SCOPE (the Scientific Committee on Problems of the Environment) was established by the International Council of Scientific Unions in 1969, to respond to a growing concern for and about environmental quality and to direct attention to existing and potential environmental issues. It serves as a non-governmental, interdisciplinary and international council of scientists that acts at the interface between the science and decision making spheres, providing advisors, policy-planners and decision makers with the analytical tools to promote sound management and policy practices. SCOPE projects help guide further research by identifying gaps in knowledge and new innovative directions for research. SCOPE has serviced the earth systems research programmes by helping to define priorities and design agendas and by appraising and synthesizing the information accumulated by these programmes. SCOPE, through cutting edge evaluations and assessments, is known for its focused attention on major issues such as world climate and global environmental change, biodiversity and ecosystem functioning and the environmental cosequences of a nuclear war. SCOPE's biodiversity in soils and sediments project is a component of DIVERSITAS, the international programme on biological diversity.

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Article

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Linking Biodiversity and Ecosystem Functioning of Soils and Sediments

Soils, freshwater sediments and marine sediments offer a new frontier of vast, poorly known ecosystems that are critical to life on earth. They are connected by similarities in biota, ecosystem processes, biogeochemistry, and, the types of processes carried out by the diversity of biota. We know a lot about the ecosystem processes in these domains through studies of functional groups of organisms, but we know much less about keystone species, or biodiversity across habitats and thus we cannot, with certainty, answer questions such as, "will a change in diversity in an agricultural soil affect the flow of energy, water and chemicals across the interconnected domains?". Linkages of knowledge across the three domains would increase our understanding of how human-driven changes affect subsurface biodiversity and functioning, and, in turn, how these impacts influence aboveground ecosystem functioning. Approaches utilizing this knowledge will identify the long term strategies needed to attain sustainable soils, freshwaters and marine systems. Syntheses of available data for comparisons of biodiversity and processes across soils and sediments are priorities.

INTRODUCTION

Our soils, freshwater and marine sediments are some of the least known biological habitats or domains on earth. These subsurface domains have typically been perceived as dark and lifeless, when in reality they are predicted to contain higher species diversity than the aboveground world (1, 2). Importantly, the functioning and linkages among these habitats may be essential to sustaining life on earth (3), yet we are only beginning to realize the extent of the interdependence of biotic interactions in subsurface habitats. We do not know if human activities such as groundwater contamination, pollution, salinization, channelization, and dam building are destroying the biodiversity in subsurface habitats (domains), or whether changes in diversity in these habitats will alter ecosystem processes and the provision of essential ecosystem services (4). We require a new synthesis across marine, freshwater and terrestrial domains as well as more effective collaboration among scientists with specialized knowledge of single domains.

The soils beneath our feet, the sediments of freshwater lakes, streams, rivers and wetlands, and the vast portion of our planet that is the ocean floor and coastal estuaries are all a continuum of interconnected ecosystems. Subsurface habitats include interfaces or transfer control zones (Fig. 1; Table 1) between land and groundwater, soils and aquatic habitats, riparian forests and wetlands and coastal to deep marine environments. These transfer control zones harbor a rich and diverse biota that facilitate and regulate the transfer of nutrients and particles across domains (4, 6, 7) (Table 1). Thus, the biota in each of the transfer control zones are critical for maintaining the continuum between the domains. These interfaces are of added importance because they are tightly connected to terrestrial vegetation and the atmosphere (Fig. 1; Table 1). Precipitation, tree leaves falling to the ground, erosion of soil and streambanks, all may end up in rivers, lakes and wetlands on their way to the oceans. Despite this connectivity, marine, freshwater and soil domains have often been studied in isolation. The cleaning of a polluted lake or ocean harbor, the movement of agricultural pesticides from soil to lakes and estuaries and the impact of chemical spills on beaches or inland soils are generally viewed as occurring separately and unconnected from the unseen diversity of organisms that provide the essential functioning of ecosystems we take for granted.

