Chapter 9: Terrestrial Systems

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EXECUTIVE SUMMARY

An assessment of what elements constitute terrestrial systems, our current state of knowledge of their spatial distribution and interactions, and how humans are impacting these systems lead us to the following statements:

(a) Important Facts
  (i) Terrestrial systems are being highly modified by additions and subtractions of system elements.
  (ii) Environmental stresses on terrestrial communities are increasing.
  (iii) The physical environment is changing faster than ever in historical times and to states that are unique in evolutionary history.

(b) Research Needs
  (i) Develop new methods to study whole ecosystem response to changing conditions at differing time and space scales.
  (ii) Develop techniques for restoring sustainable systems (restoration ecology).
  (iii) Develop the capacity (concepts, models, basic data, etc.) for predicting responses of terrestrial systems (species distribution, soil processes, etc.) to short-and long-term perturbations.

(c) Urgent Actions
  (i) Support major scientific initiatives directed toward understanding terrestrial system dynamics and predicting their response to change (e.g. International Geosphere–Biosphere Programme), and their sustainable use under increased population pressures (Sustainable Biosphere Initiative). Particularly important is the quantification of terrestrial carbon and nitrogen pools and fluxes and how modification of ecosystem structure alters these fluxes, and stemming the loss of the Earth's primary productive capacity.
  (ii) Identify and analyze current agro-ecosystems as to their inherent sustainability and their adaptability to climatic change.
  (iii) Identify and analyze environmentally critical areas (high expected impact of climate change, unusual diversity, inherent fragility, high population impact).
  (iv) Develop a global digital data base of terrestrial system components (landforms, soils, bioclimates, biomes, land use, etc.) in a compatible and readily accessible form and a program for monitoring their changing states as part of a global observing system.

1. INTRODUCTION

We as humans depend on the atmosphere, the oceans, and the land to maintain the environment in which we live. It is the land, however, that provides us with most of the food, fuel, fibre, and shelter and with 80% of the global biodiversity. Here we examine the biotic and certain physical resources that the land provides and how these resources are structured and how they are changing. We examine how well we know the components that make up our natural realm since fundamental to any understanding of the functioning or management of natural systems is knowledge of the nature of the component pieces. We show that in fact we have rather poor information on the basic building blocks of the terrestrial system. We do this in order to assess what the gaps are in our understanding of terrestrial systems, to develop a plan for eliminating these deficiencies (research needs), and to indicate priority actions.

Soil, water, and sunlight are the fundamental resources driving the productivity of the land surface. Soils affect human beings by providing the medium by which essentially all plants obtain their nutrients and water. Soils, interacting with plant cover, serve as the interface for minerals, water, and gases between the land, the atmosphere, and the oceans. They affect humans indirectly by emitting and absorbing greenhouse gases, by serving as a major reservoir and controller of the rates of movement of elements, and as a major reservoir and pump for water. Thus for managing the biosphere we need to know the character and distribution of soils and the modifications that they are undergoing due to global change, including the direct effects of human activity.

Human beings have had a major impact on the productive potential of the soil resource. The pathway from a natural ecosystem to, where possible, a robust and sustainable agro-ecosystem is difficult. Humankind has often not found this pathway, with serious degradation of the soil and land resources as a consequence. This is exemplified in the recent United Nations Environment Programme/International Soil Reference and Information Center (UNEP/ISRIC) assessment of global soil degradation (Oldeman *et al.*, 1990), as discussed in detail in Chapter 2. That study refers to the various forms of degradation that have occurred over the past 50 years or so. One should add the amounts of originally human-induced but now arrested soil degradation that occurred during the periods of colonial expansion and the agricultural occupation of North America and Australia (100–200 years ago), as well as those lands that were degraded during the times of early Mediterranean and Asian civilizations (2000–3000 years ago).

It may be reiterated that there is a clear and urgent need to further quantify and to monitor the extent, degree and the causes of the various types of human-induced soil and land degradation that are occurring globally, per region and per country; to translate this information into socio-economic and ecologic terms, and to develop practical programs to control and reverse degradation trends at local levels. The International Scheme for the Conservation and Rehabilitation of African Lands (ISCRAL) as proposed by the Food and Agricultural Organization (FAO, 1990b) may constitute a useful mechanism for such programs.

2. THE DYNAMICS OF SOILS AND LANDFORMS

The attributes of the various soils in the world can be grouped by "response times" or speed of adjustment to changing environmental conditions (Arnold, Szabolcs, and Targulian, 1990; Scharpenseel, Schomaker, and Ayoub, 1990). Response times range from rapid monthly changes to changes that are noticeable only over millennia. Many of the soil attributes that affect plant growth, the hydrological cycle and surface energy balance (transfer of sensible heat, albedo) can change within a few years. The respective response times of landforms, versus soils per se, to environmental change need to be quantified.

The moisture, temperature, nutrient/salts and organic matter dynamics of soils are easily changed. In the time perspective of global change, say 50–100 years, these changes in these parameters would not normally affect the major pedological types. There are, however, some fragile or "threshold" soils where a slight change in one of the soil forming factors – viz., temperature, rainfall, surface hydrological conditions, and direct human influence — would induce a major change in the pathway of soil formation, such as ferralitization vs. podsolization, illuviation vs. homogenization, salinization vs. leaching. Sombroek (1990a) gives some examples for the tropical and subtropical regions, where a transition to a different genetic soil group may take place within a time span of only tens of years, upon only slight changes of prevailing climatic conditions or somewhat higher frequency of extreme weather conditions. For the boreal and the subpolar regions, where global change impacts may be large, Goryachkin and Targulian (1990) predict substantial changes in soil-forming processes and shifts in zonal soil geographic belts.

Slight changes in climatic conditions may cause a substantial change in the rate of emission or sequestering of greenhouse gases; such as methane and nitrous oxides, which are predominantly of terrestrial biotic origin (see also the discussion on global biogeochemical cycles in Chapter 6). At present there is insufficient information to ascertain the factors controlling flux changes. Many point measurements – chosen in relation to their representativeness for major land units – are necessary to understand the dynamics of these fluxes, and indeed several research programs have started to do so (an example is the Terrestrial Initiative in Global Environmental Research (TIGER) Programme of the Natural Environmental Research Council (NERC), UK. The relatively few actual measurements of the moisture and temperature conditions in soil profiles, and their variation over the seasons and years, need to be extended and systematically compared and related to fluxes of soil-related methane, nitrous oxide and sulfur.

