

MISUNDERSTANDING SOIL ECOSYSTEMS

How flawed conceptions of soil have lead to flawed U. S. land, water and climate policies.

A thesis

submitted by

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Abstract

Flawed conceptual models of soil functions have been cited by soil ecologists and others as contributing to missing policy and inadequate research on soil ecosystems. Although new soil research methods and tools have provided much greater detail on the functioning of soil ecosystems, U. S. soil policy and commonly accepted models of soil systems do not reflect that knowledge. This work investigates the dominant conceptual models of soil underlying existing U.S. policy along with the diverse and interdependent drivers of soil models and related land, water and climate policies. These policy drivers include the history of U. S. land use, agriculture and environmental policy, the development of reductionist views of soil systems and the continued and often obscured interdependencies among business, farmers, legislators, government agencies, educational institutions and policy makers. The final chapter evaluates soil policy trends in the United States and abroad for their potential to positively or negatively affect soil ecosystem health.

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I: Introduction

Without functioning soil ecosystems life on earth as we know it would not exist. The condition of soil ecosystems affects global warming, carbon sequestration, the quantity and quality of fresh water, the productivity and nutritional value of plants growing in soil, the success of invasive organisms, the health of bays and estuaries and the availability of new medicines for human health. Soil ecosystems are key drivers of the global cycles of carbon, water, nitrogen, phosphorus and sulfur.

Few policy makers or scientists outside soil-related fields understand or acknowledge the complexity and extent of the ecosystem services supplied by interactions of soil's living (biota) and non-living (abiotic) components. The interactors include bacteria, fungi, invertebrates and plant roots, aboveground organic debris, inorganic particles and the water and gas-filled spaces in which these interactions occur.

The U.S. Environmental Protection Agency (EPA) has a legal mandate to protect air and water¹ but no legislative directive to protect soils or soil life. The United States Department of Agriculture (USDA) spends the bulk of its funding on strategies, research and price supports that ignore or actively harm soil life and soil water. The USDA's Natural Resources Conservation Service (NRCS) formerly the Soil Conservation Service acknowledges the existence of soil ecosystems and has a historical commitment to erosion prevention but it has conflicting missions and no legal mandates to enforce protections.

Flawed conceptual models of soil functions have been cited by soil ecologists and others as contributing to a lack of policy and inadequate research on soil ecosystems. "Black box" models² representing soil microbial life as an undifferentiated mass distinguished only by outputs of carbon dioxide (CO₂), nitrates and oxygen (O₂), or merely a "collection of discrete aggregates" with various water holding capacities are among the simplest distortions critiqued.³ An international group of soil ecologists promotes dissemination of more accurate and detailed

information on “below-surface biodiversity”⁴ to encourage better and sustainable soil and sediment management. Although new soil research methods and tools have provided much greater detail on the functioning of soil ecosystems, U.S. soil policy and commonly accepted models of soil systems do not reflect that knowledge.

In a special section in the June 1994 issue of *Science*, the journal of the American Association for the Advancement of Science (AAAS), entitled, “Soils the Final Frontier,” the editors suggested that the “opacity of soil has severely limited our understanding of how it functions” but that “perspectives are beginning to change.”⁵ Just two years before, soil biologist David Wardle, author of 169 articles on soil/plant issues, reported in his book, *Communities and Ecosystems: Linking the Aboveground and Belowground Components* that fewer than 3 percent of papers published in major ecological journals studied belowground organisms. Those who did, he reported, erroneously suggested that the field was new when in fact important work had been going on for decades and much of the basic structure and function of soil ecology was known in the 1970s.⁶ In 1974 B. N. Richards an Australian Professor of Natural Resources released *Introduction to the Soil Ecosystem*, a textbook laying out a systems model of soil functioning, clearly illustrating the links and feedbacks between soil life, soil water and global cycles.⁷

A decade earlier in her 1962 best seller, *Silent Spring*, Rachel Carson devoted a chapter to the “the myriad organisms of the soil” which by “their presence and by their activities make [soil] capable of supporting the earth's green mantle.”⁸ She reported that the consensus of a group of scientists meeting in Syracuse in 1960 to “discuss soil ecology” was that the powerful chemicals being applied to soil posed serious threats to ecosystems.⁹ (495 million pounds of pesticides were applied to U.S. agricultural soils of the 1.2 billion total pounds used in the United States in 2004.¹⁰) Wardle et al. acknowledged in the 2004 *Science* special report an “increasing recognition of the fundamental role played by aboveground-belowground feedbacks in controlling ecosystem processes and properties.”¹¹ In 2006 Wall, Fitter and Paul noted that a survey by Morris et al. (2005) of articles published between 1985 and 1995 “showed a 10-fold

increase in soil biology topics.”¹² Interdisciplinary soil researchers Ian Young and John Crawford agreed that ecologists studying aboveground systems were beginning to realize the important connections with belowground ecosystems but decried the tendency in sub fields such as soil biology, soil chemistry, and soil physics to continue as “largely independent fields...“because no one discipline will be able to understand the most complex biomaterial on the planet.”¹³

Biologist A. H. Fitter former president of the British Ecological Society in an address to the group in 2005 pointed to the independent development of soil science and ecology as accounting for the limited contribution of ecologists in current debates on the destruction of the global soil resource and its key role in the global carbon cycle.¹⁴ Soil biologist Diana Wall, Director of the International Ecosystem Research Center in the College of Natural Resources at Colorado State University and her soil ecologist colleagues at the UN Scientific Committee on Problems of the Environment (SCOPE) report that soil [land] and sediment [aquatic environments] habitat damage continues at “an unparalleled rate.”¹⁵

Why do simple, reductionist conceptions of soil persist such as the “black box” model or models of soil as principally a filtering medium or a physical support structure for plants?¹⁶ Is it merely, as some soil ecologists report, a function of insufficient cross-disciplinary approaches? What role if any have commercial interests, research funding, soil policy history, disciplinary boundaries, economic and political interests played in promoting our limited understanding of soil ecosystems? What conceptual models of soil have some stakeholders supported that have obscured what soil ecologists and microbiologists have uncovered? What points of view, what biases are embedded in the language used to describe soil that appears in journal articles, government management decisions, corporate reports, advertising and the popular press? What conceptual model and language should be presented to policy makers and to the public to make them aware of the essential aspects of soil ecosystems? A methodology section (Chapter 2) discusses the criteria used to select scientific source material that is summarized in a citation

table. (Appendix I) A discussion of historical and policy sources and the research approach used in this thesis are also discussed in Chapter 2.

To address these questions this thesis begins with a primer on soil ecosystems (Chapter 3) focused on key ecosystem processes at work in soils. This chapter and the next tracing the history of soil policy in the United States (Chapter 4), particularly the divergence of environmental and agricultural policy in the United States provide the background and context for the analysis in Chapter 5 of the three conceptual models of soil embedded in existing environmental and agricultural policies and practices and the language used to characterize soil. I then provide a conceptual model of soils that is more reflective of current knowledge of soil systems than the dominant models. The final chapter (6) reviews trends in soil education, research and policy in the United States and abroad for their potential to raise awareness of soil ecosystems and develop policies to preserve them.

The premise of this thesis is that before we can expect policymakers to correct flawed policies affecting soil ecosystems, the often unconscious flawed conceptual models they and we hold must be corrected. Our dominant conceptual model of soils needs to reflect and connect the depth and breathe of current interdisciplinary scientific evidence. Just as important to effect sound policy this new model must all be presented in language and images that clearly convey in layman's terms their essence and importance to human health and the health of our land, water and climate.

II. Thesis Methodology

Soil Ecosystem Science Sources

As part of my analysis of soil conceptual models and soil policy I offer a primer on soil ecosystems and their role in the global cycles of water, carbon and nitrogen. The primer is a brief introduction to current knowledge of soil ecosystems and global cycles as reported by academic experts with long records of engagement in cross disciplinary soil research as indicated, in part, by their publication and citation records and their roles as primary authors or editors of soil ecosystem text books and symposia papers of leading researchers in soil-related fields. The primary research fields of sources for this primer include ecology, soil ecology, soil biology, soil science, soil water science, conservation biology, soil mycology, soil biochemistry, biogeochemistry, microbiology, agronomy and crop science.

The basic references for the primer are university, graduate-level texts in soil studies written or edited by scientists with a long record of peer reviewed and frequently cited publications as indicated by a Web of Science citation database search. See the evaluation matrix for the selected authors and editors in Appendix I: Table 1 comparing numbers of articles, number of citations, years cited, names of publications, and fields of expertise. These sources are supplemented with frequently cited and often, breakthrough soil ecosystem-related articles from refereed journals including in alphabetical order the following: *Ambio*, *Applied Environmental Microbiology*, *Applied Soil Biology*, *BMC evolutionary biology*, *BioScience*, *The Bryologist*, *Conservation Ecology*, *Ecology*, *Frontiers in Ecology*, *Hydrology and Earth System Sciences*, *Issues in Ecology*, *Journal of Ecology*, *Biology and Fertility of Soils*, *Journal of Environmental Quality*, *Journal of Soil and Water Conservation*, *Microbial Ecology*, *Microbiology Today*, *Mycorrhizal Ecology*, *Natural Resources Forum*, *Nature*, *Nature Biotechnology*, *Nature Reviews Microbiology*, *New Phytologist*, *Plant and Soil*, PLoS Biology (the peer-reviewed, open-access journal published by the Public Library of Science). *Proceedings of the National Academy of Sciences of the United States of America*, *Science*, *Soil Biology and Biochemistry*, *Soil Microbiology and Soil Science Society of America Journal*.

Greatest weight is given to research reported in the last decade, confirmed by multiple studies and based on a variety of new research methods such as DNA/rRNA analysis, isotope labeling and high resolution x-ray tomography allowing in situ studies of the relationship between biotic and abiotic soil components and their connection to above ground processes. Greater weight is also given to collaborative, cross-disciplinary works produced by academic specialists investigating the relationships between soils, water and climate systems. Long Term Soil Ecosystem studies (LTSEs) of field research projects across the globe as catalogued by Duke University also provided background data for the primer and model analysis.¹⁷

Approach to Tracking U.S. Soil Policy Research and Trends

Database searches of science and policy journal articles, U.S. government records, *Lexis-Nexis* and the *New York Times* in the Fall of 2008 provided evidence of professional and popular awareness of the concept of soil as an ecosystem. In-text terms searched included “soil ecosystems,” the alternative terms “soil ecology,” “belowground processes, canopy soil ” and the traditional term, “soil science” which has not generally been closely associated with soil ecosystem models. An Academic One¹⁸ file search located 73 articles within 27 different journals that mentioned “soil ecology.” Of these only 3 journals published more than 3 articles using the term “soil ecology” anywhere in the text. “Soil ecosystem” appeared in 63 articles in 44 journals. Belowground processes appeared in 30 academic journals. In contrast, the traditional term “soil science” occurred in 6,159 academic journals, 259 magazine articles and 159 news articles. An Academic One file search for “The Fertilizer Institute” (TFI) the main U.S. industry organization for synthetic fertilizer provided an initial gauge of industry influence on soil studies. The group was cited in 52 articles in peer-reviewed academic journals, 32 magazine articles and 12 news articles.

A Web of Science Search (1/15/08) of 39,689,136 articles from 1900-2008 found only 6 articles (One was a review.) that included the term “soil policy.” The six were spread over 10 years with one each in 1997, 2003 and 2006, and 3 in 2007. All six publications are based in Europe.¹⁹ A Google Scholar

search for “soil policy: yielded 404 hits including 102 “recent” hits, the overwhelming majority of which are tied to European Union soil policy initiatives. A search of the UK-based Cambridge Scientific Abstracts (2/25/05) for the term “soil ecosystems” resulted in 112 relevant articles from a range of academic databases: *Biological Sciences*, *Biological Digest*, *Plant Science*, *Agricultural and Environmental Biotechnology Abstracts*, *Aquatic Pollution and Environmental Quality*, *Aquatic Sciences and Fisheries Abstracts*, and *Water Resources Abstracts*. These results suggest a serious neglect or ignorance of key soil ecosystem research findings in the United States by scientists and policy makers over the past decade and a growing but, limited scientific and civic interest in Europe in protecting soil as a living system.

Soil policy historical context (political, economic, legal and environmental)

Several historical texts and two legal textbooks provide the historical context for understanding the development of U.S. soil and water policy. *Managing the Environment, Managing Ourselves* by UNC Distinguished Professor of Environmental Policy, Richard Andrews, an expert on U.S. Environmental policy traces the role of interest groups in the organization and structure of government environmental agencies and policies from Colonial land grant policies to the Clinton era air, water and agriculture policies that have affected soil ecosystems.²⁰

Douglas Helms, PhD., the historian of the USDA National Resource Conservation Service (formerly the Soil Conservation Service) is lead author and editor of several essays on the role of the U.S. Agriculture Department on the development of soil analysis techniques, polices and land management practices since the 1800s. *Profiles in the History of U.S. Soil Survey*²¹ edited by Helms, Effland and Duran presents 11 essays by employees of the Soil Service that reveal conceptual models of soil that have persisted since the Congress authorized the Soil Survey in 1899 to aid in making “wise land use decisions.”

The Literature of Soil Science, edited by Peter McDonald (1994) former Cornell University Agricultural librarian, traces the development of soil studies as a “science” from the dawn of the “chemical theories period” in the mid 1800s—supporting the power of soil

“specialists” and the growth of the fertilizer industry in early 1900s—to concerns with soil quality and climate change in the 1990’s.²²

Jerry W. Markam’s *A Financial History of the United States Vol. I*²³ analyzes the role of economic decisions, including agricultural commodity speculation in the soil degradation of the 1920s and 30s sparking Roosevelt era soil reforms.

Methods for tracing current soil-related U.S. law and government policy

To evaluate current U.S. soil policy the thesis reviews and summarizes current United States Code (U.S.C.) containing major soil-related policies. These included a review of U.S.C. Title 7 (Agriculture) Title 16 (Conservation), Title 33 (Navigable Waterways) and Title 42 (The Public Health and Welfare).

For Title 16 the next level of review included the ten chapters and sections that directly address soil or water conservation on national parks, forests, range lands and private farms with particular focus on Title 16, Chapter 40, The Soil & Water Resources Conservation Law which assigns the Agriculture Department direct legal responsibility for soil protection; Chapter 12A; the Tennessee Valley Authority Act which gave an independent federal authority the power to produce, promote and disseminate synthetic fertilizer to farmers, also Chapter 3B, Soil Conservation; and Chapter 58, Erodible Land and Wetland Conservation and Reserve Program.

Key chapters of the U.S.C. reviewed in Title 7, Agriculture for attention to soils are Chapter 1, Commodity Exchange; Chapter 35, Agricultural Adjustment Act of 1938; Chapter 86, Water Quality Research, Education, and Coordination; Chapter 88, Research, including Sustainable Agriculture and National Genetic Resources Program; Chapter 94, Organic Certification; Chapter 96, Global Climate Change and Chapter 103, Agricultural Research, Extension, and Education reform.

U.S.C. Title 33, Chapter 26; The Water Pollution Prevention and Control Act (The Clean Water Act) is reviewed for its assignment of water, but not direct soil protection responsibilities to the Environmental Protection Agency,

The 125 chapters of Title 42, Public Health and Welfare were reviewed for soil related statutes. Most relevant to this thesis are Chapters 55-57: Chapter 55, the National Environmental Policy Act of 1969 (NEPA) promoting cross-media evaluation of natural resources; Chapter 56, Environmental Quality Improvement and Chapter 57, Environmental Pollution Study.

For expert commentary on case law associated with U.S. soil policies this thesis relies primarily upon Plater et. al. *Environmental Law and Policy, Nature, Law and Society*, (2nd edition)²⁴ and to a less extent on Laitos's *Natural Resources Law*.²⁵ Both are volumes in the widely read American Case Book Series and are commonly assigned texts in environmental law courses.

A review of U. S government agency funding for soil related protection, education and research (total funding, proportional spending and project selection) is used as an indicator of U.S. attention to soil ecosystem issues. A search of federal web sites using the U.S government's search service provides another indication of government policy priorities. For example, a September 2008 query (<http://usasearch.gov/search?query=soil>) yielded 102 web pages with "soil" in the title, and 100 with "corn" in the title, 104 with pesticide in the title and only one with pesticide and ecosystem in the title. A 2005 search of the EPA web site produced only one explicit soil policy-related page.²⁶

Other key resources on U.S. soil policy and practice are reports by the National Academy of Science's National Research Council (NAS-NRC) and in particular a 2000 report by its Board on Agriculture and Natural Resources (BANR) evaluating the USDA's National Research Initiative. The report criticizes the USDA for spending only 7 percent of its research budget on "merit-based peer-reviewed research" and its "poorly" supported "basic soils research" at the national level.²⁷

Investigating Conflicts of Interest in Setting and Implementing Soil Policy

Land grant colleges and local agricultural extensions services have long been known to have associations with commercial agricultural interests but the extent of those interests, their government associations and influence on conceptual models of soil are often obscured by a web of professional associations, corporate-sponsored charitable foundations and research grants, corporate lobbying organizations, and government officials. The thesis traces several links in the chain of associations

beginning with the web sites, annual reports and press releases posted by commercial lobbying organizations such as The Fertilizer Institute (TFI).²⁸ These documents link to the conferences and legislation they support or oppose, their legislative PACs and recipients, their tax-exempt, non-profit educational arms such as TFI's Nutrients for Life Foundation (NLF). Other links investigated begin with professional soil associations such as the Soil Science Society of America (SSSA) its "philanthropic arm," the Agronomic Science Foundation and their corporate partners and sponsors.

Methodology – Analysis of Soil Conceptual Models

Some conceptual models of soil/soil ecosystems are stated explicitly and clearly defined by some of their proponents or opponents such as the "black box" or the "food web" soil model. Other implicit conceptual models are embedded in and bounded by the language, definitions, diagrams, formulas and treatments of soil espoused by their proponents. From the range of implicit and explicit conceptual models of soil contained in the approximately 275 source documents reviewed for this work and with emphasis on those cited above, this thesis proposes a taxonomy of soil systems: Soil as a Physical and Chemical Medium for Plant Growth and Man-Made Structures, Soil as a Black Box, The Soil Food Web Model and Soil Ecosystems as Living Mutualistic Networks. Each soil model coalesces around a set of stakeholder interests represented in scientific and policy literature, government documents, commercial reports, news articles, and corporate promotional media.

Each of these soil models is evaluated for its scientific accuracy, its explicit or implied metaphorical content and its potential effect on local and global ecosystem sustainability. Among the questions raised are the following:

- Does a particular model contribute to an understanding of soil/water/above ground ecosystem science as presented in Chapter 3, the Soil Ecosystem Primer or does it distort by omission or factual errors?
- What conflicts of interests may be embedded in each model?
- What are the explicit or implied metaphors or associations? Does the choice of terminology draw boundaries that discourage or limit cross-disciplinary understanding?
- What are the consequences of accepting a particular model for soil sustainability, plant productivity, water resource protection and climate change policies?

III. Understanding Soil Ecosystems: A Soil Ecosystem Primer

Local and global functions performed by soil ecosystems seldom make the headlines or enter into broad environmental policy discussions despite the many scientists across the globe researching soil functions. This chapter summarizes key findings from a range of such scientific sources, (see Chapter 2) in the form of a primer. It is not intended to be comprehensive or overly technical. Rather the goal is to encourage policy makers to stop and consider how the functioning of soil systems relates to the future success of many environmental laws and regulations to protect the health of the planet.

