# Chapter 1

## Global Ecology, Networks, and Research Synthesis

*Louis F. Pitelka · Josep G. Canadell · Diane E. Pataki*

### 1.1 Introduction

The Earth System, including its terrestrial and marine ecosystems, is being altered as a result of human activities. These global changes have been well-documented (e.g., Vitousek et al. 1997; Mooney and Canadell 2001; Steffen et al. 2004). They include changes in the composition of the atmosphere, including increasing concentrations of greenhouse gases; changes in global and regional climate; habitat destruction and land cover change; increases in the amounts of reactive nitrogen compounds in the biosphere; increases in species extinction rates; and increases in the number and impacts of exotic invasive species. The extent and magnitude of human-caused changes has led Nobel laureate Paul Crutzen (2002) to propose that the Earth has entered a new geologic era, the Anthropocene – an era of human domination of the Earth System, in contrast to the previous billions of years of Earth's history when natural forces dominated the Earth.

Nowhere are the impacts of human activities more apparent than in terrestrial ecosystems, with even the most remote and pristine terrestrial systems experiencing the effects of global change. The terrestrial portion of our planet obviously supplies many of the important ecosystem services upon which our society depends, including fresh water and much of our food and fiber. Because global change has the potential to significantly alter the structure and functioning of terrestrial ecosystems, considerable resources have been invested over the past decade on research to understand the effects of global change on ecosystems. In addition, since terrestrial systems are active components of a dynamic Earth System, research has also focused on whether those changes in terrestrial ecosystems are resulting in positive or negative feedbacks to the atmosphere and physical climate system.

Since 1991, the Global Change and Terrestrial Ecosystems (GCTE) core project of the International Geosphere-Biosphere Program (IGBP) has played a leadership role in developing and coordinating an international agenda on the two research areas mentioned above (Steffen et al. 1992). Over 100 synthesis papers and 25 special issues and books were published as a result of GCTE activity, not counting the primary research-data papers that stemmed from the various efforts. A synthesis of the first five years of GCTE research was published in 1999 (Walker et al. 1999) which followed an initial project-wide effort to further define the scientific scope of GCTE (Walker and Steffen 1997). This new volume, unlike the previous ones, describes examples of research conducted under the umbrella of GCTE during the second half of the project and does not intend to provide a comprehensive overview of all research. This chapter places these contributions in a historical context and explains how they fit into the broader GCTE endeavor.

This volume also marks the end of GCTE. After more than a decade of focusing on linkages between geophysical and biological research, the IGBP has entered a new, second phase aimed at describing and understanding the interactive physical, chemical, biological, and socio-economic processes that regulate the total Earth System and the changes that are occurring in this system. Because of the tremendous advances in disciplinary research on specific components of the Earth System made during phase I of IGBP, the global change research community is well poised to undertake the types of more interdisciplinary research that will be required to advance to the next level of understanding of the Earth System. As part of the transition to IGBP II, major restructuring of the core projects has taken place. A number of projects have ended, while new projects that bring together elements of the original projects have been initiated. GCTE is now closed, but IGBP research on terrestrial ecosystems will continue under the new Global Land Project (GLP), a joint project of IGBP and IHDP (the International Human Dimensions Project), built upon the foundations of GCTE and the Land-Use and Land-Cover Change (LUCC) project. The science objectives of the GLP are described in Chap. 25 (Ojima et al. 2007, Chap. 25 of this volume).

The overarching goals of GCTE were

- to predict the effects of changes in climate, atmospheric composition, and land use on terrestrial ecosystems;
- to determine how these effects lead to feedbacks to the atmosphere and physical climate system.

In: Canadell JG, Pataki D, Pitelka L (eds) (2007) Terrestrial Ecosystems in a Changing World.
The IGBP Series, Springer-Verlag, Berlin Heidelberg

GCTE addressed these goals primarily by playing a coordinating and networking role among new and existing research projects of individual investigators. This role took a variety of forms. Through workshops and conferences involving broad representation from the international global change science community, GCTE developed and implemented a research agenda to address the goals of the project. Another successful strategy used by GCTE to advance global science was to facilitate the development of international research networks to enhance communication and integration. Workshops organized by these networks have produced a large number of synthesis books and journal articles. Still other GCTE activities have included model inter-comparisons and the development of critical databases.

