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Simulated response of conterminous United States ecosystems to climate change at different levels of fire suppression, CO_2 emission rate, and growth response to CO_2

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ABSTRACT

A modeling experiment was designed to investigate the impact of fire management, CO_2 emission rate, and the growth response to CO_2 on the response of ecosystems in the conterminous United States to climate scenarios produced by three different General Circulation Models (GCMs) as simulated by the MC1 Dynamic General Vegetation Model (DGVM). Distinct regional trends in response to projected climatic change were evident across all combinations of the experimental factors. In the eastern half of the U.S., the average response to relatively large increases in temperature and decreases in precipitation was an 11% loss of total ecosystem carbon. In the West, the response to increases in precipitation and relatively small increases in temperature was a 5% increase in total carbon stocks. Simulated fire suppression reduced average carbon losses in the East to about 6%, and preserved forests which were largely converted to woodland and savanna in the absence of fire suppression. Across the west, unsuppressed fire maintained near constant carbon stocks despite increases in vegetation productivity. With fire suppression, western carbon stocks increased by 10% and most shrublands were converted to woodland or even forest. With a relatively high level of growth in response to CO_2, total ecosystem carbon pools at the end of the century were on average about 9–10% larger in both regions of the U.S. compared to a low CO_2 response. The western U.S. gained enough carbon to counter losses from unsuppressed fire only with the high CO_2 response, especially in conjunction with the higher CO_2 emission rate. In the eastern U.S., fire suppression was sufficient to produce a simulated carbon sink only with both the high CO_2 response and emission rate. Considerable uncertainty exists with respect to the impacts of global warming on the ecosystems of the conterminous U.S., some of which resides in the future trajectory of greenhouse gas emissions, in the direct response of vegetation to increasing CO_2, and in future tradeoffs among different fire management options, as illustrated in this study.

1. Introduction

Several modeling studies have been conducted with the MC1 DGVM (Daly et al., 2000; Bachelet et al., 2001b) to investigate the sensitivity of natural ecosystems to potential climate change in the United States, both at regional and national scales (Daly et al., 2000; Bachelet et al., 2000, 2003, 2004, 2005; Hayhoe et al., 2005; Lenihan et al., 2003, 2006, in press). The results show equally plausible GCM climate scenarios can generate significant differences in the simulated future response of ecosystems. Different trends in projected precipitation have produced much of the regional variation in ecosystem response simulated by MC1 within the conterminous U.S. (e.g., Bachelet et al., 2003; Lenihan et al., 2003). Continual improvements in GCM technology and computing resources will presumably result in greater convergence among GCM-simulated climate scenarios over time, thereby reducing uncertainty related to model inputs in simulating the ecosystem response to climate change.

There are additional sources of uncertainty in simulating the ecosystem response apart from differences among climate scenarios, including those which stem from an uncertain understanding of key ecosystem processes. For example, the direct response of vegetation productivity to increasing concentrations of atmospheric CO_2 could play a key role in the future response of ecosystems, but results of various free-air CO_2 enrichment (FACE) experiments have yet to provide definitive guidance for ecosystem modelers (Boisvenue and Running, 2006). Experiments in young forest stands have shown an average 23% increase in net primary production (NPP) for CO_2 concentrations of 550 ppm as compared to ambient concentrations (Norby et al., 2005). However, experiments in older forest stands have shown little or no increase in carbon storage with increases in NPP (e.g., DeLucia et al., 2005; Körner et al., 2005; Ashoff et al., 2006). Uncertainty regarding the direct CO_2 effect and its role in the ecosystem response to climatic change is compounded by the uncertain future trend in atmospheric CO_2. In a study comparing the response of MC1 and LPJ (Stich et al., 2003) to climate change scenarios for the U.S.

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(Bachelet et al., 2003), different sensitivities to CO_2 interacting with different assumed trajectories in atmospheric CO_2 concentrations were prominent factors explaining significant differences in the responses simulated by the two models.

Additional uncertainty resides in the assumed future capacity of human intervention to alter climate-driven trends in ecosystem properties. For example, future wildland fire management could be a significant factor in the response of U.S. ecosystems to a changing climate. Past and present fire regimes in the U.S. are strongly controlled by climate at multiple time scales (Swetnam and Betancourt, 1998; Whitlock et al., 2003; Westerling and Swetnam, 2003; Schoennagel et al., 2004), and there is growing evidence that rising temperatures throughout the western U.S. are driving recently observed increases in wildfire frequency and area (Westerling et al., 2006). Fire is a global control on vegetation structure (Bond 2005, Bond et al., 2005), and fire disturbance has triggered abrupt changes in vegetation structure and composition in response to past changes in climate (Green, 1982; Overpeck et al., 1990; Clark 1990; Keely and Rundel, 2005). Decades of fire suppression have significantly altered vegetation structure and fire regimes in the U.S., especially in the semi-arid forests of the West (Covington and Moore, 1994; Allen et al., 2002; Schoennagel et al., 2004), and wildland fire management will continue to shape vegetation and its adjustment to climatic change into the future.

Here we describe the results of a modeling experiment designed to investigate the effect of different levels of fire suppression, CO_2 emission rate, and the direct CO_2 effect on the ecosystem response to climatic change simulated by MC1. Results were calculated as averages across simulations for different GCM climate scenarios to reduce variation associated with different climatic projections and to focus the investigation on the response to the CO_2 and fire treatment factors.