The Scientific Committee on Problems of the Environment (SCOPE), Committee on Soil and Sediment Biodiversity and

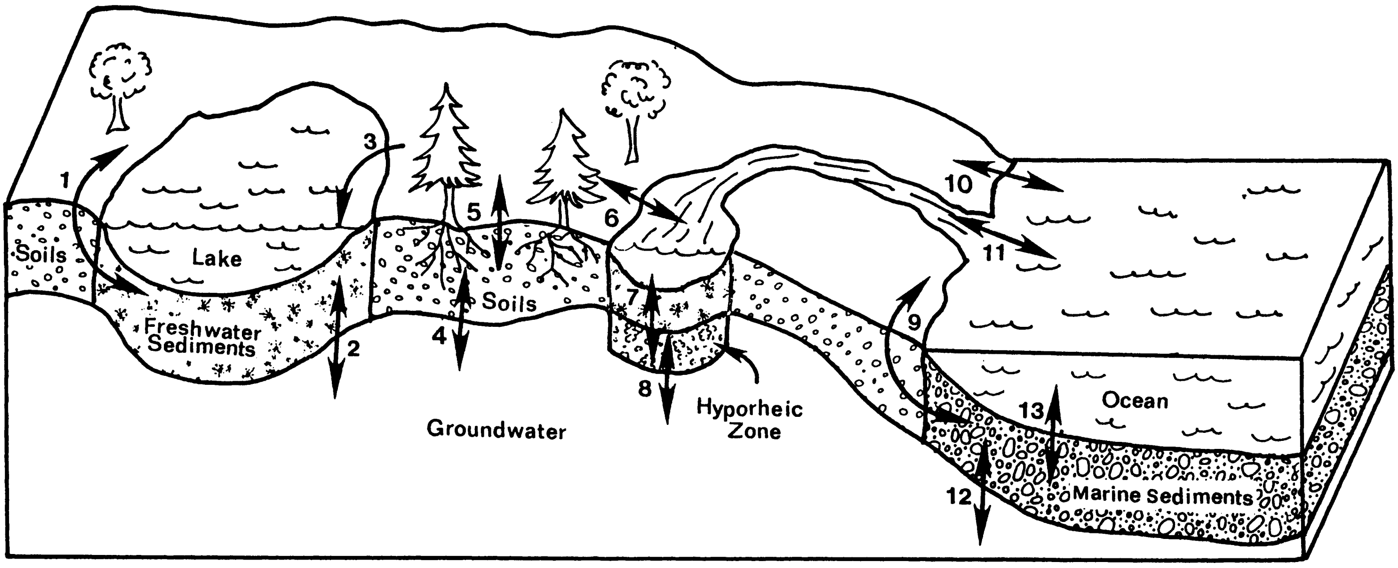

Figure 1. Critical transition zones. The most critical habitats may be those occurring at the juncture of two habitats such as where soils meet groundwaters, freshwater sediments meet groundwater, or groundwater meets surface waters. These ecotones act as differentially-permeable membranes influencing the movement of energy, materials and information across surface and sub-surface environments. They serve as temporary or permanent sinks of organic or inorganic matter from the catchment. Their filtering and retention ability vary and are linked to the rock matrix, sediment particle size, permeability and inputs. These zones exhibit a high biogeochemical activity, especially in areas or periods of slow or medium flow through an anaerobic and then aerobic sediment layers. These habitats harbor rich species assemblages whose impact on the ecological processes varies over space and time (5, 6).

Table 1. Interfaces or transfer control zones often determine the physical and biological state of adjacent terrestrial and aquatic systems. The biota living in these interfaces regulate the movement and fate of materials. The interfaces can be located by a number in Figure 1, and are described, with an example of the ecosystem processes that occur there by a corresponding number in Table 1.

Interface	Examples of Interface Processes
1. Soils-freshwater sediments-atmosphere	Cycling of nutrients such as C, N and P, nutrient and particle transfer, biogeochemical cycling
2. Freshwater sediments—lake water—ground water	Recapture/loss of sediment nutrients from/to lake water and ground water
3. Soils-freshwater	Net primary productivity, leaching of nutrients
4. Soils-ground water	Recapture/loss of nutrients from/to ground water
5. Soils-vegetation	Net primary productivity, weathering, evapotranspiration
6. Freshwater-soils	Weathering and leaching, transfer of nutrients
7. Freshwater sediments-hyporheic zone	Transfer of organics, nutrients, particles
8. Hyporheic zone-groundwater	Gain/loss of nutrients to/from groundwater
9. Soils-marine sediments-atmosphere	Cycling of nutrients such as C, N and P, Nutrient and particle transfer, biogeochemical cycling
10. Ocean-soils	Erosion and deposition of inorganic and organic particles, nutrient cycling
11. Freshwater-ocean	Transfer of nutrients, organisms, and particles, transport/dilution of pollutants and excess nutrients
12. Marine sediments-groundwater	Recapture/loss of nutrients from/to ground water
13. Marine sediments-ocean	Nutrient cycling through decomposition and net primary productivity, secondary production, burial/metabolism of pollutants