GCTE was originally comprised of four foci: Ecosystem Physiology; Ecosystem Structure; Agriculture, Forestry, Soils; and Biodiversity. It is worth reflecting on the fact that, in the early 1990s, it was necessary and made sense for these four foci to operate fairly independently. At that point, there were models and experiments that focused only on responses of ecosystem physiology (e.g., NPP) to global change (e.g., elevated $CO_2$). Researchers were interested in how ecosystem structure (e.g., vegetation type) would respond to a changing climate without simultaneously considering effects on ecosystem physiology. Research on agricultural and forestry systems was distinguished from research on more natural ecosystems. And research on the interactions between biodiversity and ecosystem functioning (physiology) was just beginning. A measure of the progress made over the past decade is the extent to which research activities now integrate across two or more of these previously separate subdisciplines, and we will highlight examples in this chapter.

## 1.2 Carbon and Water Cycles in the 21st Century

Research on the effects of rising atmospheric $CO_2$ concentrations on terrestrial ecosystems has been a component of GCTE since its inception. At the time GCTE was founded, much of the literature on elevated $CO_2$ effects focused on individual plants grown under ideal conditions of adequate water and nutrient availability (Mooney et al. 1999). To promote and synthesize ecosystems-based research on the effects of elevated $CO_2$ on whole communities in the field, the Elevated $CO_2$ Network began to hold a series of workshops on the role of community responses, belowground processes, interactions with environmental stress, and other key uncertainties in understanding the responses of the terrestrial biosphere to elevated $CO_2$. An increasing number of experiments have addressed these uncertainties in a variety of biomes from grasslands and forests to drylands, agroecosystems, and more. As a result, our understanding of the variability and complexity of ecosystem responses to elevated $CO_2$ has improved dramatically over the past decade, particularly with regard to water and nutrient limitations to $CO_2$ responses, belowground carbon pools, and community scale dynamics (see Chap. 2 by Körner et al.).

Changes in atmospheric $CO_2$ concentrations in the 21st century will occur in concert with changes in temperature, precipitation, nitrogen deposition, and other aspects of global change. Studies of ecosystem responses to perturbations such as elevated $CO_2$ or temperature can improve future projections of critical attributes of the terrestrial biosphere such as the carbon balance (see Chap. 6 by Canadell et al.). In addition to the Elevated $CO_2$ Network, the Network of Ecosystem Warming Studies greatly added to our understanding of global change ecology by synthesizing the results of experimental manipulations of temperature in a variety of ecosystems (Rustad et al. 2001; Shaver et al. 2000; Chap. 3 by Norby et al.). However, interactive effects among multiple disturbances may not be additive and merit further investigation in the next generation of manipulative and modeling experiments. In Chap. 3, Norby et al. review ecosystem responses to warming, interactive effects of $CO_2$ and temperature, and effects of multiple of aspects of global change as assessed by experimental and modeling results. Relative to responses of individual perturbations, our understanding of interactive effects of multiple global change drivers is at a fairly early stage, and will continue to remain a critical aspect of understanding terrestrial ecosystems responses in the coming decades.

Another important contribution of GCTE was the initiation of the Biosphere-Atmosphere Stable Isotope Network (BASIN), which is still ongoing. As described by Pataki et al. in Chap. 4, the application of measurements of the isotopic composition of atmospheric trace gases in ecosystem-scale studies has provided new information about ecosystem physiology and its role in ecosystem, regional, and the global carbon cycle. Isotopes integrate physical and biological processes over space and time, and are increasingly measured in a variety of ecosystems ranging from virtually unmanaged to highly managed and human dominated. In general, human dominated ecosystems are increasingly of interest to the ecological and global change communities due to their large influence on the atmosphere and climate system, resource availability, and ecosystem services and human welfare. The effects of urbanization on biogeochemistry are reviewed by Pouyat et al. in Chap. 5 as an emerging area of critical importance in quantifying impacts of land use and land cover change, as well as the dynamics of coupled human and natural systems, which will be a focus of the new Global Land Project (see Chap. 25 by Ojima et al.).

## 1.3 Changing Biodiversity and Ecosystem Functioning

The interest in establishing relationships between biodiversity and ecosystem function arose from the realization that rates of species loss are accelerating due to human activities, particularly due to habitat lost and fragmentation among others. Given that species have different functional traits, major changes in biodiviersity could result in significant changes in biogeochemistry and other processes that regulate the Earth System (Loreau et al. 2001; see Chap. 7 by Diaz et al., and Chap. 10 by Naeem et al.). This GCTE activity quickly moved to include the effects of atmospheric composition and climate change on biodiversity (see Chap. 9 by Potvin et al.), and the effects of rapid expansions of exotic species which can profoundly change the structure and function of many terrestrial and freshwater ecosystems (see Chap. 8 by Vilà et al.).

