

# **Biological and Ecological Dimensions of Global Environmental Change**

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# Biological and Ecological Dimensions of Global Environmental Change

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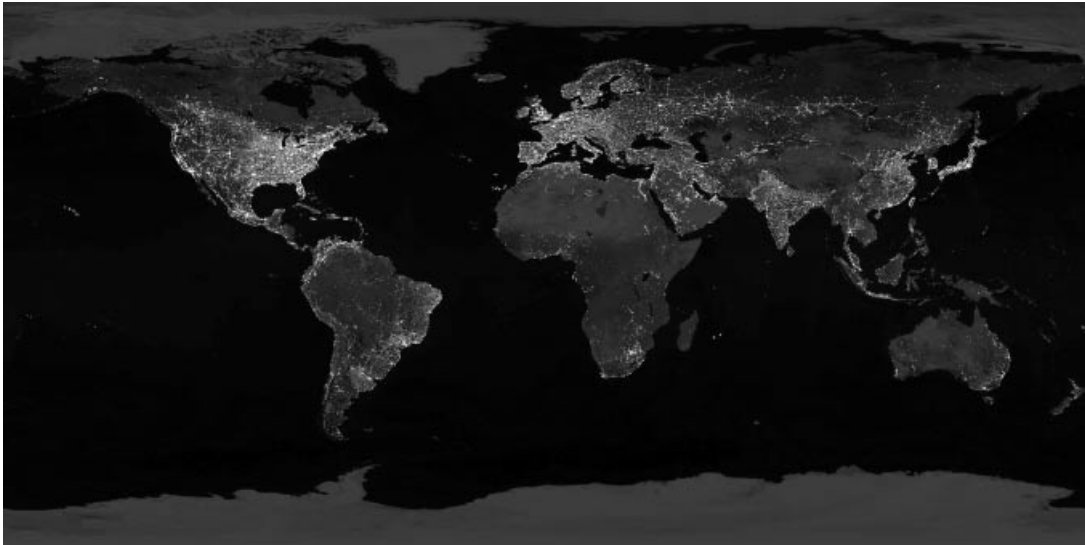
## A HUMAN DOMINATED WORLD

Humans have populated the Earth for thousands of years but not until the last few centuries have they played a major role in influencing the structure and metabolism of the global biosphere. Human-induced changes have today reached such an extent that, in some cases, they are as important or even more important than those caused by the geological and climatic forces that shaped the Earth's environment over the previous thousands of years.

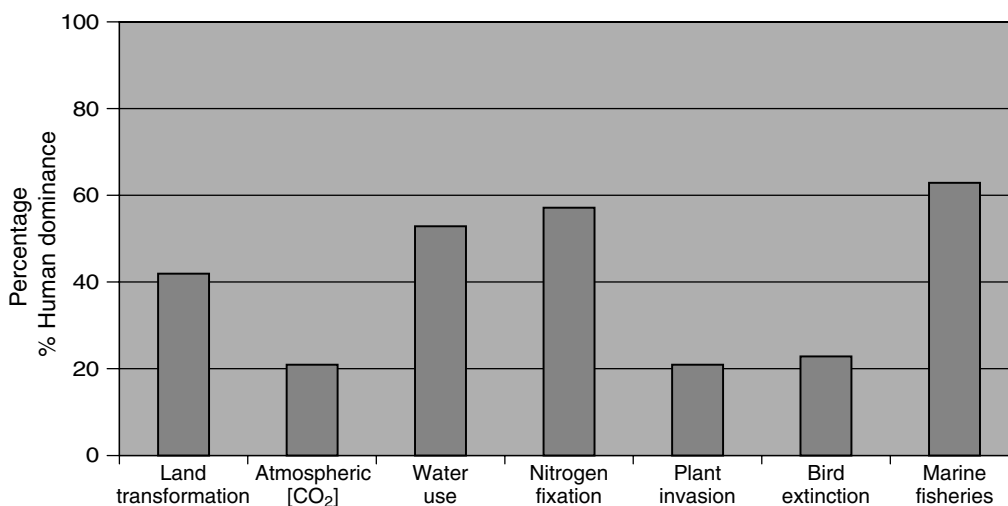
There is no doubt that the growth of human populations and associated resource consumption have been the major drivers behind the large biospheric transformations that have occurred, particularly in the last few decades. Both the total and the *per capita* exploitation of the Earth's resources have been nearly exponential for some time now. The human population has increased tenfold to 6 billion over the last three centuries along with, for example, the growth in the number of cattle (to 1.4 billion) as well as in the number of automobiles. Figure 1 provides a vivid illustration of the extent of large-scale human interference with the natural environment.

