Ecological Modelling 312 (2015) 385–405

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Coupling boreal forest CO_2, H_2O and energy flows by a vertically structured forest canopy – Soil model with separate bryophyte layer

Samuli Launiainen [a,*], Gabriel G. Katul [b], Ari Lauren [a], Pasi Kolari [c]

[a] Natural Resources Institute Finland, Environmental Impact of Production, Vantaa, Finland
[b] Nicholas School of the Environment and Earth Sciences, Duke University, Durham, NC, USA
[c] University of Helsinki, Department of Physics, Helsinki, Finland

ARTICLE INFO

Article history:
Received 18 November 2014
Received in revised form 25 May 2015
Accepted 3 June 2015
Available online 25 June 2015

Keywords:
Boreal forest
Multi-layer SVAT model
Moss layer
Energy exchange
Gas exchange
Soil water balance

ABSTRACT

A 1-dimensional multi-layer, multi-species soil-vegetation-atmosphere transfer model APES (Atmosphere-Plant Exchange Simulator) with a separate moss layer at the forest floor was developed and evaluated for a boreal Scots pine forest situated in Hyytiälä, Southern Finland. The APES is based on biophysical principles for up-scaling CO_2, H_2O, heat and momentum exchange from canopy element level to a stand scale. The functional descriptions of sub-models were parametrized by literature values, previous model approaches and leaf and moss gas exchange measurements, and stand structural characteristics derived from multi-scale measurements. The model was independently tested against eddy-covariance fluxes of CO_2, H_2O and sensible heat measured above and within the canopy, and against soil heat flux and temperature and moisture profiles. The model was shown to well reproduce fluxes and resulting scalar gradients at diurnal and seasonal timescales. Also predictions for moss moisture content and soil moisture and temperature dynamics were acceptable considering the heterogeneity in soil hydraulic and thermal properties and uncertainties in boundary conditions.

The model framework allows for (1) coupling above-ground with the soil domains through the feedbacks between soil water and vegetation mediated by the moss layer, (2) several vascular plant species or cohorts in a multi-species canopy, and (3) explicit treatment of bryophyte layer energy and water balance and bottom layer – atmosphere exchange. These features make APES well-suited for exploring feedbacks between boreal forest structure, site conditions and vegetation processes controlling ecosystem-atmosphere exchange.

1. Introduction

Being the largest biome globally, boreal forests have direct effects on regional and global climate through absorption of solar radiation and momentum, and partitioning of the net radiation into sensible *H* and latent heat *LE* (Bonan, 2008; Chapin et al., 2000; Law et al., 2002; Baldocchi, 2008; Baldocchi et al., 2000). Their appreciable carbon dioxide uptake from the atmosphere and influence on biogenic aerosol formation are now rarely disputed (Malhi et al., 1999; Mäkelä et al., 1997; Spracklen et al., 2008). Temporal variations in the structure and function of boreal forests occur at multiple scales, from seconds (e.g. radiation regime inside the canopy, leaf gas exchange, turbulent flow) to seasonal (phenology, annual cycle of functional substances) and longer (stand age, species composition, management). Spatial variability among stands is commonly associated with gradients in the climate and site type, which in turn, affect species composition and stand structure. Also, forest management does have major impacts on such forests thereby drawing significant research interest in the interplay between silviculture and the role of boreal forests in climate regulation (Esseen et al., 1997; Bengtsson et al., 2000).

Plant carbon uptake, water use and energy exchange with the atmosphere in response to environmental variations remains complex and governed by multiple interactions and feedbacks. Changes in structure and function of boreal forests affect within-canopy and soil micro-environment that then impact the rates of carbon dioxide (CO_2), water (H_2O), heat and momentum exchanges occurring within and between canopy elements as well as soil layers. When spatially integrated, these alter the bulk exchange rates between the forest ecosystem and the atmosphere as well as water, carbon and nutrient flows in catchments. Considering water and carbon fluxes in the forest stand for instance, increase of overstory leaf area leads to greater amount of precipitation being intercepted, resulting in a decreased throughfall and soil infiltration. Simultaneously,

* Corresponding author. Tel.: +358 29 532 5323.
E-mail address: samuli.launiainen@luke.fi (S. Launiainen).

http://dx.doi.org/10.1016/j.ecolmodel.2015.06.007
0304-3800/

absorption of radiation is enhanced and carbon uptake and transpiration rates from the overstory are expected to increase leading to more rapid depletion of soil water within the root zone. In coarse-textured sites, this depletion increases the probability of 'ecological drought', i.e. water deficits in the root zone, that can then modify a plethora of processes related to tree responses to climate variation, forest floor fluxes and soil processes (Skre and Oechel, 1981; Vargas et al., 2010; Williams et al., 2012; Katul et al., 2012; Zhou et al., 2013).

Delineating the causes and projecting the responses of forest ecosystems to changing environmental conditions and management requires mathematical models that describe the interplay between forest structure, micro-climate and site conditions. In canvassing available methods for representing the soil-plant-atmosphere system, the level of details within and across various compartments can be daunting and often un-balanced. For example, 3-D models of water flow in the soil-root system have been used for quite some time to describe water uptake where root-distribution and morphology is known at different resolution (Couvreur et al., 2012; Doussan et al., 2006; Siqueira et al., 2008; Simunek and Hopmans, 2009; Manoli et al., 2014). Often, such models remain primitive in their treatment of above-ground processes. Likewise, 3-D radiation models have been developed and linked to photosynthesis when spatial heterogeneity in the light environment is large (Cescatti and Zorer, 2003; Cescatti, 1997), but again, these models commonly ignore below ground-processes altogether. Other approaches that seek maximum simplicity represent the entire canopy as a single layer (big-leaf) and the entire soil-root system in a lumped layer (Porporato et al., 2004). This approach clearly misses potentially significant gradients in the micro-environment (both above and below ground) that non-linearly interact with layer-wise sources and sinks (Juang et al., 2008).