The GCTE established a focus on this topic in partnership with the emerging program of Diversitas, leading the development of what was a completely new field of research early in the 1990s. It soon became clear that functional changes due to species loss, addition or replacement could have significant impacts on ecosystem properties such as productivity, decomposition rates, nutrient cycling, and resistance and resilience to perturbations. Numerous reviews were instrumental in the development of this new field (Sala et al. 1999; Loreau et al. 2001, 2002; Hooper et al. 2005). These syntheses described some fundamental patterns (Hooper et al. 2005): *(i)* Certain combinations of species are complementary in their patterns of resource use and can increase average rates of productivity and nutrient retention, *(ii)* Susceptibility to invasion by exotic species is strongly influenced by species composition and, under similar environmental conditions, generally decreases with increasing species richness, *(iii)* Having a range of species that respond differently to different environmental perturbations can stabilize ecosystem process rates in response to disturbances and variation in abiotic conditions.

Finally, GCTE also led the development of new biodiversity scenarios with a first attempt at mapping changes in the global distribution of species due to climate and land use change (Sala et al. 2000).

## 1.4 Landscapes under Changing Disturbance Regimes

Disturbances such as fire, pests, windthrow, and harvesting are important in determining the structure and functioning of terrestrial ecosystems. Global warming and other forms of global change will further perturb ecosystems over the next decades, and will interact with the other forms of disturbance in complex ways. The chapters in this section are examples of research conducted over the past decade to better understand how changing disturbance regimes will interact with and affect ecosystems.

One of the key effects of climate change on ecosystems will be adjustments in the ranges of plant and animal species, and accordingly, of communities and biomes. It is well known from the paleoecological literature that species have migrated in the past in response to changes in climate (e.g., Davis and Shaw 2001), and relatively recent evidence demonstrates that species ranges are already beginning to change in response to contemporary climate change (Parmesan and Yohe 2003; Walther et al. 2002). A critical question given the expected rate of climate change over the next decades is whether and which species will be able to migrate fast enough to keep pace with the changing climate. The answer to this question is relevant to issues as diverse as the conservation of species and the carbon balance of ecosystems. It has been recognized for some time that models of ecosystem response to climate change must include migration, but the challenges of incorporating these effects into models are immense. A GCTE activity was devoted to this issue (Pitelka et al. 1997; Neilson et al. 2005), and in Chap. 11, Midgley et al. review our current understanding and the hurdles that still face ecologists in understanding and predicting future migrations of plants.

Migration is actually a two-part process, with one being dispersal and the second successful establishment and population growth. Disturbance by fire could be one of the most important mechanisms that would facilitate and speed up the successful establishment of migrant species. Because fire occurs across much of the Earth's land surface, it also has great significance for the carbon budget of terrestrial ecosystems. Thus, it is critically important for ecologists to understand how fire regimes might change with global change and incorporate this understanding in models of ecosystem response, especially to climate change. Keane et al. (Chap. 12) review models of vegetation dynamics that incorporate fire and describe our current understanding of global fire dynamics.

A major concern throughout global change science is the potential for non-linearities in responses of ecosystems or other components of the Earth System (Steffen et al. 2004). Fire is an example of a process that can spread non-linearly across space and generate cascading effects (see Chap. 14 by Peters et al.). Unless scientists can identify where and when non-linear responses are likely, human society will like be unprepared for their occurrence, and thus the consequences are likely to be far greater than if the response had been identified and anticipated. In Chap. 14, Peters et al. describe a general framework for understanding and predicting spatially non-linear responses to global change.

A GCTE activity that built on the understanding developed in other areas of GCTE research, including the efforts referred to above, is the development of Dynamic Global Vegetation Models or DGVMs. Early in the history of GCTE entirely different classes of models were employed to simulate how climate change affects ecosystem structure and composition vs. ecosystem processes. These models were equilibrium models that could not predict how long it would take to reach a future state or the vegetation dynamics of the process. The next development was a simple linking of vegetation and ecosystem models such that the ecosystem models used the future vegetation distribution predicted by vegetation models as inputs (VEMAP Members 1995). Meanwhile, ecosystem modelers recognized the need to fully couple vegetation and ecosystem models and make them dynamic, i.e., to develop DGVMs. Prentice et al. (Chap. 15) provide a review of DGVMs, including their successes in simulating various phenomena, as well as their limitations.

