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A steady-state approximation approach to simulate seasonal leaf dynamics of deciduous broadleaf forests via climate variables

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ABSTRACT

As leaves are the basic elements of plants that conduct photosynthesis and transpiration, vegetation leaf dynamics controls canopy physical and biogeochemical processes and hence largely influences the interactive exchanges of energy and materials between the land surface and the atmosphere. Given that the processes of plant leaf allocation is highly sensitive to climatological and environmental conditions, developing robust models that simulate leaf dynamics via climate variables contributes a key component to land surface models and coupled land-atmosphere models. Here we propose a new method to simulate seasonal leaf dynamics based on the idea of applying vegetation productivity as a synthesized metric to track and assess the climate suitability to plant growth over time. The method first solves two closed simultaneous equations of leaf phenology and canopy photosynthesis as modeled using the Growing Production-Day model iteratively for deriving the time series of steady-state leaf area index (LAI), and then applies the method of simple moving average to account for the time lagging of leaf allocation behind steady-state LAI. The seasonal LAI simulated using the developed method agree with field measurements from a selection of AmeriFlux sites as indicated by high coefficient of determination (R^2 = 0.801) and low root mean square error (RMSE = 0.924 m^2/m^2) and with satellite-derived data (R^2 = 0.929 and RMSE = 0.650 m^2/m^2) for the studied flux tower sites. Moreover, the proposed method is able to simulate seasonal LAI of deciduous broadleaf forests that match with satellite-derived LAI time series across the entire eastern United States. Comparative modeling studies suggest that the proposed method produces more accurate results than the method based on Growing Season Index in terms of correlation coefficients and error metrics. The developed method provides a complete solution to modeling seasonal leaf dynamics as well as canopy productivity solely using climate variables.

1. Introduction

The Earth is an integrated and complex system that consists of interrelated components, such as biosphere, atmosphere, hydrosphere, cryosphere, pedosphere, and lithosphere. As a key constituent component of the Earth system, the land surface interacts with the atmosphere by exchanging massive fluxes of energy and materials (Bonan, 2002). Terrestrial plants have considerable impacts on the climate by releasing water vapor to the atmosphere through transpiration and removing atmospheric carbon dioxide through photosynthesis (Beer et al., 2010). The climate, in turn, controls plant growth and subsequent physical and biogeochemical processes (Keenan et al., 2013; Zhu et al., 2017). Robust simulation of canopy processes and fluxes is then essential to understand the land surface-atmosphere interactions and hence global carbon cycle and water cycle of the Earth system.

One key to successful modeling of canopy exchanges between the land surface and the atmosphere is to develop and solve two simultaneous equations. Given that leaves are the basic elements of plants that conduct photosynthesis and control transpiration, the land surface models commonly use leaf area index (LAI) to characterize vegetation canopy (Clark et al., 2011; Dai et al., 2003; Oleson et al., 2013; Sellers et al., 1996), and thus the first equation is to simulate canopy fluxes such as gross primary production (GPP) and evapotranspiration given known LAI on the ground. Thanks to decades of scientific advances in land surface studies, the models that describe the first equation, despite differing from each other in terms of sophistication, have been

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reasonably formulated and could be generalized as follows:

$$[GPP, ET] = f(LAI, E_{1,2,\ldots n}) \quad (1)$$

where *GPP* denotes gross primary production [$gC/m^2/day$], *ET* denotes evapotranspiration [W/m^2], *f* denotes a certain function with inputs in the parenthesis, *LAI* denotes leaf area index [m^2/m^2], and $E_{1,2,\ldots n}$ denotes various environmental variables (e.g., temperature, vapor pressure deficit, photoperiod, elevation, and soil moisture).

As external environmental variables in vegetation models are typically considered as known conditions that could be obtained from observations or atmospheric circulation models, the second equation is to provide complementary LAI to the first equation by simulating the leaf dynamics solely using climate variables. Solving the second equation, as generalized as follows, essentially involves the study and modeling of vegetation phenology and its interaction with the environment:

$$LAI = f(E_{1,2,\ldots n}) \quad (2)$$

where *LAI* denotes leaf area index [m^2/m^2], and $E_{1,2,\ldots n}$ denotes various environmental variables.

Vegetation phenology modeling has been found highly uncertain in the land surface models and is challenging for reasons (Friedl et al., 2014; Richardson et al., 2012). While understanding the exact role of each individual climate factor in leaf allocation is needed for model developments, the climate drivers affect vegetation phenology through various physiological and biochemical processes with interrelated impacts. Moreover, the physiological processes of plant leaf allocation responds to climate variation relatively slowly, ranging from days to months, such that there is a need to account for the time lag effects by using preceding climate variables when simulating seasonal leaf dynamics. In response to climate conditions, plant species have evolved distinct canopy structures and their own strategies of leaf allocation to optimize the acquisition of natural resource (Givnish, 1986). Importantly, developing models of leaf dynamics requires recording influential climate variables and plant phenology simultaneously and continuously, while key phenophases, such as the events of leaf emergence, maturation, senescence, and dormancy, typically occur only once (or at most twice) in a year (Broich et al., 2014), making data from traditional field measurements limited, especially when taking the factors of weather conditions and equipment malfunctions into account. Fortunately, land surface observations from flux towers, automated camera networks, and remote sensing now offer opportunities for developing and validating comprehensive phenology models (Ganguly et al., 2010; Hufkens et al., 2012; Yang et al., 2013).

