single spectrum permits simultaneous characterization of various chemical, physical, and biological properties (115–120). In addition, the repeatability over time and reproducibility among different laboratories of this technique far exceed the performance of conventional soil analysis. Soil properties predicted from spectra may be used in an inference system to predict other important and functional soil properties using pedotransfer functions.

Research has demonstrated that regional patterns of soil degradation can be reliably mapped using automated or supervised digital information extraction, which is based on spectral and/or structural pattern recognition techniques. Extrapolation of this approach to other regions where soil degradation features are correlated with spectrally distinguishable surface characteristics is feasible. For instance, the state of land degradation in a small Mediterranean watershed was characterized using (Advanced Spaceborne Thermal Emission and Reflection Radiometer) ASTER data and ground-based spectral reflectance measurements (121).

A combination of pedotransfer functions, reflectance spectroscopy, statistical inference, and remote sensing offers the best opportunity for developing dynamic digital soil maps that would include the types and extent of soil degradation and would transform the way soil information is obtained and produced.

The challenges of halting and reversing the degradation of the provisioning, regulating, and supporting ecosystems services on which will all depend are daunting. The challenge must be met if we are to attain the MDGs and particularly to provide an environment that

can continue providing these services into the future. Many of these ecosystem services are dependent on soils and therefore the reversal of ecosystem degradation starts with the rehabilitation of soils. Our understanding of the links between specific soil properties, soil processes, and ecosystem services is too incomplete to meet this challenge. Renewed and directed efforts and partnerships among reductionist soil scientists that link soil properties to processes, ecosystem ecologists who link soil processes to ecosystem services; and landscape ecologists and agronomists who put these processes into a broader and relevant context for planning and management decisions are the way forward.

SUMMARY POINTS

1. The framework for comparing soils is based on the premise that the natural capital of soils that underlies ecosystem services is primarily determined by three core soil properties: texture, mineralogy, and soil organic matter.

2. Up-to-date descriptions and distributions of soil orders and soil attributes and constraints are given according to latitudinal belt and biomes.

3. Relationships between soil types and soil properties and biomes are described.

4. An attempt was made to relate ecosystem services to specific soil processes, soil properties, and soil constraints and attributes.

5. The need and framework for assessing soil degradation as it relates to changes in soil properties, processes, and ultimately ecosystem services are proposed.

6. The use of reflectance spectroscopy and remote sensing for simultaneous characterization of various chemical, physical, and biological properties to overcome the great limitations and costs of conventional methods of soil analysis is described.

FUTURE ISSUES

1. A dynamic, digital, global soil map needs to be developed using data from remote and on-ground sensors combined with geospatial information on elevation and climate for predicting soil types and properties for large areas for which there is currently no information.

2. A more complete set of quantitative relationships (pedotransfer functions) must be developed between soil properties, attributes, processes, and resulting ecosystem services.

3. The current state and extent of soil degradation and risk of degradation must be assessed through the use of digital soil maps and application of pedotransfer functions, linking degradation to impacts on ecosystem services.