Many changes are currently taking place (and at an accelerating pace) in the biosphere. See, for example, Vitousek *et al.* (1997) and Figure 1. These changes include:

1. The historic transformation, to various degrees of intensity, of 30–50% of the land surface, particularly the 10% converted from natural vegetation into cropland. Twenty percent of existing forest and woodlands has disappeared in the last three centuries (Figure 2).
2. Over the last four glacial periods, the atmospheric concentration of carbon dioxide oscillated between 180 and 280 ppm and not until recently have human activities (mainly industrialization and deforestation), driven carbon dioxide concentrations above this narrow window. The biogeochemical cycle of carbon is consequently perturbed on a grand scale, which must affect world vegetation patterns and climate likewise.
3. While carbon is the largest contributor to plant living matter, with about 45% of dry weight, no single life process would be possible without the action of highly specialized proteins (enzymes) for which nitrogen is the key element. Nitrogen is now being added to the biosphere by chemical synthesis (fertilizer production) and expansion of nitrogen-fixing crops at a similar rate to that of nitrogen produced naturally, thus doubling the planet's nitrogen production. The single largest change has resulted from the increased use of synthetic inorganic fertilizers in agriculture; half of the amount that has ever been used on Earth has been applied during the last 15 years. In some areas (with poorly buffered lakes and soils), the net result is acidification. In other areas, the net result is nitrogen over-fertilization, with the risk that the assemblage of species in whole biomes may change radically.
4. Humans use about 50% of the runoff that is fresh and reasonably accessible, irrigated agriculture being the most important single user. In the Northern Hemisphere, 77% of the water flowing into the oceans comes from rivers that have been regulated by dams or manipulated in other ways. This has had large impacts on the transport of sediment to the oceans and in the salinity of coastal waters.
5. Extinction rates of species due to human activities, and particularly due to changes in land use and cover, are calculated to be between 100 and 1000 times greater than in pre-human days. For instance, up to 25% of bird species have been driven to extinction. The current loss of species is comparable to those occurring during the five great extinction events of the geological past. See, for example, **Extinctions and Biodiversity in the Fossil Record**, Volume 2; **Extinctions (Contemporary and Future)**, Volume 2.
6. Invasive species are reshaping the biotic composition of the world's ecosystems. In just six nations studied, there have been over 100 000 introduced species (plants, animals and microbes) about 2000–50 000



**Figure 1** Earth city lights. (Image by Craig Mayhew and Robert Simmon, NASA GSFC, based on data courtesy of Christopher Elvidge, NOAA National Geophysical Data Center)



**Figure 2** Human alteration of various biospheric compartments. (after Vitousek *et al.*, 1997)

species per country (*see also Biological Invasions*, Volume 2). Biological invasions are now considered the second largest threat to biodiversity losses in terrestrial ecosystems after habitat destruction (*see for example Figure 3*).

7. Fisheries around the world are known to be in trouble with about 22% of recognized fisheries being overexploited or already depleted (*see Vitousek et al.*, 1997). Global fish catches have leveled in recent years.

