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REVIEW SUMMARY

SOIL SCIENCE

Soil and human security in the 21st century

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BACKGROUND: Earth's soil has formed by processes that have maintained a persistent and expansive global soil mantle, one that in turn provided the stage for the evolution of the vast diversity of life on land. The underlying stability of soil systems is controlled by their inherent balance between inputs and losses of nutrients and carbon. Human exploitation of these soil resources, beginning a few thousand years ago, allowed agriculture to become an enormous success. The vastness of the planet and its soil resources allowed agriculture to expand, with growing populations, or to move, when soil resources were depleted. However, the practice of farming greatly accelerated rates of erosion relative to soil production, and soil has been and continues to be lost at rates that are orders of magnitude greater than mechanisms that replenish soil. Additionally, agricultural practices greatly altered natural soil carbon balances and feedbacks. Cultivation thus began an ongoing slow ignition of Earth's largest surficial reservoir of carbon—one that, when combined with the anthropogenic warming of many biomes, is capable of driving large positive feedbacks that will further increase the accumulation of atmospheric greenhouse gases and exacerbate associated climate change.

ADVANCES: The study of soil is now the domain of diverse schools of physical and biological science. Rapid advances in empirical and theoretical understanding of soil processes are occurring. These advances have brought an international, and global, perspective to the study of soil processes and focused the implications of soil stewardship for societal well-being. Major advances in the past decade include our first quantitative understanding of the natural rates of soil production, derived from isotopic methods developed by collaboration of geochemists and geomorphologists. Proliferation of research by soil and ecological scientists in the northern latitudes continues to illuminate and improve estimates of the magnitude of soil carbon storage in these regions and its sensitivity and response to warming. The role of soil processes in global carbon and climate models is entering a period of growing attention and increasing maturity. These activities in turn reveal the severity of soil-related issues at stake for the remainder of this century—the need to rapidly regain a balance to the physical and biological processes that drive and maintain soil properties, and the societal implications that will result if we do not.

OUTLOOK: Both great challenges and opportunities exist in regards to maintaining soil's role in food, climate, and human security. Erosion continues to exceed natural rates of soil renewal even in highly developed countries. The recent focus by economists and natural scientists on potential future shortages of phosphorus fertilizer offers opportunities for novel partnerships to develop efficient methods of nutrient recycling and redistribution systems in urban settings. Possibly the most challenging issues will be to better understand the magnitude of global soil carbon feedbacks to climate change and to mitigating climate change in a timely fashion. The net results of human impacts on soil resources this century will be global in scale and will have direct impacts on human security for centuries to come. ■

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Large-scale erosion forming a gully system in the watershed of Lake Bogoria, Kenya. Accelerated soil erosion here is due to both overgrazing and improper agricultural management, which are partially due to political-social impacts of past colonization and inadequate resources and infrastructure. The erosion additionally affects the long-term future of Lake Bogoria because of rapid sedimentation. This example illustrates the disruption of the natural balance of soil production and erosion over geological time scales by human activity and the rapidity of the consequences of this imbalance.

REVIEW

SOIL SCIENCE

Soil and human security in the 21st century

Ronald Amundson,[1]* Asmeret Asefaw Berhe,[2] Jan W. Hopmans,[3] Carolyn Olson,[4] A. Ester Sztein,[5] Donald L. Sparks[6]

Human security has and will continue to rely on Earth's diverse soil resources. Yet we have now exploited the planet's most productive soils. Soil erosion greatly exceeds rates of production in many agricultural regions. Nitrogen produced by fossil fuel and geological reservoirs of other fertilizers are headed toward possible scarcity, increased cost, and/or geopolitical conflict. Climate change is accelerating the microbial release of greenhouse gases from soil organic matter and will likely play a large role in our near-term climate future. In this Review, we highlight challenges facing Earth's soil resources in the coming century. The direct and indirect response of soils to past and future human activities will play a major role in human prosperity and survival.

Soil is the living epidermis of the planet (*1*). Globally, soil is the medium through which a number of atmospheric gases are biologically cycled and through which waters are filtered and stored as they pass through the global hydrological cycle (*2*). Soil is a large and dynamic reservoir of carbon and the physical substrate for most of our food production. Profound changes are on the horizon for these interconnected functions—particularly sparked by changes to climate and food production—that will likely reverberate through society this century. Ultimately, the way in which we directly and indirectly manage our planet's soil will be interwoven within our future success as a species.