Special attention needs to be given to the quantity, quality and dynamics of the organic matter of the world's soils. This not only because organic matter has a large bearing on the conditions of the soils in relation to plant growth, (micro)faunal activity, and human life-support systems, but also because it represents a major carbon storage pool. Soil respiration represents about 25% of the total annual release of CO_2 to the atmosphere. The amount of carbon stored in the world soils, as fresh organic matter, stable humus or charcoal is supposedly two to three times higher than the carbon stored in the natural vegetation and in standing crops (Houghton, Jenkins, and Ephraums, 1990). Where the plant biomass is very luxuriant such as in tropical rain forests there is still as much carbon in the soil as above ground; the soils of grasslands and farmland store up to ten times as much carbon as the plants growing on them (Goudriaan, 1990). Most of this soil carbon is not fixed, and thereby an important link in the global carbon cycle; it may enter directly into the atmosphere by combustion or microbial transformations, be transported overland by wind and water erosion and then be stored in sediments of floodplains and sea or lake bottoms; it may also move down into the soil profile and be transformed into near permanent occlusions with iron and aluminium compounds, or be instrumental in the dissolution of rock carbonate and the re-allocation of the products in the soil profile or downslope.

Soils of present or former aridic regions contain carbon locked up in the form of pedogenic carbonates ("calcrete", "petrocalcic horizons"). This inorganic soil carbon pool is estimated to be as large as the stock of organic carbon in the world's soils, but has a much longer residence time.

Further quantification of the global stock of carbon in soils (topsoils and subsoils) is needed, including potential sources as well as sinks of soil carbon. We need to know how present levels of surface organic matter, and of soil micro-biomass in the various biomes and agro-ecosystems, influence the annual input of organic matter in the soil; what is the residence time of organic matter of the various soils of the world; which compounds are the most stable and at which depth; which are the microbial processes that break down soil organic matter, and how they influence the release or sequestering of greenhouse gases; and how can the dynamics of soil organic matter be modeled?

Close co-operation is needed on methodologies, site selection, and the extrapolation of studies in order to derive an improved geo-referenced data base of the world's soil organic matter status. There are national initiatives either in-country or in a network of research sites elsewhere, such as TIGER and the Stimulation Programme for Research in Tropical Forest Areas (TROPENBOS, Holland); regional programs in developing countries on soil organic matter and soil fertility such as FAO's Integrated Plant Nutrition Systems (IPNS), and those of the International Board for Soil Research and Management (IBSRAM), the International Council for Research in Agroforestry (ICRAF), the International Fertilizer Development Center (FDC) and the Tropical Soil Biology and Fertility (TSBF); soil geography-related programs such as those of FAO's World Soil Resources Office, ISRIC and the Soil Conservation Service (US–SCS). Mechanisms need to be developed to integrate these important individual efforts.

About 70% of the atmospheric methane (CH_4) comes from terrestrial sources such as wetland rice fields, marshes and swamps, ruminants (cattle) and termites. Neither the processes of microbial methanogenesis in the various soils of the world and their cover, nor those of methane oxidation in soils are as yet well understood. Indications are that the drainage of wetlands and increased nitrogen inputs are decreasing the capacity of soils to consume methane (Melillo *et al.*, 1989). Early estimates of methane production by ruminants need to be quantified over the various rangelands and pasture lands. Termites and other soil fauna as producers of methane are also poorly quantified over the different biomes.

The budget for the nitrous oxide (N_2O) exchange between ecosystems and the atmosphere has many uncertainties. At least 90% of the emissions are provisionally estimated to be of terrestrial biotic origin — either from tropical rain forests, from heavily fertilized arable lands and grasslands, or from subtropical and topical savanna soils. Soil microbiological activity forms the basis of nitrification, denitrification and diazotrophic processes that result in the production of nitrous oxides, but actual measurements on N_2O emissions on representative sites are very few.

The surface attributes of soils – color, crusting vs. porosity, degree of plant cover – influence the transfer of sensible heat and the reflection of sunlight (albedo). Soils are, moreover, a major determinant of the fluxes of water vapor, a major greenhouse gas, and a number of soil attributes influence the runoff, storage and transmittance of water, and thereby the world hydrological cycle.

In order to better quantify and understand the processes of terrestrial sources and sinks of greenhouse gases, there is a need for more measurements, at representative sites, of soil moisture and soil temperature conditions and dynamics; of the soil microbiological composition and activity, and of the quantity and dynamics of soil organic matter. Such measurements should be performed as a part of integrated or interdisciplinary research on the hydrological and soil chemical and physical effects of conversion of natural vegetation into human use (tropical forest clearing for shifting cultivation, or permanent agriculture such as perennials, grasslands or exotic trees; shrub savanna conversion into cropland by high-input soil management such as in the cerrado area of Brazil; tundra and taiga vegetation conversion into large-scale mechanized annual cropping, etc.). This research should be done with a rigorous experimental designs that are processes-oriented, on transects, paired sites and experimental catchments as is being proposed by the International Geosphere-Biosphere Programme - Global Change and Terrestrial Ecosystems (IGBP GCTE) Programme.

3. THE GLOBAL SOIL DATABASE - WHAT DO WE HAVE?

There is a confusingly large variation in soil classification systems that are utilized at national levels. There is, however, an overview inventory of the world's soil resources at a scale of 1:5 million (FAO, 1971–1978) prepared under the auspices of FAO and UNESCO. The map is mainly a compilation of a multitude of national soil maps available at the time, of differing detail and accuracy. The map utilizes 106 units based on "diagnostic (soil) horizons" and non-horizon related "diagnostic properties". The topsoil textural class of the predominant soil unit is indicated on the map, as is the average slope of the mapping unit as a whole. Areas of "non-soil" are indicated as miscellaneous land units: dunes or shifting sands, glaciers and snow caps, salt flats, rock debris, and desert detritus. Boundaries of permafrost or intermittent permafrost are indicated separately, but no other soil moisture and soil temperature characteristics are used, except implicitly in hydromorphic and desert soils. To estimate moisture and temperature characteristics, FAO devised special maps on "agro-ecologic zoning" (FAO, 1978–1981) which can be used as overlays. These zones are in fact agro-climatic regions, based on prevailing climatic conditions, and expressed in annual "length-of-growing periods". The above soil and agro-climatic data have been combined in an assessment of the population carrying capacity per country, at three different levels of land management and external inputs (FAO/UNFPA/IIASA, 1982).

There is a need to update the global soils map at the same scale of 1:5 million and to work toward a more detailed presentation that would be in digital form and compatible with biome mapping as discussed below. Recently a systematic revision of the world-level FAO/UNESCO map legend was completed (FAO, 1988), for use at the original 1:5 million scale. Digitizing of all 1:5 million map sheets, either by polygon vectoring or by gridding, has been undertaken by several organizations including UNEP-GRID in Geneva, but quantitative analysis of the polygon's composition will yield much more information.

Most existing soil classification systems are pedogenetically oriented, with varying degree of quantification of the characteristics of the soil ("morphometrics"). They take the subsurface and subsoil features as starting point, because of their supposedly more stable character than the surface and topsoil features. The topsoil features, and the associated land cover characteristics, are however important in the study of natural ecosystems and the atmospheric greenhouse functioning, and thus must be accommodated in soil mapping efforts.