The traditional static view of soil

The classic illustration of soil in textbooks and in U.S. Soil Survey handbooks shows a cross section of a grassland or an agricultural field with green shoots underlain by layers (horizons) of differently colored soils. These soil images are often labeled and described according to such qualities as texture, color, water content, indicator plants, particle size, structure and mineral constituents. Thousands of such images and classifications make up the United State Department of Agriculture's (USDA) Soil Survey database. On its educational web site, "What is Soil?" the USDA quotes the Soil Science Society of America's (SSSA) definition of soil as a "material" and as a "medium:

unconsolidated mineral or organic material on the immediate surface of the Earth that serves as a natural medium for the growth of land plants... that has been subjected to and shows effects of genetic and environmental factors of: climate (including water and temperature effects), and macro- and microorganisms.²⁹

Living, dynamic view of soil ecosystems

For soil ecologists and soil biologists the above definition fails to convey the essential role of living organisms in creating soil and in driving global biogeochemical processes including the cycling of carbon, nitrogen and water. Richter and Markewitz define soil as "a biologically excited, organized mixture of organic and mineral matter; the bio-mantle of unconsolidated material that makes life possible on planet earth."³⁰ Soil ecology according to Bardgett et. al.

(2005) “is the study of soil organisms and their interactions with their environment.”³¹ The National Academy of Science identifies soil as “a reservoir for biological and microbial diversity; and, as such, has a profound influence on the environments of all living organisms. ... Soil biogeochemical processes are fundamental and are a primary driving force for key ecosystem functions including plant productivity and water quality.”³² Maser et. al. (2008) describe soil as “the great placenta of the earth.”³³

Why, asks British ecologist Michael B. Usher, given the necessity of functioning soil ecosystems for conservation of above ground plants, do soils receive little attention in “conservation thinking?” He cites three factors: “lack of charismatic” soil organisms able “to grab the attention of the public and make an emotional and financial connection,” soil’s “poorly understood taxonomy,” and an “out-of-sight out-of-mind” attitude toward soil as reasons that “we know more about distant celestial objects than we do about the ground beneath our feet?”³⁴

Charismatic Soil Systems in the Sky

Soil ecosystems are variously referred to in the literature as “belowground subsystems,”³⁵ “underground ecosystems,”³⁶ “below-surface habitats,”³⁷ and “below-ground communities,”³⁸ terminology that draws a less compelling picture than one drawn by Rachel Carson. In her best selling 1962 book, *Silent Spring*. In the chapter entitled, “Realms of the Soil”³⁹ she describes soil as a “community of ...invisible hosts of bacteria and threadlike fungi... “interwoven” with other organisms.⁴⁰ Organisms that we now know are tightly coupled to soil include one of the most *charismatic* species on earth, the ancient coastal redwoods of N. California. Hundreds of feet above the forest floor, perched on the branches and in the crotches of the massive side trunks of these trees—the tallest on earth—are deep soils teeming with microbial, plant and animal life. Ferns, and huckleberry bushes thrive in these “aerial” soils also referred to by researchers as “canopy,” “arboreal”, or “perched soils.” Canopy botanist Steve Sillet has discovered soil up to 3 feet (91 cm) deep in the ancient redwood canopy (a soil depth that is comparable to the best agricultural soil is the upper Midwest) and an eight-foot sitka spruce growing in perched redwood

soil 50 meters (164 feet) above the ground.⁴¹ Sillet has calculated that the dry weight biomass held within the branches of a single tree in these forests, “including fern biomass and soil materials, can weigh up to 742 kg” (1632 pounds).⁴² By contrast in a study of a Canadian forest of mature tree species grown in favorable conditions the tree species with the highest biomass averaged less than 300 kg per tree.⁴³ “The largest and most complex redwood forest canopies” Sillet observes “contain enormous quantities of arboreal soil. (Extensive canopy soils are also common in the tropical rainforests of Central and South America and in temperate New Zealand rainforests.) Such soils hold large quantities of water that support aerial plants during dry periods;⁴⁴ such arboreal water sources may not be accounted for in most hydrologic models.

Misunderstood Soil Processes

Until recently many scientists incorrectly assumed that the old growth canopy was more akin to a desert. Despite recent evidence to the contrary, many above ground ecologists continue to refer to old growth forests as nitrogen-limited and look only for N-fixing trees and shrubs as natural N sources when they model these thousand-year old ecosystems.⁴⁵ Biologist Marie Antoine and others have shown that an ancient lichen (*Lobaria*) attached high in the canopy to the bark of old growth trees manufactures much of the nitrogen needed by both the plants growing in the canopy and the giant trees themselves. When the lichen dies or is blown off the trees and falls to the ground⁴⁶ mycorrhizal fungi quickly assimilate the lichen’s nitrogen and pipe it and water through the mycorrhiza’s fine network of hyphal tubes to the roots of their giant tree partners. Up to 75 percent of nitrogen required by Douglas Fir forests may be supplied by canopy lichens. Some trees shorten the pathway to acquire nitrogen needed for photosynthesis by growing roots from their branches directly into canopy soil enriched by lichens.⁴⁷

Lichens are an ancient mutualistic symbiotic association (a partnership where both parties benefit) of fungi and photosynthetic microbes (algae and/or cyanobacteria) that enabled the transition of life from the sea to land. The cyanobacterium converts nitrogen gas (N₂) from the atmosphere into plant-usable nitrogenous compounds for itself and its fungal partners and also

fixes some carbon. In the Lobaria lichen, green algae do most of the carbon fixing, extracting the carbon (C) from atmospheric carbon dioxide (CO₂) and hydrogen (H) from rainwater and fog (H₂O) to construct carbohydrates to fuel its own growth and to share with its fungal partner. The fungus provides the physical attachment and protection from desiccation.⁴⁸ Lobaria is one of 30 aerial species of lichen ecosystems ranging across many forested ecosystems. Lichens have also been shown to be important contributors of nitrogen to gray beech forests in Southern Appalachia⁴⁹ and to a lesser extent in other forest tree species. On the surface of arid and desert lands lichens form “biological crusts” with other tiny plants and soil particles protecting these fragile lands from erosion and supplying moisture and nutrients to above ground vegetation.⁵⁰

Connected soil systems and soil processes

Each living cell from the one-celled cyanobacteria to the billions of cells in a 375-foot redwood tree requires the same basic building blocks for life: nitrogen (for cell proteins, amino acids, genetic materials and the nucleic acids DNA and RNA; and for chlorophyll in plants) carbon and hydrogen (to form sugars and complex carbohydrates), phosphorus (a key element along with carbon, hydrogen and nitrogen of the ATP molecule which stores and releases cell energy), water (the “agent of transport” and the medium of chemical reactions)⁵¹ and many trace elements and compounds.

Whether above, below or on the surface of the land or in the sediments of wetlands, rivers and estuaries, similar dynamic, interconnected soil “processes” are performed by microorganisms transported across space and time by wind, by water, by soil animals and by the belowground components of aboveground plants. In most terrestrial ecosystems life underground exceeds by an order of magnitude the population and diversity of life above. A single gram of soil in the neighborhood of a root may contain 10,000 species,⁵² many as yet uncataloged, while another speck of soil only a few centimeters may be sparsely populated.

The top 5 to 30 centimeters of a single cubic meter of highly fertile grassland soil may contain trillions of microflora (bacteria, fungi and algae), billions of single-celled protozoa

feeding on bacteria and other protozoa, millions of nematodes (worms under 1mm long) feeding on any of the above and thousands of micro and macro predators including blind-springtails, turtle mites, sowbugs, spiders, ants and larvae of aerial insects grazing or preying upon smaller plants and animals.⁵³ Soil organisms are not evenly distributed across space and time in a particular soil. They congregate in the rhizosphere, the area within a few centimeters of root surfaces, where carbon-rich root exudates attract many diners.⁵⁴ They multiply when these microenvironments are favorable and decline in numbers when they are not.

To illustrate the order of magnitude of soil diversity compared to that aboveground, soil and plant ecologist David Wardle cites global estimates of one million species of fungi, and a million species of nematodes living underground compared to just 9000 species of birds above ground.⁵⁵ Ninety percent of bacteria live below ground, many in guts of other species.⁵⁶

Soil Structure, Soil Life and Water

Soil life (“soil biota”) regulate the physical structure of their habitat. This concept, according to Young and Ritz, is “perhaps one of the most under-researched” in soil science and “deserves attention.” Soil structure impacts biology,⁵⁷ they say and biology in turn impacts soil structure. Soil structures include soil pores excavated by soil plants, animals and fungi and separated by soil aggregates glued together by the secretions of soil organisms. Soil pores function at times as micro water reservoirs supporting aquatic ecosystems. At other times water clinging to the sides of air-filled pores supply humidity to these miniature atmospheres that supply oxygen to aerobic soil life. “All soil microbes are aquatic in the sense that they require the presence of moisture to function...Hydraulic flow paths determine the connectivity of the soil system”⁵⁸

Complex feedback systems link above and belowground life

Plant roots release a variety of molecules (exudates) into the soil to attract and stimulate specialist microbes and fungi in soil to supply nutrients needed by the plants. Uren et al. (2001) identify over 100 organic compounds that plants release from their roots into the soil and may

reabsorb. The list includes many familiar compounds required for human nutrition: sugars such as glucose and fructose, amino acids, organic acids, hormones, fatty acids, sterols, growth factors, enzymes, glutamine, tryptophane, ascorbic and caffeic acids, linoleic and stearic acids, PABA and B vitamins. Estimates of total photosynthetically-fixed carbon that plants may release into the area immediately surrounding the roots (known as the “rhizosphere”) vary from 25 percent⁵⁹ to 50 percent as exudates and respired CO₂.⁶⁰

Leguminous plants such as beans, clovers and acacia trees release flavonoids into the soil to draw rhizobia bacteria to inhabit nodules on the plant’s roots. The common description of such plants as nitrogen fixers is somewhat of a misnomer. It is the rhizobia bacteria on legume roots and the actinorhizal bacteria on roots of some trees and shrubs—like the cyanobacteria in lichens—that “fix” or convert inert atmospheric nitrogen (N₂) into ammonium (NH₄⁺) a reactive form of nitrogen that plants need to construct the enzyme, chlorophyll. Without the fixed N, plants could not “fix” carbon (using solar energy) from atmospheric carbon dioxide (CO₂). From the fixed carbon and from hydrogen split from water the plants form carbohydrates to grow their own tissues and to share with their microbial partners. (Free living soil bacteria, azobacter and cyanobacteria also fix nitrogen from the atmosphere and share it with plants.)⁶¹

Plants deficient in iron exude compounds that stimulate iron-releasing bacteria, known as siderophores, to release iron to plant roots in iron-deficient soils. Other bacteria release plant growth hormones in response to plant carbon releases.⁶²

These symbiotic relationships in soil have been exploited by farmers since the ancient Egyptians, but without an understanding of the nature or complexity of the feedback system. Among recent findings is that rhizobia have a second function in suppressing diseases in their host plants. Killham and Prosser (2007) report that antibiotics are provided by soil bacteria only when plants provide a sufficient supply of carbohydrates.⁶³ When excess nitrogen fertilizer is supplied, plants will divert carbon (photosynthate) away from their soil microbe partners⁶⁴ to their above ground growth increasing the plants’ susceptibility to pathogens and the soil to

erosion. When plants are grown in monocultures they encourage the growth of “deleterious” bacteria that inhibit plant growth.⁶⁵

Many incorrect assumptions about the behavior of soil microorganisms have resulted when researchers rely only on lab cultures that are very different environments from soil in the field. For example, the far greater surface area of soils in the field results in very different sorption [the retention of water or chemicals on surfaces] rates and microbe behavior. Roots growing in soil alter the chemical, physical and biological conditions in which they grow, in turn altering microbe habitat.⁶⁶ Only half of 400 identified, “high-level bacterial groups” in soil can exist in lab cultures.⁶⁷

The sticky nature of plant and microbial exudates aggregate soil particles, improving water retention and reducing erosion. The hyphae (collectively called mycelium) of free living and root bound mycorrhizal fungi physically and chemically bind together soil particles, resisting soil erosion.”⁶⁸

Plant-Fungi Symbiosis: The Neglected Role of Mycorrhizae

An estimated 240,000 plant species (about 90 percent of all vascular plants) form beneficial associations along their roots with soil fungi.⁶⁹ Similar to the fungi-algae symbiosis in lichen, the mycorrhizal (literally, “fungus roots”) partnership between filamentous soil fungi and the roots of plants has evolved over 400 million years.⁷⁰ Despite their ubiquity—“they are the most prevalent symbioses on earth,”—these relationships, according to Peterson et. al (2004) have received little attention from researchers until recently with the exception of mycorrhizal fungi’s role in supplying phosphorus to its plant partners in nutrient-limited soils.⁷¹ The mycorrhizal feedback system is much more complex than a simple fungi phosphorus exchange for plant carbon. Martin et al. (2001) describe newly recognized roles for mycorrhizal networks supporting plant growth, water and nutrient absorption and protecting plants from roots disease.⁷² Ritz calls fungal hyphae networks “the great connectors” whose transport systems have been

“largely ignored by “the majority of nutrient transport models in soils” despite their centrality to “biogeochemical cycles” and in stabilizing soils.”⁷³

Since at least the mid 1960s, soil biologists and mycologists have understood the “mutual” relationship between mycorrhizal fungi and plant roots.⁷⁴ Arbuscular mycorrhiza (AM)—so named for the fungus’s tree-like branching inside its partner’s root cells—is the most common mycorrhiza; it associates with 80 percent of plant species including most herbaceous plants and tropical trees. AM fungal hyphae extend from plant roots several centimeters into the surrounding soil increasing the roots surface area from which the plant can obtain water and nutrients. Because AM mycorrhizae have colorless hyphae “they are not visible to the unaided eye.”⁷⁵

Multi-level mutualisms

AM fungi also form mutualist relationships with nitrogen fixing bacteria, a newly identified function performed by a newly identified genus and species (*Candidatus Glomeribacter gigasporarum* by Bianciotto in 2003) so tightly coupled with the fungi it cannot be cultured in a laboratory. The bacterium was detected (with an electron microscope) in 1970 living within the spores and hyphae of AM fungi, but it was not until the late 1990’s with the availability of molecular DNA techniques that a symbiotic relationship was revealed. It appears that the bacteria supply nitrogen to the fungi in return for a share of the phosphorus the fungi supplies the plant in return for carbon compounds.⁷⁶ Much remains to be learned about the complexity of these cross-species interdependencies.

The next largest family of fungal mutualists is the ectomycorrhizal (EM) fungi that encircle the roots of many trees species and some shrubs in temperate and boreal forests. Known to the ancient Greeks and visible to the naked eye, EM fungi were recognized as early as the 1930s as important to the health of some forest tree species.⁷⁷ Little research had been conducted on their role in U.S. forest ecosystems until a revival of interest in the 1990s in the Pacific Northwest forests. EM fungi are now known to thread mycelial networks hundreds of meters long under the forest floor absorbing and transporting nutrients and water to tree roots and binding

together forest soils. Individual ectomycorrhizal mats may cover more than 20,000 acres according to mycologist, Paul Stamets. A single Douglas fir tree can over its lifetime host 200 species of mycorrhizal mushrooms, the fruiting bodies of the underground mycelia. "Fungal complexity" says Stamets "is the common denominator of a healthy forest."⁷⁸ Wardle reports evidence of extensive networks of ectomycorrhizal hyphae transporting carbon and nutrients within and possibly across species especially under the low light conditions created by forest understory trees. The finding suggests, says Wardle, the existence of above and below ground feedback mechanisms between these mutualists.⁷⁹

The fungal hyphae of both AM and EM fungi in addition to assimilating and delivering large amounts of phosphorus and water, also transport zinc, nitrogen and other trace nutrients to plant roots⁸⁰ and increase root resistance to disease-causing pathogens. For the soil ecosystem as a whole, the fungal biomass, as it grows, creates spaces for oxygen and water storage, secretes soil-aggregating substances and reduces phosphorus leaching (so common with applied fertilizers) into soil groundwater.

Mycorrhizal networks explain the paradox of massive forests trees and dense grasslands growing in so called "nutrient poor" soils (often defined as low in the mineral forms of P and N used by plants). Mycorrhizal enzymes can dissolve phosphorus from rocks and nitrogen rich tissues of dead and living organisms. Mycorrhizal fungi can transport these nutrients long distances through their hyphae back to plant roots. Keeping these nutrients inside their hyphae, mycorrhizae can deprive nutrition to pathogenic organisms that might otherwise harm plant roots and also slow litter decomposition and the release of CO₂.⁸¹

Soil Ecosystems and Global Cycles of Water, Carbon and Nitrogen

The cycling of carbon, nitrogen and water through the environment are often portrayed in scientific and popular texts as three distinct phenomena but they are intimately connected in living cells, to each other, to other nutrient cycles and to climate change. Extra cellular enzymes

released by soil bacteria and fungi play a key role in these global biogeochemical cycles; without them processes would slow and recalcitrant waste products of plants and animals (lignin, cellulose, pectins and chitin) would pile up in the environment depriving new life of necessary nutrients. The necessary inverse of photosynthesis (and also of bacterial chemosynthesis) is decomposition. Decomposition by microorganisms returns essential nutrients to the environment to maintain the cycle of life. Driving both photosynthesis and decomposition is the “free energy” organisms take from their environment; “as use of this energy cannot be 100 percent efficient” they release “waste products,” such as oxygen, carbon dioxide, methane, hydrogen and water vapor. This energy-waste cycle “is so basic” Wilkerson contends “that it can be considered *the central concept of ecology*,”⁸² and why both green plants and microbial soil life have “a large, potentially regulating effect on our planet’s climate.”⁸³

The Carbon Cycle

Most discussions of carbon and the carbon cycle in nature focus on plants, their above ground stems and leaves and to a lesser extent their belowground root environments as the primary, natural sequesters of excess atmospheric carbon dioxide in the global climate system. Soil ecosystems receive much less attention despite their ability to store more carbon and for longer periods than above ground vegetation. Estimates of global soil ecosystem carbon storage capacity and measurement methodology vary. Wall et al. (2005) report that “soils contain twice as much organic carbon as vegetation.”⁸⁴ Lal reports that “the soil carbon pool (organic and inorganic) is 3.3 times the size of the atmospheric pool...and 4.5 times the size of the biotic pool.”⁸⁵ Carbon storage capacity (combined above and belowground C retention) varies by landscape types and treatments. Killham cites studies showing that natural grassland soils retain an average of 150 tons of C per hectare compared to only 0.4 tons per hectare in aboveground biomass, that temperate forests soils retain 100 tons C per hectare compared to 6 tons in aboveground biomass, and that tropical forests hold 80 tons C per hectare belowground compared to 11 tons of C per hectare aboveground.⁸⁶ Uren estimates that 20 to 25 percent of carbon fixed by

photosynthesis above ground is released by plant roots into the soil around a plant's roots (rhizosphere) to attract symbiotic bacteria and mycorrhizal fungi.⁸⁷ Treseder and Allen cite estimates of 10±20 percent (within a range from 5 to 85 percent) of net photosynthate is allocated to mycorrhizal fungi, depending on ecosystem conditions.⁸⁸ Mycorrhizal fungi contribute to long-term organic soil carbon pools because their cell walls are 60 percent chitin⁸⁹ which is highly resistant to decay. AM fungi exude a soil aggregating glycoprotein which is also highly resistant to decay. "Glomalin alone can account for 30±60 percent of C in undisturbed soils."⁹⁰ Some of the carbohydrates (sugars and amino acids) released into the soil by plants may be reabsorbed (recovered) by the plant's roots to build more aboveground carbon-retaining tissue.⁹¹

Like their fungal and bacterial partners and predators plants also *respire*, consuming oxygen to metabolize previously plant-fixed carbon, and release CO₂ as waste. Overall, plants fix more CO₂ than they release. A key measure of climate changing potential of ecosystems is the rate of carbon captured via photosynthesis compared to the *rate* at which plant-fixed carbon is returned to the atmosphere via respiration of plant roots or soil organisms in the form of carbon dioxide or methane. Fungal slowing of decomposition is a carbon-mitigating factor that many above ground ecologists have not included in their models of forest functioning.⁹² Of 3,700 papers (500 on grasslands) studying soil carbon over many years reviewed by Johnson none measured carbon in fungal biomass. Most studies focused on soils near the surface 10-30 cm. Fungal mycelium can extend several meters below the surface holding carbon that has not been accounted for.⁹³

Two significant reports—United Nations Intergovernmental Committee on Climate Change's (IPCC) 2003 report on land use and forestry and the United States' *The First State of the Carbon Cycle Report* (SOCCR 2007)⁹⁴ do not adequately account for long-term soil ecosystem carbon sequestrations and carbon flux in natural ecosystems. These reports neglecting mycorrhizal C and focusing on above ground forest biomass conclude that old growth forests are at best carbon neutral. Luysaert et al. (2008) reviewing data from 519 studies of old growth

forests, excluding those artificially fertilized or irrigated, found that old growth forests “serve as a global carbon dioxide sink” and “can continue to accumulate carbon, contrary to the long-standing view that they are carbon neutral. . . . The commonly accepted and long-standing view that old-growth forests are carbon neutral (that is, that photosynthesis is balanced by respiration)” they note “was originally based on ten years' worth of data from a single site.”⁹⁵ Because high levels of nitrogen relative to carbon favor bacteria over fungi and more rapid recycling of soil carbon, forests treated with N fertilizer or subjected to high levels of nitrogen oxides from polluted air do not retain as much soil carbon as natural forest soil ecosystems.

