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Simulating impacts of water stress on woody biomass in the southern boreal region of western Canada using a dynamic vegetation model

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ABSTRACT

Drought-related dieback of aspen-dominated woodland has been a persistent and possibly increasing phenomenon over recent decades in the southern boreal forests of western Canada. The Integrated BIosphere Simulator (IBIS) dynamic vegetation model was modified for Canadian ecosystems (hence "Can-IBIS") and used to simulate effects of water stress on the woody biomass of aspen-dominated stands in the boreal mixedwood regions of Saskatchewan and Alberta. The modified model was evaluated using eddy-covariance measurements of CO_2 and water vapor fluxes made at a forested site and a grassland site located in the study region. The tested model captured 74% of the variation in biomass growth trajectories at 13 boreal and 12 parkland field study sites; the mean difference between simulated and observed values was approximately 1100 g C m^{-2}. Under the combined influences of climatic variation and increasing atmospheric CO_2 from 2000 to 2008, simulated values of net biomass growth were 544 and 240 g C m^{-2} for the boreal and parkland study sites, respectively. Drought-induced biomass losses at the drier sites (in both boreal and parkland regions) were simulated to be 100–350 g C m^{-2}, corresponding to an annual modeled mortality rate of 5–7% during severe drought years. These results were consistent with field measurements and other statistical studies. Changes in biomass over the nine-year period varied with geographical location and corresponded to spatial variation in monthly values of the self-calibrated Palmer Drought Severity Index. We conclude that Can-IBIS can be used to investigate annual impacts of water stress on woody biomass growth, although cumulative physiological effects of multi-year droughts on tree mortality would benefit from improved simulation of subgrid-scale (soil texture-driven) processes. In particular, two areas for further development are: (1) calibration based on the results of soil surveys at fine spatial/temporal scales; and (2) biophysical experiments to refine the representation of water stress constraints on biomass turnover.

1. Introduction

Recent effects of large-scale droughts on forest productivity have been widely reported (e.g., Allen et al., 2010; Schwalm et al., 2012; van der Molen et al., 2011; Zhao and Running, 2010), some of which may have the potential to alter the composition, structure, and biogeography of forests in many regions. In regions that are already subject to frequent droughts, such as the prairies and southern boreal forests of western Canada, climate warming is expected to continue, causing a reduction in ecosystem carbon sinks and possibly triggering the replacement of forest by parkland, shrubland or grassland ecosystems. The potential consequences of a warmer and generally drier climate for forest carbon stocks at continental to global scales imply an urgent need to improve understanding of the effects of drought, and of the mechanisms of water stress, on forest ecosystems.

Canada's boreal forest land area covers 309 Mha and 8% of the world's forest (Brandt et al., 2013), located in a high latitude region where climate warming is predicted to occur at approximately

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double the global average rate (IPCC, 2007). Climate change-induced droughts would cause increased losses of carbon to the atmosphere, through increased tree mortality, accelerated decomposition of dead organic material, reduced net ecosystem productivity (NEP), and by contributing to increased occurrence of wildfires. In Canada, the forest ecosystems most sensitive to drought are generally to be found in the southern ecoregions of the western boreal zone—which are characterized by relatively low annual precipitation and high evaporative demand during summer. Two central questions are: What is the significance of drought as a driver of large-scale tree mortality and, how can the effects of water stress on forest biomass be accounted for in dynamic vegetation models?

Recent analyses of permanent sample plot measurements (Ma et al., 2012; Peng et al., 2011) indicate that the rate of biomass change in Canadian boreal forests has varied with climatic regions. It appears that forest biomass has declined significantly in recent decades in some western Canadian boreal forests, though comparable trends were not found in eastern Canada. In reality, responses of vegetation to drought are likely to include reduced photosynthesis (Adams et al., 2009; Garcia-Quijano and Barros, 2005; Quillet et al., 2010), increased allocation to fine roots (Di Iorio et al., 2011; Wang et al., 2008), reduced water uptake and transpiration (El Maayar et al., 2009; Granier et al., 2007; Zheng and Wang, 2007), foliage loss (Landhäusser and Lieffers, 2011; Worrall et al., 2008, 2010), die-back of above-ground portions (Delbart et al., 2010; Kreyling et al., 2008), and increased mortality (Allen et al., 2010; Michaelian et al., 2010; Sala, 2009; Zeppel et al., 2011). While young forest stands (Amiro et al., 2006; Hebert et al., 2006; Spies et al., 2006) and tree seedlings (Chiatante et al., 2006; Huddle and Pallardy, 1996) may be particularly sensitive, severe drought can lead to die-back or complete mortality of mature trees that is often linked to increased susceptibility to pests and/or diseases (e.g., Michaelian et al., 2010) and depletion of non-structural carbohydrate reserves (e.g., Tague et al., 2013). Better understanding of the causes of drought and the regional responses of vegetation can contribute to more explicit representation of mortality mechanisms in dynamic vegetation models (DVM) used in global climate studies (e.g., Foley et al., 1996; Quillet et al., 2010).