Ecosystem Functioning, under the umbrella of DIVERSITAS, convened its first meeting in Wageningen, The Netherlands in April 1997. SCOPE is one of the six co-sponsors of DIVERSITAS, an international scientific program which aims to provide aid in the actual achievement of research goals and the dissemination of scientific information concerning biodiversity research. This meeting was designed to explore the linkages between the diversity of life in soils and sediments and to define research priorities. The committee was chaired by Diana Wall Freckman, Colorado State University, USA, aided by co-chairs Margaret Palmer, University of Maryland, USA (Freshwater Sediments), Lijbert Brussaard, Agricultural University, The Netherlands (Soils), and T. Henry Blackburn, Aarhus University, Denmark (Marine Sediments). Forty taxonomists, ecologists and biogeochemists from 15 countries, who are experts in either soils, freshwater sediments or marine sediments, summarized the status of knowledge within and across domains.

This meeting was co-sponsored by The Ministry of Agriculture, Natural Resources Management and Fisheries of The Netherlands, The International Union of Biological Sciences (IUBS), another co-sponsor of DIVERSITAS, as well as anonymous donors. It was unique in that it was the first meeting to integrate information from the three domains and to explore the connectedness of the species, and groups of species, to ecosystem processes across domains. The results of the SCOPE Committee meeting are presented in this and the following three (8–10) papers. This paper examines the similarities and differences in structure, functioning and diversity of the domains and provides an overview for the *Soils*, *Freshwater Sediments* and *Marine Sediments* papers that follow in this volume. For all domains, species distribution and richness, the role of individual species and suites of species in maintaining ecosystem processes—i.e., flows of water, nutrients or carbon within and among ecosystems—and the potential consequences if species are lost from the domains, were considered. For example, will changes in the biodiversity of soils or sediments affect the quality of water, the flow of energy or nutrients in transfer control zones and between domains? (Fig. 1; Table 1). Research priorities for increasing our understanding of the interconnectedness of the domains resulted from discussions to determine gaps in our knowledge.

Although participants studying the three domains initially used different terminologies, a common basis for the meeting was their combined scientific knowledge of the organisms that contribute and maintain valued ecosystem services such as clean water, food supply (fisheries, agricultural crops), soil fertility, bioremediaton of pollutants, and decay of organic matter. The subsurface biota and the services provided to society are affected by human disturbances such as intensive agriculture, elevated CO_2, pollution of soils, freshwaters and marine systems and groundwater contamination, but the magnitude of the effects is as yet unknown on a global scale (11, 12). Thus, there is a critical need to increase our knowledge of the functions of these unseen organisms and how these will be influenced by global change.

STATUS OF BIODIVERSITY RESEARCH IN SOILS AND SEDIMENTS

The Domains: Soils, Freshwater and Marine Sediments

The characteristics of the soil, freshwater and marine sediments and the organisms they support are summarized in Table 2. Our knowledge of the subsurface biota is greater for the terrestrial portion of the globe, even though marine sediments cover the majority of the earth's surface. Variation in the physical, chemical and biological properties in soils and sediments is immense, depending on the geologic processes that contributed to their formation, and human use. Soils range from sand dunes in deserts to layers of moist organic matter found in tropical and organic forests, with mineral layers beneath. Freshwater sediments include those beneath or in ponds, lakes, streams, rivers, marshes, wetlands and estuaries as well as groundwaters studied by both soil and freshwater scientists. The ocean sediments span the coastal shores to deep oceans. Although in most cases the majority of macroorganisms inhabit the top few centimeters of soil and sediments, bacteria, fungi and invertebrates can occur to hundreds of meter depths (9, 10, 20, 21).

The quality and quantity of organic matter as well as the physical and chemical characteristics in soils and sediments play a major role in structuring the types and diversity of organisms that are present in each habitat. Soils and sediments are the major global reservoirs for carbon in the form of organic matter. The marine sediments store most of the earth's carbon while the freshwater sediments that cleanse drinking water for humans have the lowest amount of carbon of the three domains. The drier, aerobic soils contain twice the organic matter found in terrestrial vegetation (13, 18). The cycling of nutrients from these large amounts of organic matter stored in soil and sediments to plant productivity is an example of an ecosystem process that is dependent on numerous taxa across all three domains (Fig. 1; Tables 1 and 3).