The Nitrogen Cycle

Nitrogen, an essential building block of all life on earth, is the most common element in earth's atmosphere present as dinitrogen gas (N_2). N_2 is “non-reactive” and thus, unusable by plants and animals. Except for lightning which transforms or “fixes” an insignificant amount of N_2 into reactive nitric oxide, nitrogen fixation in nature is performed by a single enzyme complex, nitrogenase, exclusive to a small set of bacteria. These bacteria (rhizobia on legume roots, azobacter on roots of some woody plants, cyanobacteria in lichens and free-living soil and aquatic cyanobacteria) can break the tight bonds of the N_2 molecule converting it into ammonium (NH_4^+) a reactive form of nitrogen directly usable by plants to construct carbon-fixing chlorophyll, amino acids and proteins.

Ammonium nitrogen not assimilated directly by plants is transformed by two types of *nitrifying soil bacteria*: the first group converts ammonium into nitrite (NO_2^-) from which the second type releases nitrates (NO_3^-) also usable by most plants. Once nitrogen becomes organically-bound (“immobilized”) in the tissues of plants, in their symbionts or in the organisms that consume them, it has been assumed to be unavailable for reuse until a series of animals and bacteria break it down physically and then chemically into inorganic compounds. Bacteria that decompose this soil organic matter (SOM) release as waste products: “inorganic” or “mineralized” N—ammonia (NH_3) and nitrate (NO_3^-)—that can be re-assimilated by plant roots.

A final group of bacteria, the *denitrifiers* deconstruct the nitrate back into non-reactive N₂ nitrogen and reactive nitrous oxide N₂O gas.⁹⁶

This ordered, linear model of nitrogen transformations cycling through living organisms and back to the atmosphere has since 1913 been described as the nitrogen cycle. Such a soil N “cycle” according to Stevenson and others “does not exist in nature;” the transformations of nitrogen from one form to another actually occur in a “random fashion”⁹⁷ in soil and involve many more “narrow” microbial processes than the classical view of the N cycling as a few “aggregate” processes.⁹⁸ The type and volume of microbes and the N-transforming enzymes they release into the soil vary with landscape type, temperature, moisture, plant roots, and external inputs natural and anthropogenic. Schimel et al. (2005) cite a 1987 study by Parkin that found 85 percent of all denitrification in a “soil core occurred in a single fragment of decomposing plant material.” Because soil is such a heterogeneous environment, mineralization and immobilization of N can occur at the same time in a small soil sample representing two different micro sites supporting different microorganisms.⁹⁹ Plant roots and the chemicals they release also effect the composition of microbial communities and thus the rate of N transformation.

The Missing Links in Soil Nitrogen Transformations

Absent from most N cycle explanations and contrary to the traditional notions of N cycling is evidence from studies over the past decades that mycorrhizal fungi can reduce organic matter into plant-usable nitrogenous compounds and deliver them directly to their plant partners, short circuiting mineralization pathways and preventing loss of N through leaching and denitrification. Ectomycorrhizal and ericoid fungi, most common in forests, can “access amino acid pools” in soil¹⁰⁰ as well as dissolve and process microscopic soil animals and transfer their simple organic N compounds (including urea, amines, amides, peptides and proteins) directly to plant roots.¹⁰¹ Leigh et al. (2009) have shown that arbuscular mycorrhizal (AM) fungi (associated with 70-80 percent of all plant species, including agricultural crops and grassland species) can convert large amounts of organic soil nitrogen to inorganic forms and transfer it to their plant

hosts.¹⁰² A variety of mycorrhizal fungi are likely involved in accessing organic N with each specializing in different organic compounds, a finding that laboratory studies relying on a few culturable strains have missed.

Nitrogen Saturation of Soils

The volume of reactive nitrogen cycling through soils, water bodies and the atmosphere has more than doubled in the last 50 years. The spreading of synthetically produced N fertilizers and the widespread planting of N-fixing legumes now accounts for roughly the same amount of nitrogen fixation as natural soil ecosystems.¹⁰³ In addition, reactive nitrogen released by the burning of fossil fuels and biomass and the concentrated application of animal wastes to agricultural soils exceeds natural soil systems ability to process it. Plants saturated with nitrogen and phosphorus from external sources slow or cease release of carbon exudates to support symbiotic bacterial and fungal suppliers of nutrients and disease resistance. The tradeoff for the plant is faster, fertilizer-fueled growth in exchange for greater susceptibility to disease and desiccation.

Excess nitrates (NO_3^-) from fertilizer or converted by soil bacteria from atmospheric N pollution are highly soluble in water. The negative charge of nitrates (NO_3^-) in water draining fields attracts calcium, magnesium, and potassium into the flow, reducing soil fertility and increasing soil acidity. Aluminum, which is insoluble in neutral or slightly acid soils, dissolves in acidic soils (pH 5 and lower) becoming toxic to many plants and aquatic animals. Excess N, especially in humid soils, increases the population of bacteria that emit nitrous oxide (N_2O) a green house gas (GHG) with 300 times the potency of CO_2 . N fertilizer spread on the surface of land may volatilize into ammonia (NH_3) or into nitrogen oxides (NO_x), be carried by the wind, converted by rain into ammonium (NH_4^+), nitric acid (NO) or nitrates (NO_3^-), and deposited onto distant fields, forests and water bodies increasing the activity of nitrogen-limited bacteria and the volume of carbon-dioxide and nitrous oxide GHG they release into the atmosphere. Fertilizer that is not eroded or washed away accumulates in the soil. The natural system that has evolved over

hundreds of thousands of years in soils to cycle essential nutrients, provide disease resistance and store carbon is impaired by excess nitrogen.

The Water/Hydrologic Cycle

Standard hydrologic models of local and global water cycles do not account for the role of soil organisms in the storage and movement of water. The classic physical model cycles through seven phases: 1) precipitation 2) interception of precipitation by vegetation 3) flow over or under the surface (water flowing overland or held temporarily as soil moisture or flowing to groundwater and seeping out) to 4) surface water bodies which along with soil and vegetation is subject to 5) evaporation and in the case of plants evapotranspiration as 6) water vapor which rises in the atmosphere and with 7) condensation falls again to earth as precipitation.

Temperature, soil texture (particle size and shape) and topography are generally also factored into the physical water cycle models.¹⁰⁴ These “fundamental transport processes” have been the focus of the science of hydrology in its mission to describe and model the “quantity and quality of water as it moves through the cycle.”¹⁰⁵ Hydrologic models of water storage and flow include most commonly precipitation and temperature and also soil porosity and depth, soil moisture, elevation, components of interception and anthropogenic influences including water diversion systems such as channels, conduits and reservoirs.

More detailed hydrologic models of evapotranspiration include an idealized model of leaf conductance and vegetation interception.¹⁰⁶ Such water cycle models do not account for soil ecosystems’ hydrological cycle. A subdiscipline of hydrology, ecohydrology, does emphasize the interdependence of “soil properties, vegetation and partitioning of water budget components.”¹⁰⁷ Falkenmark has redefined the hydrologic model to emphasize the need to track and maintain soil moisture, what she calls the “green water flow.” Green water—the water infiltrated into the soil from precipitation or surface flow and retained within soil pores and organic matter, above the water table—is as important, according to Falkenmark, as the “blue water flow,” her term for precipitation, runoff, groundwater flow and stream flow, hydrology’s conventional focus.¹⁰⁸

Falkenmark and Rockström argue that “water scarcity” in arid environments is not due to a lack of rainfall, “but a deficiency in green water in the root zone” of vegetation. In this model “green” water is “allocated” to support terrestrial life, including trees, crops and mycorrhizae.¹⁰⁹

A missing component in sustaining both the green and blue water flows are soil organisms. Fungi, roots and soil animals create spaces for oxygen and water storage as they grow and secrete soil-aggregating substances. Mycorrhizal fungi hold and transport soil water to plant partners. Water-filled soil pores support a moving community of aquatic organisms many of which exist in and alter lake and ocean ecosystems. Water films adsorbed to the sides of air-filled soil pores support bacteria, yeasts, protozoa, rotifers, nematodes and copepods. Biological crusts of lichen (fungi and cyanobacteria) retain moisture in arid landscapes supporting moisture and nutrient conditions favorable to higher plants positively altering the local hydrological cycle. Water also functions as a “a carrier of information” moving hormones and growth factors, as well as transporting nutrients and giving “plants shape and strength.”¹¹⁰

Soil to Sediment Flow

A little mentioned soil-related process affecting global climate cycles and global environmental health is the movement of soil particles—laden with chemicals and organic matter—through rivers and groundwater into the world’s bays and oceans. Attention has been paid to particular chemicals such as industrial toxins (e.g. mercury), pesticides (e.g. atrazine) and synthetic fertilizers (mainly nitrogen and phosphorus) on water quality, fish and shellfish. Much has been written about seasonal dead zones along coastal areas around the world attributed mainly to nitrogen pollution. Less attention had been given to human-altered soil sediment flows as an entity and to the organisms they contain when they mix with or smother marine sediment ecosystems. SCOPE the Committee on Soil and Sediment Biodiversity and Ecosystem Functioning, a scientific group established by UNESCO, focuses on this neglected area. A group of 100 SCOPE scientists and students from 100 countries study “soil, freshwater and marine sediments as continuous ecosystems supporting life above and below the surface.”¹¹¹ Marine

ecosystems altered by sediment flows from land have been shown to release greater concentrations of nitrous oxide, a climate changing gas 300 times the potency of carbon dioxide.

Soils are complex living networks upon which all life above ground relies. Traditional static images of soils and some agro-centric views fail to convey the tight coupling of soil organism functioning to the health of their above ground neighbors, water resources and climate. A change made in ignorance of soil ecosystem processes in Northern Minnesota can end up destroying life in the sediments and waters of the Gulf of Mexico. Failure to protect the thousands of miles of soil mycorrhizal threading through the forests and grasslands of the world threaten not only the native vegetation but the water they conserve and the global climate they protect by storing carbon and short circuiting the nitrogen cycle. As soil scientist David Hillel wrote nearly two decades ago, "any rational control over the impact that human activity has on the environment must be based on a fundamental understanding of the processes at work... Obviously we cannot protect what we do not understand."¹¹²

IV. A Brief History of Soil Policy in the United States

Economic, political and scientific interests have shaped the conceptual models of soil now embedded in U.S. policy. This chapter summarizes key laws and policies from Colonial times to the present that have directly and indirectly affected our understanding and treatment of soil ecosystems.

Settling the New Land and Plowing the Soil (1600s -1800s)

The theme of soil as a commodity and its persistence in contemporary U.S. policy has its roots in Colonial land policies which treated land as “virtually free... and an opportunity for economic benefit.” The first soil surveyors tried to locate the best soils for particular crops, especially tobacco. Thomas Jefferson in a letter to George Washington in 1793 described the common view of fellow Virginia farmers: “We can buy an acre of new land cheaper than we can manure an old acre.”^{113,114}

The “dominant” government land policy goal in the 1800s was to “encourage the conversion of the continent’s environmental assets into economic commodities,” using government subsidies to transfer those resources to private entrepreneurs.¹¹⁵ From 1812-1849 the Treasury Department controlled and managed the 1.5 billion acres of federal lands. When Congress transferred land management authority to the new Interior Department in 1849 it was *not* to promote better land stewardship but to offload the burden of selling new mining leases spurred by the gold rush in the West and to administer the Swamplands Act (1849, 1850 and 1860) which transferred 65 million acres of wetlands from the federal government to the states which in turn were encouraged to sell them to be drained to finance public works projects.

In 1860 farmers successfully lobbied Abraham Lincoln to support the creation of a Department of Agriculture (USDA) and system of agricultural colleges and universities funded by land grants to the states (The Morrill Act of 1860). The new network of agricultural colleges tasked with providing technical assistance to farmers also provided a means of “forming political alliances” to drive farm policy. In 1876 the USDA was authorized by Congress to set up a Forest

Service “to pay systematic attention to the nation’s forests,”¹¹⁶ but again with the goal of sustaining national forests as a commodity source. The Free Timber Act in 1878 gave residents of western states the right to “cut timber freely on public lands.”¹¹⁷ A decade later in 1877 Congress began funding agricultural research and North Carolina passed a law to fund chemical analyses of fertilizer in response to fraudulent misrepresentation in the sale of fertilizers.¹¹⁸ In 1899 to help buyers evaluate a land purchase’s potential, Congress funded a Soil Survey with the objective of “providing maps” and soil descriptions to “aid in making wise land use decisions.”¹¹⁹ The Soil Survey’s original mission, analyzing three aspects of soil (its physical structure or aggregation of soil particles, its chemical components and its hydrology) to increase the land’s commodity value, came to dominate U.S. soil policy throughout the next century.

The Homestead Acts of 1862 and 1909, offering cheap or free land to settlers willing to plow and plant crops for a minimum of 5 years on the Western prairies, resulted in the conversion of water-holding perennial prairie ecosystems to erosion and drought-prone annual crops.¹²⁰ The need to bring water to these arid lands to support crops led to a boom and bust cycle of private irrigation companies, and President Theodore Roosevelt’s rescue plan: the National Reclamation Act (or Newlands Act) of 1902. The Act added a Reclamation Service to the U.S. Geological Survey (USGS) to pay for dam construction to irrigate the degrading landscape.¹²¹

The Progressive Era to the Dust Bowl

The common theme of TR Roosevelt’s Progressive Era policy (1890-1913) was “utilitarian efficiency.” In the USDA’s Bureau of Forestry under Gifford Pinchot, the goal of conservation was “wise use;” wilderness unused was “waste.”¹²² Pinchot’s view conflicted with a growing group led by John Muir focused on preserving and providing recreational access to the remaining untouched forests. The schism led to the creation of the National Park Service in the Interior Department (1916) and the disaggregation of environmental management.¹²³ To preserve their budgets, competing federal government agencies learned to bypass their executive branch

bosses to work directly with stakeholders and Congressional committees to fund often, self-serving projects; this new policy coalition became known as the “iron triangle.”¹²⁴

Federal land policies, including the Homestead Act, poorly regulated commodities markets and a period of above normal rainfall in the early 1900s encouraged settlers to plough-up the natural, drought-resistant prairie soil ecosystem of the Great Plains, setting the stage for the great dust storms and soil destruction during the drought of the 1930s. Atmospheric scientists have concluded that pre-drought farming practices increased the duration and severity of the “Dust Bowl” drought across the Great Plains.¹²⁵ Financial policies in place at the beginning of World War I had allowed wild speculation in agricultural commodities needed to supply the war economy. The price of wheat futures doubled on the commodity markets rife with manipulation and fraud despite attempted government price and market control laws. Men with little or no farming experience hoping to cash in on the high wheat prices had bought arid acres, often on borrowed money, and planted fence-row to fence-row. Farm debt nearly tripled from 1910-1920. With the end of the war came an end to price controls; both commodity prices and farmland values plummeted leaving many farmers no resources to repair their depleted soil.¹²⁶

The drought beginning in the early 1930s compounded the man-made soil damage, severely degrading well over 100 million acres, mainly in the Southern Plain states but also across the Northern Plains and the Midwest. In the worst affected states (Texas, Oklahoma, Kansas, Colorado and New Mexico) an estimated 10 million acres of topsoil to an average depth of 5 inches just blew away.¹²⁷

The administration of Franklin D. Roosevelt (FDR) responded with the *Agricultural Adjustment Act of 1933* that did not address soil degradation in its mission. The act’s measures were solely economic: to “relieve the existing national economic emergency, by increasing agricultural purchasing power, to raise revenue for extraordinary expenses incurred by reason of such emergency, to provide emergency relief with respect to agricultural indebtedness, to provide for the liquidation of joint-stock land banks, and for other purposes.” The act enabled the

government to “temporarily” prop up the farm economy by setting prices, buying crops and warehousing surplus commodities until the “emergency” was over.¹²⁸

“Soil erosion” was addressed only in a single clause in another 1933 law, The National Industrial Recovery Act of June 16, 1933¹²⁹ which listed “soil erosion control” work as one possible job the act could fund to spur employment. Bureau of Soils Chief, Hugh Bennett convinced FDR’s administration to apply \$5 million of the act’s emergency employment funds to create a Soil Erosion Service in the Interior Department with Bennett as its head. Bennett set up demonstration projects with farmers who could sign five-year cooperative agreements to employ conservation measures such as contour plowing, terracing and planting soil-holding vegetation. The Soil Erosion Service provided the free planning, equipment, seed and seedlings for farmers and labor for the men it hired or borrowed from the Civilian Conservation Corps (CCC) to restore private farmland. Bennett timed his 1935 plea to Congress for permanent funding of his agency to the arrival of dust storms in the Nation’s Capital. As he made his argument Bennett directed the Senators attention to a window where huge, black dust clouds that originated in New Mexico had blotted out the Washington D.C. sun. Previously reluctant Senators voted to approve the Soil Conservation and Domestic Allotment Act of 1935.¹³⁰

Only three pages in length, the *Soil Conservation and Domestic Allotment Act of 1935* “recognized that the wastage of soil and moisture” on farms, pastures and forests was “a menace to the national welfare.” The act provided for a new agency “the Soil Conservation Service” to “provide permanently for the control and prevention of soil erosion and thereby preserve natural resources... and from time to time conduct surveys, investigations and research relating to the character of soil erosion.” The 1935 act transferred all the agencies dealing with soil erosion into a new Soil Conservation Service (SCS) in the Agriculture Department. Complicating the agency’s mission was a string of related, but potentially conflicting missions: floods prevention, reservoir protection, maintaining the navigability of rivers and harbors, protecting public health and public lands and relieving unemployment.¹³¹

Responding to demands for state and local control of government initiatives, the SCS law created a powerful network of 3000 “conservation districts” controlled by state law and supervisors elected by client farmers, paid with federal funds and trained by federal SCS employees.¹³² Some 88 million privately owned acres were enrolled by 1939.¹³³

The “awareness of the gravity of erosion” and the decision of FDR to “use protection and conservation of soils as a way of temporarily lowering the level of U.S. agricultural production,” according to soil scientist, Jean Boulaire was the “greatest opening in soil science.”¹³⁴ FDR advisor, Rexford Tugwell claimed the law would “pay farmers for the first time to be socially minded, to do something for all instead of for himself alone.”¹³⁵

On January 6, 1936, the Supreme Court (United States v Butler 297 U.S. 1) struck down the 1933 Agriculture Adjustment law declaring “unconstitutional” and “coercive” its provisions taxing producers to pay farmers and requiring farmers to remove a percentage of their land from production¹³⁶ (a provision designed in part to encourage soil restoration). Congress responded with a 5-page amendment to the 1935 law: The 1936 Soil Conservation and Domestic Allotment Act. The 1936 law paid farmers for *voluntary* soil conservation measures—such as planting erosion control vegetation—and approved up to \$500,000,000 to fund the program. The law added soil “preservation and improvement of soil fertility” and “diminution of exploitation and wasteful unscientific use of national soil resources” to the previous law’s focus on reducing soil erosion. The law extended farm price support mechanisms to tenant farmers and sharecroppers.¹³⁷

The 1936 Soil Conservation and Domestic Allotment Act passed to protect farmers from devastating price declines and to encourage soil conservation had unintended effects. The subsidies covered only 6 basic crops, which encouraged monoculture planting. Designed to reduce acreage in production, limit erosion and stabilize prices, the law’s conservation measures combined with price supports created a perverse incentive: To increase price support payments many intensively farmed their reduced acreage to increase yield per acre. As a result fertilizer, insecticide and herbicide use went up giving an advantage to the best-capitalized growers and

agribusiness.¹³⁸ The iron triangle of government agencies, congressional committees and stakeholders flourished under the New Deal and has retained to the present day these “temporary” subsidies for a small group of intensively farmed commodity crops.

