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Predicting canopy biophysical properties and sensitivity of plant carbon uptake to water limitations with a coupled eco-hydrological framework

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ABSTRACT

Variations in soil water availability and atmospheric water demand impact seasonal canopy dynamics are often represented by the fraction of photosynthetically active radiation (FPAR) and leaf area index (LAI) under a coupled eco-hydrologic framework. Changes in FPAR and LAI lead to changes in evapotranspiration (ET) and gross primary productivity (GPP), coupling the water and carbon cycles. In this study, a predictive Dynamic Canopy Biophysical Properties (DCBP) model is adapted to predict daily FPAR and LAI forced by observed and modeled meteorological and root-zone soil moisture conditions, respectively. Vegetation green-up and die-off responses to temperature (*T*), vapor pressure deficit (*VPD*), soil water potential (ψ_{soil}), and photoperiod (*Pht*) are modeled through a modified form of the growing season index (GSI). The DCBP model parameterizations of seasonality (*T* and *Pht*) and intraseasonal water stress (*VPD* and ψ_{soil}) are calibrated separately for distinct plant functional types (PFTs) and soil types using a Bayesian estimator. To investigate the impact of dynamic phenology on modeled GPP and hydrologic processes, phenology predicted by the DCBP model is input to the Duke Coupled Hydrology Model with Prognostic Vegetation (DCHM-PV), and hydrologic conditions are input to the DCBP model to specify water availability constraints. The coupled model framework was evaluated against AmeriFlux tower data and remotely sensed FPAR and LAI products. Sensitivity analysis of the predicted daily FPAR, LAI, and GPP to the diurnal cycle of root zone water indicates that mid-day soil water availability is the primary control on seasonality across different PFTs and soil textures in the DCBP model. Further, calibrated parameters describing plant-water relations change significantly depending on whether the inference period used in the data assimilation includes persistent meteorological drought, thus effectively resulting in distinct plant water use strategies in the DCHM-PV. The dynamics of water stress recovery are examined by mapping seasonal phenology into the phase space of soil water stress and carbon uptake. In the Southeast U.S., simulated annual differences in GPP can be as high as 350 g C/m^2/year with ET increases up to 125 mm/year during wet years. These values represent first order estimates of the dynamics of plant-water use feedbacks on the water and carbon budgets, and highlight the need to incorporate vegetation-specific phenology responses to water availability in order to accurately estimate the terrestrial carbon storage component of the global carbon budget at local and regional scales.

1. Introduction

Photosynthesis is constrained by ecosystem water availability, temperature, and sunlight (Farquhar et al., 1980; Farquhar and von Caemmerer, 1982). Extreme weather events (e.g., droughts, heat waves, cold snaps, and large storms) alter these external conditions, interrupting normal plant development and inhibiting healthy plant function during the growing season. When the plant life cycle is stunted, vegetation undergoes less efficient photosynthesis and will uptake less carbon in comparison to healthy conditions. Changes in the frequency and duration of droughts and extreme weather events are expected to increasingly impact areas with dense vegetation in the future (Richardson et al., 2013; Sheffield and Wood, 2007; Meehl and Tebaldi, 2004). Consequently, there is a critical need to understand how changes in atmospheric and soil conditions control and limit plant growth and development and how this will impact carbon uptake by vegetation (e.g. Kim et al., 2015; Caldararu et al., 2014). This study evaluates water, light, and temperature limitations on growing season productivity by using a coupled modeling approach to estimating carbon uptake across different vegetation types where both photosynthesis and the seasonal dynamics of canopy biophysical properties are physically constrained by concurrent meteorological and soil

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hydrological states.

Healthy plant function and growth requires specific ranges of temperature, sunlight, soil moisture, and atmospheric water vapor (Zhao and Running, 2010). Thus, these environmental factors are often incorporated into models of vegetation phenology (e.g., Kim et al., 2015; Caldararu et al., 2014; Forkel et al., 2014; Migliavacca et al., 2012; Stöckli et al., 2008; Jolly et al., 2005). Canopy seasonal dynamics manifest as canopy greenness, represented by leaf area index (LAI), and canopy light availability, referred to as the fraction of photosynthetically active radiation (FPAR). Changes in these canopy biophysical properties in response to inter- and intra-seasonal changes in temperature and light and water availability modulate and control the variability in carbon assimilation rates (Lowman and Barros, 2016; Sun et al., 2011; Tian et al., 2010). It is difficult to predict how accounting for temperature, light, and water limitations on canopy seasonal dynamics will impact estimates of carbon uptake at daily, seasonal and annual time scales because the relationship between LAI and gross primary productivity (GPP) varies across ecosystems and soil types (Lowman and Barros, 2016). Further, LAI decreases due to defoliation during drought and increases upon refoliation once favorable meteorological conditions resume (Man et al., 2013; Snyder et al., 2012; Welp et al., 2007; Greub and Wedin, 1971). How canopy biophysical properties respond to specific atmospheric and soil conditions will vary for different vegetation types, meteorological regimes, and physiographic regions. Root water uptake and transpiration modulate canopy response at local scales.

