Effect of Canopy Architecture on Carbon and Water Fluxes: A Numerical Experiment

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Abstract: In this study, we used a spatially-explicit ecohydrological model as a framework for a numerical experiment to explore the implication of canopy architecture on the simulated ecophysiological processes in a boreal ecosystem. We constructed two modeling scenarios (*CLUMPED* and *RANDOM*) that differed only in the manner in which canopy clumping index (Ω) was parameterized within the model and analyzed the simulated ecophysiological processes. We considered the spatio-temporal distribution of the two main ecohydrological indicators: the gross primary productivity (GPP) and evapotranspiration (ET) under the two scenarios. We hypothesized that Ω can affect the partitioning of light distribution in the canopy and hence the accuracy of the simulated GPP and ET via leaf physiological variability. From the preliminary results of this numerical experiment, we concluded that errors in the parameterization of canopy architectural properties had considerable effects on the magnitudes of the simulated ecophysiological processes directly through changes in canopy RT and indirectly through changes in soil water balance-based feedback mechanisms. Hence, we believe that it is important to explicitly consider Ω in ecological models because it can govern the partitioning of light inside a canopy.

Keywords: Canopy architecture; Canopy Clumping Index; Spatially-Explicit Ecohydrological Model; Numerical Experiment; Photosynthesis Anomaly; Evapotranspiration Anomaly

Introduction

High latitude boreal forests play a major role in the global climate dynamics. Vegetation in these ecosystems is dominated by coniferous forests, whose canopy architectures are highly clumped and non-randomly distributed in space. This is an adaptation to facilitate a greater amount of light penetration deep into the canopy for photosynthesis. The probability of the transmission of a beam of light through the canopy can is greatly controlled by the nature of the canopy clumping, which is conventionally denoted by the clumping index (Ω). Currently, very few regional scale models explicitly consider canopy architectural properties to realistically represent canopy radiative transfer (RT) mechanism that in-turn affects leaf physiology and the related feedback mechanisms, which greatly govern the simulated results. Considering this, our overall objective was to explore whether detailed information on the canopy architecture is an essential requirement in order to realistically simulate ecophysiological processes of C and water fluxes in a spatially explicit manner.

In this study, we used the BEPS-TerrainLab V2.0 model of Govind et al. (2009 a and b) as a framework for a numerical experiment to explore the implication of Ω on the simulated ecophysiological processes in a boreal ecosystem. We constructed two modeling scenarios (*CLUMPED* and *RANDOM*) that differed only in the manner in which Ω was parameterized within the model and analyzed the simulated ecophysiological processes. We considered the spatio-temporal distribution of the two main ecohydrological indicators: gross primary productivity (GPP) and evapotranspiration (ET) under the two scenarios. We hypothesized that Ω can affect the partitioning of light distribution within the canopy and hence the accuracy of the simulated GPP and ET via leaf physiological variability. Changes in ET due to Ω can also affect the nature of the soil water balance via canopy water interception and can cause a feedback loop that further affect the leaf physiology.

1. Modeling of Ecophysiological Processes at Leaf Scale and Upscaling to the Canopy

BEPS-TerrainLab V2.0 is a spatially explicit model that simulates the hydrological, ecophysiological and biogeochemical processes and the related feedback relationships in a tightly coupled manner. A detailed description of this model can be found in Govind et al. (2009 a and b).

