

1 Introduction

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1.1 Managed Ecosystems and the Future Supply of Raw Materials

Managed ecosystems provide most of our food, much of our wood and fiber and increasingly are being considered as a source of renewable energy. Forecasting the ability of managed ecosystems to continue these vital roles under global atmospheric change has been the subject of a great deal of modeling effort. Model projections reviewed by the Intergovernmental Panel on Climate Change (IPCC 2001a) suggest that the increased temperature and decreased soil moisture that would otherwise lower crop yields will be offset by the direct fertilization effect of rising carbon dioxide concentration ($[\text{CO}_2]$; for a review, see Long et al. 2005). Averaged across the globe, total crop yield may rise; but this would be achieved by generally lower yields in the tropics and increased yields in the temperate zones. The IPCC (2001a) projected that world grain prices, an indicator of the balance between supply and demand, will continue to fall during through this century. However, model projections can only be as good as their parameterization; and establishing the effect of elevated $[\text{CO}_2]$ on yield is more challenging than for other abiotic factors. Yet it is critical, since it is CO_2 that provides the security in these projections. Without the “ CO_2 -fertilization” effect, global climate change would cause large losses in food supply and other products of managed ecosystems. For the world’s major crops, vast quantities of data are available which show how yields are affected by inter-annual and geographical variation in temperature, precipitation and soil moisture. This information is used to parameterize and validate models. Approximately 150 years ago, atmospheric $[\text{CO}_2]$ was ca. 260 ppm, but in February 2006 it reached 382 ppm, possibly for the first time in several million years. The increase in global atmospheric $[\text{CO}_2]$ in 2005 was the largest since records began. At the current accelerating rate of increase, we expect global $[\text{CO}_2]$ to reach 700 ppm by the end of the twenty-first century, according to estimations presented in the third assessment report of the IPCC

(2001b). But, unlike temperature and precipitation, $[\text{CO}_2]$ is spatially remarkably uniform across the globe. So, in contrast to temperature and precipitation, there is no consistent spatial variation on which to estimate yield responses to increasing $[\text{CO}_2]$. And it is not easy to experimentally alter its concentration within managed ecosystems, except by enclosing them. As a result, most information about crop responses to elevated $[\text{CO}_2]$ is from greenhouses, laboratory-controlled environment chambers, and transparent field chambers, where released CO_2 may be retained and easily controlled. Most of our information about the responses of managed ecosystems to rising $[\text{CO}_2]$ are from such environments, with the implicit assumption that enclosure does not significantly alter response. Plants grown in protected environments commonly appear very different to those in the field. It has therefore been uncertain whether the response of chamber-grown crop plants to elevated $[\text{CO}_2]$ will equal that of the crop in the open. FACE (free-air CO_2 enrichment), the subject of this book, is the one technique that does allow the impacts of future $[\text{CO}_2]$ on managed ecosystems be assessed without otherwise altering the environment. Although systematic side-by-side (FACE vs enclosure) trials are lacking, there is now sufficient information from FACE to show by statistical meta-analysis that the effects of elevated $[\text{CO}_2]$ on managed ecosystems differ significantly from chamber studies. Most notably, the yields of our major C3 grain crops (rice, wheat, soybean) are enhanced by elevated $[\text{CO}_2]$ by only half the amount observed in enclosures and assumed in the IPCC model projections (IPCC 2001a; for a review, see Long et al. 2005). Elevation of $[\text{CO}_2]$ to 550 ppm in FACE, the level expected by 2050, resulted in no increase in yield of the C4 cereals sorghum and maize, when a ca. 10 % increase is assumed in model projections (Leakey et al. 2006). By contrast, the yield increases of managed forest systems in FACE at elevated $[\text{CO}_2]$ are larger than those found in enclosure studies (Ainsworth and Long 2005). Given that production fuels ecosystem processes, these findings show the need to reassess how rising $[\text{CO}_2]$ will impact managed ecosystems via FACE. The following sections detail these findings.