There is, with the advance of modeling techniques, a growing need for both local and global geo-referenced information on individual attributes of soils and terrain units for use in the assessment of agricultural production potential, for identifying alternative sustainable uses of the land including forest use and silviculture, for identifying soil pollutant buffering capacity, and for global change studies. The kinds of information needed are: surface roughness, surface sealing/crusting, surface color in relation to reflectance; amount, type, stability and vertical distribution of organic matter; soil biologic activity; surface runoff, soil moisture storage and transmittal properties; soil temperature régimes, drainage and flooding conditions; soil nutrient status and storage capacity; but also relatively simple attributes such as bulk density per layer horizon. The latter are also needed to express soil characteristics and properties, as commonly given on a weight basis, in units-of-volume as used by modelers of climate and plant growth.

Soils do, however, not stand alone on the surface of the Earth; they are closely related to landforms: mountains, hills, plateaus, terraces, undulating uplands, plains, bottomlands, etc. Within the broad context of geological materials, climatic conditions and geomorphologic history, each facet of the present-day landforms has its own soil and associated hydrological régime. Soil formation has also a significant landscape-lateral element (Ruellan, 1985). Experienced soil geographers are aware of these landform–soil relationships and use it to delineate the spatial patterns, both in detail and scaling to large areas – often with remote sensing imagery as auxiliary tools.

No program has, however, been developed at the continental or global level to combine the nature and distribution of landforms (and their surficial geologic materials and hydrological régimes) with soils in a single integrated quantitative database. The only effort, in a generalized and therefore rather qualitative way, is a recent 1:15 million scale wall chart on the "Present Status of Landscapes of the World" prepared by the Institute of Geography of Moscow State University. The lack of a systematic landform–soils inventory at global level is partly due to the absence of an accepted multi-categorical hierarchical system of describing and distinguishing landforms. Nevertheless, a degree of consensus exists on "orders of land relief": primary continental subdivisions; physiographic provinces; relief sections; repetitive landscape patterns; relief facets; relief sites. Bridges (1991) in a recent book on the main landforms per continent, applies such orders of relief.

The technique of Digital Terrain elevation Modeling (DTM), translating topographic map features and remotely sensed altitudinal information into a digital form suitable for computer analysis, is now in an advanced stage of development and can be very helpful in generating global landform information.

Hydrological features of the landscape also need to be considered in an inventory and evaluation of soils and landforms. Hydrological attributes of the land are: the degree of surface runoff in relation to slope, land cover and surface crusting or sealing; infiltration, storage, percolation of water, and horizontal hydraulic conductivity; phreatic levels; spring line and seepage situations; areas with saline/sodic ground-water subject to rise; and the

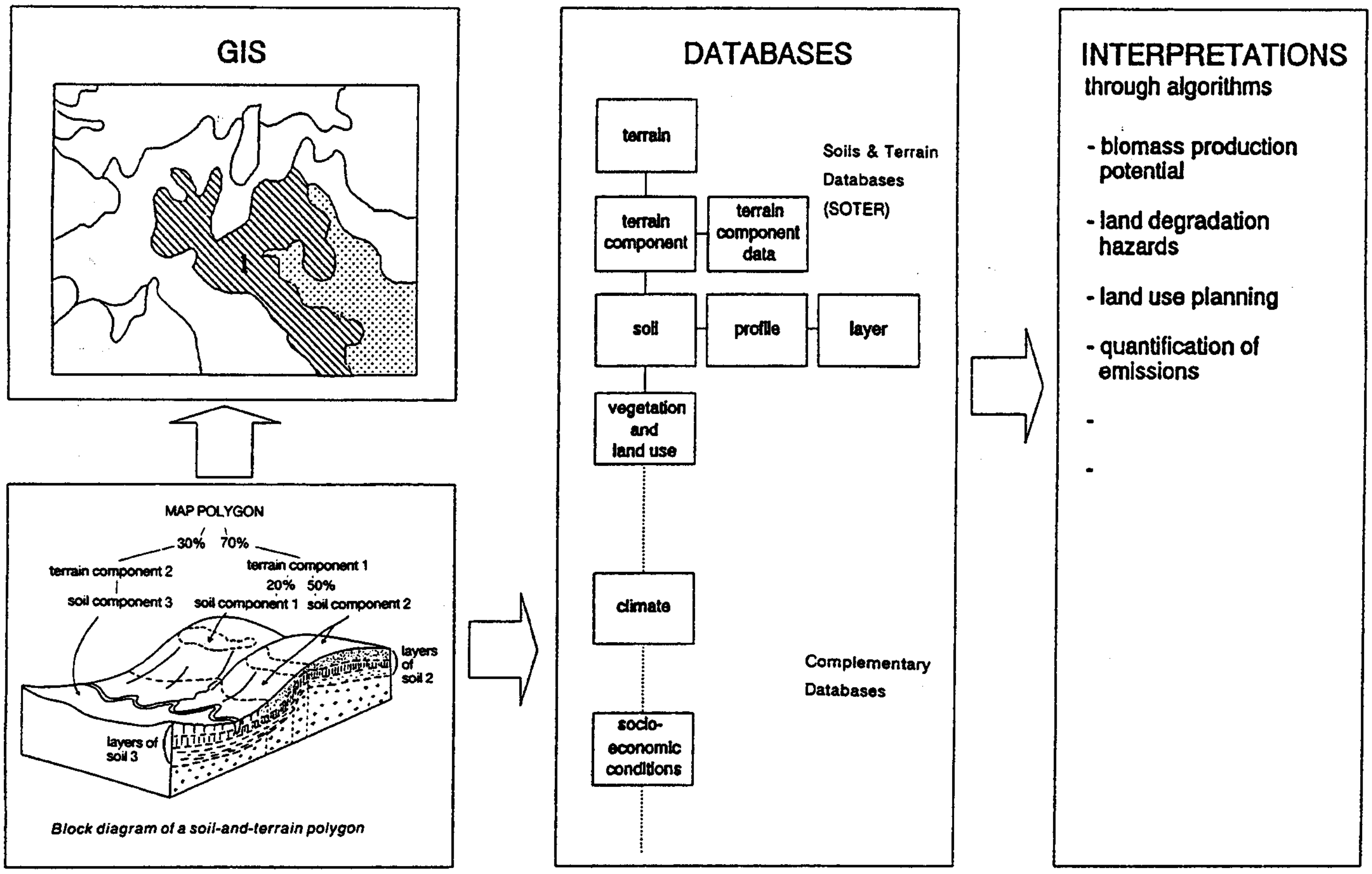


Figure 1: Structure of a computerized land resource information system.

characteristics of flooding and rainwater submergence régimes of low terraces, bottomlands, floodplains and deltas. For the latter, a classification scheme is needed, encompassing length, depth, velocity and regularity of flooding or overland flow within and outside the temperature determined annual plant growing period; as well as the sediment load and the chemical characteristics of the waters, upon which a systematic global inventory can be undertaken (see Aselmann and Crutzen, 1989 for a first effort in relation to methane emissions). International action plans on better water use for sustainable agricultural development, such as the International Action Programme on Water and Sustainable Agricultural Development (WASAD) of FAO (1990c) need to utilize both global and local geo-referenced data bases on hydrological conditions, as described above, linked to associated natural resources and to diffuse or point sources of pollution (see Chapter 10 for detailed discussion of the world's freshwater resource).

