Science AAAS

Soil Carbon Sequestration Impacts on Global Climate Change and Food Security

R. Lal, *et al.*

Science **304**, 1623 (2004);
DOI: 10.1126/science.1097396

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R. Lal

The carbon sink capacity of the world's agricultural and degraded soils is 50 to 66% of the historic carbon loss of 42 to 78 gigatons of carbon. The rate of soil organic carbon sequestration with adoption of recommended technologies depends on soil texture and structure, rainfall, temperature, farming system, and soil management. Strategies to increase the soil carbon pool include soil restoration and woodland regeneration, no-till farming, cover crops, nutrient management, manuring and sludge application, improved grazing, water conservation and harvesting, efficient irrigation, agroforestry practices, and growing energy crops on spare lands. An increase of 1 ton of soil carbon pool of degraded cropland soils may increase crop yield by 20 to 40 kilograms per hectare (kg/ha) for wheat, 10 to 20 kg/ha for maize, and 0.5 to 1 kg/ha for cowpeas. As well as enhancing food security, carbon sequestration has the potential to offset fossil-fuel emissions by 0.4 to 1.2 gigatons of carbon per year, or 5 to 15% of the global fossil-fuel emissions.

The global soil carbon (C) pool of 2500 gigatons (Gt) includes about 1550 Gt of soil organic carbon (SOC) and 950 Gt of soil inorganic carbon (SIC). The soil C pool is 3.3 times the size of the atmospheric pool (760 Gt) and 4.5 times the size of the biotic pool (560 Gt, fig. S1). The SOC pool to 1-m depth ranges from 30 tons/ha in arid climates to 800 tons/ha in organic soils in cold regions, and a predominant range of 50 to 150 tons/ha. The SOC pool represents a dynamic equilibrium of gains and losses (Fig. 1). Conversion of natural to agricultural ecosystems causes depletion of the SOC pool by as much as 60% in soils of temperate regions and 75% or more in cultivated soils of the tropics. The depletion is exacerbated when the output of C exceeds the input and when soil degradation is severe. Some soils have lost as much as 20 to 80 tons C/ha, mostly emitted into the atmosphere. Severe depletion of the SOC pool degrades soil quality, reduces biomass productivity, and adversely impacts water quality, and the depletion may be exacerbated by projected global warming.

Carbon Management and Sequestration Center, The Ohio State University Columbus, OH 43210, USA. E-mail: lal.1@osu.edu

Terrestrial ecosystems contributed to atmospheric CO_2 enrichment during both the preindustrial and industrial eras (Table 1). During the preindustrial era, the total C emission from terrestrial ecosystems was supposedly about twice (320 Gt or 0.04 Gt C/year for 7800 years) that of the industrial era (160 Gt or 0.8 Gt C/year for 200 years) (*1*). Between 1850 and 1998, the emission from fossil-fuel combustion (270 ± 30 Gt) was about twice that from the terrestrial ecosystems (136 ± 55 Gt) (*2*). The latter includes 78 ± 12 Gt from soil, of which about one-third is attributed to soil degradation and accelerated erosion and two-thirds to mineralization (Table 1). The estimates of historic SOC loss range widely, from 44 to 537 Gt, with a common range of 55 to 78 Gt (*3*).