Leaf-level processes (GPP and ET) are upscaled to the canopy using corresponding fractions of LAIs as weighting terms that correspond to variability in leaf physiological statuses mainly due to the two main resources, light and water. BEPS-TerrainLab V2.0 employs a modified sunlit-shaded leaf strategy i.e. the *four-leaf approach* to spatially upscale leaf-level processes to the canopy scale. It is assumed that within the two light regimes (sunlit and shaded), there are two states of moisture regimes, i.e. canopy is comprised of 4 physiologically-distinct leaf-types based on the differences in light and water status. In this model, upscaling of leaf-scale ecophysiological process to the canopy-sacle (P_o) is conceptualized in the following manner. Firstly, leaf-level ecophysiological processes are calculated using leaf-specific parameters and then upscaled to the canopy using respective LAI fractions as shown below.

$$P_o = \left[P_{sun,unsat} LAI_{over,sun} . \mu + P_{sun,sat} LAI_{over,sun} (1-\mu) \right] + \left[P_{shade,unsat} LAI_{over,shade} . \mu + P_{shade,sat} . LAI_{over,shade} (1-\mu) \right] \quad (1)$$

where,

$$\begin{aligned} P_{sun,sat} &= f_x (R_{y,sun} \;\; g_{s,sun,sat}) \\ P_{sun,unsat} &= f_x (R_{y,sun} \;\; g_{s,sun,sat}) \\ P_{shade,sat} &= f_x (R_{y,shade} \;\; g_{s,shade,sat}) \\ P_{shade,unsat} &= f_x (R_{y,shade} \;\; g_{s,shade,unsat}) \end{aligned} \quad (2)$$

For this approach, firstly the LAI of a canopy is partitioned into sunlit and shaded LAI-fractions as shown below:

$$LAI_{sun} = 2.Cos\theta . \left[1 - \mathrm{e}^{\left(\frac{-0.5.\Omega.LAI}{Cos\theta} \right)} \right] \quad (3)$$

$$LAI_{shade} = LAI_{total} - LAI_{sun} \quad (4)$$

Further, the effects of soil moisture regimes on the leaf physiological status are considered. It is assumed that rhizosphere wetting patterns proportionately influence the physiological variability of the canopy under a given light regime. This is manifested through the variable μ (Gale and Grigal, 1987), the fraction of roots in the unsaturated zone and (1 - μ) and the fraction of roots in the saturated zone. This operation finally results in 4 LAI fractions that have unique physiological statuses which vary in space and time.

The function f_x in the equation 1 can be either the Penman Monteith (PM) equation (for transpiration) or the temporally-integrated Farquhar model of Chen et al. (1999) for GPP. Both these functions use leaf-specific radiation and conductance terms. Leaf-specific stomatal conductances (g_s) are calculated using a Jarvis (1976)-like model. Here, scalars represent various environmental factors including radiation and soil moisture status. ET is the sum of transpiration and evaporation. Evaporation from the forest-floor is calculated as the weighted sum of moss evaporation and soil evaporation which is calculated using the PM equation using surface-specific conductance values. Evaporation from the leaf surface is also calculated. For the understory canopy, a *quasi-big-leaf approach* is employed as the upscaling strategy. Moss photosynthesis and evaporation are calculated using Chen et al. (1999) and the PM equation respectively. However, no spatial upscaling mechanism is considered because it assumed to be "uni-layered".

2. Site Description

Our numerical experiment focused on a 50 km^2 boreal watershed, which includes the Eastern Old Black Spruce site (EOBS) of the Canadian Carbon Program (CCP), located at 49.69°N and 74.34°W, Quebec, Canada. This region lies within the humid continental sub-arctic boreal biome in Canada. Since mid-2003, an eddy covariance (EC) tower at EOBS has been making continuous high frequency measurements of the fluxes of mass and energy between the landscape and the atmosphere. Black spruce is the dominant species in this boreal ecosystem. Paper birch and aspen can also be found on elevated locations along esker ridges.

3. Modeling Scenarios

CLUMPED- This scenario used species-specific Ω, the values of which were parameterized based on rigorous ground measurements using the TRAC instrument and Digital Hemispherical Photographs. This scenario represented a realistic representation of Ω and has been exhaustively validated with EC measurements at EOBS for two years in the previous studies.

RANDOM- This scenario assumed that leaves in a canopy are randomly distributed. Thus all the species were given a constant Ω value=1.