A Working Group of the International Society of Soil Science (ISSS) has developed a proposal for a world soils and terrain digital database at an average scale of 1:1 million, acronymed SOTER (World Soils and Terrain Digital Database), to be completed in a 10 to 20 year period. A number of pilot and priority areas were identified, and UNEP provided funding to the International Soil Reference and Information Center in Wageningen (ISRIC) for a first pilot area in South America, viz. adjoining portions of Argentina, Brazil and Uruguay. Since then a procedures manual for map and database compilation has been prepared (van Engelen and Pulles, 1991) and training at the national level has started. A database structure using a relational data base management system was developed, and an international panel assessed various Geographic Information Systems (GIS) suitable for SOTER.

The essence of the approach is to screen all existing data in an area, whether or not registered on official soil and landform maps, and where necessary to complement these with remote sensing information. The data are then rearranged for the database, going from landform and terrain component features to soil layer attributes (Fig. 1). For all soil attributes, quantitative data or class limits are used. Those attributes that cannot yet reliably be quantified from available data, or from limited additional field and laboratory measurements, are flagged as such, for amendment at a later stage. Subfiles give the details of very representative individual soil profiles (International Soil Information System, ISIS) and will complete the information. Algorithms and computer programs are being developed for the use of such a comprehensive database for a number of purposes, for instance the risk assessment of several forms of soil degradation.

The SOTER initiative has already obtained the conceptual support of UN organizations such as FAO and

UNEP; the Consultative Group of International Agricultural Research Centers such as the International Service for National Agricultural Research (ISNAR); the IGBP Data and Information Systems unit (DIS); and many national institutions on land resources assessment. Priority areas to be entered in the data base in advanced state of planning are: Central America, parts of West Africa and Eastern Africa, the Danube catchment area, central USSR, and South-eastern China. The sequence of other areas can be related to the needs of IGBP core programs, in particular with respect to the envisaged 100 land system research sites of the Global Change and Terrestrial Ecosystems (GCTE) and the planned Regional Research Centers of the Global Change System for Analysis, Research and Training (START).

In summary, in spite of the vital link between soils and human welfare we do not have an adequate information base from which to evaluate the soil resources available and how they are changing. Our global soil database, as for most natural resources, is uneven and poor in quality. We call here for an integrated effort to remedy this through a concerted program. This program would provide a uniform, readily accessible database of soils and terrains that would be compatible with comparable databases for climate, hydrology, vegetation, and current agricultural land use. Such a database would be a vital tool for defining the interaction among these realms in developing global Earth System models as well as providing information for policies and strategies relating to the management of regional and global soil resources. This database of soils would involve improving the global soils resources inventory utilizing modern techniques. It would further involve studies of soil genesis as well as a global assessment of soil productivity and degradation. Periodic updating of the system will allow monitoring of the changes that will occur as a consequence of expected climatic change and population increase.

4. BIOCLIMATIC RESOURCES

Data bases on landforms and soils information are useful in assessing the biotic functions of the land only in combination with information on local bioclimatic conditions; amounts and temporal distribution of precipitation, temperature (means and extremes), solar inputs, evapotranspiration, wind speeds, and other biologically sensitive climatic parameters.

Although we now have techniques for modeling the world's climates in response to changing forcing functions this information is not yet sufficiently regionally specific to give us spatially detailed bioclimatic information (Dickinson *et al.*, 1989).

Because of its inability to move in short time-scales, the natural vegetation integrates the overall effects of individual climatic parameters acting on plant growth. It is therefore no surprise that most of the traditional climatic classifications at a global level have used the occurrence of natural vegetation types to identify class limits for the various climatic zones. Since, in addition to light and nutrients, plant growth requires moisture and warmth in varying amounts, such limits have been related mainly to hydric and thermic régimes.

There are a number of classifications of the world's bioclimates available including Köppen, (1931) that is based on thermal and hydric criteria and Thornthwaite, (1931) which utilizes precipitation and thermal efficiency indices. The Holdridge (1959) system, which has been generalized to a global level (Leemans, 1989), takes into account biotemperature (the sum of monthly temperatures in excess of freezing and averaged over the years) and the ratio of annual potential evapotranspiration over annual precipitation. Also available are continental maps on calculated soil moisture and temperature régimes for crop growth suitability of the US Soil Taxonomy system (Van Wambeke, 1981, 1982, 1985).

Even using the same climatic station databases, such as those applying the World Meteorological Organization's (WMO) Climate Data Management System (CLICOM), the results of these classification approaches are different because of the different combinations of the criteria utilized. Their simplicity is attractive for modeling purposes, but not necessarily adequate. At regional and local levels more climatic detail needs to be taken into account. The bioclimatic scheme developed by Papadakis (1961) can be considered to be more complete for application at a regional level, because it includes various essential features such as winter severity, summer heat, duration of the frost-free season, and duration, intensity and annual position of the humid and dry seasons. The concepts of Papadakis were taken up and elaborated by FAO for its agro-ecological zones project (AEZ) for developing countries, for application both at continental and at country level, and with food crop suitability assessment as its main aim. The major agro-climates in the AEZ approach are delineated on the basis of the mean daily or monthly temperatures during the growing period. Moisture régimes are quantified through the concept of reference length-of-growing period defined as the duration, in consecutive days, when moisture supply from precipitation and soil moisture storage permits crop growth. In the regional climatic inventories 20 reference length-of-growing period zones are mapped with 30-day intervals, for the whole of Africa, Asia and Latin America, and interpreted for all important food crops. Country-level detailed zoning has been carried out for Kenya, Bangladesh and China, allowing the definition of more specific land use options. The AEZ approach of FAO has not yet been systematically extended to temperate and cool regions, although examples are available for Canada, northern China and western Australia.

It may be evident that a more complete and more uniform effort for bioclimatic zoning at both global and regional or country levels is called for. The availability of world climatic data in digital form now makes it possible to tailor studies on climate–soils–vegetation/land use interactions to a much more specific level. Detailing of the (agro)-ecological zoning approach of FAO, and its extension to temperate and cold regions, may be the quickest way to accomplish this. The results will also offer reference material for the spatial and temporal dynamics of isolines of global biomass production potential as inferred from repetitive remote sensing imagery provided by NOAA-AVHRR satellite (the National Oceanic and Atmospheric Administration Agency – Advanced Very High Resolution Radiometer), as discussed below.