Soil is commonly thought of as the ~1-m-thick layer of biogeochemically altered rock or sediment at Earth's surface that has acquired numerous qualities during its exposure to the atmosphere that greatly distinguish it from its geological sources (*3*). Soil-forming chemical reactions create micrometer-sized electrically negative clay minerals that impart soil with plant nutrient retention capabilities (*4*). The electrical charge characteristics of soil, combined with its small particle size and high surface area, allow it to temporarily store rain and snow melt for plant use and provide sufficient residence time for a multitude of chemical reactions to occur that may remove or reduce the toxicity of contaminants. The water stored in soil—termed green water (*5*)—serves as the source for 90% of the world's agricultural production and represents ~65% of global fresh water (*5*). Last, the intimate intermingling of life—plant, animal, and microbial—within the soil matrix drives redox reactions that control many elemental cycles (*6*) and creates a reservoir of organic C that greatly exceeds the C in the global atmosphere and biosphere (*7*). The microbial communities that mediate these redox reactions are now believed to represent much of Earth's total biodiversity (*8*), but the nature, function, and economic potential of this soil biosphere is only beginning to be probed (*6*).

Soil, due to global variations in climate, geology, and biota (*3*), has tremendous spatial diversity. More than 20,000 soil types (or soil series) have been identified and mapped in the United States alone (*9*), and the number identified increases as land area investigated increases. If the soil series–to–land area relationship (*10*) is extrapolated to global ice-free land area, the results suggest that there are more than 300,000 series on the planet. The response of these soils to perturbations can be extremely varied because of their diverse chemical, physical, and biological characteristics, suggesting the importance, as a simple precautionary principle, of maintaining segments of this diversity for the stability and resilience of global biogeochemical systems in the face of anthropogenic disturbances.

Human Imprint on Soil

Humans altered the ecosystems they encountered as they began their spread across the globe. However, the most momentous development in human landscape change occurred with the invention and adoption of agriculture (*11*). Most agricultural practices involve the removal of the natural flora, the simplification of biodiversity to favor monocultures, and the physical disruption of the soil. Since the Industrial Revolution, expanding populations have relied on the exploitation of more and more soil for a corresponding growth in food production. Today, ~12% of ice-free land is in cropland, and 38% is used for combined cropping and grazing (*12*), an area roughly equivalent to the land area covered by ice and scoured or otherwise disturbed during the last glacial maximum (Fig. 1A). In addition to the similarity in area, the agricultural impact on soil processes rivals or exceeds the effect of those ice sheets in both rapidity and magnitude.

Undisturbed soils have the characteristic, as result of a number of feedback mechanisms, of being able to retain many of their features indefinitely over time—their thickness, C content, and nutrients, for example—a condition that is equatable to sustainability (Fig. 2). Cultivated soils are highly modified forms of their wild predecessors and may thus be viewed as domesticated soils (*9*). One key characteristic is that domesticated soils seldom are able to maintain the qualities of their original conditions, and these changes greatly affect their productivity and their impact on surrounding geochemical cycles. The efforts to improve the management and conservation of these domesticated soils, and the preservation of portions of their remaining wild ancestral stock, will be among the most important challenges this century (*9*, *13*). Analyses of the combined agricultural and urban impact on soil series in the United States, for example, revealed large areas in the agricultural heartland where more than 50% of the soil series had been domesticated. Soil diversity, like biodiversity (*14*), provides an array of human-valued goods and services. Among the most apparent issues is the ability of soil to provide sustained agricultural production.

The domesticated soil landscape is one of Earth's most valuable commodities. For example, nearly $3816 billion (U.S. dollars) in agricultural products were produced globally in 2012 (*15*). However, agriculture is competing with increasing urban and suburban soil demands. The conversion of soil to urban land is largely irreversible on human time scales. There is uncertainty both in the present and the future distribution of urban land on Earth (Fig. 1B). A recent meta-analysis suggests that between 1970 and 2000, an area greater than the size of Denmark was urbanized, and that in the next 20 years, 1.5 million km^2 of land (the size of Mongolia) will be urbanized (*16*). The conversion of farmland to urban areas must be weighed against the fact that our most productive soils have already been exploited and that demand for food production will continue to increase.