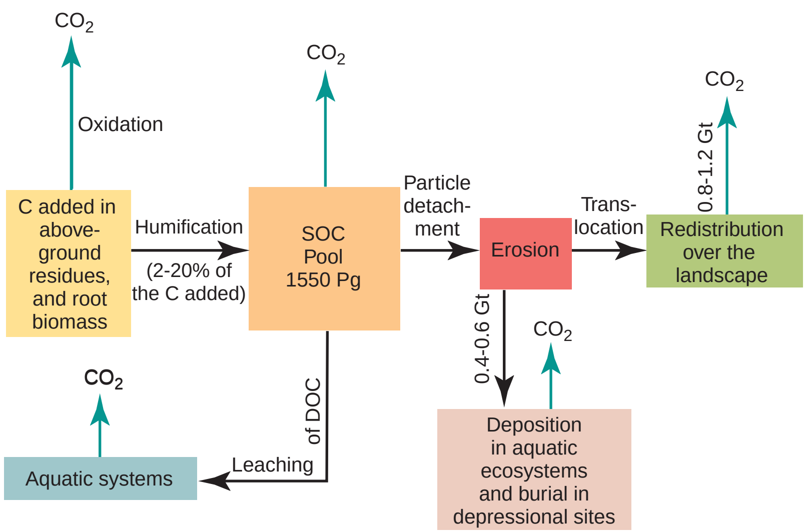

Fig. 1. Processes affecting soil organic carbon (SOC) dynamics. Arrows pointed upward indicate emissions of CO_2 into the atmosphere. There may also be emission of CH_4 under anaerobic conditions, although most well-drained soils are a sink of CH_4. DOC, dissolved organic carbon.

Soil Carbon Sequestration

Carbon sequestration implies transferring atmospheric CO_2 into long-lived pools and storing it securely so it is not immediately reemitted. Thus, soil C sequestration means increasing SOC and SIC stocks through judicious land use and recommended management practices (RMPs). The potential soil C sink capacity of managed ecosystems approximately equals the cumulative historic C loss estimated at 55 to 78 Gt. The attainable soil C sink capacity is only 50 to 66% of the potential capacity. The strategy of soil C sequestration is cost-effective and environmentally friendly (table S1).

The rate of increase in the SOC stock, through land-use change and adoption of RMPs, follows a sigmoid curve, attains the maximum 5 to 20 years after adoption of RMPs, and continues until SOC attains another equilibrium. Observed rates of SOC sequestration in agricultural and restored ecosystems depend on soil texture, profile characteristics, and climate, and range from 0 to 150 kg C/ha per year in dry and warm regions (*4*), and 100 to 1000 kg C/ha per year in humid and cool climates (*5*–*8*) (fig. S2). With continuous use of RMPs, these rates can be sustained for 20 to 50 years or until the soil sink capacity is filled (*8*, *9*). The SOC sequestration is caused by those management systems that add high amounts of biomass to the soil, cause minimal soil disturbance, conserve soil and water, improve soil structure, enhance activity and species diversity of soil fauna, and strengthen mechanisms of elemental cycling (Fig. 2, table S2). Common RMPs that lead to SOC sequestration are mulch