From a modeling perspective, water stress is generally assumed either to operate on stomatal conductance directly, or to reduce photosynthetic capacity, causing a feedback on stomatal conductance (e.g., Kucharik et al., 2000; Delbart et al., 2010; Wang et al., 2012). Dynamic schemes for allocating photosynthate (i.e., net primary production, NPP) may also imply a growth response to water stress, by increasing the fraction of NPP allocated to roots when water stress is considered to limit water uptake. In stand-based forest productivity models drought-induced mortality can be represented as reduced probability of seedling survival. For mature trees, drought effects contributing to increased individual tree death might be captured as an increase in the intrinsic ("background") mortality rate. However, many models do not represent drought effects because there are several theories about the causes of tree mortality (Quillet et al., 2010), and how these are mediated by drought, so it is difficult to decide which is the most appropriate for general application. Developing mechanistic tree mortality algorithms for use in DVMs is challenging (Wang et al., 2012), but necessary to improve the prediction of productivity responses to climate change and hence, to improve projections of future forest carbon budgets. Therefore, assessing the impacts of water stress on forest ecosystems requires a more quantitative understanding of ecophysiological responses, including drought-induced mortality mechanisms, and their consequences at fine spatial and temporal scales.

In this study, a well-established DVM was modified to simulate effects of water stress on the biomass of aspen-dominated stands in the boreal mixed wood and aspen parkland ecoregions of Saskatchewan and Alberta. Model parameterization and validation were based on meteorological and eddy-covariance data obtained from the Fluxnet-Canada archive and a regional study of aspen (*Populus tremuloides* Michx.) productivity and survival. The main objectives of this study were: (1) to simulate the major effects of drought on woody biomass using water stress constraints in a dynamic vegetation model (i.e., Can-IBIS); and (2) to investigate the sensitivity of woody biomass to varying levels of drought intensity in the southern boreal and prairie regions of western Canada.

2. Methods

2.1. Sites and measurements

The Climate Impacts on Productivity and Health of Aspen (CIPHA) study was established in 2000, to monitor health and dieback of aspen-dominated stands across the western Canadian interior (Fig. 1; also see Hogg et al., 2005; Michaelian et al., 2010). Within CIPHA, there are 13 long-term research sites located in the southern boreal forest (denoted BOR from here on) and 12 in the subhumid ecoregion that extends between the true boreal forest and the open prairies, generally known as the aspen parkland (denoted PRK from here on), as listed in Table 1. The aspen parkland is now predominantly agricultural, as most of the prairie grassland and some of the woodlands have been converted to cropland or pasture.

The ages of the 25 CIPHA sites ranged from 50 to 89 years at the end of the study period (2000–2008), with 1940 being the mean date of stand establishment. At each CIPHA study site, three pure aspen stands were selected within a maximum distance of 30 km from one another. Two plots were established in each stand, 50–100 m apart and at least 50 m from the stand edge. Total height and stem DBH (diameter at breast height, 1.3 m) of every tree in each plot was measured in 2000, 2004 and 2008 (see Hogg et al., 2005 for methodological details). Annual tree health assessments (i.e., tree status and incidence of insects, diseases, and other damage agents) were conducted within each plot during the early part of the growing seasons (late May to July) of 2000–2008. Tree-ring analysis was conducted on all plots during 2004–2005 and in 2008. Tree-ring data and tree health assessments were used to estimate annual stand-level tree biomass using the Canadian national equations of Lambert et al. (2005).

2.2. Model description

In this study, version 2.5 of the Integrated BIosphere Simulator (IBIS) of Foley et al. (1996) was modified extensively for application to Canadian forest ecosystems, and hence named "Can-IBIS". Like IBIS, Can-IBIS is a one-dimensional representation of soil, vegetation and atmosphere interactions, allowing it to be run for individual sites and on spatial grids of various scales. The model includes the soil biogeochemistry model of Kucharik et al. (2000), which is based in turn on Verberne et al. (1990) and the CENTURY model of Parton et al. (1993). Litter is tracked separately from fine roots, foliage and woody biomass, and each of these are split into metabolic, structural and lignin (recalcitrant) pools in addition to microbial biomass and non-protected, protected and passive soil organic matter pools, each with appropriate decay coefficients. Can-IBIS also features a plant–soil nitrogen (N) cycling model (Liu et al., 2005), superimposed on the Kucharik et al. (2000) model, which tracks the transformations of nitrogen from above- and below-ground litter pools based on C:N ratios of each litter and soil C component and a set of N control modifiers. The resulting concentrations of soil nitrate and ammonium are combined with