Soil and Climate Security

A relatively stable climate has been the stage on which the great human inventions of agriculture and industrialization have evolved, and direct or indirect human impacts on soil C cycling processes will have much to do with atmospheric greenhouse gas concentrations and the associated climate implications by the end of this century.

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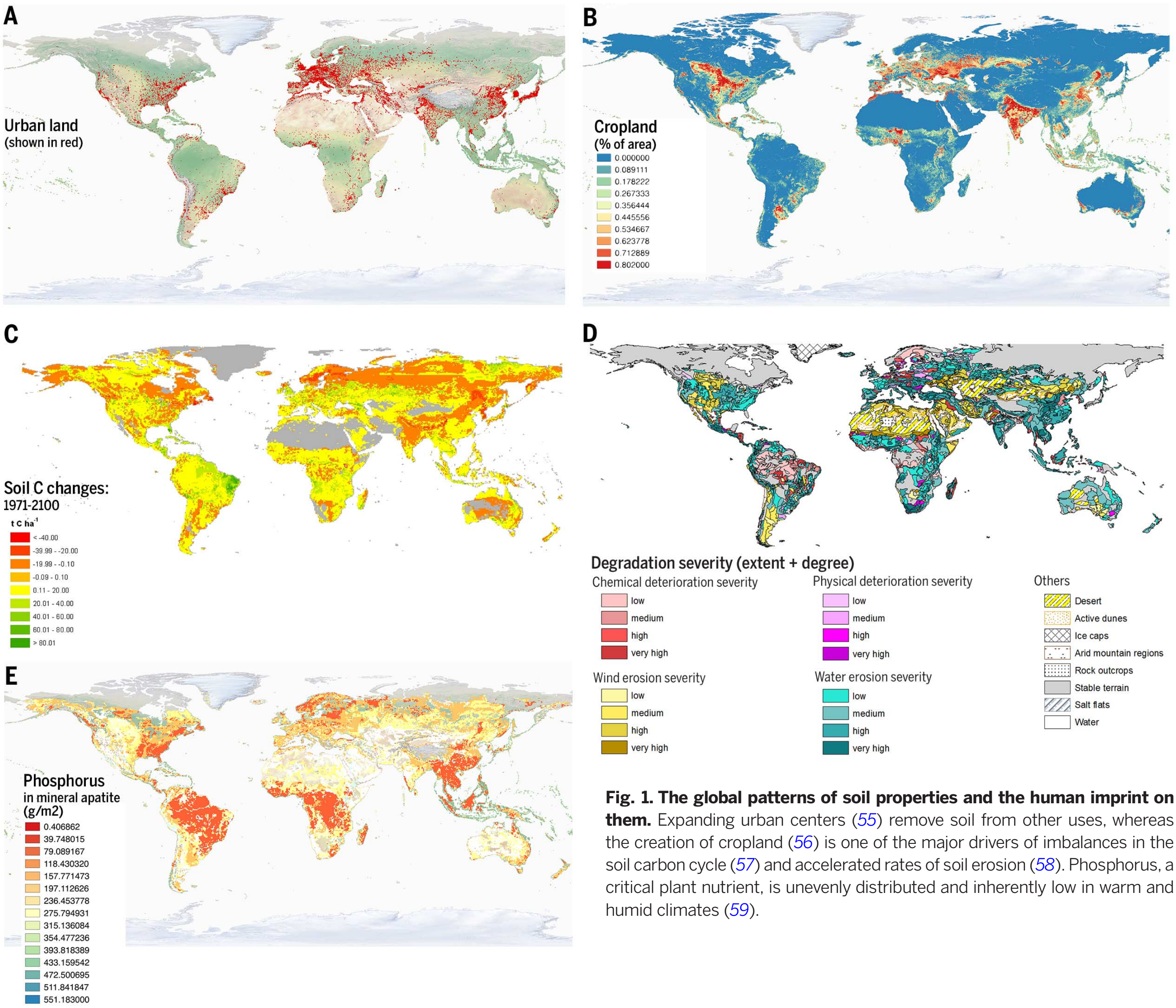

Fig. 1. The global patterns of soil properties and the human imprint on them. Expanding urban centers (*55*) remove soil from other uses, whereas the creation of cropland (*56*) is one of the major drivers of imbalances in the soil carbon cycle (*57*) and accelerated rates of soil erosion (*58*). Phosphorus, a critical plant nutrient, is unevenly distributed and inherently low in warm and humid climates (*59*).