Soil protection efforts were also diminished by conflicting and overlapping responsibilities for land management in two cabinet departments, by the creation of an authority beyond the influence of either department and by the influence of powerful agriculture and timber lobbies. FDR’s Secretary of Agriculture and Secretary of the Interior argued over which one should be responsible for conservation issues. Roosevelt appointed a National Administrative Review Committee which recommended that Interior be renamed the Conservation Department and that all federal agencies concerned with protection of federally-owned soil, forest and water resources be moved to the new Department. The Agriculture Department’s Forest Service, timber interests and the American Federation of labor objected to the proposal, which was defeated in Congress in 1939. The Soil Conservation Service remained in the Agriculture Department.¹³⁹

Federal Regional Planning, Soil, Water and the TVA

FDR’s reorganization proposals were part of his broader support of national and regional planning, including a permanent National Resource Planning Board, as successor to the previous federal planning agencies created by the administration to support particular laws. In 1933 FDR had proposed to Congress a centralized authority to plan and carry out the environmental and economic repair of the entire Tennessee River watershed “without outside interference,” such as from competing government agencies, congressional committees, industry and labor lobbyists. Prior to the Depression, river flooding exacerbated by poor farm management and deforestation along the 900-mile river had severely eroded “85 percent of the valley’s 13 million acres of cultivated land” creating deep gullies in 2 million of those acres and impoverishing much of the region’s population. Silt from eroded soils also impaired river navigation.¹⁴⁰ Beginning in the late 1920’s influential members of Congress lobbied to reopen World War I (WWI) era nitrate munitions plants in the Tennessee Valley to produce fertilizer for poor southern farmers with

depleted land. (The federal government had dammed the Tennessee River at Muscle Shoals during WWI to power the government nitrate plants to produce military explosives.)¹⁴¹ The Tennessee Valley Authority (TVA) Act of 1933 created a planning agency with centralized regional power and scope as FDR envisioned and the federal fertilizer facility regional congressmen wanted. In addition to providing for flood control, navigation, national defense and the development of power, the Authority's mission was also "to improve, increase, and cheapen the production of fertilizer and fertilizer ingredients,"¹⁴² marking the beginning of federally subsidized, hi-chemical input agriculture in the United States and the stovepiping of U.S. soil research and policy. In a 1938 press conference following the devastating Ohio River floods Roosevelt described his administration's new approach to environmental problems pioneered by the TVA as "a synchronized program to tie in the entire field of flood prevention and soil erosion." At the same time, the TVA—given the power to limit outside interference—"banned agencies such as the Soil Conservation Service from its domain."¹⁴³

By 1934 the Authority's National Fertilizer Development Project plants were producing nitrogen, phosphorus and potassium fertilizer and distributing free fertilizer to selected farmers to encourage their neighbors to switch from crop rotation and manure to synthetics. Over the next 15 years factory-produced nitrogen and phosphorus fertilizer use in the Tennessee River Valley grew at three times the rate of the rest of the country. The pattern was repeated during the Second World War (WWII) when ten new munitions plants were built producing 730,000 tons of ammonia per year; this resulted in a huge surplus of nitrate production capacity following the end of the War. The federal government's solution was to again convert munitions factories to fertilizer production and to market new high-yielding hybrid crops that require high N inputs to spur synthetic fertilizer demand.¹⁴⁴

New Deal Water Legislation and Soil

Because hybrid grains require more water than traditional drought resistant strains the U.S. government subsidized water projects to irrigate farmers' fields. Accepting that to manage

soil you had to manage water Congress had passed the Flood Control Act of 1936 dividing responsibility again, this time between the War Department's Army Corps of Engineers to "improve" waterways for "flood control and allied purposes" and the Department of Agriculture (USDA) responsible for managing waterways to reduce runoff and soil erosion. As a result of this law and subsequent congressional allocations, over the next 20 years the USDA's Soil Conservation Service morphed from a soil protection agency into a "small water projects program" with most of its funding devoted to building head water dams and channelizing streams.¹⁴⁵ Touted as flood control measures many stream channelization projects were undertaken to drain land for agriculture or development. By removing flood-reducing meanders in rivers and streams, soil erosion and flood damage often increased contrary to promised improvements. These drainage systems also sped the flow of fertilizer and pesticides from fields to river systems and estuaries.

Soil Policy Post WWII to the 1960s

By 1950 U.S. ammonia production capacity had grown from 1.6 million tons in 1946 to 2.6 million tons supplying fertilizer to support increased planting of hybrid grain planted in dense monocultures. As well-watered monocultures attract more plant pathogens than mixed crops, the government was soon promoting another chemical solution, new pesticides, many based on nerve gases developed for the War. Between 1948 and 1968 total U.S. agricultural grain production increased 45 percent on 16 percent fewer acres while annual synthetic pesticide use increased 168 percent. Higher yields of corn, wheat and soy led to lower prices and huge surpluses which increased government per bushel subsidies to farmers and drew the government into the construction and management of grain storage facilities and by the early 1970s programs to encourage export of agricultural surpluses.¹⁴⁶

In the late 1950s and 1960s yet another government agency added soil to its portfolio of concerns. The U.S. Atomic Energy Commission (AEC) wanting to understand the effect of radiation on soil life funded soil ecology studies, an area neglected by the SCS with its focus on

soil geology and chemistry. The AEC's studies of energy and interactions of organisms in ecosystems led to the creation of the International Biological Program (IBP) to investigate how carbon and energy flowed through soil ecosystems in order to "manipulate them for the betterment of mankind."¹⁴⁷

The Modern Environmental Movement and Soil

The passage of the National Environmental Policy Act (NEPA) in 1969 is generally recognized as the birth of modern federal environmental policy with its promise to address ecological issues (though not explicitly soil) in an integrated way:

"the Congress recognizing the profound impact of man's activity on the interrelationships of components on the natural environment...it is the continuing policy of the Federal Government in cooperation with State and local governments to use all practical means and measures ...to create and maintain conditions under which man and nature can exist in productive harmony, and fulfill the social economic and other requirements of present and future generations of Americans."¹⁴⁸

NEPA requires all federal agencies to document potential significant adverse environmental affects and evaluate alternatives for proposed federal projects. The law also established the Council on Environmental Quality (CEQ) to provide "guidance to federal agencies regarding compliance with NEPA." CEQ regulations in 1979 and 1986 established NEPA compliance practices throughout the federal government.¹⁴⁹

A single line in NEPA, Sec 102 (2) requiring that an Environmental Impact Statement (EIS) "be prepared for all major federal actions significantly affecting the quality of the environment" is "the basis" according to Plater "for virtually all NEPA case law, "including the right to know and the right to sue" the federal government for non-compliance with the law's provisions. Following NEPA's passage, nearly 200 bills were introduced into the U.S. Congress to weaken or repeal the law. All failed to pass,¹⁵⁰ given public support for environmental laws. NEPA was successfully invoked against the Soil Conservation Service (SCS) in a 1972 court case that reflected SCS's conversion, according to critics, from an "erosion-control agency whose motto was 'stop the rain where it falls' to the business of managing small streams to carry water

away from the land” and with it fertilizer-laden sediment.¹⁵¹ The Flood Control Acts of 1936, 1944 and 1954 created Drainage Districts controlled by local agribusiness and farmers who were empowered by the law to award contracts and assess fees. The law worked to the short-term advantage of District-member landowners who could grant “easements” to the government to construct self-serving drainage projects on their land and categorize them as flood-control projects eligible for federally funding.

In 1972 the Natural Resources Defense Council’s (NRDC) sued the Soil Conservation Service to stop 66 miles of channelization of the meandering Chicood Creek in North Carolina arguing that the SCS had initially failed to file an EIS and when SCS did file the impact statement, it did not adequately consider the loss of wetlands and the “cumulative” impacts including stream flow and “soil and air.” The SCS also did not, as the law required, consider alternatives.¹⁵² The SCS claimed the project’s “purpose was flood prevention, but not to protect lives, mainly to promote agriculture by adding ditches and drains to create arable land from ‘useless marshes.’”¹⁵³ The U.S. Appeals Court halted the project, eventually brokering a compromise preserving most of the streams natural meanders and wooded wetlands.

The next decade would see a weakening of NEPA. In 1986 President Ronald Reagan weakened the CEQ rules for EIS and added cost/benefit analysis regulations. The Rehnquist Supreme Court “consistently narrowed NEPA’s coverage” with Rehnquist writing in a 1978 opinion that although “NEPA ‘established significant substantive goals for the Nation,’ its actual requirements for the agencies are ‘essentially procedural.’” In a 1989 case the Supreme Court ruled that, “NEPA merely prohibits the uninformed—rather than unwise—agency decisions.”¹⁵⁴

Soil, the Clean Water Act and Agricultural Immunity

The Water Pollution Prevention and Control Act (a.k.a., the Clean Water Act of 1972 as amended in 1977 and 1987) empowers the EPA to establish and to enforce regulations to “restore and maintain the chemical, physical and biological integrity of the Nation’s waters.”¹⁵⁵ No such federal law protects the biological integrity of soil or sediment in water bodies. Soil is regulated

indirectly by the federal government only if it contributes regulated pollutants to the water running over or through it or carries toxins airborne (violations of the Clean Air Act). Rather, soil is protected only as a “resource” in federal law.

The Soil and Water Resources Conservation Law (USC Title 16, Chapter 40, Sec 2001) the key federal soil law, assigns the Agriculture Department direct legal responsibility for soil protection as a “resource” to be “appraised,” conserved and used, *not* regulated. Arrangements with states to protect resources are to be “cooperative,” not mandatory. Resource appraisals are to be designed to provide assistance to land owners and agricultural conservation programs, to be “responsive to long-term needs of nation.” The Secretary of Agriculture is required to submit “comprehensive appraisals” on the “quality and quantity of soil, water, and related resources, including fish and wildlife habitats” every 7 to 10 years, “including the impact of farming technologies, techniques, and practices” on those resources with data on current Federal and State laws, policies, programs, rights, regulations and ownerships. Continuing Reagan era requirements, resource data must include “the costs and benefits of alternative soil and water conservation practices” and alternative irrigation techniques.

Neither the soil conservation law (USC Title 16) nor the agricultural law (USC Title 7) makes mention of soil ecosystems or the importance of soil biota to soil quality and ecosystem functioning. As agriculture has become more concentrated and vertically integrated, farms and commercial forests continue to escape many of the environmental regulations imposed on industry and government lands. “Despite its large and widespread environmental impact, the U.S. agriculture industry has never been subject to “an explicit or systematic environmental policy,” contends Richard Andrews. U.S. agriculture has instead had a “commodity production policy” with a “few environmental issues tacked on... Agriculture has had detailed economic regulation...more than any other business sector: “production controls, [and] market stabilization price supports.”¹⁵⁶

The Clean Water Act regulates point source pollution to waterways. The law defines those sources as “discharges at a single [identifiable] location,” but at the behest of the farm lobby the law was written with an exclusion for agriculture:”

‘The term, point source “does not include agricultural stormwater discharges and return flows to agriculture.”’¹⁵⁷

With no regulation of agricultural runoff, a major cause of eutrophication of water bodies and declining aquatic populations, farmers have no mandate to reduce chemical inputs that also damage soil life. Although the Environmental Protection Agency is by law responsible for setting standards and guidelines for the use of hazardous chemicals, an agriculture law, the Water Quality Research, Education, and Coordination Act (7 USC, Ch 86) makes the Department of Agriculture “the principal Federal agency responsible and accountable for the development and delivery of educational programs, technical assistance, and research programs for the users and dealers of agrichemicals to insure that...the use, storage, and disposal of agrichemicals by users is prudent, economical, and environmentally sound...”¹⁵⁸ Ironically the law assigns the Agriculture Department the responsibility for educating its farmers on the hazards its agrochemicals pose only for water *not* for the soil they till.

The Agriculture Department has also been given the authority by Congress to measure and account for agricultural carbon emissions and to establish its own Global Climate Change Program (7USC, Ch 96). The law’s provision for carbon cycle research sets up a Consortium for Agricultural Soils Mitigation of Greenhouse Gases, acting through Kansas State University and affiliated with eight other land grant colleges.¹⁵⁹ The Kansas State group has been researching soil biota and in particular the influence of mycorrhiza on soil carbon, a significant shift in focus for USDA funds. Recent legislation passed by the U.S House of Representatives,¹⁶⁰ however, once again exempts agriculture from external environmental standards and regulation. The bill grants USDA the power to determine agricultural carbon offsets setting standards that will likely be more lenient than those set by the EPA for the rest of the economy.

Re-linking Conservation to Agricultural Subsidies

Beginning in the 1970s with government policies encouraging increased grain production, the Great Plains began once again experiencing widespread soil erosion caused by wind. After several failed attempts to unlink commodity payments and the conversion of grasslands to erosion prone croplands, a coalition—of ranchers, owners of land damaged by wind borne soil from eroded croplands and conservationists—succeeded in getting the “sodbuster” and “swampbuster” provisions into the 1985 Farm Bill (The Farm Security Act of 1985) (16USC Ch 58 - Erodible Land and Wetland Conservation and Reserve Program [CRP]). CRP provisions make farmers who convert grasslands to annual crops on highly erodible lands or farmers who drain wetlands ineligible for other USDA support programs.¹⁶¹ But as with the soil conservation legislation of the 1930s the current Conservation Reserve Program does not prevent a landowner who sets aside one parcel of land to protect from intensively farming a bordering parcel in a manner that impairs its soil ecosystem and may leach harmful chemicals into protected lands and neighboring water bodies.

Although the government provides no direct subsidies to organic farmers for organic practices that prevent erosion or protect wetlands from chemical runoff, a new law in 1985 provided funds to set national organic standards, indirectly promoting consumer confidence in their product claims. The law defines organic agriculture more by what it prohibits (synthetic fertilizers and pesticides) than by what it promotes. The law does require organic producers seeking certification to submit an “organic plan” that “shall contain provisions designed to foster soil fertility, primarily through the management of the organic content of the soil through proper tillage, crop rotation, and manuring,” practices that can protect soil ecosystems and carbon storage but do not guarantee it.

Only a few federal agencies, none by statute, have promoted soil ecosystem research and protection: a rangeland group within the Department of Interior’s Bureau of Land Management, soil carbon researchers in the Department of Energy and some groups within the USDA’s Natural

Resources Conservation Service (NRCS is the successor to the Soil Conservation Service). The NRCS provides educational material for schools on soil ecology and publishes online and in print a highly popular, Soil Ecology Primer. It was last updated in 2004.¹⁶²

The concept of soil as a commodity to be managed for short-term economic gain is embedded in the earliest practices and laws of the United States. From Lincoln era laws—giving free land to anyone willing to plough arid grasslands better suited to grazing—to Depression era laws subsidizing intensive agriculture with commodity payments and free synthetic fertilizer developed in labs U.S. soil policy has always been agro-centric and short-term. The separation of soil policy, managed with voluntary programs by the Agriculture Department, from all air and water policy, regulated by the Environmental Protection Agency, has led to the neglect of soil ecosystem protection.

V. Soil Conceptual Models

The Role of Conceptual Models in Scientific Understanding

Much has been written on the practice and results of “ecological modeling” both conceptual and quantitative. Ecologist Leland Jackson et al. (2000), who trace ecological systems modeling to back to 1974, define a conceptual model of an ecosystem as “a skeleton” from which “research questions are formulated” into equations (quantitative, predictive models).¹⁶³ Such models are typically applied to above ground and aquatic ecosystems, not soil systems.

Soil microbiology researchers Anthony O’Donnell et al. (2007) propose a broader and deeper definition of a conceptual model as “an abstraction that represents a synthesis of what is regarded to be the essential knowledge required to address a particular set of questions.” They agree that the “stronger test of a model is to place it in a mathematical framework in which predictions can be tested quantitatively against data,” but they argue that “synthesis” is a prerequisite to “integration of necessary disciplines to design key experiments” and in their view this synthesis is incomplete in soil research: “Currently there is no conceptual model for the interactions between physical and microbiological processes in soil.”¹⁶⁴

Environmental Scientist David Wilkinson suggests we take a step back from the conceptual model to examine the origin of the questions the model appears to answer. “A process based approach” to developing a conceptual understanding of natural systems, says Wilkinson, generates very different questions from a “reductionist” approach, for example in understanding soil carbon storage.¹⁶⁵ A process-based approach, he argues, would lead to a wider understanding that peat lands store more carbon than rain forests¹⁶⁶ and that the description of some ecologists of the Amazon rain forest as the “lungs of the world” is a misleading metaphor.¹⁶⁷ Most of the oxygen released to the atmosphere by photosynthesis in tropical forests is quickly consumed by soil microbial and root respiration, processes that release CO₂ back into the atmosphere at a recycling rate that is approximately carbon neutral.