These examples illustrate the extent of human interventions in many of the Earth's key compartments and processes. Recognition of this situation has led Nobel Laureate Paul Crutzen (2000) to propose that mankind has entered a new biogeophysical era that he has called the *Anthropocene*

(*see Anthropocene*, Volume 1). This idea is intended to sharpen the distinction between the current human-dominated world (starting around the 1800s) and the previous Holocene era that spanned the post-glacial period of the past 10 000–12 000 years when the Earth's climate and metabolism were exclusively controlled by geological forces. In this respect, *anthropocene* refers not only to the large scale of human interventions but also to the fact that these various drivers affect all terrestrial and aquatic ecosystems on Earth.

Finally, we should draw a distinction between biospheric changes due mainly to continental- and global-scale modifications of the chemical and radiative properties of the environment (climate greenhouse warming, stratospheric ozone depletion and acid deposition) with the direct changes



One new alien species  
has been established in the  
Bay of San Francisco every:

- 36 weeks since 1850
- 24 weeks since 1970
- 12 weeks since 1980

**Figure 3** Invasion rate in San Francisco Bay (data from Cohen and Carlton, 1998). Image courtesy of MITI, ERSDAC, JAROS and the US/Japan ASTER Science Team

in the characteristics of the physical environment (forest clearing, urbanization, irrigation, etc.). The emphasis in this volume is on the former but in the real world, several stresses operate simultaneously on the biosphere. This kind of behavior will be considered in volume three, and the consequences for policy formulation will be discussed in volume four. The Intergovernmental Panel on Climate Change (IPCC) process (*see Intergovernmental Panel on Climate Change (IPCC): an Historical Review, Volume 4*) is a shining example of how to move from science to policy, certainly to be emulated with respect other biospheric changes in coming decades. To cite three examples,

1. How will wheat yields be affected over the next several decades, as a result of increasing frequencies and

intensities of both ground-level ozone episodes, and of increasing heat waves and droughts? (not to mention globalization of markets, bioengineering, and changes in food preferences).

2. How will salmon and cod stocks respond to changes in technology, sea temperatures and ocean currents, and national and international regulations?
3. How will ecosystems respond to rising carbon dioxide concentrations and climate warming? (This question is addressed in several papers in this volume.)

### THE CHANGING METABOLISM AND STRUCTURE OF THE BIOSPHERE

Over the last two centuries, the extraordinary changes that have taken place in the land surface and in the atmosphere

over the land have had large impacts on biospheric structure and metabolism. From an Earth metabolic perspective, the large conversion of land since the early 19th century has reduced the terrestrial biosphere's capacity to produce organic matter (amount of carbon stored in plants per year) by 5% and has released 182–199 Pg of carbon (1 Petagram is 1 billion tonnes) to the atmosphere. Changes in land use and cover have been responsible for 33% of the increased concentrations of carbon dioxide observed in the atmosphere.

Earth observing systems can already detect the changing metabolism and structure of the biosphere. For instance, analyses of monthly air samples around the world for carbon dioxide and other chemical species have shown that the difference between the higher concentrations in the winter, when carbon dioxide release from respiration is the prevailing process, and the lower concentrations in the summer, when carbon dioxide uptake is the prevailing process, has increased between 20 and 40% over the last two decades. This is the result of changes in the strength of key metabolic processes such as photosynthesis (carbon dioxide uptake) and plant and microbial respiration (carbon dioxide emissions), and the length and intensity at which these processes operate in different parts of the planet. Satellite-sensed canopy development (greening) at the beginning of the growing season shows an increased length of this biologically active season in the Northern Hemisphere, specifically an advance of about one week in the onset of the spring drawdown of carbon dioxide. Using similar techniques, it has been shown that terrestrial net primary productivity of some regions in the world has increased over the same period.

The primary driver of these changes is thought to be increased air temperature although higher photosynthesis rates due to carbon dioxide fertilization and nitrogen deposition may have also contributed to some degree.

Changes in the metabolism and structure of the biosphere may well be the best proof that global change is taking place. A large body of evidence on the existence of these changes has been compiled over the past few years, including changes in key physiological processes as well as species redistribution in land and aquatic systems.