Organic C stored in soil is the balance between plant inputs and microbially mediated metabolic losses as CO_2 (Fig. 2). In unperturbed conditions, soils achieve steady-state C pools on time scales of centuries to a few millennia. The total store of soil organic carbon is still uncertain, but recent estimates suggest pools on the order of 2300 gigatons (Gt) in the upper 3 m (*7*). Soil cultivation and clearing has caused a major fraction of total anthropogenic greenhouse gas emissions since the 19th century (*17*). Cultivation is a major disruption to the natural C balance in soil, one that alters the physical and biological structure of soil, effectively igniting, through microbially mediated processes, a vast store of labile C that has accumulated over millennia (*18*). During the first few decades that soil is cultivated, up to 50% of the carbon pool is oxidized to CO_2; eventually, a quasi-steady-state soil C pool is achieved (*19*). Based on the global agricultural land area, cultivation has likely released between 50 and 70 Gt of C to the atmosphere over the course of human history (*20*), and the combined cultivation and biomass burning contributions to atmospheric CO_2 exceeded that of fossil fuel emissions well into the 20th century (*17*). However, the agricultural imprint on atmospheric greenhouse gas concentrations appeared much earlier in the Holocene (*21*). Early spikes in atmospheric CO_2 and CH_4 corresponded to agricultural expansion in Mesopotamia and in China (*22*). Much of the historical C loss was from the soils of forests and grasslands of the northern latitudes. However, today the locus of land alteration has shifted to the equatorial latitudes, and up to 10% of global anthropogenic CO_2 emissions are from a combination of biomass burning and soil cultivation in the humid and subhumid tropics (*23*).

Under changed management or through land abandonment, global agricultural soils have the capacity to reapproach their original C storage and regain up to a half a decade of present fossil fuel emissions (over a multidecade period). Better stewardship of domesticated soils that leads to higher organic matter contents is a valuable practice from an ecological perspective and from an agronomic point of view (*24*). There is now a large body of research on the rates of C sequestration under differing management practices. However, there are limits to these practices as a means of mitigating continued fossil fuel emissions. First, a serious concern with management-based soil C sequestration strategies is that they are dependent on restricted management options in a highly decentralized and economically driven agricultural sector (*25*). A change in land ownership, or a change in factors driving agricultural practices, can rapidly release much of regained C. Second, the effectiveness of soil C sequestration is time dependent. For example, if all potential soil sequestration strategies were established, they would initially serve as a sink of about 1.3 Gt of C year^{-1} (Table 1) (*26*), but this sink term would be expected to decline nonlinearly to low sequestration rates over a period of several decades as a new soil C steady state is reached (27). Equally as important is the difficulty of actually achieving this maximum potential, which involves multiple governments and millions of individual land managers. Last, soil management effects on the global C balance are inherently small relative to the climate-driven changes to soil C storage that will occur in this century.

Soil C storage is well documented to decline with increasing temperature and decreasing soil moisture, and soil C storage patterns mirror global climate zones (28, 29), with secondary impacts by bedrock, topography, and soil age (20). Soil C pools are the balance between plant inputs and microbial decomposition (Fig. 3), and the responses of these processes to anthropogenic climate change are considered to be large, (in the case of inputs) poorly constrained (30), and complicated by temperature and moisture interactions. Anthropogenic increases in atmospheric CO_2 may drive increased net primary production (NPP) as long as nutrient and water limitations do not occur (31), which ultimately may have a negative feedback on atmospheric CO_2 through increased inputs to soil C (Fig. 3). On the other hand, increasing air temperatures warm soil, melt permafrost, and stimulate biological metabolism of soil carbon pools, driving what appears to be a large positive feedback process (32) (Figs. 1C and 3). Based on current earth system modeling, additions of soil C by increased NPP (relative to an 1850 BCE reference date) are projected to be between 160 and 1230 Gt by 2100, whereas C losses by increased decomposition are projected to be between 104 and 629 Gt (31). Overall, models suggest net soil C changes from a loss of 72 Gt to gains of 253 Gt by 2100 (31). However, such exercises include great uncertainties in both projected gains (by CO_2-enhanced photosynthesis) and losses (by soil warming) and in assumptions about long-term ecosystem response to ever-increasing CO_2 concentrations. One important uncertainty is the response of northern latitude soils to warming, which could result in net soil C losses between 50 to 150 Gt (32, 33). Last, the current generation of earth system models has difficulty in matching present-day soil carbon storage patterns (34), and tuning the models is challenged by empirical uncertainties in the global soil C pool of more than 770 Gt (34), an uncertainty similar in size to the present atmospheric C pool.