Physicist and mathematician Stephen Wolfram questions the notion that “the ultimate test of any model is its agreement with experiment.” In some of his own experiments “when the model is simple” and the experiment “complex” sometimes it is the design of the experiment, or a failure in observation or interpretation of results that leads to a wrong conclusion, says Wolfram, *not* the model. Systems in nature, Wolfram cautions, cannot be modeled with “absolute certainty.” We can only try to “deduce the rules from observation” and despite our “best efforts” may get it wrong.¹⁶⁸

Several researchers have investigated the role of conceptual models in creating barriers to communication across academic disciplines. Heemskerk et al. (2003) report on an exercise they conducted to develop a conceptual model building process to help policy makers “better understand the biological factors that drive ecological change.”¹⁶⁹ They brought together current and recent graduates in sociology and ecology to develop conceptual models of human effects on ecosystems based on data sets and metadata from Five Long-Term Ecological Research (LTER) sites across the United States. They found that ecologists had difficulty modeling non-ecological interactions, that sociologists preferred qualitative modeling, and that natural time scales did not coincide with management and research time scales. Interestingly, none of the groups included any aspect of soil ecosystems in their model diagrams of the five LTER research sites although these studies focus on the functioning of soils over long time scales including a study at Duke University, the LTER network coordinator.¹⁷⁰

How and why does a particular scientific conceptual model develop and persist within fields even as new research data challenges that model and how does one science-based model beat out competing models and come to dominate government policy? Thomas Kuhn, an historian of science, in his influential 1962 book, *Structure of Scientific Revolution*, attributes the persistence of flawed models to the reluctance among members of scientific subdisciplines to resist the essential conservative nature of “normal science.”¹⁷¹ In Kuhn’s view, according to cell biologist Robert Strohmman, “normal science” is practiced out of consensus in which scientists

seek out further details supporting a field's existing "paradigm," which Kuhn defined as a set of beliefs and procedures. The dominant paradigms are perpetuated by scientists who are drawn to "the work laid out by the paradigm;" they develop new technology that supports the existing paradigm and that technology "dominates the training of the next generation of scientists."¹⁷² As a result, the original paradigm can be "illegitimately extended"¹⁷³ says Strohmman. Slowly "anomalies" are discovered that challenge the model, and "ultimately the original scientific paradigm falls of its own weight," if, and only if, according to Kuhn, a new paradigm is available to replace and bring about a paradigm shift:

A scientific paradigm never fails simply out of a comparison with nature. It will never be surrendered ...unless and until a new paradigm is waiting in the wings."¹⁷⁴

New conceptual models for explaining the functioning of soil ecosystems have been waiting in the wings for more than three decades. Yet the old paradigms, the old conceptual models of soil, remain embedded in current law, research and practice. Is this just a function, as Kuhn contended, of a conservative norm within scientific disciplines or are other forces outside of science important factors in setting the agenda, promoting language, metaphors and popular notions that perpetuate imprecise and incomplete conceptual models of soil systems that serve their financial or other political ends?

This chapter examines four science-based conceptual models of soil, from simplest to most complex, that have driven or now challenge U.S. soil policy. Each model reflects the dominant view of its proponents as to what soil data is most important to collect and investigate and how to frame that data to influence policy. The boundary between one model's conception and the next is porous like the medium being described.

The examination of each of the four conceptual models raises the following questions:

- What is the history or origin of this conceptual model of soil?
- How are the terms associated with this model defined by proponents? What are the guiding metaphors that characterize the model?

- Who are the primary proponents? What conflicts of interests may be embedded in each model?
- What U.S. laws and policy are connected with this model?
- What misconceptions or missing information characterize this model?
- Does the model define or imply boundaries that discourage or limit cross-disciplinary and cross media understanding?
- What are the consequences of accepting the model for soil sustainability, plant productivity, water resource protection and climate change policies?

1. Soil as a Physical and Chemical Medium for Plant Growth and Man-Made Structures

Origins, Metaphors and Concepts of Soil Fertility and Soil Chemistry

In the Colonial United States soil was treated primarily as a *medium* to be evaluated and molded for specific income producing activity. Soil surveyors were expected to determine a soil's suitability for economic use—for growing particular crops, raising livestock, producing timber, supporting buildings, dams, or roadways or for building on filled wetlands. The U.S. Soil Survey established by Congress in 1899 focused on the visual and geological classification of soils (later adding soil texture as an indicator for soil moisture) to estimate the agricultural potential of the country's newly acquired frontier.

The early U.S. Soil Survey staff was populated by two competing groups, geologists and chemists, and focused on mapping and classifying agricultural soils. The geologist Milton Whitney, heading the survey in 1894, emphasized visible characteristics of soil—describing the layers (horizons) of soil above bedrock, soil colors (hue value and chroma) soil texture and moisture—as key elements of soil fertility.¹⁷⁵

The early soil chemists of the survey led by E.W. Hilgard conceived of soil as “a more or less static bin for plant nutrients.”¹⁷⁶ Despite some contrary early voices in the Soil Survey and the Soil Conservation Service, promoting more holistic views of soil—including the concept of soil as a body, the importance of soil organisms, and the dynamic interactions between plants, soils and biota—the physical/chemical model has persisted as the dominant model in the USDA,

among many soil scientists, agronomists and industry supporters. Smith et al. (2002) characterize current versions of these Soil Survey models as “soil as structural mantle” and “soil as water transmitting mantle,”¹⁷⁷ both lacking any reference to soil biology.

The Soil Survey continues to be a key activity of the National Resources Conservation Service (Successor to the Soil Conservation Service) continuing its focus on soil taxonomy, visual inspection and units classified according to soil geology, soil color, texture, soil temperature, mineral content, organic matter and hydrology. The geological roots of the soil survey have resulted in “numerous soil taxonomies”¹⁷⁸ of orders, suborders, great group classes, subgroups known as taxons, descriptive family name, classes and finally individual soil series.¹⁷⁹ Soil surveyors continue to group soils into series which combine a place name followed by texture designation as in ‘Jordan sandy loam.’ Static standard-sized classification “units” with fixed area boundaries¹⁸⁰ are plotted on a map. The language of soil classification gives little indication of the complex interconnected, dynamic nature of soil. Chemical soil analyses focus on acquiring data to fit soil samples into existing soil categories. These include measures of aluminum saturation, calcium carbonate, salt content, acidity (pH), iron, phosphate retention and water-soluble sulfate. Soil nitrogen and organic carbon estimates are derived from combustion methodologies that release nitrogen gas while reducing soil biomass to carbon-containing ash. These procedures remove any trace of the life that may have contributed to the soil’s chemistry and the growth of its vegetation.¹⁸¹

The notion of soil as a chemical medium was firmly established in the 1840s. The German chemist Justus von Liebig theorized that a simple combination of chemical elements was the basis of plant growth and that the addition of organic matter served only as a reserve of minerals to be released later by decomposition of “plant remains.”¹⁸² Liebig defined “plant nutrients” as essential chemicals without which a plant could not complete its full life cycle. The testing medium was a soilless liquid similar to modern hydroponic growing systems relying entirely on adding synthetic chemicals, primarily N, P and K. He popularized Sprengle’s “law of

the minimum,”¹⁸³ the notion that a crop’s yield is proportional to the nutrient most deficient in the soil. The deficiency model does not account for interactions among soil nutrients (above and below ground) or the economic cost of the inputs necessary to reach a maximum yield as did Mitscherlich’s law of diminishing yield, first proposed in the early 1900s.

Liebig's book, *Organic Chemistry and its Application to our Agriculture and Physiology*, written in the 1840’s, was widely read. Several of his American students influenced by his theories returned to the United States to found agricultural experiment stations. Although Liebig’s soil analysis method—burning representative vegetation and testing the remaining ash for the presence of nitrogen (N), phosphorus (P) and potassium (K)—to determine a field’s chemical fertilizer application did not accurately reflect the condition of soil, Liebig’s general model of agricultural chemistry has persisted, including the notion that mineral N, P and K are the individual keys to plant growth. Mitscherlich’s law accounted for the effects of chemical interactions, supporting a soil fertility model in which “nutrients [are] blended in correct proportion for the world’s major crops to achieve maximum yields commensurate with the cost of the fertilizer.”¹⁸⁴

Peter McDonald identifies the period from 1850 to 1910 as the “chemical theories period” of agriculture.¹⁸⁵ A popular metaphor for the dominant soil chemistry practiced at the time was of the “bank balance,”¹⁸⁶ or the “balance-sheet theory of plant nutrition”¹⁸⁷ where harvested crops withdraw from the soil essential chemical “nutrients,” which have to be returned to the soil to insure a successful crop “yield” the following season. Soils lacking chemical “crop nutrition” were described as “worn-out.”¹⁸⁸ Liebig’s theories, wrote Jean Boulaire, French historian of soil science and agronomy, in 1994, are still the “fundamental laws of agronomy.”¹⁸⁹

Helms refers to this model of soil chemical sufficiency as the “traditional view of soil fertility”¹⁹⁰ without clearly defining “soil fertility.” Although numerous historical, academic, government and commercial documents refer to the condition of a soil’s fertility and to the collective noun, fertilizer, derived from the noun fertility, few explicitly define the term. A search

of USDA's National Agricultural Library (NAL) Thesaurus and Glossary produced no definitions of soil fertility, but it does define "fertilizer:"

"any organic or inorganic material of natural or synthetic origin which is added to soil to provide nutrients, including nitrogen, phosphorus, and potassium, necessary to sustain plant growth."¹⁹¹

USDA/NAL describes 60 types of fertilizer, mostly isolated chemicals and mixtures, predominantly nitrogen, phosphorous and potassium; several soil fertilizer subcategories including fertilizer applications, nutrient availability and plant nutrition; and soil science-related terms such as soil exhaustion, soil sickness, soil productivity, but soil fertility remains undefined.

The Soil Science Society of America (SSSA) defines soil fertility as "the quality of a soil that enables it to provide nutrients in adequate amounts and in proper balance for the growth of specified plants or crops."¹⁹² Whether the nutrients needed to produce "specified crops" are of long-term benefit to a range of other desired plants is not considered. SSSA definitions equate fertility with "nutrients," and nutrients with fertilizer. Fertilizer, according to the SSSA glossary is "any organic or inorganic material of natural or synthetic origin (other than liming materials) that is added to a soil to supply one or more plant nutrients essential to the growth of plants." A "complete fertilizer" according to SSSA is "a chemical compound" containing "significant quantities of all three primary nutrients, N, P, and K" and possibly other nutrients.

Supporting the traditional view of soil fertility and plant nutrition as abstracted from soil biotic sources is the 2007 *Handbook in Plant Nutrition* by academic plant scientists Allen Barker and David Pilbeam. Like Liebig they define a "plant nutrient" as "a chemical element that is essential for plant growth and reproduction"¹⁹³ The Handbook's and the USDA's National Resource Conservation Service's (NRCS) list of "essential" plant nutrients consists of 17 elements: three non-mineral elements (carbon dioxide, hydrogen and oxygen) and 14 mineral elements found in soil—six "essential macronutrients (N, P, K, calcium (Ca), magnesium (Mg) and sulfur (S)) and eight "essential micronutrients" (boron, chlorine, copper, iron, manganese,

molybdenum, nickel and zinc).^{194,195} Notions of the “essentiality” of a chemical element are often based on Aaron and Stout’s three criteria developed in 1939:

- (1) The element is required to complete a plant’s life cycle
- (2) No other element substitutes for it.
- (3) All plants require the element.¹⁹⁶

By this reasoning cobalt, required by nitrogen-fixing bacteria living freely in the soil, in water and in the nodules of legume roots, is not an “essential” nutrient because not all plants require it.¹⁹⁷ Cobalt is merely listed as one of four “beneficial” elements—cobalt, selenium, silicon, sodium (NRCS) or, one of six—with the addition of aluminum and vanadium (Barker and Philbeam). Without key microorganisms’ use of cobalt to synthesize nitrogen from the atmosphere, terrestrial and aquatic plants in natural landscapes could not survive and life as we know it may not have evolved.

“Regardless of whether nutrients are supplied from organic or synthetic sources,” according to Barker and Philbeam, “it is still the same inorganic elements that plants are absorbing,”¹⁹⁸ implying that *only* the 17 defined chemicals are important to the development of plant life and that ecosystem processes involved in producing these chemicals are unimportant. This synthetic/organic equivalence model does not account for the protective effects of beneficial soil organisms on soil ecosystems or the negative environmental effects of leached synthetic fertilizers on soil and water health. International Soil Science Society member, John Ryan called the “widely-held public perception that chemical fertilizers are harmful,” erroneous and “a Trojan horse.”¹⁹⁹ This chemical-only view of soil systems, tying nutrient input to “yield” of a desired aboveground crop is also the view espoused by fertilizer industry trade groups, a number of soil scientists, many agricultural extension services and some horticultural organizations.

In the reports and publications of fertilizer industry trade groups, the industry’s mined and manufactured chemicals are synonymous with essential plant nutrients and presented as clearly superior to organic soil and plant management practices. Plants are erroneously presented

in fertilizer industry literature as passive absorbers of soil nutrients, rather than the active producers of exudates, vitamins and enzymes as demonstrated in numerous experiments. The industry assigns the active and corrective role in soil not to its living members but to its “deficiency” correcting chemicals often applied in response to visual diagnosis.

The rise of the fertilizer industry and its influence on soil models

At Rothamsted in England in the 1830s, an experimental agricultural estate, fertilization experiments using deposits of bird guano and nitrate deposits from South America resulted in greatly increased grain yields. The focus on soil chemistry in England as well as Germany, France and the United States led to the growth of large fertilizer and shipping monopolies and a rapid depletion of Peruvian guano and ancient Chilean nitrate supplies. As deposits declined and world politics intervened, British researchers soon patented an acid processes to extract mineral phosphate from animal bones and rocks. Germany quickly developed and marketed its own synthesized “superphosphate.” Liebig promoted the use of synthesized and recycled industrial and mining waste to supply chemicals depleted by annual crop harvests.

With new sources of phosphorus and potassium deposits discovered in the United States and the United Kingdom, mining interests began to heavily market these and industrial sources of NPK to farmers. Beginning in 1883 a group of industry leaders formed the National Fertilizer Association (NFA) to promote mined fertilizer use.²⁰⁰ In the U.S, the fertilizer industry ran ads in farmer magazines. Articles in government farm bureau publications also promoted synthetic fertilizers. Fertilizer merchants purchased thousands of copies of a \$1 handbook on fertilizers written by respected soil chemist, E. B. Voorhees, Director of the New Jersey Agricultural Experiment Station, and distributed them free to farmers. In the early years (1890’s-1920s) of the government agricultural station soil scientists generally considered synthetic sources of fertilizer as expensive alternatives to animal manures and nitrogen-fixing crop rotations. Use of synthetics was recommended only when sufficient organic sources were not easily available.²⁰¹

Legislation Reinforcing the Physiochemical Model

Depression Era soil legislation reinforced the physiochemical soil models. The Soil Conservation Service focused on stopping the physical erosion of soil with control measures such as contour plowing, terracing and planting soil-holding vegetation. The Tennessee Valley Authority (TVA) Act put the U.S. government in the chemical fertilizer research and production business with a mandate “to “improve, increase, and cheapen [its] production.”²⁰² The TVA, independent of other government agencies and oversight, became the chief government cheerleader for the chemical model of soil, particularly among the thousands of U.S. farmers to whom it gave free fertilizer and hybrid seeds in demonstration projects.

From the 1950s to 1970s much of the fertilizer technology and fertilizers used in the United States and abroad was developed at TVA plants, supporting a new iron triangle of government, non-profits (initially the Rockefeller and Ford Foundations) and industry in exporting the “Green Revolution” of chemical fertilizer (mainly petroleum-based nitrogen fertilizer), hybrid seeds and irrigation. By 1981 over \$40 million of public funds had been expended. Although TVA’s fertilizer research funding was ended by Congress in the early 1990s, its influence continues at home and abroad. To avoid legal limitations, in 1974, TVA’s international fertilizer activities were transferred to a USAID-sponsored, private non-profit, the International Fertilizer Development Center (IFDC) set up on TVA land using TVA facilities to promote chemical fertilizers in developing countries.²⁰³

The Modern Agrochemical Industry and the Physiochemical Model of Soil

The exclusively chemical model of soil continues to be promoted by the Fertilizer Institute (TFI) the lobbying arm of U.S. miners, manufacturers, importers and distributors of fertilizer, mainly N, P and K and sulfur. Its brochure entitled, “Nutrients for Life” (the eponymous name of its non-profit, tax-exempt educational foundation) describes the fertilizer produced by its commercial membership as “a precise, controlled and environmentally friendly way to provide plants with these natural and safe nutrients...critical to the growth, development

and health of plants.”²⁰⁴ TFI literature suggests that the Dust Bowl was due in part to lack of commercial fertilizer to combat desertification.²⁰⁵ No mention is made of the crucial role of organic matter and soil biota that serve to retain soil moisture and resist desertification. No mention is made of the water pollution problems of synthetic nitrate fertilizer leaching into groundwater and surface waters and the negative effects N and P fertilizer have on the transfer of N, P and other plant-promoting substances by soil mycorrhizal fungi and N provided by nitrogen-fixing soil bacteria. TFI describes its members’ chemical fertilizers as the “food that plants need to generate the food humans eat.”²⁰⁶

Conflicts of Interest, Industry and U.S. Soil Policy

The self-described “national leader on legislative policy that impacts the fertilizer industry,” TFI contributes to candidates who reject calls to reduce N fertilizer use. It spent over 50 percent of its \$6.1 million budget in 2007²⁰⁷ and 53 percent of its \$6.7 million revenue in 2008 lobbying government officials and contributing via its political action committee, FERT PAC, to fertilizer-friendly candidates for Congress.²⁰⁸ TFI’s notes in its 2008 annual report that it “works in close cooperation on a regular basis with numerous regulatory agencies” including the USDA and the EPA. For TFI, the “big story” in 2007 was the 14 percent rise (from 2001-2006) in world fertilizer demand—“an increase of 20.6 million nutrient tons... nearly equivalent to a new U.S. market.”²⁰⁹ TFI describes in its 2008 Annual Report its “pre-emptive approach in discussing fertilizer supply and demand with members of the U.S. House and Senate agriculture committees, hosting briefings for committee members and staff”²¹⁰ on climate policy and agriculture. It commissioned a report by agribusiness consultant Doane Advisory Services “that surfaced during the [Congressional] debates” warning that early versions of the Lieberman-Warner Climate Security Act would significantly reduce farm income, by increasing the price of synthetic fertilizers associated with climate change. TFI reports 84,777 downloads of the Doane Report since its release in June 2008.²¹¹

TFI also promotes its soil model and policy agenda through “charitable” contributions to its tax-exempt, Nutrients for Life Foundation whose stated mission is “to better educate the public about the tremendous benefits of fertilizers.”²¹² The Foundation produces pro-fertilizer curriculum distributed free to middle and high schools as part of its project, “Nourishing the Planet in the 21st Century.” TFI says the program has been “favorably reviewed by the Smithsonian Institution” to which TFI has contributed one million dollars to underwrite the current Smithsonian National Museum of Natural History’s “Dig It! The Secrets of Soil” exhibit.²¹³ TFI reports that it “collaborated to advocate for and provide input on the sections of the exhibit showcasing fertilizers’ contributions to food security and a healthy environment.”²¹⁴ No mention is made in the exhibit at the tax payer-funded institution of the negative effects of excess N and P fertilizer on soil processes and the nation’s bays and estuaries.

TFI’s dominant educational message is that healthy soils are by definition ones that have been supplemented with synthetic NPK fertilizer. The plant/soil model (See Figure 1 below.) promoted by TFI in its educational programs omits water and any representation of the network of soil biota that can supply the labeled nutrients along with dozens of other plant growth and disease-resistant compounds. The U.S. Geological Survey (USGS) posted the graphic below, supplied by a fertilizer industry trade group to its government web site to illustrate an educational brochure promoting fertilizer use.