DGVMs and most other types of models described in this section do not simulate individual plant species but rather group species into a relatively small number of *plant functional types*, or PFTs, with similar morphological and physiological traits. Lavorel et al. (Chap. 13) describe the efforts to develop useful and logical classifications of plants into PFTs.

## 1.5 Managing Ecosystem Services

Many of the GCTE activities directly contributed to a better understanding of the provision of goods and services for the well-being of human societies, and how those goods and services were being altered by changes in atmospheric composition, climate and land use. However, the single biggest contribution came from the focus on "agroecology and production systems" which dealt with the effects of global change on the production of food as a key component in global food security. A number of networks and consortia were established to study individual crops including wheat (see Chap. 16 by Porter et al.), rice, potato, pastures, and forest plantations. Key outcomes from this research were a better understanding of the benefits of increasing atmospheric $CO_2$ on crop production and how warming, nutrients, and water modulate that response, either by dampening it or by enhancing it depending on the particular combination. Temperature thresholds for crop failure were also identified for some of the rice varieties growing under elevated $CO_2$ and warming. This research naturally included the role of agricultural pests in reducing food production and how climate change is likely to alter pest-plant dynamics (see Chap. 17 by Sutherst et al.).

The work in agroecosystems also extended to the integration of food/fiber production and biogeochemistry to fully account for plant-soil feedbacks, and with that the study of soil carbon sequestration which yielded one of the important legacies of GCTE, a global soil organic matter database and a number of carbon sequestration assessments under different climate and management scenarios (SOMNET; see Chap. 18 by Smith et al.).

A key development which required higher level integrative research was the one on complex agroecosystems and farm-level integration of the management of single units of land with multiple crops, as separate subsystems, or as a single interconnected complex systems. The latter are still the systems that much of the world's population relies on for food and fiber despite an overall push for intensification and simplification.

Two additional chapters complement what is perhaps one of the most critical trade-offs in managing ecosystem goods and services, that between carbon and water. Chap. 19 by Jackson et al. focuses on this trade off in conversions to forests and shrublands, and Chap. 20 by Reynolds et al. focuses on a new paradigm to explain the natural and human dimensions of land degradation in arid and semi-arid regions.

## 1.6 Regions under Stress

The GCTE made a substantial effort to initiate research on the effects of global change on terrestrial ecosystems in parts of the world where little research or capacity existed despite playing key roles in the functioning of the Earth System.

Early in the 1990s the GCTE developed the transect approach for global change research, establishing 15 transects in critical regions of the world to cover most environmental conditions and biomes/ecotones with special attention to highly sensitive regions (e.g., high latitudes and tropical regions) (Canadell et al. 2002).

The transect approach has evolved over the years to comprehensive regional studies building upon the initial research undertaken during the 1990s. In this book we present research focusing on several key sensitive regions in the world including tropical Asia (see Chap. 21, Murdiyarso et al.), regions affected by the Monsoon climate (see Chap. 22 by Zhou, and Chap. 23 by Kohyama et al.), and high latitude ecosystems (see Chap. 24, McGuire et al.).

## 1.7 The Way Forward

As noted earlier, the GCTE has now ended, but clearly there is still much to do to understand the effects of global change on terrestrial ecosystems. Research on terrestrial ecosystems will continue under the auspices of the new Global Land Project (GLP), a joint project of the IGBP and the International Human Dimensions Program (IHDP). The GLP will integrate research elements from both GCTE and the Land-Use and Land-Cover Change (LUCC) project, the latter already jointly sponsored by the IGBP and IHDP. A major goal is to treat human activities and decision-making as an integral part of the terrestrial system, the so called human-environment system. The final chapter of this book, Chap. 25 by Ojima et al., describes the science objectives of the GLP and the innovative research agenda on land for the next decade (GLP 2005).

In addition, GCTE has also contributed a great deal to the development of the scientific agendas of the Global Carbon Project (GCP) and the Global Environmental Change and Food Systems (GECAFS), both joint projects of the new Earth System Science Partnership (ESSP). The ESSP has brought together IGBP, IHDP, the World Climate Research Program, and Diversitas, and has developed a highly interdisciplinary and integrative research agenda to support Earth System sustainability.

