



Assessing nitrogen controls on carbon, water and energy exchanges in major plant functional types across North America using a carbon and nitrogen coupled ecosystem model



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ABSTRACT

A carbon and nitrogen coupled dynamic vegetation ecosystem model (CLASS-CTEM^{N+}) was used to assess the effects of nitrogen controls on simulated carbon, water and energy exchanges in a range of vegetation ecosystems. Standardized meteorological forcing data and eddy covariance flux measurements of carbon, water and energy from 32 FLUXNET sites covering eight major plant functional types (PFTs) across North America were used in the analysis. Two versions of the model, a carbon and nitrogen (C–N) coupled version and carbon (C) only version, were employed. Simulated diurnal, daily, seasonal and annual values of gross ecosystem productivity (GEP), ecosystem respiration (Re), net ecosystem productivity (NEP), net radiation (Rn), sensible heat flux (H), latent heat flux (LE) and vegetation biomass and soil carbon stocks were compared with available measured values to evaluate the model's performance in each PFT.

The C–N version of the model simulated annual mean NEP for all sites was 211 g C m⁻² yr⁻¹, compared to 174 g C m⁻² yr⁻¹ from observation and 253 g C m⁻² yr⁻¹ by the C version, respectively. Overall, the inclusion of a nitrogen cycle with the carbon cycle in the model resulted in better accuracy scores (e.g., reduced RMSE by 0.31, 0.10 and 0.09 g C m⁻² yr⁻¹ in the C–N version relative to the C version, for GEP, Re and NEP, respectively) when compared with observations. Simulated Rn, H and LE were usually improved with the inclusion of a nitrogen cycle, but the changes were not always statistically significant at the site level as they were with carbon exchanges. Results indicated the simulated N limitation effects varied among PFTs, but were strongest for boreal forests during the early-growing season. Evaluation of N deposition impacts on GEP, NEP and biomass pools showed considerable variability between and within forest types due to non-linearity of N effects and spatial heterogeneity of C and N cycle interactions. Inclusion of the N cycle in the model will help in its application at regional and global scales to evaluate N availability impacts on the C cycle in terrestrial ecosystems and to determine N cycle feedbacks on Earth's climate.

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1. Introduction

Terrestrial vegetation ecosystems play an important role in regulating Earth's climate. Rising atmospheric carbon dioxide (CO₂) levels which can enhance photosynthesis, the so-called CO₂ fertilization effect (Dolman et al., 2010), and enhanced deposition of reactive nitrogen (N) on land surfaces, have affected terrestrial vegetation ecosystems (Gruber and Galloway, 2008) and the global climate (Arneeth et al., 2011). Studies suggest that increases

in atmospheric N deposition in industrialized regions have contributed significantly to the terrestrial carbon (C) sink, particularly through enhancing vegetation growth in N limited areas (Quinn Thomas et al., 2011), such as the boreal forest (Fleischer et al., 2013).

Large uncertainty exists in the exact contribution of N deposition (or N fertilization) on the historical and future C sink (Heimann and Reichstein, 2008; Reay et al., 2008). There is evidence that N-limitation may suppress maximum photosynthesis rates and hence the response of C uptake to increasing atmospheric CO₂, particularly in forests (Bonan, 2008; Nadelhoffer et al., 1999). Leaf N controls on photosynthesis may also affect stomatal conductance, and hence, evapotranspiration and the energy balance (Dickinson

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et al., 2002). Warming may increase the availability of mineral N to plants and has the potential to stimulate C storage in plants (Meilillo et al., 2002). N limitation may also alter plant respiration due to changes in plant tissue N content (Reich et al., 2008). The impact of increased N availability in soils is even more uncertain; some studies suggest that soil C may decrease with increased N availability, while others suggest no change or increases in C storage (Reay et al., 2008). Thus, it is currently unclear how changes in N availability would affect C sequestration in vegetated ecosystems under enhanced atmospheric CO₂ concentrations and warmer temperatures. Understanding of N cycling impacts on C, water and energy exchanges in terrestrial ecosystems is necessary to produce accurate climate change scenarios that include the major feedback mechanisms, in particular those related to plant and soil nutrient status.

A key development since the IPCC Fourth Assessment Report (AR4) is the emergence of coupled global C–N cycles in operational Earth System Models (ESMs) (IPCC et al., 2013). While recent studies agree in general, that the future net C uptake of global terrestrial vegetation can be reduced by N limitations, and that warmer temperatures can result in increased soil N mineralization with increasing C uptake (Goll et al., 2012; Sokolov et al., 2008), which reduces the C cycle's sensitivity to changes in temperature and precipitation (Bonan and Levis, 2010; Sokolov et al., 2008; Thornton et al., 2009), the relative magnitudes of these C–N integrated effects diverge between model studies, leaving the exact contribution of N deposition on the historical and future C sink uncertain.

