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Impacts of climatic and atmospheric changes on carbon dynamics in the Great Smoky Mountains National Park

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Model simulations suggest that rising atmospheric CO_2 compensates for the adverse effects of ozone stress on ecosystem carbon dynamics in Great Smoky Mountain National Park.

Abstract

We used the Dynamic Land Ecosystem Model (DLEM) to estimate carbon (C) storage and to analyze the impacts of environmental changes on C dynamics from 1971 to 2001 in Great Smoky Mountain National Park (GRSM). Our simulation results indicate that forests in GRSM have a C density as high as 15.9 kg m^{-2}, about twice the regional average. Total carbon storage in GRSM in 2001 was 62.2 Tg ($T = 10^{12}$), 54% of which was in vegetation, the rest in the soil detritus pool. Higher precipitation and lower temperatures in the higher elevation forests result in larger total C pool sizes than in forests at lower elevations. During the study period, the CO_2 fertilization effect dominated ozone and climatic stresses (temperature and precipitation), and the combination of these multiple factors resulted in net accumulation of 0.9 Tg C in this ecosystem.

Keywords: Carbon storage; Multiple stresses; Air pollution; Ozone; Carbon dioxide

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1. Introduction

Forests have been major carbon (C) sinks in the United States (US) during the 20th century (Turner et al., 1995). The balance of this C sink can be affected by global climatic and atmospheric changes, and global forest NPP has increased in the last 20 years due to changes in these factors (Boisvenue and Running, 2006). Many natural forests in the US are in Class I Wilderness areas. These areas are generally located in more remote regions and are protected by Federal regulations (Department of the Interior (DOI), 1982), and include 16 national parks and other protected, ‘‘near-natural’’ environments. These forests can store large amounts of C, and play an important role in the regional and global C balance. Global change effects that are primarily transmitted via the atmosphere are likely to be detectable in these protected mountainous-forested ecosystems, especially at high altitudes where the ecosystems are generally considered to be sensitive to climate change. These forested ecosystems, therefore, may serve as locations where the environmental impacts of climatic and atmospheric change can be studied directly. Furthermore, meteorological, hydrological, and forest types change strongly over relatively short distances in mountain regions. As a result, the ecosystem C storage and its responses to global change also differ dramatically along the altitudinal gradients. Therefore, the strong altitudinal gradients in mountainous environments provide unique and sometimes the best opportunities to analyze global change processes and their impacts on C dynamics of natural forests (Becker and Bugmann, 2001).

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The most significant atmospheric change during the last two centuries is the rapid rise of atmospheric CO_2 concentration which has been suggested to result in global climate change. Studies showed that the increased atmospheric CO_2 concentration can enhance forest growth and C sequestration capacity (Tian et al., 2000), thus providing a negative feedback at the atmospheric level. The beneficial effect of CO_2 fertilization, however, could be offset by the damaging effects of other air pollutants such as tropospheric ozone (Adams et al., 1986; Chappelka and Samuelson, 1998; Felzer et al., 2004). To understand the effects of global change on C dynamics of forests in national parks, the effects of CO_2 (Ellsworth, 1999; Loya et al., 2003), climate (Tian et al., 1998), ozone (Chappelka et al., 1988; Pye, 1988; Chappelka and Chevone, 1992), and their interactions (Ollinger et al., 1997; Tian et al., 1999, 2000; Boisvenue and Running, 2006) should be investigated. Furthermore, the various responses of different plant functional types to these stressors are also important (Reich, 1987; Chappelka and Samuelson, 1998; Weinstein et al., 2001). The large number of possible combinations and long-term periods over which they operate, however, make it nearly impossible to investigate the effects of multiple stresses on ecosystem C storage through controlled experiments (Ollinger et al., 2002). Integrated process models, which include the physiological responses of ecosystems to atmospheric and climatic changes can be quite useful in such multiple stressor studies (Ollinger et al., 1997, 2002; Martin et al., 2001; Felzer et al., 2004; Hanson et al., 2005; Karnosky et al., 2005).

In this study, we use the Dynamic Land Ecosystem Model (DLEM), an integrated ecosystem process model (Tian et al., 2005) that couples major biogeochemical and hydrological cycles to make daily and spatially-explicit estimates of carbon fluxes and pool sizes in Great Smoky Mountains National Park (GRSM) from 1971 to 2001. DLEM is able to address responses of terrestrial ecosystems to multiple stresses including changes in climate, atmospheric composition (CO_2 and ozone), land use, and natural disturbances. The GRSM represents forested ecosystems typical of the eastern mixed pine hardwood regions in the US (Whittaker, 1966), a region that has long been recognized as being strongly affected by elevated ozone concentrations (Neufeld et al., 1992; Mueller, 1994; Chappelka and Samuelson, 1998; Weinstein et al., 2001). GRSM is located downwind of large urban and industrial areas that generate large amounts of air pollutants or their precursors (Christine et al., 1994). Many field studies have revealed that GRSM forest growth has been inhibited by ozone pollution (Neufeld et al., 1992; Somers et al., 1998). Simulations have been conducted by Weinstein et al. (2001) to investigate the effect of ozone stress on photosynthesis and succession of a forest community in the Twin Creeks area of GRSM. Comprehensive evaluation of the impacts of multiple climate and atmospheric stresses on ecosystem productivity and C storage of the whole GRSM region has not yet been attempted. The purpose of this study was to use a model simulating approach to estimate the changes in GRSM C storage from 1971 to 2001 and to analyze forest responses to climate change, CO_2 fertilization, tropospheric ozone stress, and the interactions of these multiple stresses.