As indicated above, changes in plant and animal phenology have also been linked to changes in temperature around the world but most especially at high latitude sites where temperature changes have been the largest. Earlier timing of reproduction has been found for many bird species in a number of countries, as well as advances in the arrival time of migratory birds. In the last few decades, an increase in forest production in several countries in Europe has been related to changes in climate. The lengthening of the growing season is the most common response found, particularly in cold ecosystems of high latitudes.

Changes in phenology and physiology ultimately result in changes in plant and animal abundance and distribution. These changes have been well documented in coastal communities of macro-invertebrate species and with plankton and fish species in the open ocean (increasing abundance of southern species and a decrease of northern species in the Northern Hemisphere). Poleward shifts and movement towards higher elevations of plant and animals have been associated with warming trends regionally with well documented shifts in the ranges of many species, including American, British, and European butterflies and insects. Species shifts also include viruses and parasites harmful to human health.

Coastal zones are also undergoing multiple changes, some linked to increased frequency of the El Niño Southern Oscillation (ENSO), with effects on species distribution and stability of coral reefs around the world. Equally important, leveling of fishery harvests and loss of biodiversity is spreading in coastal zones due to dead zones caused by nitrogen pollution. Accelerated nitrogen cycling on land produces NPP (net primary production) decline and forest dieback under chronic heavy nitrogen loads.

Finally, land transformation affects the water cycle and land surface properties. Both have major feedbacks to local and regional weather and climate, which in turn influence the type of vegetation structure that can exist. To put this effect in perspective, catchment studies indicate that water yield decreases 25–40 mm for each 10% increase in tree cover while increases in transpiration of water taken up by deep roots may account for as much as 50% of the observed responses.

Many contributions in volumes 2–5 elaborate on these themes, but of special relevance are the following in Volume 2:

- A series of essays on many of the world's biomes – e.g., the boreal forest, temperate deciduous forests, temperate grass lands, etc. . . .
- **Natural Systems: Impacts of Climate Change;**
- **Plants – from Cells to Ecosystems: Impacts of Global Environmental Change;**
- **Biological Invasions;**
- **C<sub>3</sub> and C<sub>4</sub> Photosynthesis;**
- **Carbon and Energy: Terrestrial Stores and Fluxes;**
- **Carbon Cycle;**
- **CO<sub>2</sub> Enrichment: Effects on Ecosystems;**
- **Nitrogen Cycle;**
- **Nitrogen Deposition on Forests;**
- **Phenology;**
- **Plant Growth at Elevated CO<sub>2</sub>;**
- **Plants – Carbon Balance and Growth;**
- **Remote Sensing, Terrestrial Systems;**
- **Temperature Increase: Effects on Terrestrial Ecosystems.**

## THE EMERGING SCIENCE OF GLOBAL ECOLOGY

Realization of the existence of global environmental problems such as increasing atmospheric carbon dioxide, the stratospheric ozone hole, and other changes more continental in nature, such as nitrogen deposition and acidification of land and aquatic systems, has extended the ecological sciences towards the new field of *global ecology*. In this connection, the global environmental issues mentioned above have been found to be related through the global biogeochemical cycles. Thus understanding the interactions amongst these cycles is fundamental to human attempts to preserve global life-support systems. There is therefore an obvious practical need to develop a new type of global science.

The new global ecology saw its beginnings during the International Biosphere Programme (IBP) during the late 1960s with a focus on primary productivity of the earth's ecosystems (*see International Biosphere Program (IBP) – a Foundation for Global Studies*, Volume 2). It was not until the onset of the International Geosphere–Biosphere Programme (IGBP), however, that the ecological sciences together with other disciplines began to develop a more integrated bio-geophysical Earth system science. This new program also focused on the nature of the human perturbation and how it is changing the Earth's functioning. The IGBP has operated in more than 60 countries and has led the thinking on global change research for more than 10 years. It is now entering phase II with a further emphasis on integration and interdisciplinary research (*see IGBP Core Projects*, Volume 2).