Organisms and Species Richness

The variability of life, or biological diversity, is measured by the amount of genetic variation, the richness of species and the richness of the many different types of ecosystems (4). Although all species may eventually go extinct, humans are accelerating the rate at which species are lost on a global scale. We are aware that the estimates of diversity for bacteria, fungi and invertebrates in the subsurface habitats are vast and that a majority of these species have not been described. The gap in this knowledge is even bigger that that for vascular plants and vertebrates (1, 22). Every phylum of organisms known above-surface is represented below the surface, and millions of these organisms often exist in a single cubic meter of soil or sediment.

There are many reasons why most species are unknown, including:

- The domains are opaque habitats, making it difficult to identify organisms *in situ* (particularly in deep marine waters and groundwaters).
- The variety of life in a shovelful of soil or sediment ranges in size from microscopic fungi, bacteria, archaea, protozoa, and microfauna, to larger (centimeters to meters) vertebrates and invertebrates.
- At present, there are few scientists with taxonomic expertise able to identify the organisms.
- Mechanisms for differentiating between taxa remain poorly developed.

Table 2. Characteristics of the three domains.

	Soils	Freshwater Sediments	Marine Sediments
Global Coverage	1.2×10^8 km^2 (17)	2.5×10^6 km^2 (16)	3.5×10^8 km^2 (19)
Carbon Storage	1500 Gt (18)	.06 Gt (14)	3800 Gt (13)
Organic Content	High (18)	Low (18)	Low (18)
Hydrology	Dry (15)	Permanently flooded	Permanently flooded
Oxygenation	Generally oxic	Oxic-anoxic	Oxic-anoxic (15)
Salinity	low	low	high
Pressure	low	moderate	high

Table 3. Representative functional groups and organisms are listed for some ecosystem processes common to soils, freshwater sediments and marine sediments. These functional groups are important for global transfers and cycling of nutrients and energy.

Functional Groups	Representative Ecosystem Processes	Organisms
Bioturbators	mix and redistribute organic matter, particles and microorganisms to depths	polychaetes, oligochaetes, crustaceans, molluscs, echinoderms in sediments; vertebrates (gophers, lizards), earthworms, termites, ants in soils
Primary producers	create new biomass stabilizing soils and sediments	algae, plant roots
Shredders	rip and tear organic matter preparing it for decay by other organisms	decapods, stoneflies in freshwater sediments, chilopods, isopods in soils
Decomposers	return carbon and essential nutrients to soils and sediments for primary production	bacteria and fungi breakdown organic matter into nutrients (C, N,P, etc.) in soils and sediments
Nitrogen fixers	only mechanism for entry of atmospheric N_2 into the biosphere	symbiotic bacteria (e.g. *Rhizobium*). asymbiotic bacteria (e.g. *Cyanobacter, Klebsiella, Azobacter*)
CO_2 producers	respiration, transfer of forms of carbon	roots, organisms
Trace gas production	denitrification, N_2O production, methanogenesis	denitrifying bacteria, methanogenic bacteria

- It is difficult to develop consistent sampling techniques across domains (23). In marine systems sampling is tremendously expensive and time consuming.
- Seasonal fluctuations in organism populations may influence species quantification.
- The temporal and spatial (micrometers to meters) scale of the habitats is extremely varied, requiring study at many different resolutions.
- The species within a given food-web change with the physical and chemical environment, the quality of organic matter, climate and geography.
- Many species spend part of their life cycle above the soil and sediments making sampling less precise.

These factors all contribute to making quantification and comparisons of biodiversity problematic within even a single domain. However, even with these uncertainties, it is still clear that the number of species in soils and sediments is extremely high, much higher than described for terrestrial aboveground habitats (22).