One of the challenges for C–N coupled modeling is to represent and quantify micro-scale processes of C–N cycle dynamics and uncertainties at the ecosystem level, which is limited to the available observations, to constrain models at large scales. In our previous study, N controls on C and water exchanges were analyzed in a temperate conifer forest in Ontario, Canada using a newly developed C–N coupled model, CLASS-CTEM^{N+} (Huang et al., 2011). CLASS-CTEM^{N+} is a process-based dynamic global vegetation model (DGVM) derived from two existing models: The Canadian Land Surface Scheme (CLASS) (Verseghy and Lazare, 1993; Verseghy, 1991) and the Canadian Terrestrial Ecosystem Model (CTEM) (Arora and Boer, 2003, 2006, 2005a,b), with a newly incorporated representation of soil–plant nitrogen (N) cycling algorithms (Arain et al., 2006; Huang et al., 2011; Yuan et al., 2008). Simulated values of soil–plant N contents and C and N fluxes were compared with available observation-based estimates for the study period (2003–2007). Model results showed that a proper representation of N controls on photosynthetic uptake and canopy conductance results in more plausible simulations of observed C and water fluxes. However, CLASS-CTEM^{N+} was not tested in other key biomes or plant functional types (PFTs).

Aimed at increasing the utility of C–N interactions from site-level simulations to represent and constrain performance towards regional to global scales, in this study we expand on the analysis of Huang et al. (2011) by systematically examining the model performance with respect to simulated C, water and energy fluxes and pools using observations from 32 FLUXNET sites across North America, spanning over 168 site-years and 8 PFTs as classified by the International Geosphere–Biosphere Programme (IGBP). Specific objectives are: (1) evaluation of the models' parameterizations for simulating C, water and energy dynamics in major PFTs using FLUXNET direct observations; (2) investigation of N constraints on C and water exchanges in different regional PFTs; and (3) assessment of C sequestration responses under increasing N deposition levels. The C–N coupled model simulations and parameters will serve as a strong foundation for future regional and global scale and long-term modeling studies.

2. Methods

2.1. CLASS model

The CLASS model was developed at Environment Canada for use in the Canadian Global Climate Model (CGCM) (Verseghy and Lazare, 1993; Verseghy, 1991, 2000). CLASS was originally designed with a composite canopy, composed of amalgamated properties of up to four vegetation classes (needleleaf trees, broadleaf trees, crops and grass) plus urban areas. The grid-cell is also divided into vegetated and bare soil fractions, each with and without snow cover, which are treated separately. There are three soil layers (with depths of 0.1, 0.25, and 3.75 m), a variable depth snow layer where applicable, a single vegetation canopy layer (which intercepts both rain and snow), prognostic soil temperatures and liquid and frozen soil moisture contents. Surface properties such as roughness length and albedo are functions of vegetation type, and soil moisture and texture. The absorption of visible and NIR radiation is based on vegetation-dependent visible and NIR albedo and transmissivity, while net long-wave radiation absorbed by the canopy is based on the sky-view factor, which describes the degree of the canopy closure. The original canopy conductance parameterization used in CLASS was similar to that of the Jarvis model (Jarvis, 1976), where canopy resistance (r_c) is expressed as a function of minimum stomatal resistance and a series of environmental dependences whose effects are assumed to be multiplicative. Later, two leaf (sunlit and shaded) C and soil–plant N cycle modules were incorporated into developmental versions of CLASS known as C-CLASS and CN-CLASS, respectively (Arain et al., 2002, 2006).

2.2. CTEM model

CTEM (Arora and Boer, 2003, 2005a,b, 2006; Arora, 2003) was developed at the Canadian Centre for Climate Modelling and Analysis (CCCma), Environment Canada, to simulate dynamic vegetation and carbon cycling in the Canadian Earth System Model (Arora et al., 2009, 2011). Version 1.2 of CTEM used here simulates the terrestrial ecosystem processes of photosynthesis, autotrophic and heterotrophic respiration, leaf phenology, allocation, biomass turnover, litterfall, and mortality, and prognostically determines the carbon in the model's three live (leaves, stem and root) and two dead (litter and soil C) pools. These processes are modeled for nine PFTs in CTEM that are linked directly to the four broad PFTs of CLASS (see Table 1): needleleaf trees are divided into evergreen and deciduous sub-types, broadleaf trees are divided into evergreen and cold- and drought-deciduous sub-types, and grasses and crops are divided into C₃ and C₄ sub-types.

Photosynthesis in CTEM is based on the biochemical model of Farquhar et al. (1980), Collatz et al. (1991, 1992) and its application for C₃ and C₄ pathways in CTEM is described in Arora (2003). The coupling between photosynthesis and canopy conductance is based on vapor pressure deficit (Leuning et al., 1995) and when coupled to CTEM, the stomatal resistance calculated by the Jarvis type parameterization in CLASS is not used. The photosynthesis or gross ecosystem productivity (GEP) and autotrophic respiration (Ra) and heterotrophic respiration (Rh) parameterizations are described in Arora (2003). Net primary productivity (NPP = GEP – Ra) is allocated to leaves, stem, and roots depending on water availability, light limitation and leaf phenological status. Prognostic leaf area index (LAI) is then determined from the leaf C and specific leaf area (SLA) (Dickinson et al., 1998).

Phenology in CTEM is based on a carbon-gain approach. Leaf onset is initiated when it is beneficial for the plant, in C terms, to produce new leaves. Leaf offset is initiated by unfavorable environmental conditions, including shorter day length, cooler temperatures, and low soil moisture (Arora and Boer, 2005a).

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