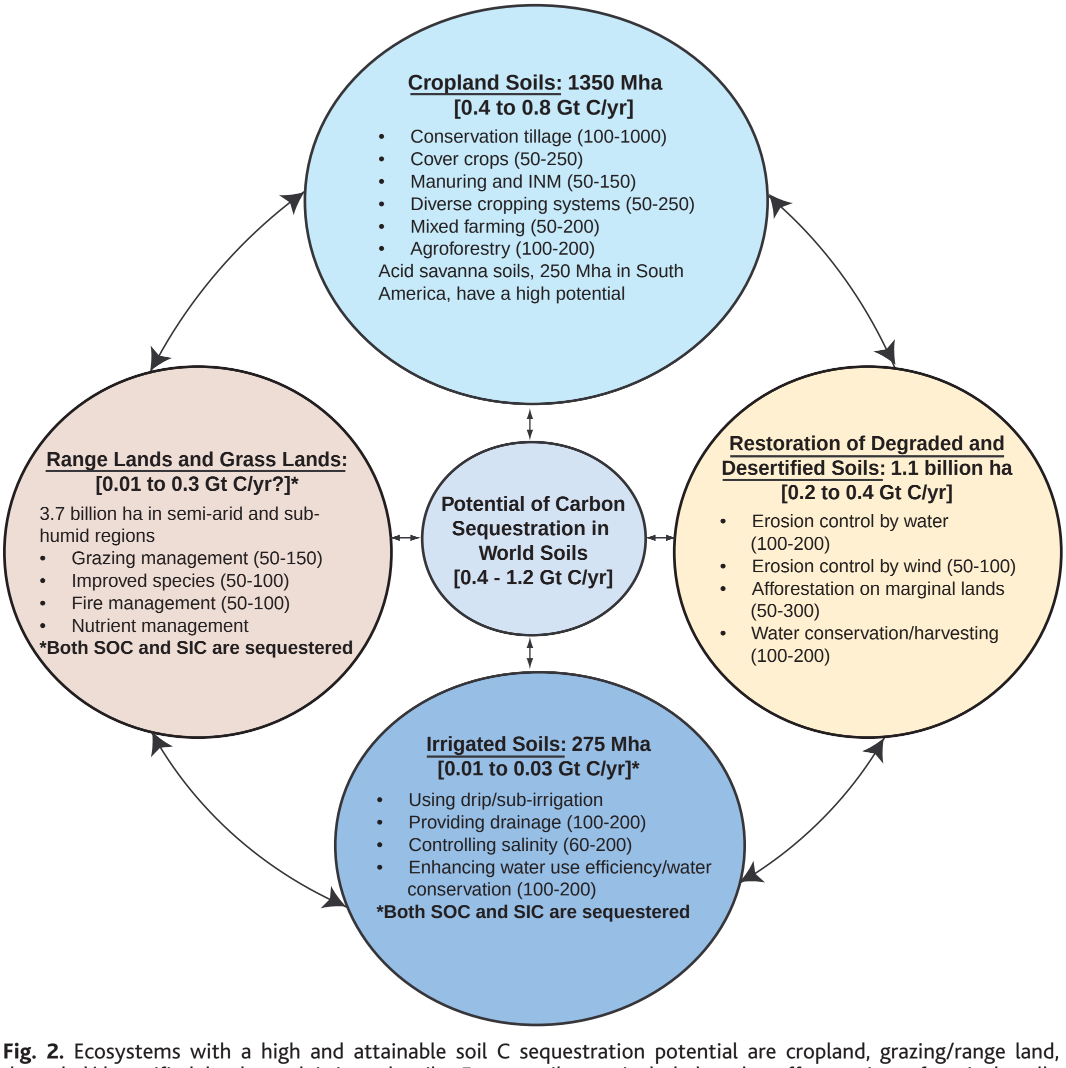

Fig. 2. Ecosystems with a high and attainable soil C sequestration potential are cropland, grazing/range land, degraded/desertified lands, and irrigated soils. Forest soils are included under afforestation of agriculturally marginal and otherwise degraded/desertified soils. Reforestation of previously forested sites have small additional soil C sequestration. The potential of C sequestration of range lands/grassland is not included in the global total because part of it is covered under other ecosystems, and there are large uncertainties. Rates of C sequestration given in parentheses are in kg C/ha per year, are not additive, and are low under on-farm conditions. [Rates are cited from (*2*–*9*, *15*, *25*, *37*–*39*) and other references cited in the supporting material.]

farming, conservation tillage, agroforestry and diverse cropping systems, cover crops (Fig. 3), and integrated nutrient management, including the use of manure, compost, biosolids, improved grazing, and forest management. The potential of SOC sequestration also lies in restoration of degraded soils and ecosystems (*10*) whose resilience capacity is intact. The rate of SIC sequestration as secondary carbonates is low (5 to 150 kg C/ha per year) and is accentuated by biogenic processes and leaching of carbonates into the groundwater (*11*, *12*), especially in soils irrigated with water containing low carbonates.

Soil Carbon Sequestration for Mitigating Climate Change

Estimates of the total potential of C sequestration in world soils vary widely from a low of 0.4 to 0.6 Gt C/year (*9*) to a high of 0.6 to 1.2 Gt C/year (*13*). Thus, the potential is finite in capacity and time. Nonetheless, soil C sequestration buys us time until the alternatives to fossil fuel take effect. Some issues related to this strategy are as follows:

1) Agricultural chemicals. Most RMPs involve C-based input. It takes 0.86 kg C/kg N, 0.17 kg C/kg P_2O_5, 0.12 kg C/kg K_2O, 0.36 kg C/kg lime, 4.7 kg C/kg of herbicides, 5.2 kg C/kg of fungicides, 4.9 kg C/kg of insecticides (*14*), and 150 kg C/ha for pumping groundwater for irrigation (*15*). Tillage operations emit 15 kg C/ha for moldboard plowing, 8 kg C/ha for chisel plowing and heavy tandem disking, 6 kg C/ha for light tandem disking, 11 kg C/ha for subsoiling, 4 kg C/ha for cultivation, and 2 kg/ha for rotary hoeing (*16*). Therefore, conversion from conventional till to no-till farming reduces emission by 30 to 35 kg C/ha per season (*16*). Similarly, a judicious use of C-based inputs is essential to enhancing use efficiency and minimizing losses. However, inputs are needed not for soil C sequestration per se, but for increasing food production and ensuring sustainable use of soil and water resources.