Some of the developments in global change research have been accompanied by technological innovation that has allowed measurements to be made over large regions of the globe, over the entire Earth for that matter. One such technological tool has been the satellite with the capacity to measure variables related to biospheric metabolism such as NPP and evapotranspiration (*see Global Ocean Observing System (GOOS)*, Volume 2; *Global Terrestrial Observing System (GTOS)*, Volume 2). The wide coverage and the high frequency of measurements has made it possible to track the phenology of plant cover (*see Phenology*, Volume 2) as well as historical changes in land surfaces.

New technology (e.g., eddy covariance, and free air carbon dioxide enrichment technology (FACE)) has also enabled us to manipulate and measure ecosystem quantities and processes at larger scales (dozens of m<sup>2</sup> to several hectares, and small watersheds) than previously in order to study the effects of present and future environmental conditions (Figure 4) (*see Long-term Ecological Research (LTER) System*, Volume 2). New knowledge resulting from observations and ecosystem experiments using these new technologies has been fundamental to increasing our

understanding of ecosystem controls and the processes involved. This type of information is also the basis for the development and validation of biospheric models that simulate key functional and structural parameters of the Earth's ecosystems. *See*, for example, **Biome–BGC Ecosystem Model**, Volume 2.

The new Earth system science, fundamental to global change research, includes a large body of disciplinary work but the greatest challenge is in integrating research from multiple disciplines and developing appropriate linkages and constraints using both bottom-up and top-down approaches.

A good example of how such an integrated approach has been successful is the research done to explain the changes in interannual variability of atmospheric carbon dioxide concentrations. First, there is the global network of surface-based carbon dioxide monitoring stations, which provides the data on global trends in carbon dioxide concentrations. Then there is an integrated suite of top-down satellite data, plot-level bottom-up flux measurements (eddy covariance), and ecosystem experiments, which can explain why interannual variability occurs (Figure 5). The satellite-based normalized difference vegetation index (NDVI), for instance, might indicate earlier leaf-out in temperate and boreal forests. Ground-based measurements of leaf area document the phenomenon locally, and temperature measurements yield its probable cause. Eddy flux can then be used to measure the consequences of earlier leaf-out on the annual carbon balance for the ecosystem. Finally, ecosystem manipulative experiments (e.g., elevated carbon dioxide and temperature experiments) can provide the mechanistic information necessary to forecast changes under simulated global environmental change. Information on other intermediate-scale processes such as disturbances, succession and dispersion are also needed to understand the full range of controls on functioning and structure at multiple scales of space and time (*see also CO<sub>2</sub> Enrichment: Effects on Ecosystems*, Volume 2).

Global change research is also moving quickly towards better understanding of the nonlinear nature of the biosphere's behavior. Systems at any level of organization often display surprising and unexpected changes in response to continuous or sudden changes in the environment. Questions such as: Will NPP of terrestrial ecosystems change proportionally to changes in atmospheric carbon dioxide and temperature or are there thresholds, switch points or flip flops? Will the gradual deforestation of the tropics incrementally reduce biodiversity or are there fragmentation thresholds beyond which species extinction takes place more rapidly? The implications of nonlinear responses to global change are critical for the design of new research (*see Chaos and Cycles*, Volume 2; *Non-equilibrium Ecology*, Volume 2) and the development of suitable policies to deal with unexpected system behavior (*see Monitoring in*