5. BIOTA

5.1 Biotic diversity – numbers and kinds

Surprisingly, in spite of systematics being one of the oldest natural science disciplines, we have an inadequate assessment of the biotic richness of the Earth. What we do know is uneven across groups. It is estimated that we have described less than 15% of the world's estimated over 1,000,000 microorganisms (di Castri and Younès, 1990) whereas we probably know over 99% of the world's bird species, which number somewhere about 9000 species (Clements, 1978). Estimates, which are only that, of the number of species on Earth are in the realm of ten million (May, 1988) (see Chapter 11). The rapid destruction of tropical forests (as high as 200,000 km^2 y^{-1}), where biotic richness is centered, is threatening the principal storehouse of the world's biodiversity. Elsewhere in this volume these losses, and the social-economic drivers of this devastation are treated in detail. Here we focus not on diversity as an issue per se, or as a human resource, but rather on the consequences of species losses to the functioning of ecosystems. Biotic diversity encompasses not only the numbers of species but also numbers within populations. Needless to say the loss of one half of the elephants of Africa in a single decade (Matthiessen, 1991) or of over 80% of the forests of the Ivory Coast in the last 35 years (Myers, 1990) is an enormous biotic impoverishment of the biosphere. Also being reduced or modified, as discussed below, are other components of biodiversity: races within species, varieties of habitats as well as landscapes.

The world's species richness can be collapsed considerably when considered functionally. At the most general level, for example, all organisms can be categorized as either producers, consumers, or decomposers. Finer level categorizations can be utilized for examining ecosystem function such as nitrogen fixers, photosynthetic pathway, particular energy source utilization, pollinator, etc. Similarly, organisms can be grouped based on structural traits related to size and shape, such as trees, shrubs, and herbs for plants, or at finer structural levels, such as canopy or understory, evergreen or deciduous, etc. As one moves from the grossest to the finest categories the numbers of species involved in each decline. This means that at the higher levels of categorization there is a great amount of apparent replication of function. We do not know whether this replication of function represents redundancy or whether critical functional roles are assumed by the various components of a functional group under normal environmental fluctuations on time scales of decades to centuries.

It is important to resolve these issues. For example, in order to model the Earth's global metabolism, or its altered biotic structure with changing climate, we must categorize the Earth's biota into meaningful functional groups. Equally urgent is assessing the impact of losses of biodiversity, in all its dimensions on Earth System functioning. The International Geosphere-Biosphere Programme (IGBP) and the Scientific Committee on Problems of the Environment (SCOPE) in conjunction with the International Union of Biological Sciences (IUBS) are presently addressing these concerns.

Organisms interact not only with their physical environment but also with their biotic milieu. This is an important consideration in viewing the impact of species additions or deletions to ecosystems as is noted below.

6. BIOTIC INTERACTIONS

The biota of any region display varying degrees of interdependencies, the most basic being energy related as noted above. Food webs describe the energy dependency in an ecosystem. Any system, although it may contain thousands of species, will be tied together by these basic relationships. At a finer level though complex linkages may be seen. Specific energy-source interactions between species are called links. The average number of linkages in a given energy chain is about four with the maximum being about ten (Cohen, 1990). Although many species in the foodweb will be generalists, there are specialists that serve to multiply the numbers of chains in any given food web.

In addition to energy transfer interactions, there are interactions that are involved in the transfer of genetic information. These mostly relate to pollination systems – the transfer of pollen among flowering plants through an animal vector. Of the approximately 250,000 species of vascular plants a large percentage are pollinated by animal vectors, preponderantly insects, many of which are generalists and pollinate many different kinds of plants.

In any given community there will also be a wide range of biotic interactions that may be classified as mutualistic – something is given for something gained. Most plants (75–80%) (Hawksworth, 1991), for example, harbor fungi associated with their roots (mycorrhizal fungi) that derive energy from their host while giving in return nutrients. Again, while many of these fungal species are generalists, indiscriminately affecting plants irrespective of their taxonomic status, there are some that are species specific.

Another vital mutualistic relation is between nitrogen-fixing bacteria and their hosts, generally leguminous plants. These interactions are crucial to ecosystem functioning since they provide the preponderant pathway for atmospheric nitrogen to be transferred to the soil. Strains of the nitrogen-fixing bacterium *Rhizobium*, tend to have somewhat narrow host specificities, in some cases extremely so. Isolates of *Rhizobium leguminosarum*, for example, may infect some pea (*Pisum sativum*) cultivars, but not others (Young and Johnston, 1989)

Thus in the categorizations of biotic capital of our world we can view species as independent entities, and additionally as components of a web of interactions. These webs have both temporal and spatial dimensions. Migrating birds may have vast geographic ranges and be involved in numerous species, and even different ecosystem interactions, whereas some mutualistic relations between a plant root and a fungus can be species specific and at a cellular level.

The terrestrial system can thus be viewed as a tapestry of many species, woven into complex patterns representing biotic interactions found in the living landscape. These patterns fall into assemblages of organisms and their interactions that are called ecosystems, or in a geographic context, biomes. We now view what we know of these biomes, or landscape units, and subsequently how humans are affecting them by modifying the biotic interactions as well as even the species present.

7. BIOMES – THE GREAT MULTIPLIERS

In the simplest form the biotic communities of the world have been described by the dominance of the principal plant growth form, e.g. grassland, shrubland, or forest, either evergreen or deciduous. A next level of categorization divides these basic forms among various generalized climatic types, such as temperate or tropical grasslands, Mediterranean or desert scrublands, and so forth. These units have been further subdivided by the occurrence in a particular biogeographic province, which begins to capture the species peculiarities of the biotic community since these are generally few common species among biogeographic provinces. Categorizations below this level become increasingly localized and species dependent. Knowledge of the distribution and nature of the large-scale units is important for understanding global metabolism, for example, and the finer categories for localized land management.

We have a fairly precise knowledge of the broad limits of the higher units of biome categorization on Earth and have had for a long time. This information is now available in digital form for 1 degree latitude grid sizes (Matthews, 1983). Also available, in digital form, for 1/2 degree grid units is the theoretical distribution of biomes based on bioclimatic constraints of vegetation types (Emanuel, Shugart, and Stevenson, 1985) as well as world ecosystem complexes (Olson, Watts, and Allison, 1983). There are currently efforts to bring these and climate and soils databases together into functional models for understanding vegetation dynamics of the globe (Prentice *et al.*, 1989). It is essential to do this in order to achieve the capability for predicting how biomes will respond to climate change as well as how climate change will affect feedbacks of terrestrial systems to the atmosphere.

The above information on geographic extent of particular biome types is used as multipliers for point measurements of system function, such as primary productivity, in order to assess, for example, global fluxes of carbon. Measurements of primary production are generally only made on tens of square meters of land surface and then multiplied by 10^6 km^2 to give global fluxes for various biome types. Obviously small errors in areal process measurements can have large effects on global estimates of fluxes. Estimates of the global living biomass have gone from over 1000 billion tonnes to about half this amount over several decades due primarily to the use of average rather than extreme values of point measurements of standing biomass (Olson *et al.*, 1983) but also due to real loss of living carbon stores. Thus there is a need to provide better estimates on both sides of this equation – the process and the biome extent.