The Growing Season Index (GSI) is a daily metric of phenologic stage (canopy greenness and foliar development) based on concurrent meteorological conditions (Jolly et al., 2005; Stöckli et al., 2008). The atmospheric and land surface variables that impact plant phenology and are used to calculate GSI are temperature, length of time exposed to sunlight (i.e. photoperiod), and plant water stress (Jolly et al., 2005; Jolly and Running, 2004). Temperature and photoperiod modulate the seasonality of phenology; for example, they signal when plants should begin sprouting and flushing leaves. Atmospheric water demand, a proxy for potential evaporation, is represented by vapor pressure deficit (VPD) and determines variability in leaf growth and shedding that occurs intermittently during the growing season. Prior research has shown that total (i.e. realistic) water stress impacts on canopy greenness and carbon uptake cannot by captured by VPD alone (Sims et al., 2014; Kim et al., 2015), and that soil moisture exerts an important control on vegetation phenology (Caldararu et al., 2014; Forkel et al., 2014; Zhou et al., 2013; Migliavacca et al., 2012).

Viskari et al. (2015) and Stöckli et al. (2008) successfully demonstrated the effectiveness of using data assimilation (DA) techniques to constrain model forecasts of canopy biophysical properties using observations. In both studies, predicted phenological cycles reasonably reproduce start and end of season dates that correspond to bud-burst and leaf-drop. Further, Viskari et al. (2015) point out that modeling the sensitivity of the plant life cycle to environmental factors is key to predict fall leaf senescence. The emphasis here is on modeling the temporal evolution of canopy biophysical properties throughout the year. The goal is to predict LAI and FPAR toward improving carbon uptake estimates. For this purpose, a coupled model framework is proposed and tested where predicted FPAR and LAI are constrained by atmospheric and soil water conditions within a land-surface hydrology model that concurrently modulates water, heat and carbon fluxes, thus coupling the water and carbon cycles.

Specifically, DA is used first for estimating Dynamic Canopy Biophysical Properties (DCBP) model parameters in the context of a coupled eco-hydrological framework, including soil water availability and atmospheric water demand feedbacks on FPAR, LAI and GPP. FPAR and LAI forecasts depend on daily changes in the GSI driven by sub-daily changes in atmospheric and soil water availability determined by the hydrology model. The parameters of the modified GSI index functions used here vary by plant functional type and soil texture and are estimated by assimilating Moderate Resolution Imaging Spectroradiometer (MODIS) MOD15A2 FPAR and LAI products using an Ensemble Kalman Filter-based (EnKF) model. The Bayesian approach allows for quantifying uncertainties in the parameter estimates. In the present work, the propagation of parameter uncertainties to model outputs are examined by running Monte Carlo simulations of the coupled hydrology and canopy models. Vegetation-specific parameters required for the prognostic phenology model are estimated through an EnKF-based data assimilation model. DCBP model parameter estimates that depend on the time-period selected for DA. The objectives of this manuscript are:

(1) to determine an appropriate timescale to represent the feedbacks among phenologic and hydrologic processes and capture the intra-seasonal variability of canopy biophysical properties;
(2) to evaluate sources of uncertainty in the data assimilation step that estimates prognostic phenology model parameters, and uncertainty propagation through to the coupled land-surface eco-hydrology model with dynamic vegetation;
(3) to understand how specific vegetation water exchange processes control phenologic responses to water stress; and
(4) to quantify how incorporating dynamically varying FPAR and LAI in a coupled land surface eco-hydrology model impact estimates of carbon uptake and evapotranspiration under wet and dry conditions.

2. Methods

2.1. Overview

The Duke Coupled Hydrology Model with vegetation (DCHM-V) is merged with a prognostic model for Dynamic Canopy Biophysical Properties (DCBP) that estimates the phenologic indicators of FPAR and LAI based on concurrent atmospheric and soil conditions within the model. The DCBP model is based on the Growing Season Index (GSI) originally developed by Jolly et al. (2005) and implemented by Stöckli et al. (2008). The GSI describes water, light, and temperature controls on plant growth and senescence. Here, a modified form of the GSI is used that includes an explicit dependence on soil water potential, and thus root-zone soil moisture demand, in addition to the original dependence on atmospheric water demand represented by VPD. The prognostic phenology model uses the GSI at the daily timescale to determine new leaf growth. The method consists of using Beer's law to relate a prognostic phenology state indicator to the biophysical state variables of FPAR and LAI (Sellers et al., 1996).

2.2. Land surface eco-hydrology model

The DCHM-V is a physically-based land-surface hydrology model with coupled water and energy balances and a biochemical representation of photosynthesis (Lowman and Barros, 2016; Garcia-Quijano and Barros, 2005). The DCHM-V consists of (1) a mass balance to solve for runoff, soil moisture, and soil temperature, (2) an energy balance to solve for soil temperature and determine latent, sensible and ground heat fluxes, (3) snow accumulation and snowmelt physics, and (4) a biochemical formulation of leaf photosynthesis (Barros, 1995; Devonec and Barros, 2002; Garcia-Quijano and Barros, 2005; Gebremichael and Barros, 2006; Yildiz and Barros, 2005, 2007, 2009; Tao and Barros, 2013, 2014; Lowman and Barros, 2016). Here, the model is implemented in 1-D (column) where water and energy fluxes are evaluated at individual pixels between the atmospheric boundary layer and three soil layers in the upper horizons including a superficial layer and two deeper layers in the rooting zone. Each column represents the land surface as a single soil texture (selected based on the predominant soil type) and land cover class with its own surface roughness and soil hydraulic properties.