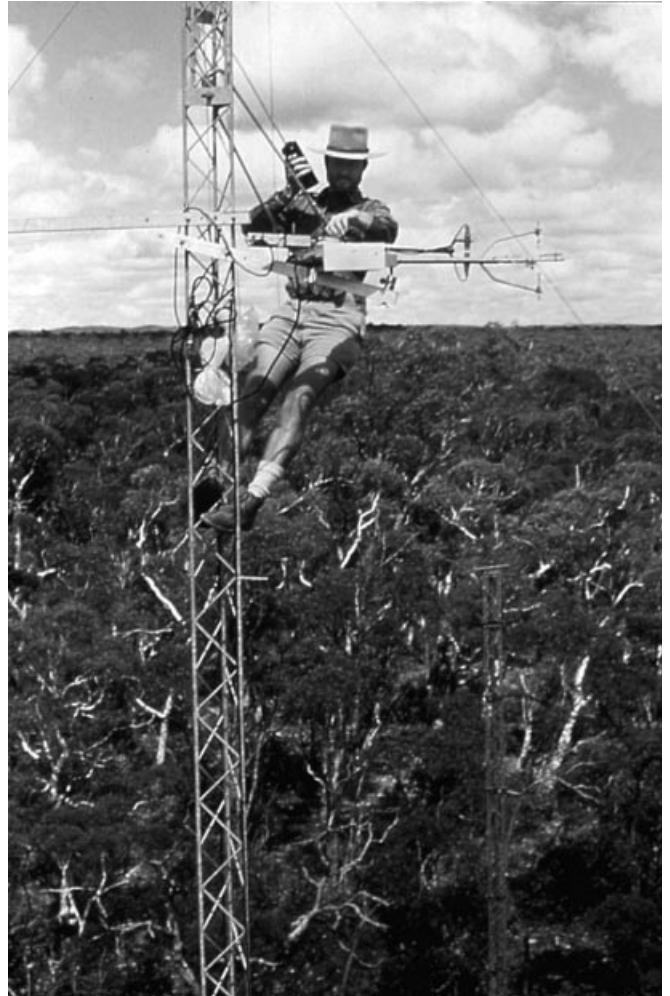
(a)



(d)



(b)