The data sets referred to above have been assembled from many different sources and are not of high resolution. Resources, both financial and human, are not adequate to evaluate rapidly the extent as well as the nature of the Earth's biome types. We do, however, now have the capability of utilizing satellite imagery for obtaining both functional and structural information on vegetation. This information is global in extent and is gathered at repeated time intervals giving an assessment of the changing properties of the global terrestrial system. The AVHRR on the NOAA satellite collects information on the spectral properties of the Earth's surface. This information is being utilized to obtain measures of the absorption of photosynthetically active radiation, and hence photosynthesis (Sellers, 1985). Temporal measures give seasonally changing productivity of the Earth's vegetation types and bioclimate as discussed earlier. Information can also be derived on the exchange of water vapor of the Earth's various vegetation types.

One km^2 resolution AVHRR images compiled at monthly intervals are now available for a number of places on the globe. An effort to implement a global mapping project should be made at a centralized facility, as is being proposed by the IGBP. This information, which would be accessible in digital form, should be made available to users via mass storage media. To complement these measurements data should be assembled at the same resolution for soils, land cover and land use change, and topography. The 1 km^2 resolution represents probably the finest detail that is feasible at this time for global studies. This resolution involves 1.49×10^8 grid cells and a formidable challenge for the remote sensing community; however, this number is only a fraction of the number of nucleotides being sequenced in the human genome project.

Of course, neither the relatively fine global resolution of the 1 km^2 satellite measurements nor the large-scale ground based measurements of landscape types and changes will tell us all we need to know about the functioning and alterations of terrestrial systems. With the resources and time that are available there needs to be intensive attention given to in-depth studies, and protection schemes evolved, for particularly sensitive and critical ecosystem types. For example, (Myers, 1990) has identified 18 global hot-spots in tropical and Mediterranean climatic areas that encompass only 0.5% of the Earth's land surface but yet which contain 20% of the Earth's plant species. Habitats in all of these areas are threatened by destruction. Efforts need to be made to identify and analyze regions of high fragility and that are particularly sensitive to climate change and to a growing human population. The International Geographic Union (IGU) has launched a program to identify and assess such critical environmental zones. Looking at soils, landforms, hydrological and bioclimatic conditions in conjunction, on the basis of quantified geographic databases of sufficient detail (resolutions of 1–10 km), one can identify, delineate and analyze environmentally critical areas. Some already obvious examples of areas that are particularly sensitive to human-induced changes in land cover, and/or to climatic change are:

(a) mountain slopes in tropical areas, especially those covered with soft volcanic materials (land- and mudslides);
(b) floodplains and low terraces of river-catchments that are subject to deforestation in their upper reaches (flashflooding; salinization under aridic conditions; white sand podzolization or laterite/plinthite formation and hardening, in humid tropical regions);
(c) wetlands, delta's and coastal lowlands with high population pressure (salinization, acid sulphate soil formation, transformation of peat and mangrove areas);
(d) upland areas of hitherto stabilized dunes and cover sands in desert fringe areas (wind and water erosion);
(e) hummocky terrains in permafrost fringe areas (solifluction processes; loss of soil organic matter);
(f) areas with sandy soils in regions with high degree of pollution by chemical compounds and heavy metals, especially when acidification processes are active (chemical-time-bomb hazards).

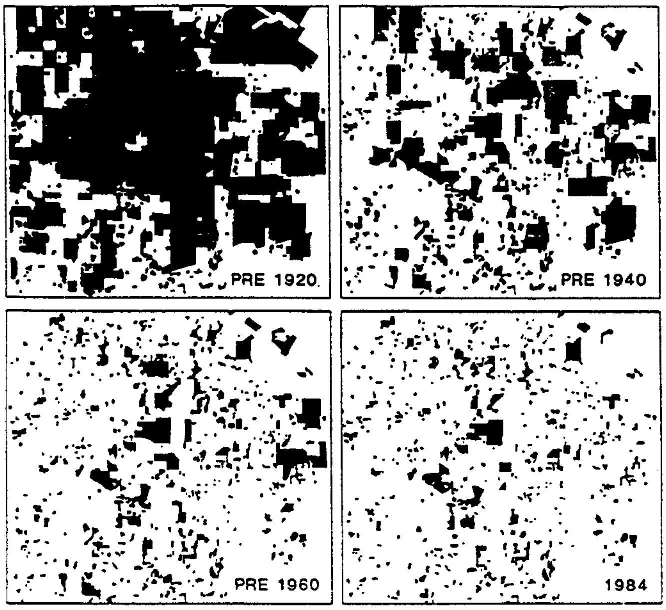
8. SYSTEM PROCESSES

Knowledge of the global extent of the Earth's terrestrial biomes provides, as stated, the multipliers for describing the storage and fluxes of energy, minerals, and water at regional and global dimensions. The terrestrial biota serve as regulators and pumps of these stores and fluxes. Although the distribution and structure of the Earth's biota is controlled by the environment, at the same time the biota has a major influence on environmental, features through ecosystem feedbacks. For example, vegetation structure and water use influences the transfer of energy and mass, directly influencing the physical climate system. Deforested areas will have a different influence on local climate than forested zones. In addition, the biota influences atmospheric properties through the direct emissions of gases that in turn alter atmospheric radiative properties and hence influence climate (Mooney *et al.*, 1987).

In addition to the coupling between the land biota and the atmosphere there are many coupled processes between land and the water. The high productivity of coastal marsh systems is fed by the nutrients moving in from upland systems. The coupled land and water systems have been one of the most impacted on the Earth by human activities, primarily through water diversions or land fill. In addition to land–water and land–air interactions, there are important linkages among various landscape units. An extreme case may be the fertilization of Amazonian forests by minerals transported by air from Africa.

The past few years has seen the active development of a new science, Earth system science, as exemplified through the International Geosphere–Biosphere Programme, that is attempting to quantify these linkages between the functioning of the terrestrial system with that of the atmosphere and ocean, through biogeochemistry and climate systems. This effort has shown, for example, the close ties between climate and plant water balance as noted above. It has further shown how altering the vegetative cover of the Earth has also changed the CO_2 content of the atmosphere.

Thus far we have viewed briefly the Earth's biotic building blocks and how they interact and function together as large Earth-system units. We now turn to how



KELLERBERRIN STUDY AREA 1600km^2
UNCLEARED LAND

Figure 2: Fragmentation of a western Australia landscape. From (Saunders, Hobbs, and Arnold, in press). Such fragmentation alters the radiative, water and nutrient fluxes across the landscapes as well as the characteristics of the residual populations in the residual natural "islands" (Saunders, Hobbs, and Margules, 1991).

these units are being stressed and restructured by human activities.