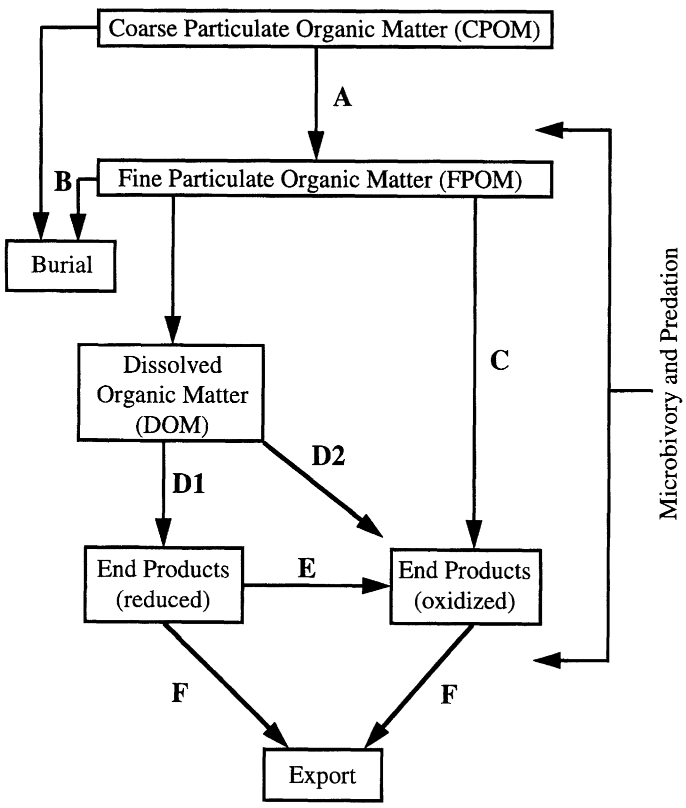

Figure 2. Participants agreed on a simple conceptual model to illustrate commonality in the patterns and mechanisms of organic matter decay occurring in domains of soils, freshwater and marine sediments. The model emphasizes control of decay by similar functional groups of biota in each of these domains. Details such as the important species that are responsible for transfers between the various boxes can be added to the model as necessary for each domain. Conceptually, the model indicates that organic matter reaches soils and sediments as coarse particulate organic matter (CPOM), and is broken into fine particulate organic matter (FPOM) by [A] actions of microbes and fungi, by [A] "shredders", and by [A] physical disaggregation in aerobic (containing oxygen) environments. The CPOM and FPOM can be buried [B], and in aerobic environments and anaerobic (lacking oxygen) environments, both physical forces and the "bioturbators" are important in moving, burying, and breaking up the FPOM to dissolved organic matter (DOM). In anaerobic environments fermentation occurs as bacteria and fungi breakdown FPOM to DOM. In aerobic environments, FPOM can be broken by microbes and fungi [C] to an oxidized end product (usually CO_2); humic materials (very resistant to further degradation), can form in aerobic and anaerobic environments. Humic materials may be transported out of the system as an efflux, along with other final breakdown products, such as methane (CH_4). The DOM can be degraded by [D1] bacteria anaerobically to reduced end products or [D2] to oxidized end products. Reduced end products can be oxidized by bacteria and fungi [E], if oxygen is available, or lost as efflux [F].

Geographic Distributional Patterns

Compared with aboveground habitats, we know very little about the natural patterns of diversity for species in soils and sediments, either in disturbed or pristine environments. For example, although it is known that aboveground diversity is higher in tropical regions (1), whether this translates into greater soil or sediment diversity is just beginning to be explored (24). Only a minute portion of the earth's subsurface habitats have been examined for species richness and abundance. There is no global biogeographical synthesis for any group of organisms in soils and sediments, although we know that some soil and sediment genera are cosmopolitan; some genera of marine polychaetes and some genera of soil and sediment nematodes, bacteria and other groups have worldwide distributions. Several regional syntheses and some comparative studies across selected latitudes (tropical, temperate, polar) exist for many groups of organisms in all domains, particularly groups within the macrofauna. For example, soil earthworms do not occur in most deserts and differences exist in benthic (occurring at the bottom of a body of water) diversity among regions, e.g., South Australian waters are much more diverse than in the North Sea. Based on these studies, there is a need for increased sampling to determine biodiversity in developing countries, i.e., South America, Africa, Asia and particularly tropical regions, and in deeper ocean sediments.

In contrast to our knowledge of broad regional and latitudinal distributions, diversity in soils and sediments on a geographically small scale is better known. Distribution of organic matter, the type of organic matter, types and sizes of marine sediments, the size of the pore spaces in soils and sediments, depth within soil or sediment, oxygen availability, and distance from shore to deeper waters, are just a few factors that appear to influence species diversity at local scales (Table 2). These factors create spatial and temporal heterogeneity in which organisms exist at different and yet inter-connecting hierarchical levels (25).

