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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.

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.

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der the plow and put people accustomed to a humid and equable climate in semiarid landscapes where their farming habits helped accelerate soil erosion (*2*, *3*).

The third great wave of erosion came after 1945, when modern medicine, rapid population growth, and other factors propelled a new frontier into the world's thinly populated tropical rain forests. Heavy rains and steep slopes in, for example, Rwanda and Guatemala have lately brought about some of the highest recorded rates of soil erosion. At the same time, however, effective soil conservation has spread since the 1930s, especially in North America and Europe. Nonetheless, in global terms the past 60 years have brought human-induced soil erosion and the destruction of soil ecosystems to unprecedented levels (*3*).

Soil Management

Soil management practices have developed in response to the twin challenges of depletion and erosion, as well as the less common problems of salinization and soil compaction. Problems of soil management have provoked much reflection, especially in societies with traditions of leisured, literate landowners. The ancient civilizations of the Middle East, the Mediterranean, India, and China all produced texts concerning soils, collecting knowledge crucial to the agricultural surplus on which each depended. Farmers have invented many techniques to forestall soil erosion, the most important of which was probably terrace building, found on all inhabited continents and even remote oceanic islands. The earliest, apparently in Arabia, date from at least 2000 B.C.E. Few farming practices are as widespread in space and time, testimony to the perceived efficacy of terraces, despite their heavy labor requirements. When properly positioned and maintained, they partially stabilized soils, but in circumstances of labor shortage often deteriorated quickly (*4*, *5*). Modern soil conservation efforts, which from the 1930s were increasingly sponsored by governments, employed combinations of several additional techniques such as contour plowing, use of cover crops, conservation tillage, and various impediments to wind and water—all of which had historical precedents.

Coping with nutrient depletion has also occupied farmers for millennia. The earliest farmers—and many later ones, too—practiced shifting agriculture with a long fallow (20 to 30 years). Mobility was their solution to nutrient depletion. Sedentary farmers, however, had to recycle organic material or else watch their yields plummet over time—and if they were feeding cities, it would not take long before nutrients such as nitrogen and phosphorus ran low. Where domestic animals were kept, animal manure provided an admirable remedy. In the Americas before Columbus, the paucity of domestic livestock meant minimal manure. Mesoamerican and Andean farmers compensated with elaborate intensification techniques, including irrigation, terracing, and wetland raised fields. In East Asia's rice zones, low-nitrogen pig manure was supplemented by reliance on night soil. In 1649 Tokyo, toilets that emptied into streams or canals were banned so as to maximize the collection of human excrement (*6*). However, such methods carried heavy costs: Wherever populations relied on manure or night soil, they suffered heavily from infectious diseases contracted by handling excrement.

By recycling organic material, farmers reduced nutrient loss, but they could not prevent it. However, early farmers often practiced crop rotations with legumes (and, in the tropics, natural fallows with leguminous plants) that did restore nitrogen. The world's first farmers, in southwest Asia, recognized the restorative properties of legumes very quickly and rotated peas and lentils with their cereal crops. Soybeans, peas, beans, and chickpeas in East Asia, lentils in India, peanuts in Africa, and beans in the Americas all served the same purpose, and were indispensable to cereal and root crop production. Alfalfa and clover helped fix nitrogen in the soils of grazing land. Without any conception of nitrogen, farmers around the world followed practices that fixed atmospheric nitrogen in their soils (*6*). Had they not learned to do so, there would be no cities or civilization anywhere on earth.

Soil Knowledge

Staving off the recurrent problems of fertility decline required the development of a finer knowledge of soils. Farmers everywhere developed soil tests, seeking information beyond what they could gather at a glance. For example, the Roman writer Columella described a procedure whereby one dug a hole and refilled it. If the refilled earth formed a pile, it was a fertile soil. If the refilled earth did not come up to ground level, the soil was poor (*7*). A British colonial officer observed the same test being used in Malabar, India, in the 1820s (*8*).

Farmers and agronomic writers widely recognized the problem of soil nutrient depletion, although they did not understand it in chemical terms until the 19th century. Remedies such as the use of night soil are mentioned in texts as old as *The Odyssey*. Ancient texts from China and the Mediterranean recommended green manuring, in the forms of crop residues, seaweed, kitchen ash, and more, from at least the third century B.C.E. (*9*). The value of animal manure was clear from the earliest domestications of livestock and is mentioned widely in ancient texts.

The development of soil knowledge has resulted in extensive systems of classification. These may be based on landscape and profile morphology; on soil texture, color, water content, indicator plants, particle size, and structure; or on mineral constituents of soils. Ancient Chinese soil classification systems, for example, were numerous and elaborate. The oldest one extant, presented in the book *Yugong*, written about 500 B.C.E but representing older ideas, included characteristics such as soil fertility, color, texture, moisture, and associated vegetation. It recognized nine varieties of soil in northern China. A subsequent text, *Guan Zi*, written about 200 B.C.E., distinguished 90 soil types, using a much broader set of criteria. On the basis of these and other texts, several authors claim a Chinese origin for pedology (*10*).

Likewise, the Vedic literature of ancient India included discussion of soils, usually together with landforms, erosion, flooding, sedimentation, vegetation, land use, water, and/or human health. One text, the *Vishnu Purana*, usually dated to the first century C.E. (but it too is probably a distillation of older oral traditions), offers a classification based mainly on color (*8*). The Roman author Varro, also of the first century C.E., offered a classification distinguishing rock, marble, rubble, sand, loam, clay, red ochre, dust, chalk, ash, and carbuncle (*11*).