2) Nutrients required. Carbon is only one of the elemental constituents of humus. It is estimated that sequestration of 1 Gt of C in world soils would require 80 million tons (Mt) of N, 20 Mt of P, and 15 Mt of K. In comparison, the global fertilizer use in 2000 was 136 Mt (*17*). However, there are several sources of nutrients for C sequestration, including biological nitrogen fixation, recycling from subsoil, aerial deposition, use of biosolids, and crop residues. One ton of cereal residue contains 12 to 20 kg N, 1 to 4 kg P, 7 to 30 kg K, 4 to 8 kg Ca, and 2 to 4 kg Mg. Annually, 3 Gt of residues of grain crops are produced globally (table S3), which if recycled rather than removed for fuel and other uses, would improve soil quality and sequester C. Crop residue is also a potential source of energy by direct combustion, or for production of ethanol or H_2. It can be used either for biofuel production or to sequester C and improve soil quality. The economics of these two competing uses need to be assessed.

3) Soil erosion and deposition. The SOC is preferentially removed by wind- and water-borne sediments through erosional processes. Some of the SOC-enriched sediments are redistributed over the landscape, others are deposited in depressional sites, and some are carried into the aquatic ecosystems (Fig. 1). Although a part of the C translocated by erosion may be buried and redistributed (*18*), the rest is emitted into the atmosphere either as CO_2 by mineralization or as CH_4 by methanogenesis. Erosion-induced deposition and burial may be 0.4 to 0.6 Gt C/year compared with perhaps 0.8 to 1.2 Gt C/year emitted into the atmosphere (Fig. 1) (*19*). Quantification

of emission versus burial of C is a high priority. Yet, an effective soil erosion control is essential to sustainable use of agricultural soils and improving environment quality.

4) Extractive farming practices. The annual depletion rate of nutrients for sub-Saharan Africa (SSA) caused by low-input/subsistence farming is estimated to be 40 kg of NPK/ha of cultivated land since the mid-1960s (*20*). Mining SOC from soil for nutrients through organic-matter decomposition has an effect on the atmosphere similar to that of fossil-fuel combustion. Therefore, RMPs must enhance rather than deplete SOC pool and soil fertility, increase rather than maintain or decrease crop yield per unit use of fertilizer and other inputs, and improve rather than degrade soil quality.

5) Societal value and hidden benefits. Commodification of soil C is important for trading C credits. Carbon trading markets have existed since 2002, especially in European Union countries (*21*). The low current price (\$1/ton CO_2) of SOC may increase with emission cap and regulation. For the concept of SOC credits trading to become routine as a part of the solution to mitigate climate change, the ability to measure short-term (3- to 5-year) changes in SOC pool exists (*22*), but the price of soil C must be based on both on-site and off-site societal benefits (table S4). Undervaluing soil C can lead to a "tragedy of the commons."

6) Hydrologic and carbon cycles. Because renewable freshwater is scarce, a projected increase in cereal production by 56% between 1997 and 2050 (*23*) must occur on the same or smaller land area and with the same or less water. Thus, linking the hydrologic and C cycles through conservation of water resources is crucial to improving agronomic yields and to soil C sequestration in dryland. The low SOC stock in rainfed agriculture can be enhanced through water conservation, water harvesting, and water-efficient farming systems. Enhancing SOC stock in dryland ecosystems through no-till farming is important to drought management: a truly win-win option (*24*).

7) Soil C sequestration and global warming. Global warming is a "century-scale" problem and a "global commons" issue. Soil C sequestration is a related but separate issue with its own merits of increasing productivity, improving water quality, and restoring degraded soils and ecosystems, irrespective of the global-warming debate. Offsetting fossil-fuel emissions by achievable SOC potential provides multiple biophysical and societal benefits (table S3). Furthermore, soil C sequestration is a bridge across three global issues—climate change, desertification, and biodiversity—and a natural link among three UN conventions.