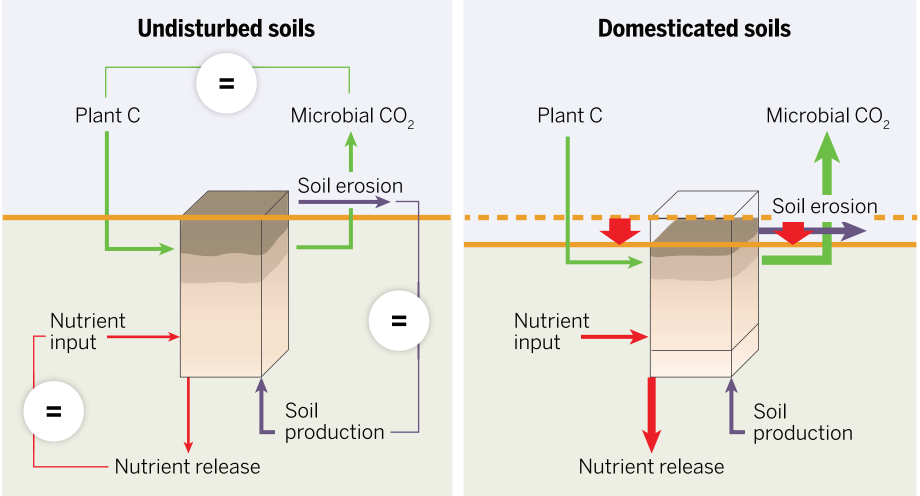

Fig. 2. Changes in the balance of important soil processes caused by human disturbance. Many soil characteristics are the balance or the result of a number of processes that respond to changes in environmental variables (3). However, properties such as hillslope soil thickness, organic carbon storage, N content, and other features attain steady state in intervals of a few centuries to millennia and appear capable of regaining stability. Human intervention in soil processes many times exceeds natural perturbations and thus exceeds the resiliency of soil to recover to its original condition. Viewed broadly, steady state is a quantitative measure of soil sustainability.

Table 1. Published estimates of soil C sources and sinks for the 21st century.

Management Type	Maximum Flux (Gt of C year^{-1})	Reference	Cumulative Flux (Gt)
	Carbon Sinks		
Increased net primary production		(31)	160 to 1230
Erosion	0.40	(37)	40
	Management		
Cropland management	0.36	(26, 27)	
Grazing land management	0.37	(26, 27)	
Restore degraded land	0.18	(26, 27)	
Restore organic soils	0.36	(26, 27)	
Total for management	1.26		16.4*
	Carbon Sources		
Land clearing†			250
Soil warming			
Boreal regions		(32)	50–270
Globe		(34)	104–629
Total			
Net balance			–188 to +137

*Based on maximum new cropland by 2050 (10 billion ha) (68) and assumed loss of 25% of an average C content of 10 kg m^{-2} (29). †Calculated assuming exponential decline to an ultimate landscape saturation after 50 years.

Still debated is the impact of soil erosion on the global C cycle. When agricultural soil is lost by water or wind erosion, the surficial, and most C-rich, material is preferentially removed, which accelerates the decline in the soil C pool. Rates of soil C replacement by crops and plants are rapid enough in certain situations to maintain soil C levels at a steady state under the condition of constant erosion—e.g., creating an ongoing sink (35). This sink represents a net reduction in atmospheric CO_2 only if the eroded C is not reoxidized. Because some depositional environments are conducive to partial preservation of buried C (lakes, reservoirs, basins, floodplains), the net effect of accelerated agricultural erosion was first suggested to be a global C sink of 0.6 to 1.5 Gt year^{-1}, a rate similar to the total global land sink (35). If the eroded C is largely oxidized, however, it may result in no net sink (or possibly even a net source) (36). The most recent estimates suggest that agricultural erosion of soil C may be 0.40 ±0.20 Gt of C year^{-1} (37). If we benefit from an unintended C sink due to soil erosion, any benefits must be clearly balanced against the related losses of nutrients and reduction of environmental quality that require fossil fuel energy to remediate (38).