Both scenarios used the same spatial datasets, meteorological data, soil hydraulic and biological parameters as in Govind et al. (2009 a and b), except for the Ω parameterization.

4. Results and Discussion

Preliminary results of this study show that on an annual basis, there were considerable differences in the GPP and ET simulated by the two scenarios. The spatial distributions of the differences (*RANDOM-CLUMPED*) in estimates of the annual ET and GPP under the two scenarios are shown below, vis-à-vis a landcover map (Figure 1). GPP was overestimated in almost all landcover types and at all LAI ranges in the *RANDOM* scenario. For ET, wetland locations showed large differences. This could be because in addition to the direct effects of canopy RT which governed leaf physiological statuses which controlled transpiration; soil water balance was also altered consequently. Under the *RANDOM* scenario, in wetland locations, there was an increased wetting of soil due to decreased transpiration also increased evaporation from the forest floor.

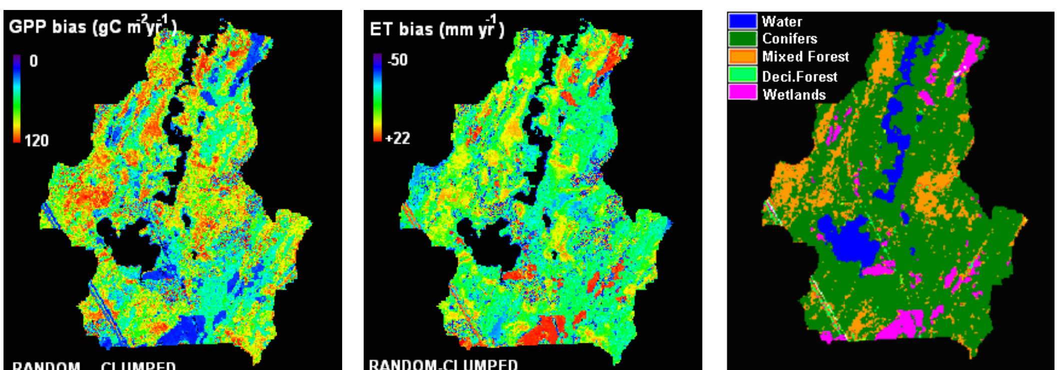

Figure 1. Difference maps of the pixel-to-pixel comparison of the simulated ecophysiological processes (annual sum) under the two scenarios. A land-cover map is also shown for a comparative analysis

A pixel-to-pixel comparison of the annual ET and GPP under the two scenarios revealed that in general, the *RANDOM* scenario overestimated the ecophysiological processes relative to the *CLUMPED* scenario. GPP was highly more sensitive to Ω than ET. This could be because ET has both transpiration (biological) and evaporation (physical) components. Increased clumping (decreasing Ω value from 1) made the canopy more non-random and allowed more radiation to be penetrated through the canopy without being intercepted by the foliage and therefore decreased sunlit LAI and increased shaded LAI. Theoretically, the partitioning of sunlit and shaded LAI varies with season owing to changes in the solar zenith angle. The ratio between sunlit and shaded LAI greatly depends on the magnitudes of the total LAI and the day of the year. Although preliminary results strongly support our hypothesis, further studies are required to better understand the complexities and non-linearities that create these anomalies.

Conclusion

From the preliminary results of this numerical experiment, we conclude that errors in the parameterization of canopy architectural properties have considerable effects on the magnitudes of the simulated ecophysiological processes directly through changes in canopy RT and indirectly through changes in soil water balance-mediated feedback mechanisms. Hence, we conclude that it is important to explicitly consider Ω in ecological models because it can govern the partitioning of light inside a canopy. This affects leaf physiology, and C and water fluxes. Mapping of clumping index using multi-angular remote sensing techniques in conjunction with precise ground measurements and RT modeling can greatly benefit coupled C and water cycle modeling at regional and global scales.

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