Table 1. Estimates of pre- and postindustrial losses of carbon from soil and emission from fossil-fuel combustion. Data were compiled from diverse sources (*1–3*). Ruddiman (*1*) estimated the emission from land-use conversion during the postindustrial era at 0.8 Gt C/year for 200 years at 160 Gt C.

Source		Historic carbon emission (Gt)
	Preindustrial era	
Fossil-fuel combustion		0
Land-use conversion at 0.04 Gt C/year for 7800 years		320
	Postindustrial era	
Fossil-fuel combustion (since 1850)		270 ± 30
Land-use conversion		136 ± 5
Soil cultivation	78 ± 12	
Erosion	26 ± 9	
Mineralization	52 ± 8	

8) Other greenhouse gases. Enhancing SOC stock increases the soil's capacity to oxidize CH_4, especially under no-till farming (*25*), but may also exacerbate emission of N_2O (*26*). Fluxes of CH_4 and N_2O may change the CO_2-mitigation potential of soil management practices and must be considered along with SOC sequestration.

9) Soils of the tropics. Because of its severe depletion and degradation, the C sink capacity of soils of the tropics may be high, but the rate of sequestration can be low. The need for enhancing soil quality is also more urgent in soils of the tropics than in soils of high latitudes because of low crop yields. Yet, the challenge is greater because of weak institutions, limited infrastructure, and predominantly resource-poor agriculture systems. Soil-restorative farm policies must be implemented to mitigate soil-degradative trends.

10) Permanence. Soil C sequestration is a natural, cost-effective, and environment-friendly process. Once sequestered, C remains in the soil as long as restorative land use, no-till farming, and other RMPs are followed. Soil sink capacity and permanence are related to clay content and mineralogy, structural stability, landscape position, moisture and temperature regimes, and ability to form and retain stable microaggregates.

Soil Carbon Sequestration and Global Food Security

Global hotspots of soil degradation with a high priority for soil restoration and C sequestration include SSA, central and south Asia, China, the Andean region, the Caribbean, and the acid savannas of South America. Complete residue removal for fodder and fuel is a norm in south Asia and Africa. Thus, depletion of SOC stock from the root zone has adversely affected the soil productivity and environmental quality of these regions. Simply put, poor farmers have passed on their suffering to the land through extractive practices. They cultivate

Fig. 3. Important recommended management practices are no-till farming, cover crops, manuring and agroforestry. (**A**) Long-term no-till plots were established at the International Institute of Tropical Agriculture, Ibadan, in 1971 and continued through 1987. The adoption of no-till by small landholders in Africa and Asia has been constrained by removal of crop residue mulch for fodder and fuel, nonavailability of a proper seed drill that can cut through the residue, and prohibitively expensive herbicides. (**B**) Agroforestry, sowing wheat under the canopy of poplar, is widely practiced in Punjab, India. Other combinations of trees and crops and forages may be beneficial to sustainable use of soil-water resources and C sequestration in site-specific situations.

marginal soils with marginal inputs, produce marginal yields, and perpetuate marginal living and poverty. As a source of nutrients for growing crops, the SOC pool is a mean of production in subsistence farming systems of SSA, which accounts for only 2.5% of the fertilizer consumption and 2% of the world's irrigated land area, both essential to SOC sequestration. Benefits of RMPs cannot be realized in severely degraded soils depleted of their SOC stock—soil's life support system. An optimum level of SOC stock is needed to hold water and nutrients, decrease risks of erosion and degradation, improve soil structure and tilth, and provide energy to soil microorganisms. The SOC is a biomembrane that filters pollutants, reduces sediment load in rivers, decreases hypoxia in coastal ecosystems, degrades contaminants, and is a major sink for atmospheric CO_2 and CH_4. Fertilizer application is an important strategy of increasing crop yield in SSA (*27*), but its effectiveness is enhanced when used in conjunction with crop residue mulch (*28*) or trees (*20*). Increase in SOC stock increases crop yield even in high-input commercial agriculture (*29*), but especially in soils where it has been depleted (*30*). An increase of 1 ton of SOC increased wheat grain yield by 27 kg/ha in North Dakota, United States (*29*), and by 40 kg/ha in semi-arid pampas of Argentina (*31*), 6 kg/ha of wheat and 3 kg/ha of maize in alluvial soils of northern India (*32*), 17 kg/ha of maize in Thailand (*33*), and 10 kg/ha of maize and 1 kg/ha of cowpea in western Nigeria (*34*). High SOC stock is also needed to maintain consistent yields through improvements in water and nutrient holding capacity, soil structure, and biotic activity. The critical limit of SOC concentration for most soils of the tropics is 1.1% (*35*). Increasing SOC concentration from a low of 0.1 to 0.2% to a critical level of 1.1% is a major challenge for tropical ecosystems. Yet, a drastic reduction in the SOC pool in SSA and elsewhere must be reversed in order to advance food security. An 18-year experiment in Kenya showed that the yield of maize and beans was 1.4 tons/ha per year without external input and 6.0 tons/ha per year when stover was retained and fertilizer and manure were applied. The corresponding SOC stocks to 15-cm depth were 23.6 tons/ha and 28.7 tons/ha, respectively (*36*). This is the type of quantum jump in crop yields needed at the continental scale to ensure food security in SSA. The vicious cycle of declining productivity–depleting SOC stock–lower yields will have to be broken (Fig. 4) by improving soil quality through SOC sequestration in order to free much of humanity from perpetual poverty, malnutrition, hunger, and substandard living.