Introductions and Loss of Species

On a local scale, examples of endemic species are known to occur in soils, freshwater and marine sediments. However, human activities are leading to the introduction and establishment of non-native species that change the natural community composition and affect ecosystem function. Examples of introductions include a species of earthworm, *Amynthas hawayanus*, introduced to the forests of the northeastern United States, that reduced surface organic matter and caused an increase in water runoff and soil erosion (26); the sabellid polychaete *Sabella spallanzanii*, a large filter feeder from the Mediterranean, that has established dense populations in Corio Bay, Port Phillip Bay, Victoria and Coburn Sound in Western Australia and completely changed the water flow patterns and modified the benthic communities (27); and the zebra mussel, *Dreissena polymorpha*, a fast growing abundant freshwater bivalve from Europe that is invading many lakes and rivers elsewhere covering the bottoms, fouling water-intake pipes, and altering nutrient levels and ecosystem productivity (28). Multiply these three examples by the thousands of species that have been introduced to soils and sediments, and large-scale changes in ecosystem functioning can be presumed.

Our knowledge of species loss, or of endangered species, is poorly documented for organisms in the subsurface domains. Yet we know, as a general rule, that physical disturbance, such as plowing and dredging, decrease and change diversity in marine sediments, freshwater sediments and soils. Across biomes, we do not know if subsurface species loss is severe, or how severely ecosystem services have been affected. Likewise, information on keystone species, those species that may be less abundant, but that have strong effects on the functioning of ecological communities and ecosystems (29, 30), is minimal for soil and sediments. Much more work is needed to fully determine the impact of these keystone species. However, it is likely that the decline or loss of key species in functional groups (especially root symbionts) from natural soil systems, such as rhizobia (bacteria that live in symbiosis with certain plant species and fix atmospheric nitrogen for use by the plant), or species of mycorrhizae (fungi that grow in association with plant roots and increase phsophorus uptake for plants) would, in turn, affect other interacting species in the ecosystem, suggesting major changes in ecosystem processes (Table 3).

Functional Groups of Organisms

Much of the research that relates biodiversity to ecosystem functioning in the three domains has focused on functional groupings rather than specific identifications of taxa. A functional group consists of species that have similar effects on a specific ecosystem-level biogeochemical process (7). Some functional groups and the ecosystem processes they perform that are common to all domains are presented in Table 3. Ecosystems have far more species than the number of processes, and when more than one species perform a similar function in one ecosystem process, this is considered functional redundancy. It does not mean that all species can be substituted equally to assure the maintenance of the process. Species vary in the amount and type of contribution they make to a process, so loss of a species may be incompletely compensated for by the other functionally similar species (4). Furthermore, not all species interact equally with other species such that the effects of losing a particular species could propagate throughout the ecosystem in unknown and unpredictable ways.

In soils and sediments, functional groups are based on incomplete knowledge, i.e., the known role of only a few species within a group, since most organisms have yet to be identified. As more information on the natural history of the organisms becomes available, such as their feeding preference, data can be compiled to determine if species have similar functions, the degree of functional redundancy, whether loss of a species would curtail a particular ecosystem function, and the effect on interactions with other species.

From studies of functional groups, we know a lot about the functioning of soils and sediments (Table 3). Similarities exist in the processes carried out by different functional groups of organisms in soil and sediments and would appear to be important on a global scale. For example, the functional group of bioturbators that mixes surface and deep freshwater and marine sediments shares many characteristics with species in soils that mix organic matter and materials across depths. The bioturbators create new pores and channels for air and water flow and stabilize soil and sediment structure. Algae utilize light to create new biomass thus stabilizing soils and sediments. Bacteria and fungi in all domains are the primary organisms responsible for the decay of organic matter. Many groups of bacteria, for example, the methanogenic bacteria that produce CH_4 (methane), have similar functions in soils and sediments. Protozoa, nematodes, Acari (mites) and other invertebrates have representative species in soils and sediments that feed on and transport the bacteria and fungi, thus regulating the rate of organic matter decay. Predation by soil and sediment animals redistributes energy and nutrients to higher levels in the food web of soils and sediments, such as to vertebrates and trees and the atmosphere, a process which is particularly important in the transfer control zones (Fig. 1; Table 1).

Disturbances to soils and sediments alter ecosystem processes, but the link of these alterations to functional groups and individual species within functional groups has not been clearly established. Disturbances to soils and marine sediments, e.g., pollutants, heavy metals are reflected in changes in the composition of the functional groups and species of certain phyla, e.g., Nematoda, contributing to their use as indicators of the status and trends of ecosystems (31). We still have to identify how such changes in functional groups affect ecosystem processes.