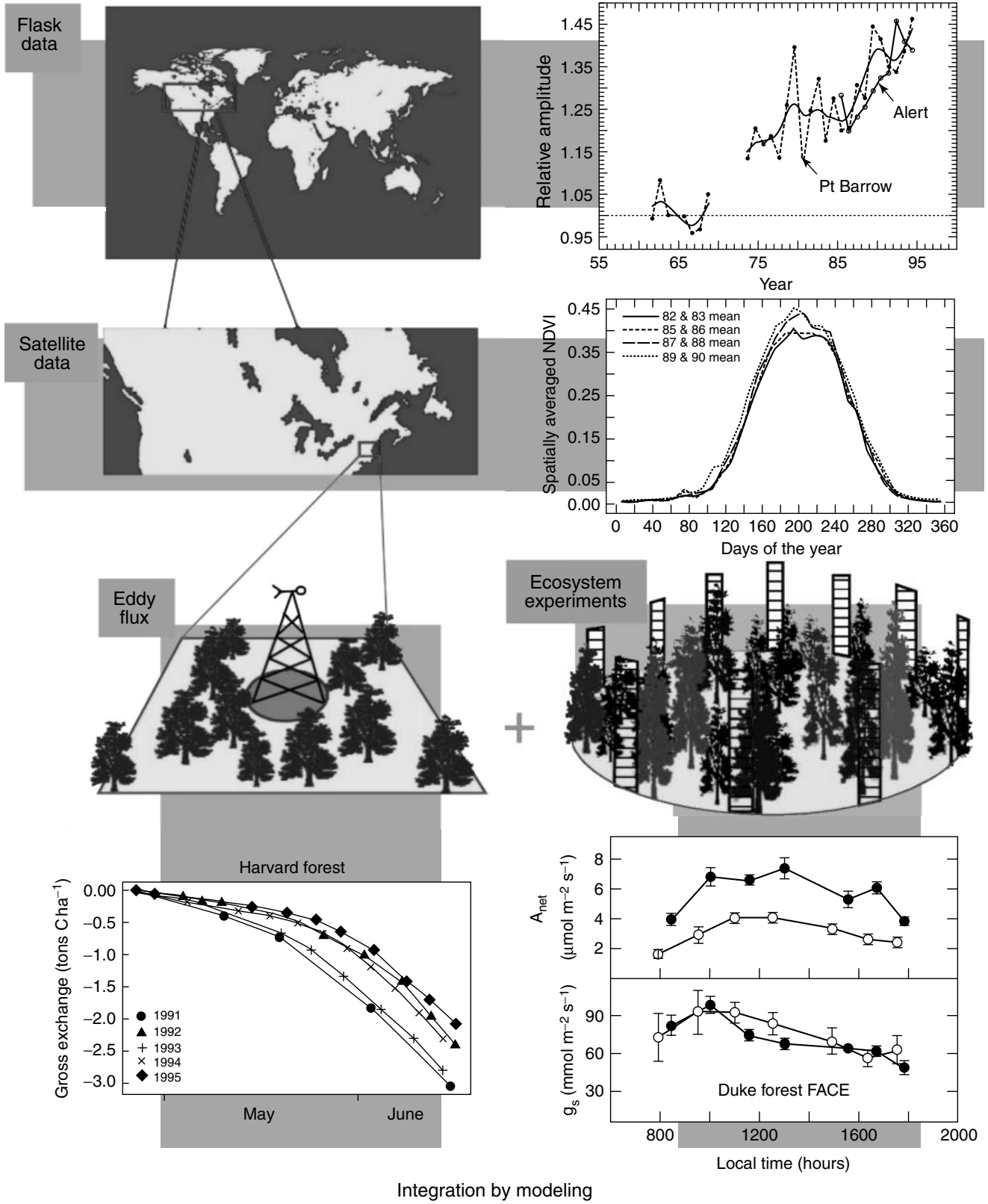


(e)



(c)

**Figure 4** Large-scale ecosystem manipulation experiments and observations: (a) FACE facility at Duke University, Durham, North Carolina, USA (photo: Pep Canadell); (b) ecosystem warming experiment using a passive nighttime warming roof in Denmark (CLIMOOR) (photo: Claus Beier); (c) Throughfall Displacement Experiment (TDE) in the Walker Branch Watershed temperate forest study area, Oak Ridge, Tennessee, USA (photo: Pep Canadell); (d) Elevated CO<sub>2</sub> open top chambers in Jasper Ridge, Stanford University, California, USA (photo: Pep Canadell); (e) measuring net ecosystem exchange of carbon dioxide using an eddy covariance system, Australia (photo: Greg Heath, CSIRO)



**Figure 5** Measuring the carbon metabolism of the biosphere with a multi-technique approach (Canadell *et al.*, 2000)



### **Support of Policy: an Adaptive Ecosystem Approach,** Volume 4).

Global change research also encompasses an understanding of the richness of the world's biota and its role in ecosystem functioning and stability. The diverse assemblages of organisms that dwell in the various components of terrestrial and aquatic systems perform critical functions such as decomposition of plant and animal detritus, nitrogen fixation, and a myriad of other essential functions. However, a large fraction of living species still remains unknown, particularly in oceans and soils (e.g., only 0.025–5% of nematode species have been described). This lack of information on the elemental constituents of an ecosystem poses large impediments to further understanding the role of biota on the functioning of the world's ecosystems. As loss of species continues, one could ask how many species are needed to maintain appropriate functioning and long-term stability of an ecosystem. In other words, from a functional point of view, how many species can we afford to lose? This challenge becomes even more complex when adding the rapid redistribution of the world's biota due to the increasing levels of material flows among many parts of the world, that is, the expansion of biological invasions (*see* **Biological Invasions**, Volume 2). Thus, a main challenge is the need for the development of new science and testable hypotheses linking biodiversity and ecosystem functioning (*see also* **Biodiversity in Soils and Sediments: Potential Effects of Global Change**, Volume 2; **Functional Biodiversity**, Volume 2).