DISCLOSURE STATEMENT

Pedro Sanchez has submitted a project proposal to develop digital soil maps for the world. The other authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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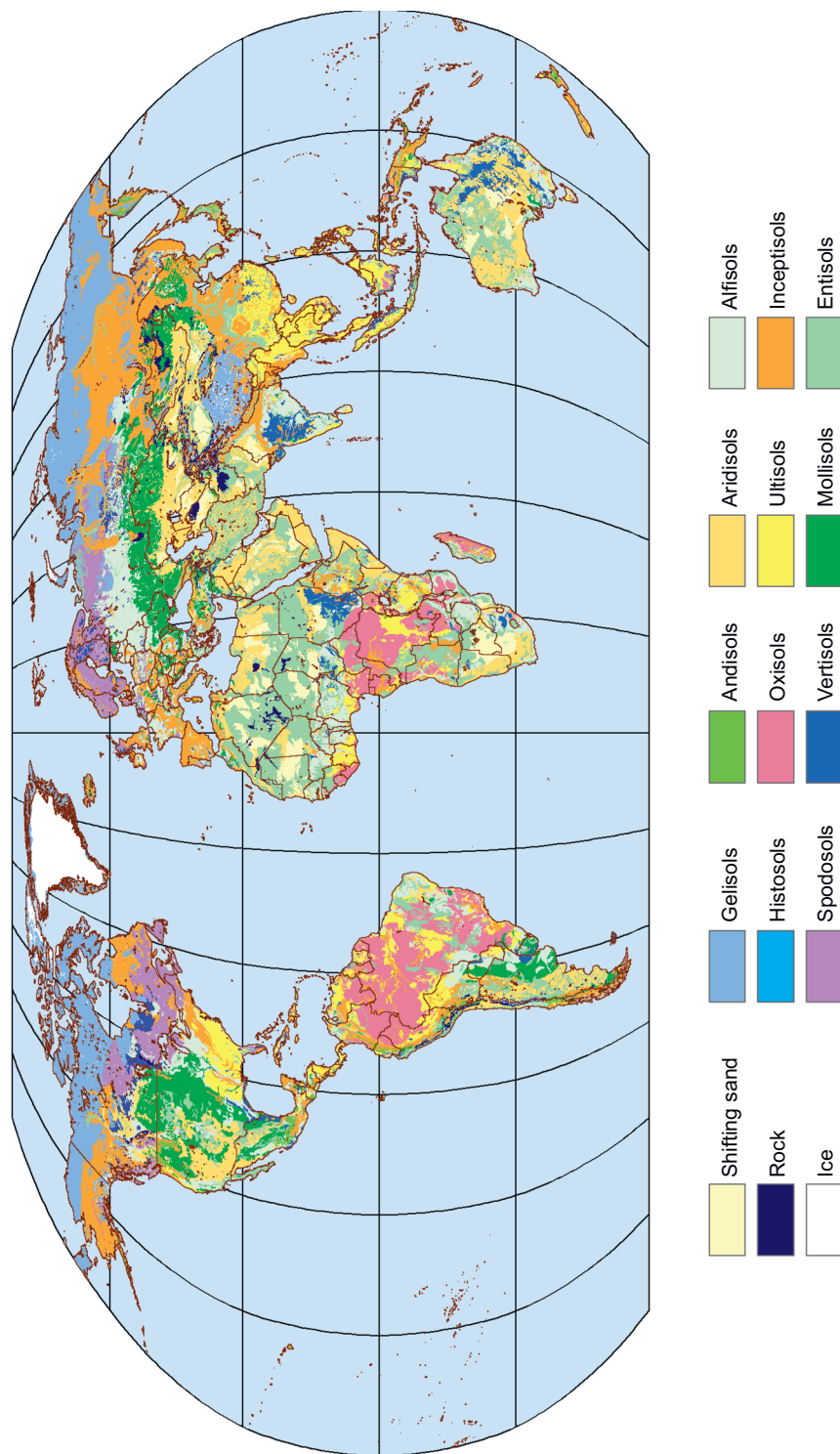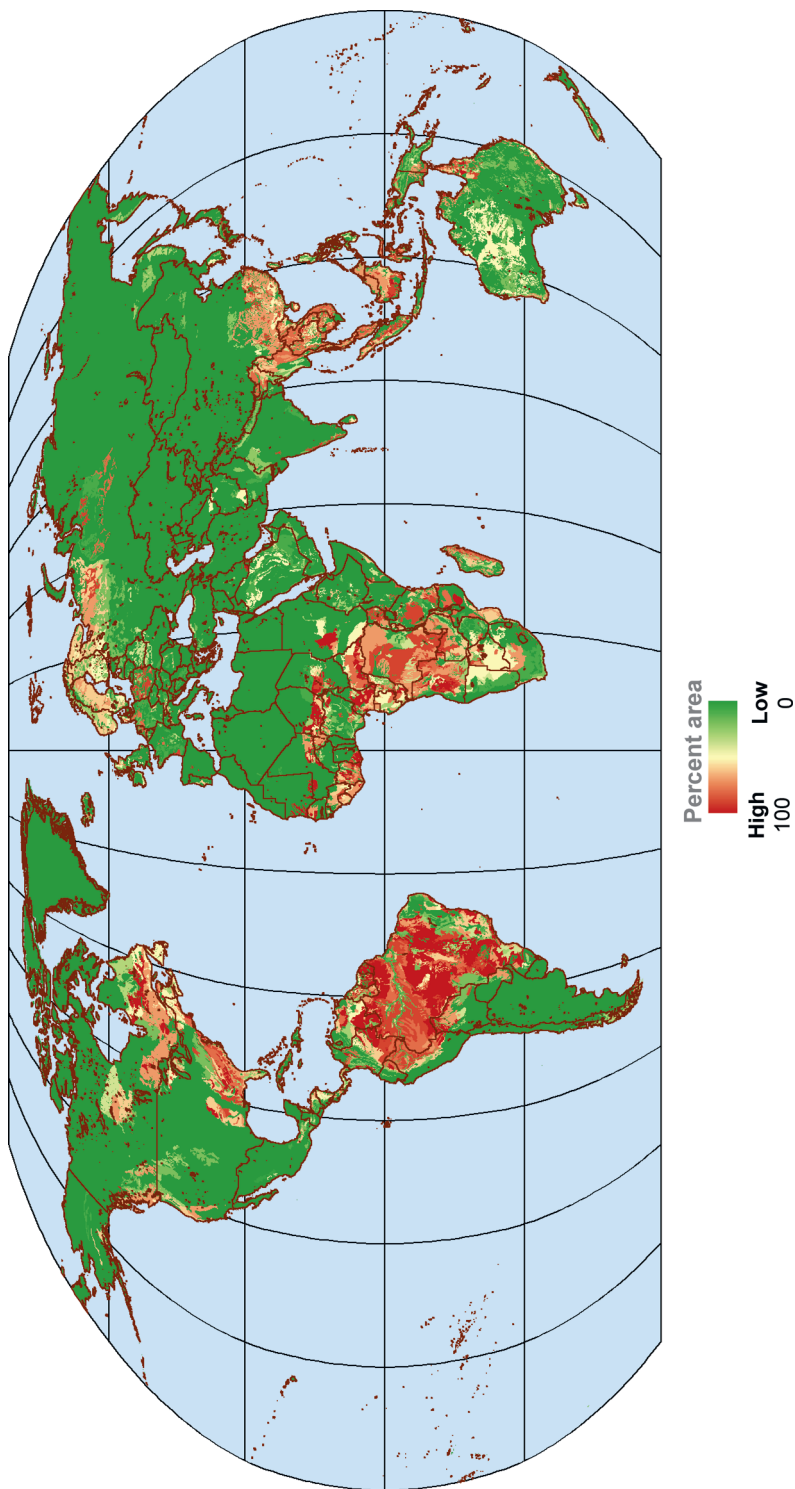
Figure 1

Global distribution of soil orders. This was mapped by the Center for International Earth Science Information Network, Columbia University, using the U.S. Department of Agriculture's Global Soil Suborder Map Data (**37**).

Percent area

High
100

Low
0

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