Even the loss of a functional group, composed of only a few species, could have detrimental effects on an ecosystem. Of the functional groups common to all domains, the shredders (Table 3) and bioturbators can be species-poor, suggesting that species loss in these functional groups would be serious and would lead to ecosystem degradation. This could also occur for functional groups of 1–2 species in extreme environments where species diversity is limited (20).

ECOSYSTEM FUNCTIONING AND SERVICES PROVIDED BY BIOTA

Similarities Across Domains

The diversity of biota contributes to making subsurface domains a critical and dynamic center for global ecosystem processes, including nutrient turnover; nutrient uptake by plants and algae; formation and decay of soil organic matter; nitrogen fixation; methane consumption and production; N_2O and N_2 production; CO_2 consumption and production; soil and sediment development and stabilization; oxygenation of soils and sediments; production of organic acids that weather rocks; transport and degradation of pollutants; food sources for higher organisms; and provision of clean water.

Several ecosystem processes common to all domains are discussed in more detail in the other SCOPE chapters in this issue of Ambio (8–10). These processes are: the decomposition of the majority of the world's organic matter; carbon sequestration; trace gas production; cycling of nutrients; cleansing of water; stabilization of soils and sediments; transport of materials (particles, organisms and gases); and primary production (synthesis of new organic matter). Processes that we identified as particularly in need of study are the effects of herbivory on primary production across all domains, and those processes affecting above-surface and below-surface interactions.

Above-surface and Below-surface Connections

The decay and decomposition of organic matter illustrates an ecosystem process where the subsurface biota are interconnected to biota above-surface (Table 3; Fig. 2). Climate, the source of organic matter, and biota are the major factors affecting the rate of decay. The decay of organic matter involves a diversity of species in all domains. These species shred, mix and digest organic matter (Coarse Particulate Organic Matter; Fig. 2) into smaller particles, transport particles to other areas, breakdown certain chemical compounds (Fine Particulate Organic Matter; Fig. 2), and decay particles of organic matter that are typically resistant to decomposition. Other organisms, not directly involved in decomposition, including many invertebrates, regulate decomposer populations through grazing and predation. As this complex process continues, end products, CO_2 or CH_4 (if no oxygen is present), nitrogenous compounds and other nutrients are released (Fig. 2). Some of the invertebrates possess specialized morphologies and physiologies that allow them to use only a certain part of the organic matter, making each organism dependent on previous steps that have occurred. This suggests that a diversity of species are essential to maintain decomposition, and is only one example of the connectedness between biodiversity and ecosystem processes that are critical for a sustainable earth.

On larger scales, such as across landscapes and interfaces of the domains, there are examples of major disturbances, primarily human-based activities—burning of fossil fuels, nitrogen fertilizer inputs—that have doubled the amount of nitrogen entering terrestrial systems and affected soil and sediment biota (11). In many ecosystems, plant species may be adjusted to low nitrogen concentrations and soil biota cannot utilize the excess nitrogen, which is transferred to the atmosphere (as nitrogen oxides) and to groundwaters and oceans (as water soluble NO_3^-) (12).

How soil and sediment species responsible for carbon mineralization will be affected by global change (32), and the impact of this on global carbon budgets, is being examined. Rates of mineralization, the process of breaking down organically bound minerals to inorganic forms, are very slow (less than 1% of the global reservoir size annually) but, because of the large soil and sediment reservoir, a small change in flux rate can significantly alter the global carbon budget (18, 33). We know that maintaining or sequestering carbon in soils and sediments is important, as an immediate breakdown of the stored organic matter would release considerable CO_2, and other trace gases (CH_4, N_2O, NO). This would decrease fertility of soils, with major economic and social consequences. For example, the halving of soil organic C when natural systems were converted to intensive agriculture during the first half of the 20th century in the central USA has led to a loss of soil fertility and an increase in inputs of chemicals to maintain crop production. The chemicals (fertilizers, pesticides) provide the same services as the soil biota (nutrients for plant growth, and biocontrol of pests) but more quickly. Computer models predict that planned management such as cover crops, no-till management, and fallow can restore much of the lost carbon (34) and soil functional groups (35, 36), but these practices have yet to be implemented on a large scale.