2. Methods

2.1. MC1 model description

MC1 is a dynamic vegetation model (DGVM) that simulates plant type mixtures and vegetation types; the movement of carbon, nitrogen, and water through ecosystems; and fire disturbance. MC1 routinely generates century-long, regional-scale simulations on relatively coarse-scale data grids (Daly et al., 2000; Bachelet et al., 2000, 2001a, 2003, 2004, 2005; Hayhoe et al., 2005; Lenihan et al., 2003, 2006, in press). The model reads soil and monthly climate data, and calls interacting modules that simulate biogeography, biogeochemistry, and fire disturbance (Bachelet et al., 2001a).

The biogeography module simulates mixtures of evergreen needleleaf, evergreen broadleaf, and deciduous broadleaf trees, and C3 and C4 grasses. The tree lifeform mixture is determined at each annual time-step as a function of annual minimum temperature and growing season precipitation. The C3/C4 grass mixture is determined by reference to their relative potential productivity during the three warmest consecutive months. The tree and grass lifeform mixtures together with growing degree-day sums and biomass simulated by the biogeochemistry module are used to determine which of twenty-two possible potential vegetation types occur at the grid cell each year. For this study, the twenty-two types were aggregated into twelve vegetation classes to simplify the presentation of results.

The biogeochemistry module is a modified version of the CENTURY model (Parton et al., 1994) which simulates plant growth, organic matter decomposition, and the movement of water and nutrients through the ecosystem. Plant growth is determined by empirical functions of temperature, moisture, and nutrient availability which decrement set values of maximum potential productivity. In this study, plant growth was assumed not to be limited by nutrient availability. The direct effect of an increase in atmospheric carbon dioxide (CO_2) is simulated using a beta factor (Friedlingstein et al., 1995) that increases maximum potential productivity and reduces the moisture constraint on productivity. Grasses compete with woody plants for soil moisture and nutrients in the upper soil layers where both are rooted, while the deeper-rooted woody plants have sole access to resources in deeper layers. The growth of grass may be limited by reduced light levels in the shade cast by woody plants. The values of model parameters that control woody plant and grass growth are adjusted with shifts in the lifeform mixture determined annually by the biogeography module.

The MC1 fire module simulates the occurrence, behavior, and effects of fire. The module simulates the behavior of a simulated fire event in terms of the potential rate of fire spread, fireline intensity, and the transition from surface to crown fire (Rothermel, 1972; van Wagner, 1993; Cohen and Deeming, 1985). Several measurements of the fuel bed are required for simulating fire behavior, and they are estimated by the fire module using information provided by the other two MC1 modules. The current lifeform mixture is used by the fire module to select factors that allocate live and dead biomass into different classes of live and dead fuels. The moisture content of the two live fuel classes (grasses and leaves/twigs of woody plants) is estimated from moisture at different depths in the soil provided by the biogeochemical module. Dead fuel moisture content is estimated from climatic inputs to MC1 using different functions for each of four dead fuel size-classes (Cohen and Deeming, 1985).

Fire events are triggered in the model when the Palmer Drought Severity Index (PDSI), the moisture content of coarse woody fuels, and the flammability of fine fuels all meet set thresholds. Sources of ignition (e.g., lightning or anthropogenic) are assumed to be always available. Area burned is not simulated explicitly as fire spread within a given cell. Instead, the fraction of a cell burned by a fire event is estimated as a function of set minimum and maximum fire return intervals for the dynamically-simulated vegetation type, the current monthly value of PDSI, and the number of years since a simulated fire event.

Because the fire module was designed to simulate the natural fire regime, total area burned in the conterminous United States over the historical period is overpredicted in comparison to observed data, especially over the last half century when fire suppression was most effective. Unpublished comparisons to observed total annual area burned showed simulated area burned was, on average, about eight times greater than observed. Accordingly, to roughly estimate the effect of fire suppression in MC1 simulations, there is a provision within the module to dynamically limit annual area burned in each grid cell to 12.5% of the unconstrained value.

The fire effects simulated by the model include the consumption and mortality of dead and live vegetation carbon, which is removed from (or transferred to) the appropriate carbon pools in the biogeochemistry module. Live carbon mortality and consumption are simulated as a function of fireline intensity and the tree canopy structure (Peterson and Ryan, 1986), and dead biomass consumption is simulated using functions of fuel moisture that are fuel-class specific (Anderson et al., 2005).

2.2. Model inputs

The climate data used to generate the MC1 simulations for this study were monthly values for the input variables (i.e., precipitation, minimum and maximum temperature, and vapor pressure) distributed on a 0.5° resolution data grid for the conterminous United States. Climate data for the historical (1895–2003) and future period (2004–2100) were generated by the VINCERA (*V*ulnerability and *I*mpacts of *N*orth American Forests to *C*limate Change: *E*cosystem *R*esponse and *A*daptation) project (Price, this issue). Two sets of three monthly future climate scenarios were generated at the 0.5° resolution from the output of three General Circulation Models (Canadian CGCM2, UK HADCM3, and Australian CSIRO Mk2) forced by two different greenhouse gas (GHG) emission scenarios (IPCC SRES A2 and B2).