## **CONCLUDING REMARKS**

This volume contains a series of articles on the basic science that underpins current understanding of the functioning and structure of the biosphere and how it interacts with the physical environment. This knowledge allows us to evaluate the extent that the effects of global environmental change will have on the world's ecosystems and provides information on the development of concepts, theory, and tools that are used for simulating future trajectories under various scenarios of global change.

When individual species are grouped together into populations and communities, new processes shape their composition and structure such as herbivory, pollination, competition, succession, nitrogen fixation, and a critical understanding of life cycles as nonlinear and often chaotic systems.

The next level of biological organization and complexity concerns ecosystems with assemblages of multi-species, above and below ground interactions, and spatially explicit resource distributions. Contributions in this volume that provide understanding of ecosystem structure and functioning include: mineral cycling, disturbances, resilience, ecosystem invasions, and carbon and energy storage and

fluxes. The volume also includes the latest understanding on current and future effects on the biosphere of increasing atmospheric carbon dioxide, nitrogen deposition, and rising air and soil temperatures.

Landscapes are the most common scale at which humans perceive and manage ecosystems. They comprise a mosaic of patches reflecting physical constraints, natural disturbance history, and land use patterns. This heterogeneity alone necessitates the use of approaches that account for the diversity of land surface properties and resulting fluxes, in addition to basic processes involved in landscape dynamics such as disturbances and dispersal, and dynamics at the interfaces (ecotones) in fragmented landscapes.

Landscape richness and distribution of species also have implications for the structure and functioning of ecosystems. Information on species richness and functional attributes is provided for some of the less studied components of the biosphere such as soils and freshwater sediments. Species assemblages sometimes change rapidly due to species extinctions and invasions of exotic species. Several contributions in this volume provide critical information on past, present, and expected future species extinctions with an analysis of what makes species most vulnerable. For individual plant and animal species, information on physiology, growth, and reproduction is also provided as key controls of structure and functioning.

The volume also reviews the major characteristics of a number of representative biomes across the world's climatic belts and their sensitivity to global environmental change (e.g., tundra is very sensitive to temperature changes). Special attention is given to some of the most vulnerable systems within biomes such as intertidal communities and coral reefs.

The highest level of complexity is the Earth system itself. This is the level at which some of the most fundamental life engines operate, particularly the various global biogeochemical cycles; carbon, nitrogen, iron. It is also the level at which major biosphere–atmosphere feedbacks take place with large impacts on regional and global climate.

The development of new tools has been critical to the advancement on global change research. The need to scale up to large regions and to the globe, and to project future trajectories of ecosystem functioning and structure has been a challenge. This volume describes some of these advances ranging from remote sensing techniques, ecosystem flux measurements (e.g., eddy covariance), manipulation experiments (e.g., FACE), the use of stable isotopes, ecotrons and other experimental facilities, etc. The information generated from the use of these techniques directly feeds into the development and testing of ecosystem and biospheric models also included in this volume.

The new research issues dealing with global environmental change have fostered the development of a new

type of science, a new type of scientist, and a new way to structure and coordinate research. The volume describes some of the international programs that have been critical to the development of the science of global change such as IGBP (*see IGBP Core Projects*, Volume 2), and how other international and regional programs and networks have played critical role in shaping the research agenda over the last decade. Such as the European Network for Research in Global Change, the Inter-America Institute for Global Change Research, the Asian Pacific Network for Global Change Research, the International Long Term Ecological Research network, and the International Global Observing Systems. Examples of regional research projects are also described such as the Boreal Ecosystems Atmosphere Study (BOREAS) and the Large-scale Biosphere–Atmosphere experiment in Amazonia (LBA) for their importance at pioneering integration within a large region (*see Boreal Ecosystem–Atmosphere Study (BOREAS)*, Volume 2; *European Network for Research in Global Change (ENRICH)*, Volume 2; *Inter American Institute for Global Change (IAIGC)*, Volume 2; *Large Scale Biosphere–Atmosphere Experiment in Amazonia (LBA)*, Volume 2; *Long-term Ecological Research (LTER) System*, Volume 2).

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