Typically, the models of plant phenology are developed separately from the canopy model of photosynthesis and evapotranspiration. One approach to characterize vegetation leaf dynamics is to simulate the timing of key phenophases such as spring onset and autumn senescence using climate variables (Melaas et al., 2016; Yang et al., 2012). For example, acknowledging temperature as one of the most important factors that affect biochemical reactions and hence leaf allocation, the Growing Degree Day (GDD) model accumulates daily temperatures to predict the occurrence of spring onset when heating accumulation reaches a certain heating forcing (Chuine et al., 1999). To account for the impacts of environmental drivers other than temperature, the GDD derivative models downregulate heating accumulation by adding constraint functions of different climate variables, such as chilling temperature, photoperiod, vapor pressure deficit, and soil water stress (Melaas et al., 2013; White et al., 1997; Xin et al., 2015a). Complex land surface models like the Community Land Model use a set of empirical functions to downregulate heating accumulation, thereby predicting spring onset and autumn senescence (Oleson et al., 2013). Other than predicting specific dates of key phenophases, biogeochemical models such as DeNitrification-DeComposition choose to first simulate optimal LAI time series using the GDD time series and then simulate stressed LAI time series using empirical functions derived based on other environmental factors (Li, 2000). Jolly et al. (2005) proposed the Growing Season Index (GSI), a product of three indices as derived from temperature, vapor pressure deficit, and photoperiod, respectively, to quantify the time series of vegetation greenness throughout the year. Note that GSI essentially downregulates GDD accumulations with additional considerations for evaporative demand and daylength. To sum up, while existing methods have varied degrees of success in simulating seasonal leaf dynamics of vegetation, most of them are largely empirical to date and thus have limitations in climate change studies (Arora and Boer, 2005).

Different from existing approaches, Xin (2016) developed a synthesized model that integrates the canopy model of photosynthesis and evapotranspiration for simulating vegetation phenology. The model, named as the Growing Production-Day (GPD) model, has an analogous form to the GDD model and its derivatives, but accumulates vegetation productivity instead of environmental temperature in time series. In essence, the GPD model considers plant photosynthetic productivity as the first-order control determining leaf allocation and applies the productivity of a hypothetical reference vegetation cover as a synthesized metric instead of environmental temperature to track and assess the climate suitability to plant growth over time. The timing of vegetation spring onset is then predicted as the optimal point that balances the inevitable conflict between greater productivity benefits and higher hazard damage risks underlying the plant strategy of earlier leaf allocation. The GPD model has explicit biological explanations and synthesizes all environmental factors that affect photosynthetic activities and hence vegetation phenology. Although the GPD model has shown to simulate the timing of spring onset for different biomes well, there is a need to develop further solutions for modeling the entire time series of seasonal leaf dynamics.

The goals of this study are to: 1) develop an approach to simulate seasonal leaf dynamics of vegetation, and 2) evaluate the model performance for deciduous broadleaf forests in eastern United States using field measurements and satellite data.

2. Methods and materials

2.1. A steady-state approximation approach

The physiological processes that regulate canopy photosynthesis and vegetation phenology do not respond to the climate variation instantaneously and simultaneously. The biochemical process of leaf photosynthesis usually takes one minute to reach the steady-state condition. In addition, plants open and close the stomata, numerous microscopic pores on the surfaces of leaves, to control the diffusion rates of carbon dioxide into leaves for photosynthesis. The stomatal conductance, a metric that measures the rates of carbon dioxide entering and water vapor leaving leaf stomata, usually takes several minutes to approach the steady state (Sellers et al., 1996). By comparison, the biogeochemical processes that plants allocate biomass to leaves could take up days to months under a changing climate (Zeng et al., 2013). Because vegetation phenology is typically modeled at daily or sub-daily time steps, it is then reasonable to treat plant photosynthesis as a near-instantaneous process on the daily or hourly basis, but simulate vegetation phenology as lagging behind the steady state. As such, the proposed method is to first solve the steady state of leaf dynamics and then account for the time lagging of leaf allocation behind the steady state.

Plants conduct photosynthesis and convert solar radiation into chemical energy to fuel all subsequent activities of organisms. Under the pressure of national selection, plants have evolved their strategies to compete resources such as light, water, and nutrients for photosynthesis (Eagleson, 2005; Menzel, 2002). As such, given unchanging environment conditions (i.e., limited natural resources), vegetation leaf dynamics would eventually reach a steady state if time approaches infinity, meaning that the total canopy LAI becomes unchanging as foliation balances defoliation under the competition pressures from