Due to absorption of solar radiation and momentum, the largest micro-climatic gradient in vegetation canopies occurs vertically, necessitating, at minimum, 1-D multi-layer soil-vegetation-atmosphere transfer models (SVAT's). Common to the multi-layer models is that they assume the planar gradients in mass, heat, and energy fluxes and micro-climatic state variables small when compared to vertical inhomogeneities across the entire canopy height. By combining canopy radiation schemes and eco-physiological principles with turbulent transport representation, they enable predictions and independent verification of stomatal and other pathways by which CO_2, water vapor, and other scalars are exchanged between leaves, canopy elements and the atmosphere across various levels within the canopy volume (Meyers and Baldocchi, 1988; Harley and Baldocchi, 1995; Leuning et al., 1995; Baldocchi and Meyers, 1998; Ogée et al., 2003; Juang et al., 2008; Olchev et al., 2008).

The utility of such model framework is that relying on quantitative biophysical representation of canopy and soil processes, most of which can be independently parametrized and verified, enables direct up-scaling from element to stand scale (and beyond). However, significant challenges still remain when describing feedbacks between the above-ground and soil domains and resolving the vegetation functioning and root water and nutrient uptake under non-optimal soil water conditions (Simunek and Hopmans, 2009; Manzoni et al., 2010; Markewitz et al., 2010; Katul et al., 2012; Zhou et al., 2013; Volpe et al., 2013). Neither are the moss layer processes in boreal ecosystems sufficiently described (Stoy et al., 2012). This layer has a fast response time scale associated with radiation fluctuations at the forest floor, an intermediate time scale response associated with drying of the soil, and a slow response time scale associated with the dynamics of stand leaf area. Addressing the above challenges require models that enable species-specific representation of atmosphere-plant exchange (Ogée et al., 2003; Olchev et al., 2008; Flerchinger et al., 2009) that is becoming possible through leaf-scale data collected to plant trait databases such as TRY (Kattge et al., 2011).

In this work, a parsimonious treatment of below and above ground processes using a 1-D multi-layer, multi-species forest canopy – soil model labeled APES (Atmosphere-Plant Exchange Simulator) that accounts for the vertical structure and functional diversity of boreal forests is proposed. The APES describes the main structural and functional compartments of a boreal forest ecosystems accommodating the effects of vascular plant species and the bryophyte layer at the forest floor as well as their interactions with the forest soil and canopy microclimate. Formulations in each layer (soil, plant or canopy air space) reflect a trade off between desirable traits of realism and simplicity. We first describe the model theory along with how its parameters are estimated. Then, we evaluate the APES predictions against ecosystem-scale CO_2, H_2O and energy fluxes and environmental data measured in a Scots pine stand at the Hyytiälä SMEAR II -station in Southern Finland. Finally, we consider the soil controls on leaf gas-exchange and bottom layer processes. In future studies, the APES is used to disentangle the leaf-area, species, soil and silvicultural controls of boreal forest H_2O, CO_2 and energy exchange.

2. Model framework

In APES, the main compartments of the forest stand are described as objects that include the governing conservation equations and contain structural and functional description of the respective part of the ecosystem (Fig. 1). The independent objects and sub-models are then linked by physical transport processes, formulated using gradient-diffusion approximations

$$f_s = -K_i \frac{\partial s}{\partial z} = g_i \Delta s, \quad (1)$$

that links flux f_s to local gradient of s $(\partial s/\partial z)$ using an exchange coefficient or conductivity K_i, or bulk conductance g_i.

The above-ground airflow sub-model represents the canopy as a horizontally homogenous porous medium, where canopy elements are randomly distributed in horizontal space. The canopy structure is primarily accounted through a vertical leaf-area density distribution $\Lambda_{l,t}(z)$ ($m^2\,m^{-3}$) satisfying the normalizing condition $LAI = \int_0^h \Lambda_{l,t}(z)dz$, where LAI is the leaf area index and h is the canopy height. The transfer and absorption of shortwave and longwave radiation, transport of scalars and momentum and partitioning of rainfall between interception and throughfall also occurs in these canopy layers, impacted by $\Lambda_{l,t}(z)$.

The forest *Canopy* object consists of one or several *PlantTypes*, which may be vascular plant species, functional groups or age cohorts distinguished by their structural properties, such as leaf or root area densities, height and leaf size, and/or by physiological characteristics such as phenology, photosynthetic capacity and stomatal conductance. Leaf gas and energy exchange is calculated separately for sunlit and shaded leaves using well-established iterative solution of coupled photosynthesis-stomatal conductance theories (Farquhar et al., 1980, 2001; Katul et al., 2010; Medlyn et al., 2012) and leaf energy balance. Solutions of soil water and heat transfer in the *SoilProfile* object are linked to physiological controls at the leaf level, and root water uptake is described by a macroscopic multi-layered root model (Volpe et al., 2013). A separate *BottomLayer* object describes water, energy and CO_2 dynamics in the bryophyte layer at the forest floor.

As time-dependent forcing variables, APES uses time-averaged (usually 1/2 hourly) meteorological variables at a reference level above the canopy. These variables include direct and diffuse photosynthetically active (Q_p) and near-infrared (Q_n) radiation, mean