The global soil C cycle has been greatly perturbed by human activity, both directly through farming and indirectly through anthropogenic climate change. All projected soil C gains and losses this century are highly uncertain because of economic, population, and political influences (which will largely affect carbon sequestration efforts) and uncertainties in the magnitude of the soil response to warming (because of the complexity of the soil C pool structure) (Fig. 3). Human changes to the global atmosphere and climate are likely to simultaneously drive both very large gains and losses of soil C—fluxes that are equivalent to decades of emissions at present

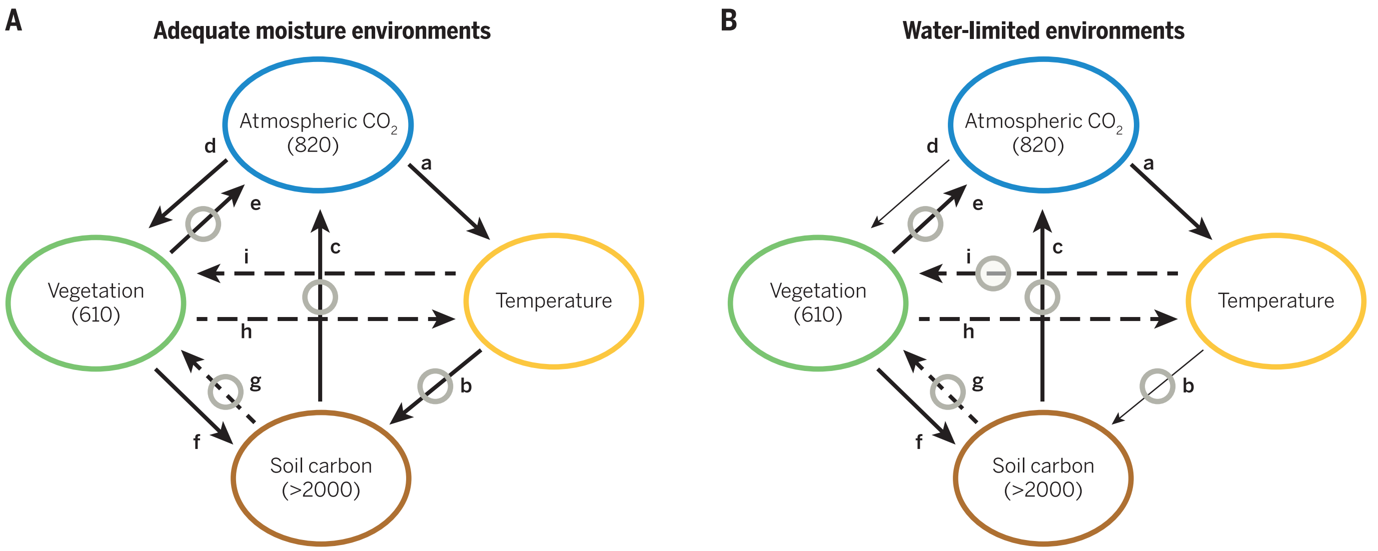

Fig. 3. A cause-effect diagram of the major soil-atmospheric CO_2 feedback processes. The values in parentheses, in the circles, are the approximate pool sizes (Gt) of C. A solid arrow represents a direct response (e.g., as CO_2 increases, temperature increases); an arrow with a circle indicates an inverse response (e.g., as temperature increases, soil carbon storage decreases). Dashed lines are for processes that are less well understood. (**A**) Environments with adequate moisture. (**B**) Water-limited environments. In (A), the a-b-c loop is a positive feedback process (even number of inverse relationship arrows), one especially important in regions of melting permafrost. The d-f-c loop is a negative feedback, one with less certain feedbacks between vegetation and soil (f-g loop) and temperature (h-i). The strength of the a-b-c- versus d-f-c loops on soil carbon pools will likely determine whether soil carbon losses in northern latitudes serve as a major source of CO_2 and CH_4 this century, a balance that also hinges on the ability of the soils to supply nutrients to plants (arrow g) in order to respond to the increases in CO_2 (arrow d). In (B), regions with limited moisture, the strengths of vegetation response to CO_2 (d) and soil carbon response to temperature (b) may be weakened (thinner arrow). In addition, the vegetation response to increasing temperature may become negative. These figures reveal the importance of soil carbon to the global CO_2 balance this century, as well as the uncertainties in the strength and direction of important processes. Arrow references are as follows: a, (60); b, (32, 33); c, CO_2 loss by respiration is the overwhelming pathway of C removal from soils; d, water efficiency response in (61); f, soil C is the balance between plant inputs and decomposition losses; g, not well constrained, but see discussion in (62); h, (63); i, e.g., (64).

rates of fossil fuel consumption. The presently unknown balance, and most importantly its sign, between the large fluxes represent considerable uncertainty for climate security (Table 1).