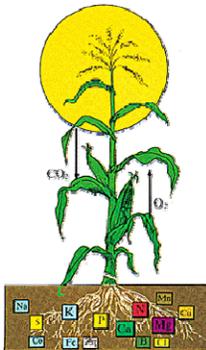


Figure 1: *From* USGS Fact Sheet: “Sustaining Global Food Supplies”
USGS Source: “The International Fertilizer Industry Association.” (Essential element H₂O is missing.)²¹⁵

The home page of the Nutrients for Life Foundation shows a grinning toddler holding a fork, her mouth full, sitting behind a stack of pancakes with fresh blueberries and butter. The caption reads, “Thanks Mom for the pancakes & NPK for the ingredients.” Typical of its interactive education videos games, is “Humanity Against Hunger” in which students play scientists helping African farmers identify the causes of shriveled maize. The only options to check in their “field manuals” are N, P, K or zinc.²¹⁶ The web site for the Smithsonian exhibit links to these TFI curriculum resources.

In addition to omitting the key functions of soil ecosystems and soil moisture in their lobbying and promotional media, TFI and its educational foundation omit the fourth component of high-input, chemical agriculture package often necessitated by the first three: hybrid seeds, fertilizer and irrigation. The unheralded fourth component is pesticides—herbicides to kill the weeds that high levels of N fertilizer encourage and insecticides and fungicides to reduce the growth of pathogenic organisms no longer inhibited by beneficial soil organisms, reduced by over fertilization and previous applications of insecticides. As with the commercial fertilizer industry, a few large transnational corporations dominate the pesticide market, donate to public research institutions and politicians and lobby government officials to influence soil policy. Syngenta Crop Protection, manufacturer of insecticides and herbicides, made a “\$100,000 Gift to the Smithsonian exhibit, “Dig It! The Secrets of Soil” passing the contribution through the Agronomic Science Foundation, the philanthropic arm of the Soil Science Society of America.²¹⁷

Although the National Resources Conservation Service (NRCS) now supports programs and an institute to study and promote understanding soil ecosystems, it also provides support for standard U.S. Agriculture Department approaches to land management that ignore the soil ecosystem considerations. NRCS’s “Soil Fertility Interpretation” follows the standard chemical approach favored by industry, listing 14 “essential mineral elements” to test in soil with the suggested addition of soil organic matter.²¹⁸

Richter and Markewitz warn of the unintended consequences (including offsite pollution of water and land and onsite loss of soil C) resulting from the “dose-response model” of soil function.²¹⁹ Associated agricultural goals of "moving up the yield curve" and "maximizing crop production" assume a closed system “separate from biota”²²⁰ argue Richter and Markewitz, but “because soils are open [biogeochemical] systems” they “are rarely depleted of their nutrients and energy.”²²¹

2. Soil as a Black Box

History, origin, definitions

Unlike the purely chemical model of soil, the black box model of soil acknowledges the role of soil life, including soil microorganism, in above ground productivity and recently has been tied to many studies of the ability of soils to sequester carbon. The conception of soil as a black box has been defended by some soil researchers as an efficient strategy to study soil processes and criticized by other soil researchers for obscuring and endangering key soil organisms. At its simplest the black box metaphor refers to the soil’s decomposition of organic matter by multiple processes defined mainly by their output not their constituent parts. In the model, the black box process transforms waste into soil, seeds into plants and organic matter into nutrients for plants to acquire.

To the stormwater manager the soil black box is a filter removing sediment from stormwater and a sponge slowing overland and groundwater flow. To the agrochemical researcher or producer, the soil black box is a chemistry kit for rendering herbicides such as atrazine and glyphosate harmless before they reach rivers or groundwater. To the farmer and the above ground ecologist the black box stores soil organic matter (SOM), the repository of carbon contained in plant roots, decomposing vegetation and soil organisms; this SOM carbon store retains moisture and slowly releases inorganic plant nutrients to support above ground vegetation.

For the climatologist the soil back box is a carbon storage bin retaining carbon that ancient and living plants have removed from the atmosphere through photosynthesis.

The Black Box Approach to Understanding Soil Organic Matter and Soil Quality

The black box model treats soil as a homogeneous medium when it is in fact, according to ecologist Joshua Schimel, “the most physically heterogeneous environment for life on the planet.”²²² The black box approach focuses on the functions of the organic fraction of soil, generally referred to as soil organic matter. Soil scientists Magdoff and van Es offer one of the simplest and clearest definitions of soil organic matter: “the living, the dead and the very dead.”²²³ But, the term soil organic matter can itself be somewhat of a black box. It is often referred to simply as SOM, an acronym that obscures its living component. Many texts and journal articles and commercial and consumer publications tout the benefits of SOM but do not define it or explain its contents. Soil tests often include a SOM percentage along with the usual chemical nutrient measurements. Composted products including animal manures, peat and biosolids (from sewer treatment plants) all tout their ability to improve SOM while ignoring any negative potential of their formulations. The U.S Department of Agriculture’s (USDA) National Resource Conservation Service’s (NRCS) Soil Quality Institute lists SOM as one of four indicators of “soil health,” a term they use interchangeably with “soil quality.”²²⁴

The USDA/NRCS established the Soil Quality Institute (SQI) in 1993 to develop a set of “soil quality” criteria to assess how well soil “performs all of its functions” in the short and long term.²²⁵ A National Research Council (NRC) 1993 report—supporting the NRCS Soil Quality Institute’s conclusion—found that single measures of soil performance such as crop yield or water quality were not sufficient. The NRC rejected the “traditional notion” (often associated with the physical/chemical model of soil) that soil quality and soil productivity were one and the same. NRC stressed the importance of “soil's biological activity...on all other soil quality attributes as indicative of the capacity of soil to “function as an environmental buffer and water regulator” as well as a producer of desirable crops.”²²⁶

As befits a black box notion of soil, NRCS's "assessments" of soil quality are indirect and the results suggestive, not definitive. NRCS cites four qualitative and quantitative "indicators," (SOM, physical, chemical and biological properties) that provide "clues"²²⁷ as to how well a soil can function. Such soil quality assessments offer an alternative to USDA's standard dose-response model based only on the 17 "essential" chemical nutrients, the four "beneficial" nutrients, soil texture and water holding capacity, pH and SOM.²²⁸ However, rather than redefining soil health, the SQI assessments add on to the traditional physical and chemical measures in the NRCS's Soil Survey. The added biological indicators listed in its 2001 guidelines are mainly visual properties such as the presence and extent of earthworms and fungi.²²⁹ The NRCS's 2009 online resource provides only two indicator methodologies: counting earth worms and measuring CO₂ from sample sites to estimate soil organisms' respiration:

Soil respiration reflects the capacity of soil to support soil life including crops, soil animals, and microorganisms. It describes the level of microbial activity, SOM content and its decomposition.²³⁰

The NRCS Soil Quality Institute's focus is on agricultural land. In northern forested lands in the U.S. earthworms are *not* an indicator of ecosystem health; they are associated with rapid removal of leaf litter, reduction in mycorrhizal fungi, erosion and the weakening of trees. Further limiting the effectiveness of Soil Quality Institute programs is that USDA's NRCS programs are for private land owners only and its soil quality assessments, like all its programs, are voluntary.

U.S. Policy and the Black Box Model

The only U.S. law requiring that the condition of the nation's soil quality be evaluated is the Soil and Water Resources Conservation Act (U.S. Code Title 16, Ch 40, Sections 2004 and 2005; last updated in 1977.) The law requires that the Secretary of Agriculture oversee a "continuing appraisal of soil, water, and related resources" including the "identification and evaluation of alternative methods for the conservation, protection, environmental improvement,

and enhancement of soil” and report the results to Congress at approximately 10 year intervals. The most recently released assessment report required by statute to be delivered to Congress is summarized in a 2006 report posted to a White House web site entitled ExpectMore.gov in the Fall of 2006. The report speaks of data and analytical tools to support “soil quality protection and improvement.” The term soil quality is repeated multiple times but without a definition. The only indicators listed to support the report’s assertion of soil quality improvement on private lands are primarily physical and chemical: reduced erosion on 6.9 millions acres of cropland soils to "T" (an undefined “tolerable rate” of soil erosion) and “reduced potential nitrogen” fertilizer run off from agricultural lands estimated at 225,000 tons.²³¹ (It does not state how many tons of N fertilizer actually did run off fields into streams and groundwater.) Soil organic matter is mentioned only once in the report, as a component of a Soil Conditioning Index (SCI) a formula for estimating soil carbon storage based on (1) organic matter from vegetation or applied manures, (2) field operations such as tillage, fertilizer, soil erosion and conservation management systems, and (3) sheet, rill or wind erosion. The resulting “biomass” calculation is claimed to “indicate” whether soil organic matter is increasing or decreasing on a defined plot of land.²³²

The Soil Microbial Black Box

At Rothamsted, the oldest agricultural research station in the world (where Liebig’s chemical model of soil was first tested in England in the 1830s) black box studies of the living component of soil biomass have been conducted for close to 30 years in long-term field projects. Philip Brookes, the leader of Rothamsted’s Soil Microbial Biomass Group in England, touts the superiority of the Group’s black box approach: “measuring the [soil] microbial biomass as a single [undifferentiated] unit,²³³ despite new molecular methods that allow increasingly finer distinctions to be made among microscopic soil organisms. Although soil microbiomass constitutes only about 1- 4 percent of total soil organic matter, it is, in the words of one of Rothamsted’s pioneers in the field, David Jenkinson, the “eye of the needle through which all organic material must pass,” accurate in assigning importance to soil microorganisms, but

nonetheless a reductionist image of the diverse life in soil biomass. Current leader Brookes also chooses a metaphor that does not convey the living complexity of the soil ecosystem. The microbial biomass, says Brookes, is “a reservoir of essential plant nutrients such as nitrogen compounds. Examples of such reservoir retention and storage functions provided by the microbial biomass says Brookes are the agricultural soils in Northern Europe that “can contain 100kg N per hectare and up to 2 or 3 times more in grasslands or woodlands soils.”²³⁴

The microbial black box focuses on nutrient flux in soil where the microbiomass of the “organic pool” is both a “sink and a source of nutrients.”²³⁵ Because soil is so complex with many thousands of interacting species and thousands of chemicals involved in transforming complex organic forms (mineralizing them into plant available nutrients or temporarily immobilizing them in the tissues of microorganisms) Brookes claims this black box “concept” offers a better way of understanding “soil nutrient dynamics” than working with individual organisms or even a “cluster of species.” The only organisms he would exempt from the approach are those which meet his standard of “usefulness:” rhizobia (the symbiotic N-fixing bacteria), the mycorrhizae (fungal symbionts of some 80 percent of the higher plants species) which Brookes concedes “have very specialized functions” and “yet to be identified” organisms that need to be conserved for their potential antibiotic properties or their ability to harmlessly degrade heavy metals in the soil.²³⁶ Brookes’s exempted organisms, however, are both the products and the producers of complex interactions with other organisms and micro soil habitats on which the black box model shines little light.

Methods of Soil Ecosystem Simplification

The biomass black box methods pioneered at Rothamsted to study soil ecosystem microbes, although a source of useful chemical data on soil processes, may so simplify the soil being tested that a distorted view and misunderstanding of the soil ecosystem results. The method physically reduces heterogeneous soils by pushing them through a 2 mm sieve to create uniform

particles. The Fumigation Extraction (FE) method prepares soil samples by killing their soil organisms with chloroform (CHCl₃ lysis) to perform an analysis of their collective chemistry. According to the Rothamsted web site, a paper explaining the FE methodology to measure soil biomass carbon is “currently the most widely cited paper in Soil Biology and Biochemistry.”²³⁷ The method has shed light on organic C, N, P and sulfur (S) soil dynamics and the effects of heavy metals from sewage sludge and of biocides on soil microbial processes. It has provided a useful model of some chemical dynamics of soil organic matter and can be an indicator or 'early warning' of changing soil conditions. Measures, for example, of glomalin, a soil aggregating protein released by AM fungi indicates the presence of some species of mycorrhizal fungi, but does not shed light on the nature of its symbioses.

A “good analogy” says Brookes for the microbial soil black box approach is “studying the forest rather than an individual tree.”²³⁸ Perhaps a better analogy than a forest would be a tree plantation where the diversity of trees (species in soil) and the streams and ponds (soil pores) threading through the forest have been discounted.

Many soil scientists and soil ecologists caution against relying solely on models that obliterate essential ecosystem characteristics such as scale, structure and biology. Soil biologist and biochemist R. P. Vorney and others argue that the effects of the diverse scales of soil habitats are lost when soils are homogenized for testing before being studied in place (in situ).

“Soil habitat” is “characterized by heterogeneities across all measured scales from nanometers to kilometers which differ in chemical, physical and biological characteristics in time and space.”²³⁹

These microhabitats, which are not randomly distributed in soil, in large part control the relationships among soil organisms and the system-altering enzymes they release according to Vorney. Researchers David Hopkins and Edward Gregorich argue that conceptual models based on small sieved soil samples (2mm or less) distort soil biochemistry because such samples exclude fresh plant residues, “the site of the most intense biological activity.”²⁴⁰ To soil scientist

Henry Lin a “crushed sample of soil is as akin to a natural soil profile as a pile of bricks is to a beautiful building.”²⁴¹ Isolated soil columns, says Lin, should be replaced more with in situ soil studies.

At Rothamsted, black box biomass methods analyzing African soils indicated that replacing synthetic P-only applications with a mix of synthetic P and manure would improve soil and crop productivity. An ecosystem approach would have considered interacting soil organisms and the potential of soil mycorrhizae to not only extract P from soils and rock and deliver it to plants but to improve ecosystem resilience. “As long as we view N [and P] mineralization as a simple aggregate process driven simply by [S]OM turnover and carbon to nitrogen ratios,” says ecologist Joshua Schimel, we will be blind to the specific roles of microbial community composition in regulating N cycling.”²⁴²

The SOM - SOC Connection

Most estimates of soils’ ability to retain or “sequester” carbon are based on black box studies of carbon extracted from soil samples that have been mixed, sieved, and either heated or chemically treated. With the exception of arid and semi arid soils containing large amounts of calcium carbonate or lime, (soil inorganic carbon or SIC) the main source of carbon in arable soils is SOM. Soil organic carbon (SOC) like SOM is the product of living organisms from above and below ground. When the model of the soil processing and retaining atmospheric carbon is of a homogenized, lifeless core of matter, it is easy to assume that samples from shallow depths collected over a brief time spans are sufficient to understand carbon fluxes.

Many journal articles have reported that N fertilization can increase SOC sequestration particularly where plant residues from dense N-enriched crops are left on the soil surface to decompose. When synthetic NPK was added in 1955 to previously unfertilized corn plots at the University of Illinois Morrow Plots (established in 1876) yields in the next few years increased 140 percent and trended upward for the first 10 years. When Khan et al. (2007) analyzed annual soil samples collected between 1955 and 2005 their results challenged the usual black box

assumptions. Soils preserved from a series of long-term cropping experiments at depths to 46 cm, well below the plow layer (0 to 15 cm) that is usually measured, synthetic “fertilization showed little, if any, benefit for soil C sequestration.”²⁴³ Natural or manured soils at depths below 15 cm often contain decay resistant fungal hyphae, plants roots, their exudates and numerous interacting soil organisms retaining and exchanging carbon. Over 51 growing seasons with a tripling of corn plant density at the Morrow plots, both native and new inputs of SOC had declined in N-fertilized plots versus those manured and rotated with N-fixing legumes. The researchers noted that their findings were consistent with several other studies (They cite over 40 studies of “various tillage systems” showing little, none or a negative effect of N fertilization on C sequestration); yet, the myth of N fertilization and carbon sequestration has persisted. Why? Other studies of short duration and shallow depths had assumed that an increase in above ground biomass residue from growing 20,000 plants per hectare in the early 1950s to 69,000 plants per hectare by 2003 would more than compensate for the nutrients removed by the plants and lead to increased SOC. Such a linear, reductionist conclusion does not consider the effects of the above ground changes and soil treatment on the soil biota dynamics controlling the cycling of carbon. (Increased N increases soil bacterial metabolism that consumes C and releases CO₂.) Kahn et al. (2007) also suspect a political and an economic rationale are responsible for perpetuating the model and the myth:

Such evidence is common in the scientific literature but has seldom been acknowledged, perhaps because N fertilizer practices have been predicated largely on short-term economic gain rather than long-term sustainability.²⁴⁴

The SOM black box model underlies USDA research funding of no-till agriculture to reduce erosion and increase carbon sequestration.²⁴⁵ The agrochemical industry, with the support of many soil scientists, promotes no-till farming as a strategy to increase use of their products: “judicious use of fertilizer,”²⁴⁶ increased use of herbicides to replace tillage as a method of weed management and pesticides to manage diseases associated with dense planting of grain monocultures. Khan et al. (2007) and other studies report that corn-belt studies of N-fertilization

of plots with “various tillage systems” showed increase in biomass but “little benefit to soil C sequestration.”²⁴⁷

The two leading herbicide manufacturers in the United States, Syngenta and Monsanto, promote their products as aids to improve soil C storage and plant health. Syngenta’s atrazine herbicide, a chemical banned in the European Union and Switzerland (its home country) and rated toxic to aquatic invertebrates by the U.S. EPA is approved by the same agency for agricultural use in the United States under a variety of brand names, many suggesting toughness and intelligence such as Bicep II Magnum,[®] Expert,[®] and Lumax.^{®248} According to Syngenta’s web site, “Well over half of U.S. corn acres, about two-thirds of sorghum acres and up to 90 percent of sugar cane acres in the United States use atrazine to control weeds.”²⁴⁹ Other U.S.-approved herbicides that are toxic to fish have brand names associated with weapons or aggressive contact sports: Fusilade DX,[®] Dual Magnum,[®] Princep Caliber 90[®] and Touchdown Total.[®] A related Syngenta web site, “resistance fighter.com,” continues the militant imagery with a clenched fist crushing a root as its banner icon.

Conflicts of Interest

Many of the studies testing pesticides for efficacy and safety have been conducted at public U.S. land grant universities with the financial support of the corporations whose products are being tested. At Kansas State University Agricultural Station and Cooperative Extension Service a short-term study of the effectiveness of two herbicides (imazaquin and pendimethalin) in reducing weeds competing with tree clones found that a combination of the two gave “good weed control” with little damage to the seedlings.²⁵⁰ The study was funded by BASF Corp., maker of the herbicides. Another study of the same two herbicides on hybrid poplar trees bred for paper pulp was conducted by Michigan State University research foresters at the University’s MAES Research Upper Peninsula Tree Improvement Center. They concluded that the BASF chemicals “provide safe and effective weed control.”²⁵¹ The only reference to soil was to its type and previous plantings; no testing was done on the effect of these toxins on soil organisms. A

subsequent annual report from the MAES Center lists BASF as a financial contributor along with Bayer Crop Science, DOW Agrosiences, LLC, Dupont Crop Protection, Monsanto Company, and Syngenta Biotechnology, Inc. Both of the above studies defined their research parameters so narrowly that ecosystem-related effects were not evaluated.²⁵²

In a recent article in the journal of the Weed Science Society of America, Adam Davis et al. (2009) report on a survey of its members' research topics. Of the 304 members (23 percent of the membership) responding, the largest number (42 percent) were studying "herbicide efficacy and maintenance," funded primarily by industry. A smaller group (22 percent) supported by public funding was investigating more complex topics of vegetation management such as invasion ecology and molecular biology. "It is long past time for weed scientists to move beyond a dominating focus on herbicide efficacy testing and address the basic science underlying complex issues in vegetation management,"²⁵³ the author's conclude. They might have added, it is also time to reject financial support from corporations who want to define and narrow scientists' research agenda in return for funding.