8.1 Modification of Biotic Complexity of Natural Systems

8.1.1 Breaking the links – Humans as editors

Superimposed upon the natural geographic patterns of biodiversity is localized biotic variability due to disturbance and microsite characteristics. Another driver of pattern is human action, either directly, or indirectly. In most parts of the world we are seeing losses of species, losses of genetic variability within a species, dramatic reductions in the population sizes of certain organisms, and a reconfiguration of landscapes (Figs. 2 and 3). In short we are seeing a simplification of the Earth's biotic richness by most measures. At the same time there are certain activities, driven by humans, that are increasing diversity of certain components of the Earth. The diversity of natural primeval landscapes was driven by local variability in substrates (e.g. riparian corridors) and natural disturbance régimes. Human activity, at low levels, increased the landscape variability by increasing local disturbances and creating biotic-rich edges. For example, the human-influenced Mediterranean landscapes have gone from being rather simple in diversity, to ones which were quite rich under early human development, to ones that are becoming simplified again, but now due to land degradation related to high population usage. In short, humans are acting as editors to terrestrial systems – they have added and deleted elements. We are modifying the overall structure of nature without, however, a comprehensive understanding of the consequences of these modifications.

Accompanying the increase in human activity was first the evolution of new races of organisms that could co-occur with humans (various weedy species) and as well as the domestication of organisms. As land use intensified and human commerce became intercontinental species of organism from one biogeographic region were moved to another, both purposefully and accidently. The disturbed landscapes of the world, which are ever increasing in extent, have become the habitat for a rather small number of highly successful invaders. Thus, although, a local biota may be enriched by the addition of these newcomers, the landscape has become depauperized since the population sizes of the endemics have often become greatly reduced. The intensification of agriculture has also resulted in the biotic impoverishment of regions since most often local crops are rather uniform genetically.

8.1.2 The Consequences of biotic alteration

We have a multifaceted problem. First, we have inadequate information of our biotic capital, as noted earlier, at virtually any level, and particularly for tropical regions. Secondly, we do not really have any good quantitative measures of how the Earth's biotic assemblages are being altered, either by species additions or subtractions. Worse yet, we have not developed adequate information to assess the consequences of these changes in terms of ecosystem functioning. There are indications that the removal of top carnivores from many of the Earth's ecosystems has profoundly altered their entire structure by changing species interactions at all levels. Many systems are still changing to a new equilibrium state as a result of these species removals (Terborgh, 1988).

What can we do to better our knowledge? We can mount an intensive effort to describe the biotic richness of the globe, in relation to geographic position, at least at a certain level and for certain groups, for example birds, butterflies, mammals, and higher plants. This could be done for 1 degree grid sizes equivalent to that now being utilized for global vegetation assessment. In time more difficult groups can be added to the global assessment. We can better estimate species and system losses by a comprehensive satellite monitoring program of land cover change as is being proposed by the IGBP. We can evaluate species additions by co-ordinating listings of regional invasive species into a global data base, as IUCN is beginning to do. Finally, we can support the program of SCOPE/IUBS/MAB to evaluate the ecosystem function of

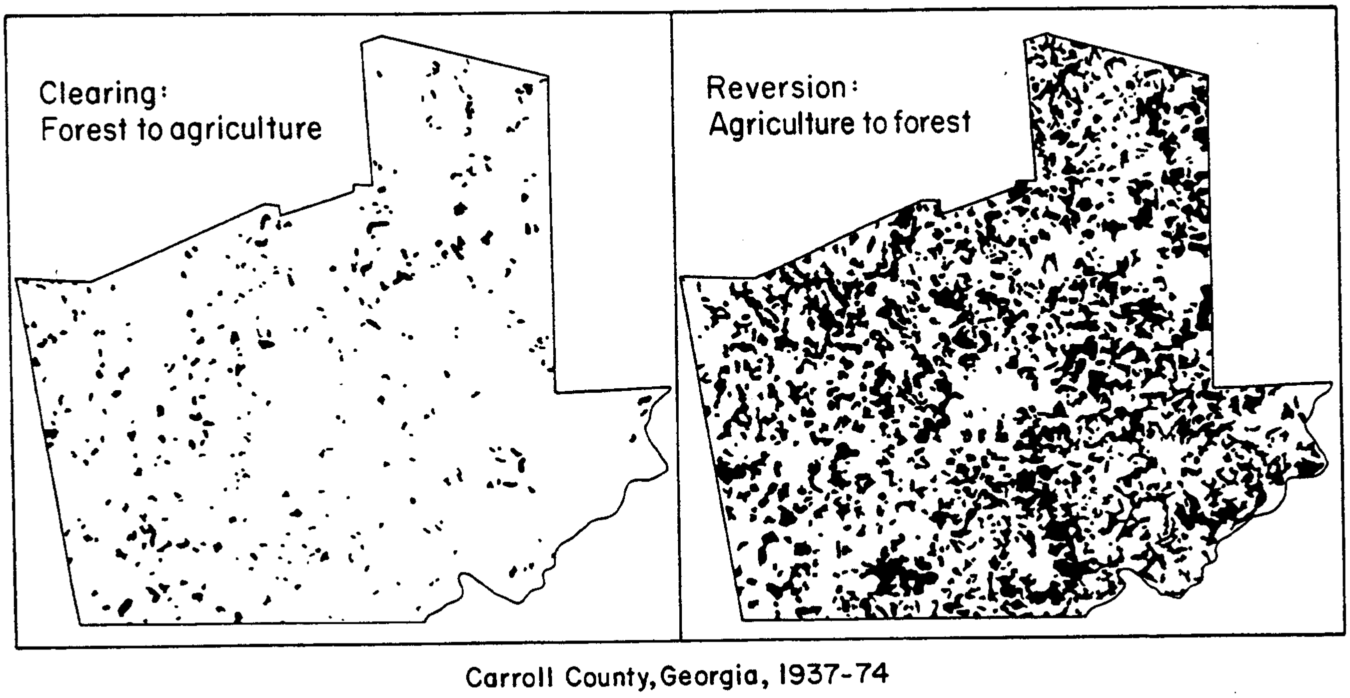


Figure 3: Reversion of agricultural land to forests in Georgia, USA. (Williams, 1989) Changing economic and social factors can result in dramatic changes in the state of terrestrial systems.

biodiversity. This program would investigate the impact of species additions and subtractions over temporal and spatial scales on ecosystem functional properties utilizing explicit controlled manipulations as well as "natural" and "inadvertent" experiments.

8.1.3 Putting the pieces back together

It is now axiomatic that no place on Earth is untouched by the influence of humans. There is no such thing as a pristine environment. As human intervention increases in pulling the fabric of terrestrial systems apart so increasing amounts of human management will be needed for either mitigating against undesirable environmental effects locally, or even globally through geo-engineering. In addition to mitigation there will be increasing needs to rebuild or regenerate natural systems that have been destroyed, including streams, tropical forests, coastal marshes and so forth. The new field of restoration ecology has been developed to meet this need. Success in this endeavor has been called the true test of how well we understand natural systems. Do we have the knowledge, not only to reconstruct ecosystems, but also to make them self-sustaining? If we do not then we must put more effort into this important endeavor.