1.2 Why are $[\text{CO}_2]$ Enrichment Studies with Managed Ecosystems Important?

Agriculture is one of the most common land uses on Earth and agroecosystems are quite extensive. Globally, 5×10^{12} ha are under agricultural management and some 13×10^6 ha are annually converted to agricultural use, mainly from forests (FAO 2002). The world resources report 2000–2001 World Resources Institute (2002) defined agricultural areas as those where at least 30 % of the land is used as croplands or highly managed pastures. According to this definition, agroecosystems cover approximately 28 % of the

total land area excluding Greenland and Antarctica and including some overlap with forest and grassland ecosystems. According to the FAO, 69 % of agroecosystems consist of permanent pastures. However, this global average masks very large differences in regional balances between crops and pastureland. On cropland, annual crops such as wheat, rice, maize, soybeans and tuber crops, which provide us with food, feed and fiber, occupy more than 90 % of the area. Thus, the share of carbon stored in agroecosystems (about 26–28 % of all carbon stored in all terrestrial systems) is about equal to the share of land that is devoted to agroecosystems. Despite the high productivity of global agriculture, much of the world's agricultural land offers less than optimal growing conditions. Soil fertility constraints include low potassium and phosphorus reserves, high sodium concentrations, a low moisture-holding capacity, or limited depth. Hence, a realistic assessment of the effects of $e[CO_2]$ has to consider the interactions between the changing additional constraints.

Between 20 % and 40 % of the world's land surface, depending on the definition used, is covered by grasslands. They are found throughout the world, in both humid and arid zones, but grasslands are particularly important features of the earth's drylands. The current volume contains two chapters on grassland from humid temperate regions only. Vast areas of rangelands, which cover more than double the global cropped area, have until now not received the attention they deserve. Only recently and for the first time have the net ecosystem CO_2 exchanges above a steppe in Mongolia been measured using the eddy covariance technique (Li et al. 2005, 2006). Moreover, grasslands provide a livelihood for 938×10^6 people (White et al. 2000), as well as forage for livestock and habitats for wildlife. Grassland vegetation and soil also store a considerable quantity of carbon. Other grassland ecosystem goods and services include cultural and recreational services, such as tourism and aesthetic gratification, and water regulation and purification.

The third class of ecosystems treated in the current volume are forests, specifically forest plantations. Forests cover about 25 % of the world's land surface, excluding Greenland and Antarctica. Although forest areas have increased slightly in industrial countries since 1980, they have declined by almost 10 % in developing countries. The greatest majority of forests in the industrial countries, except Canada, central Europe and Russia, are reported to be in "semi-natural" conditions or converted to plantations (World Resources Institute 2002). From the range of goods and services provided by forest ecosystems, the World Resources Institute considers the following five as the most important for human development and wellbeing: timber production and consumption, woodfuel production and consumption, biodiversity and watershed protection and carbon storage. Thus, forest FACE experiments seek to answer a critical question for foresters and policy-makers: Can we expect more growth and carbon sequestration in these forests in the future (see Chapters 10–13)?

The brief descriptions of the three classes of ecosystems considered in this volume convincingly highlight their economic and ecological importance. In addition, the focus of the research about the effects of $e[CO_2]$ on managed ecosystems provides two important methodological advantages:

1. Experimental manipulations of the growing conditions, such as irrigation, supply of mineral fertilizers and plants with different functional traits, offer the possibility to detect, at the stand level, interactions with other growth factors.
2. Changes of a few percent in biogeochemical cycles have major implications at the global scale, yet are unlikely to be detected in experiments elevating $[CO_2]$ in natural systems, because of the difficulty of separating $[CO_2]$ effects from the high degree of spatial heterogeneity.

Crops provide genetically uniform monocultures, planted in fields where soil, nutrients and topography are also relatively uniform. As a result, between-plot variation is minimized, allowing a high degree of statistical sensitivity. These systems also therefore serve as model, yet real-world systems, where hypotheses of elevated $[CO_2]$ effects may be tested in a cost-efficient manner, possibly providing guidance to subsequent study in natural ecosystems.