2. Methods

2.1. Study region

Great Smoky Mountains National Park, the largest Class I Wilderness area in the eastern US, was established along the border of western North Carolina and eastern Tennessee in 1934 to protect the 2079 km^2 continuous eastern mixed pine hardwood forests that consist of approximately 85% deciduous forest, 13% coniferous forest, and <2% in heath bald (MacKenzie, 1993; Figs. 1 and 2). Elevations in GRSM range from approximately 250 m along the outside boundary of the Park up to more than 2000 m in the center of the park (Fig. 1). The broad ranges of elevations in GRSM contribute to a wide variety of climates (Shanks, 1954; Busing et al., 2005). The climate is humid and warm at lower elevations, cool and wet at higher elevations (Thornthwaite, 1948). Annual precipitation at lower elevations is around 1200 mm while can be as high as 2000 mm at higher altitudes, similar to some of the wettest regions in the US (Busing et al., 2005). Overall annual average temperatures range from 10 to 12 °C.

The boreal or alpine coniferous forests [spruce-fir (*Picea abies*)] are located above 1400 m (Figs. 1 and 2). Northern Hardwood Forests dominate middle to upper elevations from 1000 to 1500 m in the park. Oak (*Quercus* spp.) is the major component in this region. Pine (*Pinus* spp.) forests grow within low-elevation regions, especially in the northwestern portion of the Park (Fig. 2).

Ozone exposures in the park are among the highest in the eastern US (Mueller, 1994; US EPA, 2001; DOI, 2002). The mean summer hourly ozone concentration was about 51 ppb (Look Rock ozone monitor site) to 55 ppb (Cove Mountain ozone monitor site) during the 1980s and early 1990s (Mueller, 1994), while damage to vegetation was found to occur at levels as low as 50 ppb. On average, ozone concentrations over the ridgetops of the park can be as high as or higher than in nearby cities, including Knoxville and Atlanta (DOI, 2002). The average ozone concentration measured in the summer of 1989–1991 at the Hendersonville station in metropolitan Nashville, for example, was 6–12 ppb lower than the value measured at Great Smoky Mountain stations (Mueller, 1994). Data from the Clean Air Status and Trends Network (CASTNET) (http://www.epa.gov/castnet/) shows that the SUM06 index [calculated as the sum of hourly O_3 concentrations above 60 ppb summed over 12 h (08:00 to 20:00) during a 3-month period] at the GRSM Look Rock ozone monitoring station in the summer of 2001 was about 27 (ppb-h). This value is higher than the 25 ppb-h that the US Environmental Protection Agency (US EPA) proposed as an alternative secondary standard (http://www.epa.gov/castnet/). Ozone pollution results in visible injury in GRSM vegetation (Neufeld et al., 1992). In a survey conducted in GRSM, Chappelka et al. (1997) reported 47% of the over 1600 black cherry (*Prunus serotina*) examined showed visible foliar symptoms of ozone injury.

2.2. The Dynamic Land Ecosystem Model (DLEM)

The DLEM (Tian et al., 2005; Chen et al., 2006) is a process-based model which couples biophysical processes (energy balance), biogeochemical processes [water cycles, carbon cycles, nitrogen cycles, and trace gas (NO_x, CH_4)-related processes], community dynamics (plant distribution and succession), and disturbances (land conversion, agriculture management, forest management, and other disturbances such as fire, pests, etc.) into one integral model system (Fig. 3). DLEM can simulate the complex interactions of multiple stresses such as climate change, elevated CO_2, tropospheric O_3, N deposition, human disturbance, and natural disturbances.

In DLEM, the carbon balance of vegetation is determined by photosynthetic rate, autotrophic respiration, litterfall (related to tissue turnover rate and leaf phenology), and plant mortality rate. Plants assimilate carbon by photosynthesis, and then use this carbon to compensate for the loss through maintenance respiration, tissue turnover, and reproduction. The photosynthesis submodel of DLEM estimates net C assimilation rate, leaf daytime maintenance respiration rate, and gross primary productivity (GPP, unit: $g\ C\ m^{-2}\ day^{-1}$). The photosynthetic rate is first calculated at the leaf level. The results are then multiplied by the leaf area index to scale up to the canopy level (Tian et al., 2005). To simulate the detrimental effect of air pollution on