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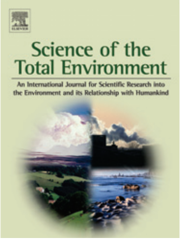

The response of terrestrial ecosystems to global climate change: Towards an integrated approach

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ABSTRACT

Accumulating evidence points to an anthropogenic 'fingerprint' on the global climate change that has occurred in the last century. Climate change has, and will continue to have, profound effects on the structure and function of terrestrial ecosystems. As such, there is a critical need to continue to develop a sound scientific basis for national and international policies regulating carbon sequestration and greenhouse gas emissions. This paper reflects on the nature of current global change experiments, and provides recommendations for a *unified multidisciplinary approach* to future research in this dynamic field. These recommendations include: (1) better integration between experiments and models, and amongst experimental, monitoring, and space-for-time studies; (2) stable and increased support for long-term studies and multi-factor experiments; (3) explicit inclusion of biodiversity, disturbance, and extreme events in experiments and models; (4) consideration of timing vs intensity of global change factors in experiments and models; (5) evaluation of potential thresholds or ecosystem 'tipping points'; and (6) increased support for model–model and model–experiment comparisons. These recommendations, which reflect discussions within the TERACC international network of global change scientists, will facilitate the unraveling of the complex direct and indirect effects of global climate change on terrestrial ecosystems and their components.

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1. Introduction

Human-induced global climate change is rapidly emerging as the single most important environmental and policy concern of the 21st century. As such, the response of terrestrial ecosystems to this global phenomenon has been the subject of intense scientific scrutiny over the past several decades, and the focus of a growing number of single- and multi-factor ecosystem-scale manipulation experiments. Results from these experiments have greatly increased our understanding of the short-term responses of terrestrial ecosystems and their components to elevated atmospheric CO_2, warming, and changes in water availability, and have provided valuable input for dozens of ecosystem-, regional-, and global scale models that are allowing us to better synthesize current understanding and project future response patterns.

Despite these advances, urgent and immediate needs remain to continue to build a sound scientific basis for national and international policies regulating greenhouse gas emissions and carbon sequestration. In order to meet these complex needs in a timely fashion, a growing consensus exists within the scientific community that it will be necessary to better integrate observational, experimental, and modeling techniques into a *unified multidisciplinary approach* to understanding ecosystem response to global change (Norby and Luo, 2004; Classen and Langley, 2005; Midgley and Thuiller, 2005; Rustad, 2006; Heisler and Weltzin, 2006; Heimann and Reichstein, 2008).

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To this end, the international research coordination network "Terrestrial Ecosystem Response to Atmospheric and Climatic Change" (TERACC) was established in 2001. The goals of TERACC are to: (1) integrate and synthesize existing whole-ecosystem research on ecosystem responses to individual global change drivers, (2) foster new research on whole-ecosystem responses to the *combined* effects of elevated atmospheric CO_2, warming, and other aspects of global change, and (3) promote better communication and integration between experimentalists and modelers. In this paper, I summarize insights from the first 5 years of TERACC, and present a framework for future opportunities to better integrate observations, experiments and models.

2. Global climate change: past, present, and future

Accumulating evidence points to an anthropogenic 'fingerprint' on global climate change driven by fossil fuel combustion and changes in land use. Since the turn of the century to 2005, atmospheric greenhouse gas concentrations have increased by ~35%, 148%, and 14% for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), respectively, and mean global temperature has increased by 0.75 °C (IPCC, 2007). Both 'recent' (past 1000 years) and geologic (past 650,000 years) reconstructions show that these increases in greenhouse gases and temperature are highly anomalous, and are currently higher than at any time in the past 650,000 years (Siegenthaler et al., 2005; National Academy of Sciences, 2006). Although more variable, changes have also been observed in patterns of precipitation, with global redistributions in precipitation amounts, and a general intensification of the hydrologic cycle leading to increases in the number of heavy rain events, and increases in the number and duration of droughts (Huntington, 2006; IPCC, 2007). Future projections indicate that these trends in greenhouse gases, temperature, and precipitation will continue, resulting in a warmer, wetter, yet drier world in the 21st century characterized by more numerous and more severe extreme events (Tebaldi et al., 2006; IPCC, 2007). These changes have already had, and will continue to have, dramatic effects on the productivity, biodiversity and biogeochemistry of terrestrial ecosystems.

3. How do we assess ecosystem response to global change?

Numerous approaches are being used to assess terrestrial ecosystem response to global change. These are discussed in broad terms here with the goal to evaluate opportunities for future synthesis and integration. Case studies highlight the need for and value in long-term experiments.

3.1. *Observations in time and space*

Observations in time and space can be made at single sites, networks of sites, and more recently, super-networks of sites. Although the accumulation of long-term records (or "long-term monitoring") is not always considered 'real science' (for a discussion, see Lovett et al., 2007), these studies provide invaluable insights and background information on ecosystem response to short-term changes in weather and long-term changes in climate. For example, Lauenroth and Sala (1992) measured precipitation inputs and aboveground net primary productivity (ANNP) at a short grass steppe site in Colorado, USA during the period 1939 to 1987. Their record shows 2 years of extreme drought (1954 and 1964) where precipitation deviated ~200 mm from the mean. Both years were also characterized by declines in ANPP. Although precipitation recovered to near normal levels in the ensuing years, ANPP showed a lag in recovery of 1–3 years, which they attribute to changes in vegetative structure. These results emphasize the value of long-term monitoring, the existence of 'lags' in response, and the importance of monitoring changes in vegetation dynamics.

At a larger scale, the National Science Foundation's (NSF) Long Term Ecological Research (LTER) network provides insights on ecosystem response to global change at broad spatial and temporal scales within the United States. This network currently consists of 26 study sites and involves the collaborative efforts of more than 1800 scientists and students (http://www.lternet.edu/). Precipitation varies from less than 100 mm/year for a tundra ecosystem at the Arctic LTER in Alaska, USA to ~2500 mm/year for a tropical rainforest at the Luquillo LTER in Puerto Rico. Temperature varies from ~−18 °C at The McMurdo Dry Valleys LTER in Antarctica to ~27 °C at the Luquillo tropical rainforest LTER in Puerto Rico. These conditions provide researcher's with a "natural" climate change laboratory. Knapp and Smith (2001), for example, used this natural gradient to demonstrate the significant, positive relationship between ANPP and precipitation for 9 of the 26 LTER sites ($r^2 = 0.83$, $P < 0.001$).

International 'super' networks of sites and scientists have also been increasing in number, scope, and value over the past decade. Examples include:

International LTER (ILTER) — 34 country-based networks of scientists engaged in long-term, site-based research; http://www.ilternet.edu/networks/index.html;
Carbo Europe — 61 sites in 17 European countries focused on understanding and quantifying the terrestrial carbon balance of Europe; http://www.carboeurope.org/;
NitroEurope — 65 partners in 23 countries focused on understanding the nitrogen cycle and its influence on the European greenhouse gas balance; http://www.nitroeurope.eu/;
TERACC — 135 sites in 25 countries focused on using experimental manipulations and models to understand ecosystem response to single and multiple elements of global change; http://www.umaine.edu/teracc/.

These networks represent various levels of coordination, collaboration and communication and provide important frameworks for continental-or-greater-scale evaluations of global change effects on terrestrial ecosystems. The draw back is that these super-networks require increased financial and logistical resources for infra-structure and coordination, and therefore must require large and stable funding commitments.

3.2. *Climate gradient studies*

Although long-term observations in time and space provide the ultimate validation of ecosystem and global scale models,