1.3 Free-Air $[CO_2]$ Enrichment

Any attempt to understand the effects of increasing atmospheric $[CO_2]$ concentration on ecosystem function must involve exposing today's ecosystems to expected future $[CO_2]$ concentrations. A solid scale-up of the results from experimental plots to the field scale has to fulfil two minimal requirements:

1. The experimental setup to increase the free-air target gas concentration should not change the microclimate within and above the canopy, including the energy balance of the plant stand.
2. The experimental plots must be large enough to permit the removal of borders with a large enough remainder to provide a reasonable yield sample.

The disregard of this second requirement leads to a seriously flawed base for scaling-up (see also Chapter 14). Free-air carbon dioxide enrichment (FACE) offers a technology which meets the first requirement by minimizing unwanted effects of the system on the plant stand, but the system is not entirely without its own limitations (see Chapter 2). FACE also allows use of the experimental plot sizes needed for a reasonable scale-up. Consequently, FACE experiments offer a distinctive platform for multidisciplinary approaches, vital in addressing the essential features of a plant stand and its soil. The experience gathered with FACE experiments during the past decade has

shown that the study of processes in the soil does require an extensive soil sampling (e.g. Van Kessel et al. 2006) and requires large plots.

Briefly, the FACE apparatus consists of a circular or octagonal system of pipes that releases either CO_2 or air enriched with the treatment gas just above the top of the crop canopy. For tall canopies (greater than 1 m), this is released at one or two additional heights below the canopy. Wind direction, wind velocity and $[\text{CO}_2]$ are measured at the centre of each plot and the information is used by a computer-controlled system to adjust the gas flow rate, controlled by a massflow control valve, to maintain the target elevated $[\text{CO}_2]$ (Long et al. 2005). FACE avoids the changes in micro-climate observed with all types of enclosure, especially warming, altered interception of precipitation and increased relative humidity, that impact evapotranspiration and feed-forward into changes in carbon uptake (Chapter 2).

The case studies presented in Section II of this volume are based on FACE technology. The different systems used include annual and perennial crops with different functional traits. Their systems vary widely in canopy structure, development of the source–sink ratios during the growing cycle and partitioning of photosynthates to the different plant parts. The plant stands were grown under a wide array of evaporative demand, soil fertility, fertilization and availability of water.

The FACE experiments are often designed to investigate fundamental mechanisms that drive ecosystem structure and function, core issues of ecology. Thus the importance of FACE experiments is not only how well they help to predict the impacts of $e[\text{CO}_2]$, but also how well they test ecological concepts in plant stands adequately representing the target ecosystem. We contend that the comprehensive studies at the large FACE sites are currently the best method to assess the impact of $e[\text{CO}_2]$. Simultaneously, they provide agronomists, foresters and breeders with the best opportunity to test and develop adaptation measures (Chapter 5).

1.4 Spatial and Temporal Scale

The effects of a major environmental variable on plants and ecological systems can be examined at spatial scales ranging from sub-cellular through to geographical regions. An example of this could be CarboEurope, which aims to understand and quantify the present terrestrial carbon balance of Europe and the associated uncertainty at local, regional and continental scales (<http://www.carboeurope.org/>). The timescales range from parts of seconds for rapid biophysical processes, to centuries for evolutionary changes. It is important to note that most field studies on the effects of $e[\text{CO}_2]$ on plants involve a step increase in atmospheric $[\text{CO}_2]$. A major assumption of these approaches has rarely been tested – that exposing an ecosystem to a single-

Managed Ecosystems and CO₂

Case Studies, Processes, and Perspectives

Nösberger, J.; Long, S.P.; Norby, R.J.; Stitt, M.; Hendrey,
G.R.; Blum, H. (Eds.)

2006, XL, 459 p., Hardcover

ISBN: 978-3-540-31236-9