8.1.4 Modification of biotic complexity: Agro-ecosystems

At least half of the global land surface is no longer covered by natural ecosystems, but has been modified by humankind for agricultural purposes: cropland, animal husbandry and plantations (see Chapter 2). Many of these managed landscapes are stable under present-day climatic and cultural conditions, although others are not. In many areas land management has resulted in an enlargement of the intrinsic biomass production potential and in some situations an increased biodiversity. Humans have made local landscapes more suitable for productive purposes by regulating runoff, terracing, clearing of stones, irrigating or draining, and by supplementing soils with lime, nutrients, and organic material. At the same time, agriculturally important plant and animal species have been improved by mass selection to become suited to local conditions resulting in a wealth of "land races". Traditional small-holder mixed farming in particular has produced diverse landscapes where wild species, crop cultivars, and domesticated animals co-occur. The sustainability of these agro-ecosystems is being threatened at present because of strong population growth and changing cultural practices that lead to the excessive use of chemical amendments and overmechanization.

There is a need to analyze the various present-day land use systems in terms of their degree of modification from pre-existing natural systems in order to determine how features of soil, microclimate, hydrology, and biodiversity and bioproductivity have been altered, and how these changes affect stability under contemporary social-economic conditions. Altered systems that are inherently unstable need to be identified along with what land management factor or climatic change element could lead to their sudden collapse. The spatial dimensions of these "collapse hazards" would require the matching of a geo-referenced data base on land use systems, as advocated in Chapter 2, with similar data bases on abiotic resources as discussed earlier in the present chapter, along with modeling of regional or local effects of climatic change.

In summary, multi- and interdisciplinary research is needed on agro-ecosystem functioning at different intensities of human impact and climatological stress as advocated by UNESCO's Man and the Biosphere Programme (MAB), and which could be incorporated into the farming systems research of the international agricultural research institutes of the CGIAR system. The results of such research would be sustainable land use options that could support modifications to varying degrees. Hopefully, such an effort would permit us to avoid the environmental mistakes that we have made in the past that have resulted in intense land degradation and accompanying human misery.

9. TERRESTRIAL SYSTEMS IN A NEW WORLD

9.1 Terrestrial systems under stress

Virtually all dimensions of our globe are changing at unprecedented rates due to the activities of a rapidly growing human population. Land cover, water and atmospheric chemistry, and species numbers and distributions are being greatly modified on a global scale. Not only is there rapid change but some of the features we see now have never existed in past history. We are tending toward a new world. This means that to a certain extent our knowledge of how the Earth operates now and has operated in the past will not be a totally reliable guide for understanding the future. There is fair agreement that our climate will be changing at a rapid rate to a warmer world. The atmosphere is becoming enriched in CO_2 going from 280 ppm in the pre-industrial atmosphere to over 350 ppm today (Houghton *et al.*, 1990). Tropospheric ozone have doubled in rural European sites this past century (Ashmore and Bell, 1991) and increases are even seen in non-industrialized tropical regions due to accelerated biomass burning (Fishman *et al.*, 1991). UV-B levels in spring in Antarctica are now far in excess than has ever been previously measured whereas at the same time there have been reductions in ground level-irradiances in the northern hemisphere due to increases in atmospheric pollutants (Frederick *et al.*, 1989). Increased atmospheric deposition of sulfur, nitrate and ammonium is significantly modifying soil chemistry and plant nutrition of European forests (Schulze, 1989). About one-third of all irrigated arable land is now salt affected (Reeve and Fireman, 1967). We do not know which systems are the most sensitive to these changing stress factors. Obtaining this knowledge is important as well as learning how to mitigate against or prepare for these changes.

Not only is the physical environment of the Earth changing but so is the biotic configuration of the continents as noted earlier. The breakdown of biogeographic barriers, both inadvertently as well as intentionally, through world commerce, is resulting in a homogenization of the world's biota. In New Zealand well over 50% of the flora is non-native and in Hawaii 40% of the plants and 95% of the mammals are non-indigenous (Mooney and Drake, 1990).

Thus in looking to the future, we cannot entirely utilize the information from the past – the world is changing very rapidly, and to states that have not previously existed. It is predicted that future climate change may be greater than that which accompanied deglacial warming (Huntley, 1991).

We do not know fully what the consequences of these changes will be on terrestrial systems. We do know that increases in tropospheric ozone has reduced agricultural productivity in the United States (Heck *et al.*, 1988), that enhanced atmospheric deposition of nutrients has reduced forest growth in Germany (Schulze, 1989) and that increased CO_2 will probably promote greater plant growth in non-nutrient and water-limited conditions (crops and marshes) but not in nutrient or temperature-limited environments (Mooney *et al.*, 1991). Biotic diversity is predicted to decrease under present climate change scenarios (Woodward and Rochefort, 1991); however, the effects of land use change will probably have a far greater detrimental effect on biodiversity in the near term.

9.2 New knowledge for the new world

How then can we plan for the future on the basis of our present knowledge? We can refine our understanding of how natural systems operate and link this knowledge together into a new class of Earth System models as being developed by the IGBP. Thus we should be able to predict to a better degree how a given change in any part of the natural world will affect other parts. We must be able to consider landscapes as operational units – with important links between the units. The knowledge that we will need comes in large part from understanding how the larger units of the landscape operate. In order to gain this knowledge we will have to magnify meaningfully information derived from small scales to larger units. We must also develop a new experimental approach built on assessment of the response of whole ecosystems to change, for example, CO_2 enrichment. It is only through such experiments that we will be able to examine the feedbacks that will occur between plants, herbivores, and decomposers in a carbon-rich environment, for example. We will further have to show how organisms respond to multiple stresses building on our experimental base of single stress responses. We will also have to learn how certain organisms will respond to unprecedentedly rapid changes. This is a very large research agenda, but one which is needed to prepare for the uncertain future.

9.3 Training the new citizens and scientists

If you plan for one year, plant rice
If you plan for ten, plant trees

If you plan for one hundred years, educate mankind.
Kuan-Tzu (as cited in Holzner *et al.*, 1983)

As terrestrial systems become increasingly impacted by the influences of a growing human population, and in the process lose the building blocks and the connections, resilience and productive capacities will decrease. The activities of individuals and their effects on biotic systems will have to be evaluated even to a greater degree. Educational efforts on interactions between humans and the environment will need to be expanded to an ever greater extent and at all age levels. Additionally we will need more scientists, of more kinds, to study, understand, and manage terrestrial systems. This societal need, which surely will increase, comes at a time when training for resource scientists (foresters, taxonomists, range managers, etc.) is actually declining. We must reverse this trend and at the same time we need to develop new kinds of scientists; scientists, for example, who understand how both natural and human social systems operate and interact, scientists that understand how terrestrial systems interact with the atmosphere and hydrosphere, scientists who can think globally. This need will have to be fulfilled by restructuring some of our traditional educational institutions as well as for the establishment of new international research and training centers as proposed by IGBP and the WCRP. We must produce the stewards and visionaries that will guide us, and the Earth Systems on the planet that support our existence, into a future filled with the uncertainties that global change will bring.

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