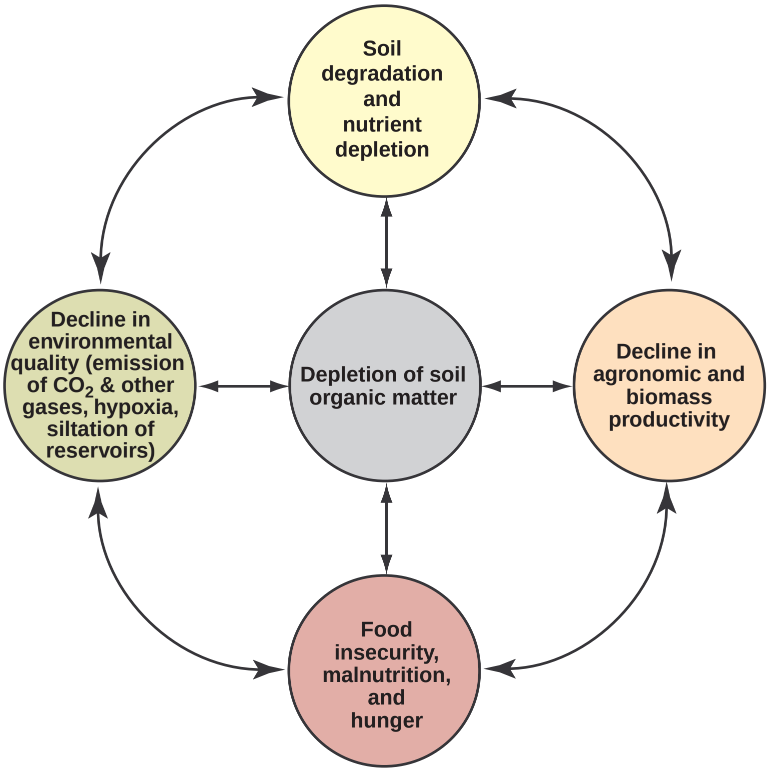

Fig. 4. Cereal yields in Africa have been stagnant since early 1970s and stand at a meager 1 ton/ha. The vicious cycle of deletion in soil organic matter–decline in crop yield–food insecurity–soil and environmental degradation can be broken by improving soil fertility through enhancement of the soil organic matter pool, which requires use of sustainable agricultural technologies for water and nutrients management, including no-till farming, composts and mulching, leguminous cover crops, water harvesting, agroforestry, and integrated farming systems, along with judicious use of chemicals. This strategy can break the tyranny of hunger.

Conclusions

Soil C sequestration is a strategy to achieve food security through improvement in soil quality. It is a by-product of the inevitable necessity of adopting RMPs for enhancing crop yields on a global scale. While reducing the rate of enrichment of atmospheric concentration of CO_2, soil C sequestration improves and sustains biomass/agronomic productivity. It has the potential to offset fossil-fuel emissions by 0.4 to 1.2 Gt C/year, or 5 to 15% of the global emissions.