## References

Canadell J, Steffen W, White PS (eds) (2002) IGBP/GCTE Terrestrial transects: dynamics of terrestrial ecosystems under environmental change. Journal Vegetation Science 13:297–448

Crutzen PJ, Stoermer EF (2002) The Anthropocene. IGBP Newsletter 41:17–18

Davis MB, Shaw RG (2001) Range shifts and adaptive responses to Quaternary climate change. Science 292:673–679

GLP (2005) Science Plan and Implementation Strategy. IGBP Report No. 53/IHDP report no. 19. IGBP Secretariat, Stockholm, 64 pp

Hooper DU, Chapin FS, Ewel JJ, Hector A, Inchausti P, Lavorel S, Lawton JH, Lodge DM, Loreau M, Naeem S, Schmid B, Setala H, Symstad AJ, Vandermeer J, Wardle DA (2005) Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. Ecological Monographs 75:3–35

Loreau M, Naeem S, Inchausti P, Bengtsson J, Grime JP, Hector A, Hooper DU, Huston MA, Raffaelli D, Schmid B, Tilman D, Wardle DA (2001) Biodiversity and ecosystem functioning: current knowledge and future challenges. Science 294:804–807

Loreau M, Inchausti P, Naeem S (2002) Biodiversity and ecosystem functioning: synthesis and perspectives. Oxford University Press, Oxford

Mooney HA, Canadell JG (2001) The Earth System: biological and ecological dimensions of global environmental change. Encyclopedia of Global Environmental Change Vol. 2, Wiley, London

Mooney H, Canadell JG, Chapin FS, Ehleringer J, Körner Ch, McMurtrie R, Parton W, Pitelka L, Schulze D-E (1999) Ecosystem physiology responses to global change. In: Walker BH, WL Steffen, J Canadell, JSI Ingram (eds) The terrestrial biosphere and global change. Implications for natural and managed ecosystems. Cambridge University Press, Cambridge, pp141–189

Neilson RP, Pitelka LF, Solomon AM, Nathan R, Midgley GF, Fragoso JMV, Lischke H, Thompson K (2005) Forecasting regional to global plant migration in response to climate change. BioScience 55:749–759

Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421: 37–42

Pitelka LF, Gardner RH, Ash J, Berry S, Gitay H, Noble IR, Saunders A, Bradshaw RHW, Brubaker L, Clark JS, Davis MB, Sugita S, Dyer JM, Hengeveld R, Hope G, Huntley B, King GA, Lavorel S, Mack RN, Malanson GP, McGlone M, Prentice IC, Rejmanek M (1997) Plant migration and climate change. American Scientist 85:464–473

Rustad LE, Campbell JL, Marion GM, Norby RJ, Mitchell MJ, Hartley AE, Cornelissen JHC, Gurevitch J, GCTE-NEWS (2001) A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. Oecologia 126:543–562

Sala OE, Chaping III FS, Gardner RH, Laurenroth WK, Mooney HA, Ramakrishnan PS (1999) Global change, biodiversity and ecological complexity. In: Walker B, Steffen W, Canadell J, Ingram J (eds) The terrestrial biosphere and global change. Cambridge University Press, Cambridge, pp 304–328

Sala OE, Chapin III FS, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke LF, Jackson RB, Kinzig A, Leemans R, Lodge DM, Mooney HA, Oesterheld M, Poff NL, Sykes MT, Walker BH, Walker M, Wall DH (2000) Biodiversity – global biodiversity scenarios for the year 2100. Science 287:1770–1774

Shaver GR, Canadell J, Chapin III FS, Gurevitch J, Harte, Henry G, Ineson P, Jonasson S, Melillo J, Pitelka L, Rustad L (2000) Global warming and terrestrial ecosystems: a conceptual framework for analysis. BioScience 50:871–882

Steffen WL, Walker BH, Ingram JSI, Koch GW (1992) Global change and terrestrial ecosystems: the operational plan. IGBP Report No. 21, Stockholm, 97 pp

Steffen W, Sanderson A, Tyson PD, Jager J, Matson PA, Moore III B, Oldfield F, Richardson K, Schellnhuber HJ, Turner II BL, Wasson RJ (2004) Global change and the Earth System. A planet under pressure. The IGBP Series, Springer, Berlin

VEMAP members (1995) Vegetation/ecosystem modeling and analysis project: comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and $CO_2$ doubling. Global Biogeochem Cycles 9:407–438

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of Earth's ecosystems. Science 277:494–499

Walker BH, Steffen WL (1997) Global change and terrestrial ecosystems. IGBP Book Series. Cambridge University Press, Cambridge

Walker BH, WL Steffen, J Canadell, JSI Ingram (1999) The terrestrial biosphere and global change. Implications for Natural and Managed Ecosystems. Cambridge University Press, Cambridge

Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin JM, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416:389–395