Soil and Food Security

The late 20th and early 21st centuries have been, for industrialized countries, an unprecedented era of increasingly low food prices (39). There are numerous factors that may reverse this trend—such as increased global demand; climate change (40); and competition for soil by nonagricultural uses, such as biofuels or urbanization. Abundant energy has been the key driving force behind our ability to maintain food production apace with an expanding population that is estimated to reach 11 billion by 2100 (41). Low-cost energy, which led to advanced agricultural machinery replacing human labor, is causing migration to urban centers. Energy is used to replace the soil nutrients removed or lost by agricultural perturbations of soil. Energy transforms atmospheric N_2 to the bioavailable NH_4 fertilizer through the energy-intensive Haber-Bosch process—constituting the first and most important green revolution (42) (Fig. 4A), one that allows us to feed the increasing global population (Fig. 4A). Before the industrial fixation of N, any increase in food production for a given country was largely due to increased soil used for production (43), and only after the advent of N fertilizer (Fig. 4A) did yields per area of major crops begin their upward trajectory (43).

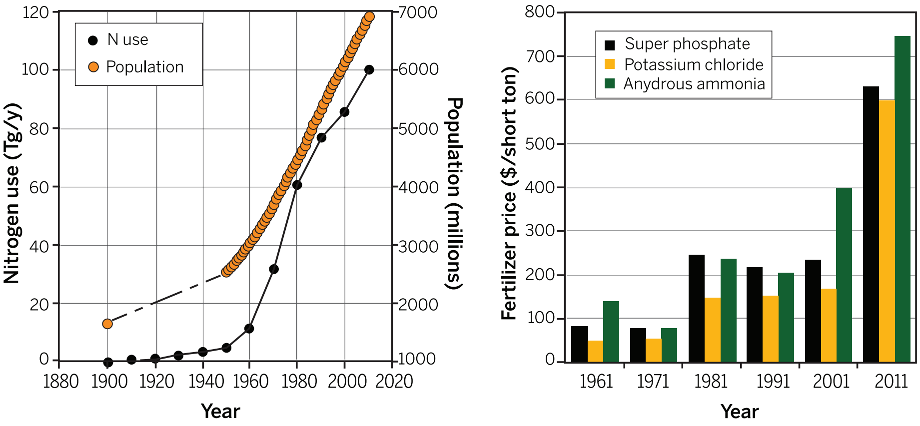

Fig. 4. The post–World War II rise in fertilizer production and cost coincides with the spike in global human populations. The growth in world population in the late 20th century (65) mirrors the increasing use of industrially derived N fertilizer. Before N fertilization, for major U.S. crops (66), wheat and other grain yields per acre increased only following World War II, coincident with the rise in the use of N fertilizer produced by the Haber-Bosch process. Prices have sharply risen (67) because global demand is straining the supplies.

Last, energy is essential to mine and transport essential plant nutrients, such as P and K, that can only be accessed from limited geological reservoirs.