3. The Soil Food Web Model

Origins and definitions

The soil food web approach opens the black box to identify soil organisms, investigate the links between them and trace the flow of energy through their habitats. Soil biologist Elaine Ingram defines the soil food web as the community of organisms living all or part of their lives in the soil. Soil ecologists Peter C. de Ruiter et al. (2005) describe food webs as "biological communities focusing on trophic [feeding] interactions between consumers and resources."²⁵⁴ Food web researchers study the effects of those interactions and resources on populations of species and the effects of population dynamics on the cycling of energy and nutrients through ecosystems. The food web model links belowground systems to above ground input from vegetation, roots, precipitation, above ground animal droppings and atmospheric gases. The

belowground community processes the above ground inputs, cycles them through their bodies and returns energy to the aboveground community via plant roots, the release of gases into the atmosphere and via creatures that straddle both worlds. Food webs are usually illustrated by diagrams showing a series of conversions of energy and nutrients, represented by arrows, connecting organisms and their food supply.²⁵⁵ The soil food web model has been closely associated in the popular press with organic and sustainable agriculture, but its origins and theories originated in studies of terrestrial and aquatic systems not soils and sediments and in natural rather than managed ecosystems.

P. de Ruiter et al. (2005) trace the modern study of ecosystems as food webs to Eugene's Odum's work on systems ecology in the 1960s.²⁵⁶ The focus on competition as the driving force in food webs extends back to Darwin's image of the "entangled bank" where species struggle for life, where "competition" is "universal" and species are at war, "feeding on each other" to survive.²⁵⁷

When we look at plants and bushes clothing an entangled bank we are tempted to attribute their proportional numbers and kinds to what we call chance. But how false a view this is! Every one has heard that when an American forest is cut down a very different one springs up; but it has been observed that the trees now growing on the ancient Indian mounds, in the Southern United States display the same beautiful diversity and proportion of kinds as in the surrounding virgin forests. What a struggle between the several kinds of trees must have gone on during the long centuries each annually scattering its seeds by the thousands; what a war between insect and insect—between insects and snails and other animals with birds and beasts of prey—all striving to increase and all feeding on each other or on the trees or their seed and seedlings or on the plants which first clothed the ground and thus checked the growth of the trees!²⁵⁸

J. Dunne traces the first use of food web terminology to V. Summerhayes and C. Elton's "relatively detailed empirical descriptions of food web processes" on the arctic island of Spitzbergen in the 1920s.²⁵⁹ They chose the term *food chain* to describe the linear, hierarchical feeding relationships they observed between species. (For example, a single food chain might have plankton at the base, plankton-eating fish in the middle and fish-eating seabirds at the top of the chain). The overlapping or parallel food chains they observed on the island they collectively termed a *food cycle*, a concept now called a food web.²⁶⁰ By the late 1970's and 1980s soil food

web researchers were developing competing quantitative models of food web structure and dynamics, some with many sub categories of food webs. They applied graph theory to map food web relationships and devised algorithms to predict the effect of data-based estimations of food web dynamics such as connectance (C), diversity (S) and food chain length (L)²⁶¹ producing a body of literature abstracted from actual landscapes and a challenge for non-experts to understand.

Current Food Web Concepts and Images

Concepts in food web ecology continue to rely on aquatic systems and above ground terrestrial systems where competition for biotic and abiotic resources along with food web structure (habitats) are the main drivers of population dynamics. “Food webs are almost always defined according to habitats, units nested within and interacting with larger systems.”²⁶² The habitat of interest may be as small as a water-filled pool a few millimeters across at the foot of a single tree or a wide range of biota inhabiting a forest. Food web theorists have proposed four distinct images of habitat structure to account for and predict the rise and demise of ecosystem populations: the Christmas tree model where a few species control the rest, the onion model where a core species influences the dynamics of the other species, the spider web model in which everything affects everything else and the internet model of major and minor hubs of activity.²⁶³

The term food web suggests the field’s emphasis on who eats whom and its historic focus on two feeding (or “trophic”) levels: plants and plant eaters (herbivores) and predators and prey. These relationships also reflect the interest of the field’s dominant researchers, animal ecologists and community ecologists.²⁶⁴ In the last two decades, according to agroecologists Teja Tschamtkel et al., (2002) interest has grown in understanding more complex above ground and aquatic ecosystem relationships (“multi-trophic interactions”) but the focus remains on resource consumption above ground.²⁶⁵ For example, studies of species succession (the shift in a habitat over time from one set of organisms to another) have been dominated by plant ecologists studying the visible.²⁶⁶

Limitations of the Soil Food Web Concept

Interest in soil ecosystems among food web ecologists is also growing, according to soil biologists Stephan Scheu and Heikki Setälä, but “lack of knowledge in food-web interaction in belowground systems is a major constraint in current ecological thinking,” given that “from the energetic perspective the belowground decomposer system is far more important than the herbivore system above ground.”²⁶⁷ Another barrier to understanding, particularly among animal ecologists, Scheu and Setälä contend, is the assumption that the consumers and the consumed are living organisms. In belowground systems, a base resource is the mixed, decaying remains of plants and animals and the excretions of living organisms, collectively known as “detritus” which is consumed by decomposers (also known as “detritivores” or detritivores) ranging from microscopic bacteria and fungi to beetles and earthworms. Unlike the relationships between plants and herbivores and predators and prey, “detritivores do not co-evolve with their non-living resource.”²⁶⁸

The food web predator-prey model led to the misclassification of detritivores as omnivores on the assumption that their principle food source was the living microorganisms embedded in the detritus. Although some detritivores such as earthworms digest soil protozoa and nematodes, they also rely on symbiotic, not competitive, relationships with other soil organisms. Increasing evidence shows that soil microorganisms survive in the guts of detritivores supplying enzymes to break down complex plant compounds. These mutualist microorganisms are excreted in casts (external rumen) from which they get nourishment and may cycle through secondary decomposers who consume the waste of primary decomposers. “The fact that detritivores for various reasons, do not fit conventional food-web categories hampers the modeling of decomposer communities.”²⁶⁹ Specialists in soil food webs argue that ecosystem models must adapt to more accurately reflect soil interactions and acknowledge that in soil systems “trophic interactions are only part of the story” and “may be even a minor part.”²⁷⁰

SOM in the Soil Food Web Model

To soil food web ecologists, soil organic matter is never an undifferentiated mass, and to understand soil dynamics it is essential to identify soil's living components and map their dependencies. Soil biologist Elaine Ingram defines soil organic matter "as all the organic substances in or on the soil including living organisms,"²⁷¹ dead plant material, detritus and surface residue, difficult to define organic, active fraction compounds that are easily metabolized by microorganisms, easily decomposable (labile) organic matter, root exudates and organic matter that is resistant to decay such as lignin fibers from plant fibers and other complex organic compounds that persist in soils after soil organisms have partially degraded them. The living component includes bacterial species consumed by single-celled protozoa that are consumed by fungal-feeding nematode worms that are consumed by fungal-feeding amoeba. Higher level invertebrates such as insects and earthworms shred leaf litter for the cycle to begin again with decomposing bacteria and fungi (many of whom live in the guts of the shredders) breaking down the remains of green plants and in the process²⁷² releasing mineral nutrients such as nitrogen and phosphorus needed by plants to photosynthesize carbon some of which will feed the decomposers.

Soil food Webs, Water and Climate Change: Conflicting Science

Healthy, diverse soil food webs are often associated with positive effects on the climate. Increased living and non-living organic matter improves a soil's water holding ability and it's pool of plant nutrients increasing-carbon absorbing plant growth and reducing the need for fossil-fuel based synthetic fertilizers. Much of the literature and research on soil food webs and carbon sequestration is agro-centric measuring the amount of carbon held in agricultural soils under various management strategies or released from soil decomposers as carbon dioxide (CO₂) and other green house gases such as nitrous oxide (N₂O) and methane (CH₄).

Excess nitrogen, for example, from external inputs to the soil food web and/or from an over-abundance of N-fixing bacteria can dramatically alter the carbon to nitrogen ratio in the soil.

Soil decomposers over-stimulated by excess N consume soil organic carbon at an unsustainable rate, releasing more greenhouse gases from the soil than above ground plants can fix. The Soil Biology Primer, posted to the NRCS web site speaks of achieving an “optimal balance” of living soil groups (e.g., bacteria, fungi and other species) as “one approach to managing the food web”²⁷³ for retaining soil carbon and moisture or improved yield of an agricultural, timber or pasture crop. An alternative approach to which the NRCS assigns equal importance is more reductionist, zeroing in on a limited number of soil web species deemed harmful (such as specific pathogens) or beneficial (such as earthworms) and chemical processes such as release of CO₂ to indicate conversion of organic matter to mineral forms.

The USDA, particularly through its funding of the Soil Carbon Center at Kansas State University and its science partners in the Consortium for Agricultural Soils Mitigation of Greenhouse Gases (CASMGs, pronounced “Kaz-ums”), promotes no-tillage, conventional agriculture as the best management practice to retain carbon in agricultural soils. Although the Kansas Center’s head is a microbiologist who has given presentations on the carbon sequestering impacts of mycorrhizal fungi and other soil organisms, the Center’s reports and web sites do not discuss soil food webs or evaluate organic agriculture as C-sequestering options.²⁷⁴ A 2009 search of the Consortium’s web site at Colorado State University finds no references to mycorrhizae or soil food webs and only a single reference to organic agriculture.²⁷⁵

CASMGs makes no reference to the long-term study (1994-2002) at USDA’s Agricultural Research Service’s Sustainable Agricultural Systems Laboratory comparing no-tillage conventional farming with minimal-tillage organic farming. The nine-year study showed that organic farming built more soil organic matter than the conventional, no-till approach which relies on herbicides for weed control, synthetic fertilizer and pesticides to reduce pathogens. All three inputs can weaken soil food webs, reduce biodiversity and break the symbiotic bonds maintaining the soil food web. Manure and cover crops supporting the food web in the organic test plot more than compensated for the carbon loss to tillage needed to reduce weeds. According

to John Teasdale, heads of the Sustainable Agricultural Systems Laboratory, “This is one of a few studies that consider the effects of rotation length and crop complexity on organic grain yields.”²⁷⁶

U.S. Policy on Organic & Sustainable Agriculture and Soil Food Webs

The first federal legislation related to organic agriculture was passed in 1990 (as Title XXI, The Organic Foods Production Act (OFPA) of the 1990 Farm Bill). The law, now categorized as “Organic Certification” in the U.S. code (Title 7, Chapter 94), defines organic agriculture indirectly by the standards it sets for a farm to be “certified organic” by a federally-approved “certifying agent.” An organic farm is one that has an approved written “organic plan” whose provisions must “foster soil fertility, primarily through the management of the organic content of the soil through proper tillage, crop rotation, and manuring.” The manure plan is designed to prevent the transmission of bacterial diseases to harvested crops. The only other statutory requirement is that the operators of a “certified organic farm” keep and retain for 5 years records detailing the “history of substances applied to fields or agricultural products; and other production and handling practices.”

The law also created a National Organic Standards Board (NOSB) to advise the Secretary of Agriculture in setting detailed standards (The National Organic Plan) for products marketed as “organic” and for certifying agents. The NOSB has adopted (1995) a definition of organic agriculture, supported by the Organic Trade Association (OTA), that incorporates Ingram’s soil food web model:

"Organic agriculture is an ecological production management system that promotes and enhances biodiversity, biological cycles and soil biological activity. It is based on minimal use of off-farm inputs and on management practices that restore, maintain and enhance ecological harmony."²⁷⁷

Federal government support for protecting the agricultural soil food web and promoting organic agriculture comes not from the NRCS, but from the USDA’s Rural Business-Cooperative

Service through its funding of the National Sustainable Agriculture Information Service (ATTRA) managed by the National Center for Appropriate Technology (NCAT).

The National Resources Conservation Service's (NRCS) Soil Quality Institute provides the aforementioned Soil Biology Primer and three other soil biology publications describing the benefits of the soil food web model, but in a booklet on soil biology and land management NRCS makes clear its intent is informational, not prescriptive:

The purpose of this technical note is to provide information about the effects of land management decisions on the belowground component of the food web. It points out changes in soil biological function that land managers should look for when changing management practices. This information is not a set of prescriptive guidelines, but is designed to increase awareness and prompt field trials.²⁷⁸

NRCS has signed a memorandum of understanding (MOU) with the Organic Trade Association to support conservation and provide information to organic producers, but has explicitly stated its refusal to promote organic agriculture:

[The NRCS] "does not have a policy of promoting organic agriculture over other forms of agriculture. It is one of many options for land use, rural economic enterprise, and resource conservation."²⁷⁹

Funding Soil Food Web Protection and Organic Agriculture

The USDA estimated total funding for its Sustainable Agriculture Research and Education Program in 2009 to be \$13.4 million with awards ranging from \$500 to \$200,000.²⁸⁰ The Sustainable Agricultural Systems Laboratory's long-term field experiment to evaluate sustainability of organic and conventional cropping systems described above received approximately \$1 million per year or 0.001 percent of the USDA Agricultural Research Service's annual \$1 billion budget.²⁸¹ In 2003 Congress approved the Organic agriculture research and extension initiative (Title 7, Chapter 88, Subchapter VII, § 5925b) allowing the Secretary of Agriculture to award up to \$3 million a year until 2007 for peer-reviewed "competitive grants to support research and extension activities regarding organically grown and processed agricultural commodities." All the law's research categories are related to marketing, processing, or breeding,

none to ecological issues. Grant winners have to obtain non-federal matching funds equal to the federal grant.

The Organic Foods Production Act allotted an initial \$5 million for establishing the organic certification program but requires organic farmers to pay for agents to certify their organic plans and receive no production or marketing subsidies. In contrast, the USDA's Agricultural Marketing Service spent \$250 million dollars in 2006 purchasing conventionally grown poultry and egg products to compensate "farmers facing poor market conditions due to excess supply." Direct subsidies to non-organic growers of commodity products, mainly corn, wheat, cotton, soybeans, cotton, and rice are expected to total \$11.4 billion in fiscal 2009 and have averaged \$15 billion per fiscal year since 2002. "The largest 10.0 percent of farms in terms of gross receipts received 58.7 percent of all government payments in 2007."²⁸²

The State of the Soil Food Web and Organic Agriculture

The OTA's vision of an organic system that supports biodiversity, biological cycles and soil biological activity has been embraced by many small and mid size farms. But the USDA's loosely defined legal standards have allowed many large producers to stray from practices that protect soil ecosystems. Rather, these "industrial organic" operations, according to Michael Pollen, follow the conventional input-output model of chemical-based agriculture using less harmful external inputs, including tons of imported compost, organic plant-based insecticides, beneficial insects, intensive tilling, torching to control weeds, and imported mined organic fertilizers such as rock phosphate and Chilean nitrate.²⁸³ Rivers and groundwater are protected from toxic runoff and produce is pesticide-free. Little if any carbon is sequestered on site to support soil ecosystem life and services and still more CO₂ is released in producing and transporting crop inputs.

Beyond the Soil Food Web Model

Critics of the traditional soil food web model claim it fails to systematically account for three types of interactions: parasitism, decomposition and mutualism. With its focus on "predator-

herbivore-primary producer feeding interactions” and “elusive concept of soil quality”²⁸⁴ the traditional soil food web model has enabled landscape practices in fields, forests and rangelands that impair soil ecosystem processes and services including water quality, water quantity, nutrient cycling and carbon sequestration.

Dunne and others propose that the food web model be “extended to a broader framework of “ecological networks” that is more inclusive of different components of ecosystem biomass flow, and that takes into consideration different kinds of species interactions that are not strictly trophic.”²⁸⁵ The ecological networks notion, like the food web model, is more commonly associated with terrestrial ecosystems; the term has recently been applied to a European-wide landscape conservation scheme to re-link disconnected animal and plant habitats.

To Wardell the food web with or without extensions ignores the importance of above ground-belowground connections and concentrates on larger soil invertebrates at the expense of “arguably the world’s most important keystone organism group, i.e, nitrogen-fixing soil-dwelling bacteria,” mycorrhizae and other mutualist soil microorganisms.²⁸⁶ Most soil food webs, argues Wilkinson, treat decomposers as “a black box labeled “soil microflora,” ignoring the significance of decomposer waste products such as CO₂, O₂ and heat.²⁸⁷ Scheu and Setälä find little in food web theory to recommend it as a model for soil ecosystems as “there is little experimental evidence that competition really is a major structural force in soil animal communities.”²⁸⁸

Mutualism, not competition or predation, is to many soil ecologists the dominant driver in natural soil ecosystems and thus, is the subject of the fourth and final soil conceptual model proposed in this work.

4. Soil Ecosystems as Living Mutualistic Networks

History, Origins and Definitions of Mutualism

Millions of years before mammals roamed the earth photosynthesizing bacteria teamed up with fungi to enable their transition from the sea to dry land. Traces of these ancient reciprocal

relationships known as “mutualisms” can be found in soil ecosystems across the planet. From tiny crocuses to the largest trees on earth, some 85 to 90 percent of all vascular plants—an estimated 240,000 species,²⁸⁹ including nearly all edible grains, tubers and fruits—form mutual associations along their roots with soil mycorrhizal fungi. Nitrogen fixing bacteria living in nodules on the roots of a small group of plants may be the most widely recognized of soil mutualists and are the basis of much of the world’s agriculture.

Mutual associations in biology occur across, not within, species and contribute to the fitness of the partners involved. Agrawal et al. (2007, citing Bruno et al. [2003]) describe mutualisms as “positive interactions on community structure and function” compared to the negative soil interactions from competition, predation and pathogens.²⁹⁰ Mutualism is at the positive end of a continuum of symbiotic (space-sharing) relationships; commensalism (one benefits, the other is unaffected) is in the middle and parasitism (one benefits, the other is damaged) is at the negative end. Non-symbiotic mutualisms are also common in soil ecosystems where species that are not physically connected supply nourishment or protection to one another; for example, free-living soil bacteria feed on carbohydrates exuded by plants and release into the soil growth-stimulating hormones for plants to absorb.

Douglas H. Boucher traces the concept of mutualism in nature to the time of Aristotle who marveled at crocodiles allowing plovers to safely enter their mouths to consume leeches.²⁹¹ Seed dispersal by birds and pollination by bees are two commonly cited above ground mutualisms. Since the dawn of agriculture farmers understood the value of rotating legumes with non-N-fixing crops without understanding the legume’s mutual relationship with rhizobium bacteria.

The influence of the Industrial Revolution and Darwin’s theories promoted competition and struggle as the dominant path to progress. Mutualism took on a political connotation and the support of the working class. Major discoveries of mutualisms in the 1880s and 1890s included mycorrhiza and N-fixing nodules on legumes. By the 1970’s many ecologists saw competition as

the driving factor in ecosystems with mutualism of minor interest. A mathematical representation of two-species mutualisms (the phase-plain model) developed in the 1930s—and according to Boucher rediscovered numerous times over the next 50 years—shows that "both species attain higher densities together than when they exist alone and when the product of the mutualism coefficients exceeds one."²⁹²

Why focus on only one driver of soil interactions?

Many soil ecologists have complained that the neglect of soil mutualisms—which are much more common in soil than above ground—provides a distorted picture of soil ecosystems. Focusing on mutualism restores the balance. "Predation as a way of life is not fundamental to ecology...yet predators and prey are often most mentioned in ecological studies," complains Wilkinson.²⁹³ The decomposers which he cites as equal in importance to photosynthesizers are also often mutualists—the gut bacteria breaking down cellulose in soil beetles and worms, the mycorrhizal fungi dissolving rocks to supply phosphate to their plant partners, the detritivores breaking down plant litter and releasing minerals reabsorbed by the plants.