Soil knowledge acquired special importance when and where population pressure and land shortage impinged, as in the ancient Mediterranean. In less crowded lands, mobility normally offered the simplest solution to problems of declining agricultural productivity; hence, the social significance of soil knowledge, and the incentive to refine it, dwindled. Since about 1750, however, human populations almost everywhere grew rapidly, and the resulting pressures on food supplies brought persistent misery. Consequently, questions of soil fertility became central, and modern science addressed them in ways that revolutionized the human condition. European scientists took the lead in formulating new theories of soil fertility. In the 1840s, Justus von Liebig (1803–1873), one of the founders of organic chemistry, developed the idea that minerals such as nitrogen, phosphorus, and potassium were required for plant growth. This approach, refined over the next century, especially by John Lawes (1814–1900), remained at the heart of soil science, although not without challenges.

A more biological conception of soils, in some ways reminiscent of ancient views, arose late in the 19th century, notably in Germany and Russia. The decisive moment came in the 1880s when Hermann Hellriegel (1831–1895) and Mikhail Voronin (1838–1903) figured out the process of nitrogen fixation by microorganisms associated with the roots of leguminous plants. In effect, they uncovered the hidden pathways of the nitrogen cycle, as von Liebig had discovered hidden limits upon plant growth. As a result, Vasily Dokuchaev (1846–1903) proposed an integrated and ecological approach to soil science, drawing upon mineralogy, geology, chemistry, meteorology, biology, and geography. Dokuchaev, like Eugene Hilgard (1833–1916), an American of German birth, is frequently cited as the "father" of soil science. The integrated approach informed the increasingly elaborate soil classification systems developed for the Food and Agriculture Organization and the U.S. Department of Agriculture. While still concerned with fertility, soil science increasingly has turned to the ecological function of soils and to the degradation they suffer (*12*).

Nitrogen Synthesis

In von Liebig's lifetime, population growth and urbanization gradually intensified the problems of nutrient shortage. With improved transportation, however, modern farmers maintained soil fertility with fertilizers from afar, tapping the nutrient banks built up over millennia by seabird colonies. Guano from Chile and Peru counteracted soil fertility decline on the farms of Western Europe and eastern North America from the 1830s, but it was always scarce and expensive. The big breakthrough that made nitrogenous fertilizer comparatively cheap came with the work of the German chemist Fritz Haber (1868–1934). By 1913, Haber found a way to synthesize ammonia from the air, the basis of all subsequent nitrogenous fertilizer. For reasons connected to world wars and the Great Depression, Haber's work had limited impact until the 1950s, but ever since, the problem of nutrient depletion has been treated by various forms of soil chemotherapy, chiefly nitrogenous fertilizer, at least by farmers who could afford it. Without it, the world's farms could feed only two out of three of today's 6.3 billion people (*6*).

Soil ecosystems remain firmly, but uncharismatically, at the foundations of human life. The intensity and scale of modern soil use and abuse suggest there is much yet to be discovered about soils and their relations with people. Equally, current behavior implies that there is much that is already known that is not yet converted into prevailing practices. Soil ecosystems are probably the least understood of nature's panoply of ecosystems and increasingly among the most degraded. Correspondingly, soil history remains the least understood, and least recognized, aspect of environmental history.

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REVIEW

Ecological Linkages Between Aboveground and Belowground Biota

David A. Wardle,[1,2]* Richard D. Bardgett,[3] John N. Klironomos,[4] Heikki Setälä,[5] Wim H. van der Putten,[6] Diana H. Wall[7]

All terrestrial ecosystems consist of aboveground and belowground components that interact to influence community- and ecosystem-level processes and properties. Here we show how these components are closely interlinked at the community level, reinforced by a greater degree of specificity between plants and soil organisms than has been previously supposed. As such, aboveground and belowground communities can be powerful mutual drivers, with both positive and negative feedbacks. A combined aboveground-belowground approach to community and ecosystem ecology is enhancing our understanding of the regulation and functional significance of biodiversity and of the environmental impacts of human-induced global change phenomena.

The aboveground and belowground components of ecosystems have traditionally been considered in isolation from one another. There is now increasing recognition of the influence of these components on one other and of the fundamental role played by aboveground-belowground feedbacks in controlling ecosystem processes and properties (*1*–*4*). Plants (producers) provide both the organic carbon required for the functioning of the decomposer subsystem and the resources for obligate root-associated organisms such as root herbivores, pathogens, and symbiotic mutualists. The decomposer subsystem in turn breaks down dead plant material and indirectly regulates plant growth and community composition by determining the supply of available soil nutrients. Root-associated organisms and their consumers influence plants more directly, and they also influence the quality, direction, and flow of energy and nutrients between plants and decomposers. Exploration of the interface between population- and ecosystem-level ecology is an area attracting much attention (*5*, *6*) and requires explicit consideration of the aboveground and belowground subsystems and their interactions.

Here we discuss recent advances in our understanding of the links between these two subsystems. We first outline how the aboveground subsystem influences the belowground subsystem and vice versa. We then discuss biodiversity links between the aboveground and belowground subsystems. Finally, we explain how the study of aboveground-belowground interactions may assist our understanding of the consequences of human-induced global change phenomena.

How Aboveground Communities Drive the Belowground Subsystem

It has long been recognized that soil organisms are responsive to the nature of organic matter

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