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Soil–plant nitrogen cycling modulated carbon exchanges in a western temperate conifer forest in Canada

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Abstract

Nitrogen controls, on the seasonal and inter-annual variability of net ecosystem productivity (NEP) in a western temperate conifer forest in British Columbia, Canada, were simulated by a coupled carbon and nitrogen (C&N) model. The model was developed by incorporating plant–soil nitrogen algorithms in the Carbon-Canadian Land Surface Scheme (C-CLASS). In the coupled C&N-CLASS, the maximum carboxylation rate of Rubisco (V_{cmax}) is determined non-linearly from the modelled leaf Rubisco-nitrogen, rather than being prescribed. Hence, variations in canopy assimilation and stomatal conductance are sensitive to leaf nitrogen status through the Rubisco enzyme. The plant–soil nitrogen cycle includes nitrogen pools from photosynthetic enzymes, leaves and roots, as well as organic and mineral reservoirs from soil, which are generated, exchanged, and lost by biological fixation, atmospheric deposition, fertilization, mineralization, nitrification, root uptake, denitrification, and leaching. Model output was compared with eddy covariance flux measurements made over a 5-year period (1998–2002). The model performed very well in simulating half-hourly and monthly mean NEP values for a range of environmental conditions observed during the 5 years. C&N-CLASS simulated NEP values were 274, 437, 354, 352 and 253 g C m^{-2} for 1998–2002, compared to observed NEP values of 269, 360, 381, 418 and 264 g C m^{-2}, for the respective years. Compared to the default C-CLASS, the coupled C&N model showed improvements in simulating the seasonal and annual dynamics of carbon fluxes in this forest. The nitrogen transformation to soil organic forms, mineralization, plant nitrogen uptake and leaf Rubisco-nitrogen concentration patterns were strongly influenced by seasonal and annual temperature variations. In contrast, the impact of precipitation was insignificant on the overall forest nitrogen budget. The coupled C&N modelling framework will help to evaluate the impact of nitrogen cycle on terrestrial ecosystems and its feedbacks on Earth's climate system.

Keywords: Nitrogen cycle; Photosynthesis; Net ecosystem productivity; Canadian Land Surface Scheme; Eddy covariance; Temperate conifer forest

1. Introduction

Land surface schemes are key components of global climate models (Pitman, 2003). They control the exchange and storage of energy, water and carbon (C) between the land-surface and the atmosphere. The Canadian Land Surface Scheme (CLASS; Verseghy, 2000) is one of several such schemes and is the operational soil–vegetation–atmosphere–transfer (SVAT) package of the Canadian Global Climate Model (Flato et al., 2000). Recently CLASS has been further improved by incorporating photosynthesis and

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respiration algorithms for C_3 and C_4 plants, known as C-CLASS (Arain et al., 2002; Wang et al., 2001), and by including a dynamic vegetation model, namely the Canadian Terrestrial Ecosystems Model (CTEM) (Arora and Boer, 2005).

In C-CLASS, photosynthesis algorithms are based on the biogeochemical model of Farquhar et al. (1980) and relate canopy assimilation with stomatal conductance, following Ball et al. (1987). However, similar to the most current carbon coupled land surface schemes, a key C-CLASS parameter, known as the maximum carboxylation rate of Rubisco (V_{cmax}), is prescribed for plant functional types or species. V_{cmax} is known to have a strong association with leaf nitrogen content (Dang et al., 1997; Field and Mooney, 1986; Reich et al., 1997) and tightly relates to overall plant–soil nitrogen cycling (Dickinson et al., 2002). It is affected by environmental factors such as radiation, temperature, precipitation and soil moisture, directly or indirectly, through plant–soil carbon and nitrogen cycling.

Many studies, such as Schlesinger and Lichter (2001) and Shaver and Chapin (1986), reported nitrogen availability limitations on plant growth in northern hemisphere terrestrial ecosystems, particularly in forests. Sellers et al. (1997) described suppressed photosynthetic rates and lower stomatal conductance in boreal forest ecosystems due to poor soil nutrient status, particularly nitrogen in soils. This phenomenon is expected to be further aggravated in the future because of increasing temperatures and atmospheric CO_2 concentrations. Rising temperatures may cause higher evapotranspiration leading to lower soil and plant water status and hence reduced plant growth (Grant et al., 1999). On the other hand, rising temperatures may also cause higher plant respiration and soil organic matter decomposition, resulting in improved soil nutrient (nitrogen) availability. Currently, the scientific community is exploring for how long likely enhancement in nitrogen availability, through organic matter decomposition and/or atmospheric deposition, would support future plant growth. Various elevated-CO_2-studies suggest downregulation of plant photosynthetic capacity after initial stimulation under high CO_2 concentrations due to constraints on nutrient (nitrogen) supply (Long et al., 2004).

Hungate et al. (2003) suggested that nitrogen deposition rates, which have increased many fold during the last few decades, would not be enough to support increased plant growth predicted by global climate change models. Therefore, nutrient cycling, in particular nitrogen cycling, may have important feedbacks on global environmental change (Davidson et al., 2000; Schimel, 1995). A thorough understanding of plant–soil nitrogen cycling processes, and their control on canopy assimilation and water use, is essential to accurately predict responses of terrestrial ecosystems to future climate change.

In this study, we incorporated a plant–soil nitrogen (N) cycling scheme in C-CLASS (Arain et al., 2002) following Dickinson et al. (2002) with a few modifications. In the coupled C&N-CLASS, the V_{cmax} is determined non-linearly from the modelled leaf Rubisco-nitrogen, using a relationship derived from investigations by Warren and Adams (2001). Hence, variations in canopy assimilation, and thus stomatal conductance, are modulated by leaf nitrogen status through Rubisco enzyme. In the model, leaf nitrogen status tightly associates with overall soil–plant nitrogen cycling, particularly with root N uptake processes. Modelled root N uptake, which is governed by plant growth-dependent N demands and storage capacity, is determined by soil inorganic ion transportation to root interface and absorption into root. Unlike Dickinson et al. (2002), we defined non-structural C pool increment as a function of both leaf and fine root biomass C, with a range of prescribed C:N ratios for N storage (due to either reallocation or excess soil supply) or reuse. In C&N-CLASS nitrogen uptake rate can be enhanced or limited by plant growth, depending on N demand and non-structural storage capacity. This modification has helped to solve carbon uptake underestimation during initial canopy development (low leaf area index, LAI) periods as mentioned by Dickinson et al. (2002). Performance of the coupled C&N-CLASS model was evaluated using eddy covariance flux data measured over 5 years (1998–2002) in a mature temperate conifer (Douglas-fir) forest. Diurnal, seasonal, and annual variability in ecosystem C exchanges simulated by the coupled C&N-CLASS model were compared with the same fluxes calculated by the default C-CLASS model. The main objectives of the study were (i) to determine nitrogen controls on photosynthetic uptake in a forest ecosystem, and (ii) to describe the responses of soil–plant nitrogen dynamics and net ecosystem productivity (NEP) to seasonal and interannual climate variability.

2. Model description

2.1. A brief overview of the photosynthesis submodel in C-CLASS

CLASS is a physically based land-surface model that simulates energy and water exchanges from the