Soil mutualisms are often multilevel conveying multiple feedbacks and benefits involving more than two species as well as abiotic resources. Sherri Morris cites recent studies that "show fungi are actually involved in acquisition of almost any limiting nutrient in soil depending on partnering species."²⁹⁴ What we don't know about these organisms, especially those that can only be studied in place, is much greater than what we do know. More detailed explanations of mutualisms, soil networks and global cycles are presented in Chapter 3, "Understanding Soil Ecosystems: A Primer."

Upending conventional models, rejecting the dominant paradigms, resetting boundaries

Agro-centric, monoculture notions of fertility as defined by soils tests measuring high levels of mineral N, P and K in bulk soil provide little insight into the productive capacity of perennial landscapes, forests, grasslands and savannahs. For example, low NPK readings may

indicate efficiency of nutrient cycling between above and belowground mutualists in forests, *not* insufficiency as so many assessments of forests soil claim. A soil ecosystem network that can support massive stands of 300-foot trees, themselves supporting aerial soils teeming with life, is hardly unproductive or infertile. Acres of corn monoculture measuring high levels of NPK that have reduced or eliminated mutual symbiotic links to P-obtaining fungi and N-fixing bacteria, that have lost the mutualists' disease-suppressing benefits and that as a result of over-fertilization, leak synthetic nutrients and pesticides into groundwater and rivers are not efficiently-fertile soils.

The conventional models of nitrogen cycling from the atmosphere through N-fixing bacteria to plant tissue and the slow decomposition of plant and animal remains into inorganic nitrogen (the mineralization-immobilization model of N-cycling) have been shown to be at best incomplete and oversimplified. The role of mutualists in upending this model is not commonly understood. Many soil ecologists have reported over the last decade on the paradigm-shifting discovery that mycorrhizal fungi—associated with forest, grassland and agricultural crops—can dissolve organically bound nitrogen in the tissues of microscopic soil animals into amino acids and deliver those proteins directly to their plants partners. (The N-cycle is discussed in more detail in Chapter 3.) Many respected soil ecologists in the United States and abroad have reported these findings in peer-reviewed journals and in edited collections of soil ecosystem papers. (Franci Martin, Silvi Perotto and Paola Bonfante, 2001; Rien Aerts, 2002; David Coleman, D.A. Crossley, Jr., and Paul F. Hendrix, 2004; Roger Finlay and Anna Rosling, 2006; Alaister Fitter, 2005; David Johnson, Jonathan R. Leake and David J Read, 2006; Sherri J. Morris and Christopher B. Blackwood, 2007; Kathleen Treseder, Claudia I. Czimczik, Susan E. Trumbore and Steven D. Allison, 2007; Joanne Leigh, Angela Hodge and Alastair H. Fitter, 2009) The above list is offered as evidence and in response to one of the few widely published studies with negative findings. This study used sterilized soil in a greenhouse.²⁹⁵ In 2008 Treseder et al. reported that their study in Alaskan soils “confirmed the hypothesis that ectomycorrhizal fungi may access soil amino acid pools under natural conditions.”²⁹⁶ Johnson et al. report that the

“unequivocal demonstration that ectomycorrhiza and ericoid mycorrhiza could access organic forms of nutrients directly and thus bypass the traditional view of the nitrogen cycle” was “perhaps one of the most significant findings in plant and fungal ecology during the last decade”²⁹⁷ yet, it was not widely reported in related scientific fields or reported at all in the agricultural or popular press.

Another model-shifting development regarding soil mutualisms was the discovery in the late 1990s of multilevel mutualisms among plants, fungi and bacteria (described in Chapter 3). Traditional conceptual models of landscape soils categorize them as fungal-dominated (forests) *or* bacterial-dominated (grasslands and agricultural lands). Electron microscopy and DNA analysis have detected mutualist bacteria living at the junction of mutualist AM fungi inside the root cells of plants.²⁹⁸ The identification of these mutualist, physio-bio-chemical relationships has shed new light on the complexity of tradeoffs in services between soil mutualists and their above ground partners.

Networks of Mutualists

The boundaries of soil studies in agriculture and forestry, particularly intensively managed commercial timber lands, are often too shallow and too narrow to accurately account for mutualism’s processes and benefits or the chemical model’s failings. Like the rivers, streams, creeks and ponds of a surface watershed, the roots of above ground plants and their mycorrhizal networks physically connect, alter and nourish the habitats they pass through. Unlike riverine networks the soil’s connecting organisms are not passive. An elaborate biochemical feedback system between plants and soil organisms and among soil organisms recruits beneficial relationships and resists pathogenic ones.

This living chemical and physical network calibrated by evolution and climate is not fairly represented in the language of agronomy, hydrology or climate science and as a result its influence is underappreciated. Plants do not just passively absorb nutrients conveniently released into the soil by hitchhiking-rhizobia and bacterial decomposers or deposited by farmers and

gardeners. Plants exude a variety of molecules into the soil to attract specialist microbes and fungi to either enter their roots cells to directly supply the needed services or to release into the soil needed nutrients, growth hormones, anti-pathogenic agents and other compounds. (Chapter 3 lists some of the over 100 feedback chemicals identified to date.) Plants also reabsorb compounds they previously deposited in the soil suggesting a still richer complex relationship with their symbionts.

Policy Consequences of Ignoring the Mutualist Networks and Conflicts of Interest

The importance of fungal network transport to water acquisition by plants and atmospheric carbon sequestration has been underreported in hydrological and climate literature. The extensive review of carbon storage studies in old growth forests by Luyssaert et al. (2008)²⁹⁹ (described in Chapter 3) demonstrates continued misperceptions of the role of soil ecosystems in global cycles and the effect of those flawed models on respected scientists at the IPCC who incorrectly reported that old growth forests are at best carbon-neutral, a conclusion at odds with that reached by soil ecologists after extensive, long-term research.³⁰⁰

As soil ecologists begin to unravel mycorrhiza's multi-function, cross species mutualisms and exoenzymes, many fear that plant scientists who have developed genetically modified versions of mycorrhizal plants are altering soil ecosystems they do not understand. Krinsky et al. reported in 1995 that conceptual models of the behavior of genetically modified soil organisms (GMOs) were seriously out-of-date. They cited a study that found that a genetically-modified strain of a common decomposer bacterium destroyed mycorrhizal fungi in agricultural soil.³⁰¹

The development of GMO trees to supply the pulp paper industry raises even greater concern for unintended consequences, given that trees are long-lived and have root-mycorrhizal networks that can transport tree root exudates well beyond the confines of a plantation's boundaries. These trees have been genetically modified to weaken the lignin compounds that protect the tree roots from desiccation and disease in order to make the industrial process of converting wood pulp into paper more efficient. Little consideration has been given to the effect

weakened lignin may have on mycorrhizal fungi. Research suggests that when environmental conditions are not supportive of mycorrhizal associations these fungi can become saprophytic, consuming the root tissues they have previously nourished.

A recent Scientific American editorial criticized “agritech companies [that] have given themselves veto power over the work of independent researchers. Monsanto, Pioneer and Syngenta have “forbidden the use of the seeds for any independent research” and threatened to sue any scientists researching any “unintended environmental side effects.” The magazine’s editors say the EPA should require, “as a condition of approving the sale of new seeds, that independent researchers have unfettered access to all products currently on the market.”³⁰²

The distortions of reductionist-only approaches to understanding and researching soil ecosystems and their effects on local and global environments have been well documented. Combining these scientific misconceptions with the reward of large profits for ecologically questionable pursuits magnifies the danger of those distorted models.

VI. The Future of Soil Policy

The United States does not yet have a soil ecosystem policy. Responsibility for appraising the nation's soils and addressing the environmental effects of agriculture continues to reside with the United States Department of Agriculture (USDA) rather than the Environmental Protection Agency (EPA) which does not have a soil strategy. The National Science Foundation (NSF) has launched a new systematic study of the Earth's "critical zone" inviting proposals to research the space between the vegetation canopy and groundwater.³⁰³ Several soil studies are included in currently funded projects but Congress has determined that priority funding should go to institutions in states that traditionally do not receive NSF funding.

The European Union (EU) and Switzerland are now the leaders in developing soil ecosystem protection policies that include regulating all soil uses including agriculture. Soil policy initiatives are being developed in an integrated way, supporting research, devising protections and educating the public. EU soil analyses note the decline in soil biodiversity by including the impacts of chemicals on soil life, along with their impacts on water. They include sewerage sludge, nitrates, biocides and fertilizers in that integrated analysis. Policy proposals include promoting agricultural measures such as organic production and environmental practices that have a positive impact on soil biodiversity.³⁰⁴

Switzerland, home of one of the world's largest manufacturers of herbicides and GMO seeds, has produced a soil policy vision statement with protections far exceeding any yet produced by the United States or the European Union. Produced by the Swiss Federal Department of the Environment, Transport, Energy and Communications, it presents a vision of cross-media soil protection that integrates research, education and regulation as well as soil, water and climate policy. Protection of soil needs to be "embedded" in the public mind, the Swiss environment agency asserts, along with recognition of the role of soil biota in preserving soil functions. The policy lists ten key points of soil protection in the future including precautionary measures to protect soil regardless of its use, the concept of soil as a public good to be handed down to future

generations, the need for independent scientific rigor in researching soil systems and a requirement to devise enforcement mechanisms to protect soil ecosystems.³⁰⁵

An international assessment of agricultural knowledge, science and technology (IAASTD) sponsored by the United Nations has taken a different approach from agribusiness to understanding agriculture's impact on soil ecosystems and livelihoods. The IAASTD initiative brought together 400 traditional and non-traditional world experts to assess the role of modern and traditional agriculture "in reducing hunger and poverty, improving rural livelihoods and facilitating environmentally, socially and economically sustainable development."³⁰⁶ The multistakeholder, "geographically-balanced" group consisted of 30 government and 30 civil society representatives, a total of 900 stakeholders from 110 countries to "ensure ownership of the process and findings."³⁰⁷ In IAASTD's 2009 report, *Agriculture at a Crossroads*, the stakeholders suggest a range of options to achieve sustainable agricultural communities and to restore soil health, biodiversity, forests, water and air quality. They critically assess the "Green Revolution" for its neglect of nutrient rich foods, reduced genetic diversity, overuse of fertilizers, irrigation and harmful pesticides. They acknowledge the negative effects that both traditional and modern agricultural practices have had on sustainable production, particularly on "mycorrhizal associations [that] are essential to plant establishment and survival, especially in degraded environments."³⁰⁸ The report promotes integrated crop and livestock production as an ancient, common and sustainable production system. Twenty-five years of agroforestry research, combining the best of scientific, technical and traditional knowledge, they argue, "have developed techniques and strategies to assist farmers to reverse soil nitrogen depletion without the application of fertilizers"³⁰⁹ and excess irrigation. Finally, the report³¹⁰ proposes the creation of an independent U.N. agency to deal with marketplace monopolies that impede the economic success of sustainable agricultural producers in developing countries.³¹⁰

Conclusion

A review of soil policy history shows that many efforts over the last 75 years, including the National Environmental Policy Act in 1969, to more effectively integrate conservation measures, have been defeated or weakened by narrow interests or misunderstanding of linked ecological systems. In the 1970s the United States took the lead in protecting the environment with the passage of stringent regulations to protect air and water but failed to integrate these policies and failed to include soil ecosystem protection. Failure to make connections between life in the soil, above ground productivity and clean water have resulted in many policy failures, leading, for example, to a dead zone the size of New Jersey in the Gulf of Mexico where no fish can survive and to densely-planted fields of corn in Iowa where the ground water is toxic and more carbon is released into the air than is stored in the soil. An agro-centric U.S. soil policy that has put short-term production above long term soil sustainability has been reinforced by two conceptual models that dismiss the importance of understanding the rich connections among soil biota, abiotic resources and above ground processes.

The models of soil that have dominated U.S. policy—the physiochemical and the black box models of soil—support the economic interests of agribusinesses that lobby against alternative concepts and practices. The weak financial support by the USDA for organic agriculture and the overuse of fertilizers and pesticides are indicative of ignorance of soil ecosystems and their role in regulating climate and protecting water. The soil food web model was a first step in opening the black box concept of soil that has immunized citizens, politicians and farmers from confronting soil practices that impair soil ecosystem services.

Soils are unique in the ubiquity of their mutualistic associations across species, space and time, and in the multilevel complexity of those associations. Many past and current soil practices have severed these mutual associations weakening and sometimes destroying the above ground life they support while reducing the soil's ability to retain water, store carbon and moderate the climate. When we can look at an old growth forest and can imagine its aerial and subterranean

soil networks—of roots, aquatic pools, N-fixing bacteria, fungi, protozoa, nematodes, beetles, truffles, moles and thousands of other interacting species—with miles of mycorrhizal and saprophytic fungal threads knitting it all together, perhaps then, we will insist that soil ecosystems be protected.

APPENDIX I: TABLE 1 SOIL ECOSYSTEM LITERATURE CITATION SEARCH
 2008 Web of Science Database Search of Soil Ecosystem Researchers Authors/Editors of Key Soil Ecosystem Texts

Author	Affiliation	# of soil-related articles	citation years	most citations of an article & publication	3 highest # citations as a principle author	Most cited as principal author	Article date	principle co-authors	Publication Name	Common co-authors
Gadd, GM	Prof. Microbiology U. Dundee	195	1978-2008	344	344,181,93	Interactions of Fungi with Toxic Metals	1993		<i>New Phytologist</i>	
						Microbial Treatment of Metal Pollution	1993		<i>Trends in Biotechnology</i>	
Wardle, David	Pro. Soil Sci & Plant Ecology UK, NZ & Sw.	169	1970-2004	592 - in Science	202,191,155	Biodiversity & Plant Litter	1997		<i>Oikos</i>	
						Ecological Linkages between above and Belowground Biota	2004	Bardgett, Klironomos	<i>Science</i>	Bardett
Fitter, A.H	Prof, Biology, York U., UK	141	1974-2008	159	152,141,121	An Architectural Approach to the Comparative Ecology of Plant- Root Systems			<i>New Phytologist</i>	
						An arbuscular mycorrhizal fungus accelerates decomposition and acquires nitrogen directly from organic material			<i>Nature</i>	Ingham, Coleman
Wall, Diana (ne: Freckman)	Prof. Soil Ecology, Colorado St. U.	138	1972-2006	670	58,41 ,37	Interactions underground - Soil biodiversity, mutualism, and ecosystem processes	1999	Moore JC	<i>Bioscience</i>	
						Linking biodiversity and ecosystem functioning of soils and sediments	1997	Blackburn, Brussaard	<i>Ambio</i>	
Paul, E. A.	Prof. Soil Sc., Colorado St. U.	118	1961-2007	126	126,121,117	Criteria for Measurement of Microbial-Growth and Activity in Soil	1978	Nannipieri, Johnson	<i>Soil Biology & Biochemistry</i>	Nannipieri

Author	Affiliation	Articles	Years	citations	Most cited	Key titles	Yr.	Co-authors	Journal	
						Carbon Flow, Photosynthesis, and N-2 Fixation in Mycorrhizal and Nodulated Fava Beans	1982	Kucey	<i>Soil Biology & Biochemistry</i>	
Bardgett, Richard	Prof. Ecology, Lancaster U., UK	109	1991-2008	191	155, 152, 136	Ecological Linkages between above and Belowground Biota	2004	Wardle, Klironomos	<i>Science</i>	Wardle
						Changes in soil fungal :bacterial biomass ratios following reductions in the intensity of management of an upland grassland	1996	Hobbs, Frostegard	<i>Biology&Fertility of Soils</i>	
Nannipieri, P	Prof. Agri-Biochem, U. Florence. It Editor in chief of Journal Biology & Fertility of Soils	94	1979-2008	97	97,97,23	Microbial diversity and soil functions	2003	Ascher J, Ceccherini	<i>European Journal of Soil Science</i>	
						Changes in Amino Acids, Enzyme-Activities and Biomasses During Soil Microbial Growth-	1979		<i>Soil Science</i>	
Wilkenson, D. M.	Reader in Environmental Science Liverpool John Moores U.,UK	44		37	37,22.15	Metal Resistance in Trees - The Role of Mycorrhizae	1995	Dickenson, NM	<i>Oikos</i>	
						The evolutionary ecology of mycorrhizal networks	1998		<i>Oikos</i>	
Richards, BN	Assoc. Prof Nat.Resources, U. New England, Australia	20	1961-85	108	108,25,18	Effect of Reforestation on Turnover of N-15 Labeled Nitrate and Ammonium in Relation to Changes in soil Microflora	1977	Jones, JM	<i>Soil Biology & Biochemistry</i>	
						Role of Mycorrhiza in Nitrogen Fixation	1964	Voight, GK	<i>Nature</i>	

ENDNOTES

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- ¹ *Water Pollution Prevention and Control (Clean Water Act of 1972 as Amended in 1977 and 1987)*, U.S. Code, Title 33, Ch. 26, Sec. 1251.
- ² Richard D. Bardgett, Michael B. Usher and David W. Hopkins, ed., *Biological Diversity and Function in Soils*, Ecological Reviews (Cambridge, UK: Cambridge University Press, 2005), 231-43. p. xiii.
- ³ Ian Young and Karl Ritz, "The Habitat of Soil Microbes," in *Biological Diversity and Function in Soils*, ed. Bardgett, Richard D., Michael B. Usher and David W. Hopkins (Cambridge, UK: Cambridge University Press, 2005).
- ⁴ D.H. Wall, V. Behan-Pelletier, A.P. Covich and P. Snelgrov, "Hidden Assets: Biodiversity Below-Surface," in *UNESCO-SCOPE Policy Briefs* (Paris: UNESCO, 2007).
- ⁵ Andrew Sugden, Richard Stone and Caroline Ash, "Ecology in the Underworld," *Science* 304 (2004).
- ⁶ David A. Wardle, *Communities and Ecosystems: Linking the Aboveground and Belowground Components* (Princeton: Princeton University Press, 2002). p. 1, 43.
- ⁷ BN Richards, *Introduction to Soil Ecosystems* (Harlow Essex, U.K.: Longman Group, 1974).
- ⁸ Rachel Carson, *Silent Spring* (Boston: Houghton Mifflin, 1962). p 56.
- ⁹ *Ibid.* p 63.
- ¹⁰ Craig Osteen and Michael Livingston, "AREI Chapter 4.3: Pest Management Practices," USDA ERS, www.ers.usda.gov/publications/arei/eib16/Chapter4/4.3/.
- ¹¹ David A. Wardle, Richard D. Bardgett, John N. Klironomos, Heikki Setälä, Wim H. van der Putten, and Diana H. Wall, "Ecological Linkages between Aboveground and Belowground Biota," *Science* 304, no. 5677 (2004). p 1629.
- ¹² Diana Wall, Alastair H. Fitter and Eldor A. Paul "Developing New Perspectives from Advances in Soil Biodiversity Research," in *Biological Diversity and Function in Soils*, ed. Bardgett, Richard D., Michael B. Usher and David W. Hopkins (Cambridge, UK: Cambridge University Press, 2005). p. 4.
- ¹³ IM Young and JW Crawford, "Interactions and Self-Organization in the Soil-Microbe Complex," *Science* 304, no. 5677 (2004): 1634-37. p 1634.
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