SUMMARY OF RECOMMENDATIONS

Soil and Sediment Biodiversity and Ecosystem Functioning

The elucidation of species diversity involved in soil and sediment-mediated ecosystem processes must be a high priority for global biodiversity efforts. We need a four step approach:

i) A world-wide synthesis on the status of knowledge of the "unseen" soil and sediment biodiversity and relationship to ecosystem processes.

ii) Systematists and ecologists, in an interdisciplinary approach, should examine the relationship between ecosystem functioning and biodiversity within or across domains in a series of international comparative experiments. Rigorous hypothesis testing is essential. The "Life in the Soil" experiments (http://www.nrel.colostate.edu/soil/lifeinthesoil.html) (37) which are underway internationally, have detailed criteria which should be considered as a basis for these subsurface experiments. Individual nations lack a critical mass of expertise for identifying the subsurface biota, and this effort will increase the numbers of experts and the opportunities for training and education. International experiments will build new cross-disciplinary linkages, and will produce economies of scale through our recommended use of existing sites of long-term research sites (Environmental Change Network in the UK, LTERs in the USA, Ecological Monitoring and Assessment Network in Canada), which already have a wealth of baseline data.

iii) Synthesis of information that is important to the connectivity between these domains. This effort will contribute on a global scale to the discovery of unique species, to knowledge of "hot spots" or habitats of high diversity, and the habitat range for species important in ecosystem processes. From this we will learn how species loss will affect ecosystem processes such as mineralization, and how human-driven changes impact the status of these ecosystems. This scientific information is necessary for management plans that consider linkages between ecosystems, such as agriculture, municipal water agencies and marine shipping harbors.

iv) Globally, increase the number of people trained in systematics and taxonomy, and other techniques that will aid identification of the species in soils and sediments.

RESEARCH PRIORITIES

An interdisciplinary approach to research should be encouraged between systematists, ecologists, biogeochemists, molecular biologists, physicists, modelers, soil scientists, biogeographers, hydrologists, and other scientists to provide information on:

- key taxa in ecosystem processes for each domain and across domains;
- loss of key species and how this loss affects the processes in which they participate;
- feedback mechanisms connecting above- and below-surface species and their functions;
- the natural history and interactions of the species, including trophic relationships and food preferences, to determine if functional group categories are adequate, and the extent of functional redundancy;
- species important for bioremediation of pollutants within and across domains;
- the identity of organisms that with disturbance, could adversely affect soil and sediment functioning;
- the role of species in global processes, such as atmospheric trace-gas production and consumption;
- ecophysiological adaptations of the key biota, important for determining which taxa are more at risk to disturbance, and how the dispersal of organisms occurs. Research is needed to determine which organisms become invasive, how these will affect ecosystem functioning, and to establish the economic contribution of soil and sediment biodiversity to global sustainability.

TRAINING PRIORITIES FOR SOIL AND SEDIMENTS

There is an urgent need for more systematic and taxonomic expertise on biodiversity within and across domains. Expertise should be developed globally, and particularly in countries where knowledge of the biota of soil and sediments is lacking. Resources must be generated for a data base that contains the geographic location and stage of career of existing taxonomists so that training of new students and postdocs for poorly known groups of soil and sediment biota can be properly focused. Training in novel methods, e.g. internet education, electronic transfer of images, satellite links, should be included.

Systematics and identification of biota should be organized through a biodiversity informatics approach to assure global access of information. This should be accompanied by development of user-friendly identification aids for key taxa, including electronic, on-line image libraries, which will facilitate global biodiversity assessments for subsurface environments.

Similar methods are lacking for sampling biota across the three domains, or even within a domain. Standardized protocols need to be developed for sampling different groups of organisms to facilitate inter-site comparisons. Other disciplines such as engineering, atmospheric sciences, medicine, and chemistry should be encouraged to develop and transfer techniques for exploring and discriminating life at the microscale in soils and sediments.

Resources are needed to support the preparation of a comprehensive manual for taxonomists and ecologists, combining new techniques with the older techniques that are still of use. This should be available in hard copy for developing nations and fieldwork, as well as on the world wide web.

POLICY

The taxa in soils and sediments perform vital functions for humans. Organisms in soils and sediments contribute to bioremediation of pollutants, soil fertility, cleansing of water, sustainable fisheries, and a productive agriculture. Research and synthesis that connects the organisms and ecosystem processes in soils and sediments is a new approach to land and water management. Benefits include increased options for sustainable land use and environmental management, with potential economic benefits to nearshore habitats, marine harbors, wetlands and soils.

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