Agricultural soil erosion is one of the most destructive human perturbations to soil sustainability. Given little opportunity or desirability for further agricultural expansion, stewardship of our existing domesticated soil is essential for sustained human prosperity. Yet despite the importance of soil conservation, the implementation of practices to minimize soil erosion has not followed apace with the severity of the problem. The most pervasive mechanism of soil erosion is via water. Before European contact and the removal of native vegetation by plowing and cultivation, the geological mechanism of soil erosion on most uplands was by slow, biologically driven creep (*44*). The removal of plant cover allows the mechanism of erosion to change to raindrop dislodgment of soil particles and their subsequent removal by overland flow, which is a far more rapid erosional process. For example, recent analyses of U.S. erosion rates before European contact place the average rate at about 21 m My^{-1} (My, million years) (*45*). Today, erosion rates in the central United States can exceed 2000 m My^{-1} (*45*), whereas the rates of soil erosion in portions of the loess plateau of China approach 10,000 m My^{-1} (*46*) (Fig. 1D). This eroded sediment is ultimately replaced by the conversion of the underlying sediment or rock into new soils with the addition of organic matter and nutrients through biological mechanisms. Until the past decade, the pace of this replacement process was poorly known, and the acceptable rates of soil erosion on agricultural lands were placed at 400 m My^{-1} or more (*47*). Numerous studies of natural rates of soil production now suggest rates between 50 to 200 m My^{-1} for many environments, indicating that the pace of erosion in numerous agricultural areas is, or until recently has been, unsustainable (*47*). Not only does the loss of soil remove nutrients from the site of agricultural production (*38*), but the sediment generated adversely affects local drainages, water bodies, and regional aquatic ecology. Last, the maintenance (or even the improvement) of agricultural production in the face of accelerated rates of soil erosion is energy intensive. Although microbial symbiosis with plants can fix atmospheric N to bioavailable forms and can substitute for N fixed by the Haber-Bosch process, there is no biological or atmospheric source for rock-derived nutrients, such as P, K, and Ca.

Although natural processes of soil production and formation replace or release nutrients, the paces of these processes are slow relative to our anthropogenic use rate (Fig. 2). The transport of crops from the site of production to other locations remove plant-essential nutrients from the soil, potentially causing deficiencies that limit potential production levels (*48*). This further drives a dependence on the mining and distribution of macronutrients from geological sources, which can create economic inequalities or geopolitical conflicts between nations (*49*) (Fig. 1E). The growing demand for P has recently caused an increase in the cost of rock phosphate from about $80 per U.S. ton in 1961 to up to $450 per ton in 2008. Prices since then have fluctuated but are now at about $700 per ton (*50*) (Fig. 4). In addition to cost is the related issue of access. Morocco is estimated to have the world's largest geological P reserves, much of it in disputed territory (*49*). The United States, on the other hand, has only about 2% of global P resources (*51*). At current rates of retrieval, the most productive mine in the United States will be depleted in 20 years (*49*), which will force it to become increasingly reliant on imports to sustain its agricultural and industrial sectors.

Because most other P-reliant countries lack the geological resources to indefinitely sustain current use, the only means to confront the decline in reserves (other than conversion from domestic to imported P) is to develop a more coherent and integrated program of P (and other nutrient) recycling. The loss of nutrients in our human and animal waste streams is environmentally damaging and economically problematic. Regaining control of these resources, now largely considered waste, would go far toward substantially lowering the demand for imported nutrients and other resources (*52*). In addition to P, other soil nutrients appear to be entering periods of limitation or high demand (Fig. 1F). For example, K (potash) prices were ~$875 per metric ton in 2009 and are expected to reach $1500 by 2020.

The 21st Century Challenge

Humans have domesticated our soil resources and the planet (*12*, *53*). This domestication has in turn perturbed a number of soil cycles such that they are no longer in balance, and the imbalance is changing soil in ways that will affect future generations and their climate (Fig. 2). Soil management must be geared toward passing a habitable, albeit highly altered, landscape to the generations that follow—one where our exploitation of, and impacts on, soil resources is adjusted to the pace of our planet's renewal. These strategies should focus on regaining a balance in (i) organic C inputs and losses, (ii) soil erosion and production, and (iii) release and loss of nutrients. Soil sustainability—based on quantitative principles and measurements of soil erosion and production, soil nutrient loss and release, and soil carbon loss and return—must be the ultimate goal for managing the global soil resource and should serve as the driving principle for soil research that will support this management.

These are challenging goals that will be difficult to achieve. The solutions will require an effort commensurate with the magnitude of the problems. First, effective solutions to soil sustainability, much like the approaches required to contend with climate change (*54*), must involve highly multidisciplinary research in novel intellectual settings or institutions. Second, the ultimate success of any innovation requires a dialog and interface with policy makers and public institutions, the ultimate "deciders" in broad-scale social change. These linked efforts will depend on continued, and arguably much greater, investments in knowledge and innovative knowledge transfer and simply different ways of conceptualizing and approaching problems. From our vantage point, the future of Earth's soil resources is tenuously in our control or within our ability to sustain it into the future. Only those on Earth in 2100 will know how well we succeeded.

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