Soil organic carbon is an extremely valuable natural resource. Irrespective of the climate debate, the SOC stock must be restored, enhanced, and improved. A C-management policy that includes regulation-based trading soil C must be developed. Likewise, a widespread adoption of RMPs by resource-poor farmers of the tropics is urgently warranted. The soil C sequestration potential of this win-win strategy is finite and realizable over a short period of 20 to 50 years. Yet, the close link between soil C sequestration and world food security on the one hand and climate change on the other can neither be overemphasized nor ignored.

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40. This work was sponsored by the Carbon Management and Sequestration Center, School of Natural Resources, Ohio Agricultural Research and Development Center, and the Climate Change CIRIT, The Ohio State University, Columbus, OH.

Supporting Online Material
www.sciencemag.org/cgi/content/full/304/5677/1623/DC1
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VIEWPOINT

Breaking the Sod: Humankind, History, and Soil

J. R. McNeill[1]* and Verena Winiwarter[2,3]

For most of history, few things have mattered more to human communities than their relations with soil, because soil provided most of their food and nutrients. Accordingly, some of the earliest written documents were agricultural manuals intended to organize, preserve, and impart soil knowledge. Indeed, ancient civilizations often worshipped the soil as the foundry of life itself. For the past century or two, nothing has mattered more for soils than their relations with human communities, because human action inadvertently ratcheted up rates of soil erosion and, both intentionally and unintentionally, rerouted nutrient flows.

Our distant ancestors found their food by hunting and foraging. They depended indirectly on soils to support plant growth, but they did not much alter soils by their actions, except where they routinely burned vegetation. With the transitions to agriculture (which probably happened independently at least seven times, beginning about 10,000 years ago), human dependence upon, and impact upon, soils became more direct and more obvious. Neolithic farmers, in southwest Asia and elsewhere, depleted soils of their nutrients by cultivating fields repeatedly, but they simultaneously enriched their soils once they learned to keep cattle, sheep, and goats, pasture them on nonarable land, and collect them (or merely their dung) upon croplands. They also worshipped deities that they connected not only to fertility in livestock and women, but also to soil productivity.

When a population lived amid the fields that sustained them, the net transfer of nutrients into or out of the fields remained minor, as after shorter or longer stays in human alimentary canals and tissues, nutrients returned to the soils whence they had come. Urban life changed that, systematically drawing nutrients from fields to cities, from whence wastes left via streams or rivers, en route to the sea. So civilization, with its systemic links between cities and hinterlands, over the past 5000 years has posed an ongoing challenge for farmers trying to maintain soil fertility.

[1]Edmund A. Walsh School of Foreign Service, Intercultural Center 600, Box 571035, Georgetown University, 3700 O Street, N.W., Washington, DC 20057–1035, USA. [2]Institute for Soil Research, University of Natural Resources and Applied Life Sciences, A-1-80, Vienna, Austria. [3]Institute for Interdisciplinary Studies, A-1070, Vienna, Austria.

*To whom correspondence should be addressed. E-mail: mcneillj@georgetown.edu

Soil Erosion

In most settings, agriculture promoted soil erosion, although to highly varying degrees. On a global scale, soil erosion occurred in three main waves. The first arose as a consequence of the expansion of early river-basin civilizations, mainly in the second millennium B.C.E. Farmers left the valleys and alluvial soils of the Yellow River, Indus, Tigris-Euphrates, and lesser rivers (or from the Maya lowlands) and ascended forested slopes, where they exposed virgin soils to seasonal rains. The loess plateau of north China, for example, began to erode more quickly during this period, earning the Yellow River its name (*1*). Over the next 3000 years, farmers in Eurasia, Africa, and the Americas gradually converted a modest proportion of the world's forests into farmland or pasture and thereby increased rates of soil erosion, but the fertile soils of the world's grasslands were little affected.

That changed in the 16th to 19th centuries when, in a second great wave of soil erosion, stronger and sharper plowshares helped break the sod of the Eurasian steppe, the North American prairies, and the South American pampas. The exodus of Europeans to the Americas, Australia, New Zealand, Siberia, South Africa, Algeria, and elsewhere brought new lands un-

Fig. 1. A 16th-century Italian fresco of a cultivated field.