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A risk-benefit model to simulate vegetation spring onset in response to multi-decadal climate variability: Theoretical basis and applications from the field to the Northern Hemisphere

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ABSTRACT

Vegetation spring onset regulates canopy photosynthetic activities and subsequent ecosystem processes, thereby influencing the complex interactions between the biosphere and the atmosphere. Robust models that predict the timing of vegetation spring onsets are required to account for the ecosystem response and adaption to climate variability. Here, a risk-benefit model is proposed to account for the fundamental tradeoff underlying plant leafing strategies: earlier timing of leaf-out events leads to greater vegetative carbon gain but higher risks associated with hazard damages. The proposed model named the Growing Production-Day (GPD) model uses the cumulative productivity of a hypothetical reference vegetation cover as the overall benefit and predicts the events of vegetation spring onset when a certain threshold that vegetation invests to mitigate potential hazard damages is reached. The daily canopy photosynthesis of the hypothetical reference vegetation cover is simulated by a two-leaf canopy model, which considers sunlit and shaded leaves within a canopy separately and accounts for the biogeochemical processes of canopy radiative transfer, leaf photosynthesis, leaf conductance, leaf transpiration, and soil evaporation. When validated against measurements from available flux tower sites of deciduous broadleaf forests, the two-leaf canopy model accurately simulated daily canopy photosynthesis and evapotranspiration rates, indicated by significant correlations ($R^2 = 0.787$ and 0.745 for gross primary production and latent heat, respectively) and low root-mean-square errors (RMSE = 2.25 gC m^2 day^{-1} for gross primary production and 21.53 W m^{-2} for latent heat, respectively) between the observed and modeled values. Based on the two-leaf canopy model, the GPD model predicted the dates of spring onsets accurately for three studied biomes (RMSE = 9.10, 5.54, and 12.76 days for evergreen needleleaf forests, deciduous broadleaf forests, and grasslands, respectively) as derived from the flux tower data. In addition, the GPD model could simulate the long-term interannual variation of species-level leaf onset dates as obtained from in-situ observations, and capture the spatiotemporal patterns of multi-decadal variation of vegetation spring onsets across the Northern Hemisphere as derived from satellite data. Although the GPD model requires further refinements, it shows promises with respect to simulating vegetation spring onset in response to multi-decadal climate variability.

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1. Introduction

Vegetation phenology, often characterized by the events of leaf emergence, maturation, senescence, and dormancy, outlines the periodic life span of plants (Broich et al., 2014; Zhang et al., 2003). Spring onset, which signals the initiation of a vegetation growth cycle, is one of the primary drivers that controls canopy photosynthetic activities and subsequent biochemical and physical processes within ecosystems (Churkina et al., 2005; Dragoni et al., 2011; Piao et al., 2007), thus influencing ecosystem functioning and land-atmosphere interactions (Levis and Bonan, 2004; Lotsch et al., 2003; Richardson et al., 2013). The timing of the spring onset of terrestrial ecosystems has large year-to-year variation that is highly sensitive to environmental conditions (Cleland et al., 2007; Koerner and Basler, 2010). As a result, leaf

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onset is widely viewed as a robust indicator of vegetation response and adaption to climate variability (Badeck et al., 2004; Chuine et al., 2004; Julien and Sobrino, 2009). Accurate prediction of vegetation spring phenology is therefore a key in terrestrial modeling and leads to a better understanding of the Earth system.

Given that how plant genes and environmental conditions together regulate the process of leaf allocation remains unclear to date, vegetation onset is a process that is highly uncertain in earth science studies (Jeong et al., 2012; Richardson et al., 2012) and is often modeled using climate factors (Lieth, 2013). Among a variety of external drivers, the temperature cue is generally accepted as a key factor that determines leaf emergence and vegetation development (Melaas et al., 2015; Richardson et al., 2006; Sparks et al., 2000; Wang et al., 2011). Warming temperature enhances enzyme activities and expedites nearly all biochemical reactions in plant cells, thereby allowing for early leaf expansion. Chilling temperature in wintertime could stimulate vegetation spring onsets, but its role remains under debate, as the overall effect differs considerably among species (Cesaraccio et al., 2004). The photoperiod cue also plays an important role in regulating the timing of plant leaf flushing, and its impact varies both within and among species (Polgar and Primack, 2011). Water availability, such as precipitation and soil moisture, affects the leaf onset of short vegetation such as steppe and meadow (Jin et al., 2013; Liu et al., 2013; Shen et al., 2011), especially in water-limited areas, but appears to have limited impacts on woody plants, whose roots are long enough to assess abundant water in deep soil layers. Topographical factors such as slope, aspect, and elevation could influence vegetation leaf onset considerably (Hwang et al., 2014; Hwang et al., 2011). For example, the Hopkins' bioclimatic law states that the onset of spring is delayed by approximately one day for every 30 m increase in elevation (Fitzjarrald et al., 2001). In phenology modeling studies, topographical factors are often considered to affect leaf onset through their influences on climatic factors such as temperature and photoperiod. To summarize the current observational evidence, almost all environmental factors that regulate plant growth and photosynthetic activities could influence the timing of leaf onset to a certain degree, and their impacts are often interrelated, making it difficult to understand the exact role of each individual factor.

To account for the sensitivity of vegetation spring onset to temperature variation, many terrestrial biosphere models use a temperature-based Growing Degree-Day (GDD) model or its derivative models to simulate leaf onset (Cramer et al., 2001; Kaduk and Los, 2011; Kucharik et al., 2006; Yang et al., 2012). The GDD model accumulates heating temperatures as the energy requirement for leaf expansion, where its family can be generalized by synthesizing the influence of related climatic factors as follows (Xin et al., 2015b):

$$t_{SOS} \text{ such as } \sum^{t_{SOS}} (T_a - T_b) \times \prod f_s(x) \geq F_{GDD} \tag{1}$$

where t_{SOS} denotes the date of vegetation start-of-season (SOS) [day]; T_a denotes daily mean air temperature [°C]; T_b denotes the base temperature [°C]; $f_s(x)$ denote dimensionless scalar factors that account for various environmental limitation on temperature accumulation given the environmental factor x; and F_{GDD} denotes the forcing threshold for heating temperature accumulation when leaf onset occurs [°C day]. The daily heating temperatures are accumulated over time as indicated by the summation operator Σ. The scalar factors $f_s(x)$ typically have values in the range between 0 and 1, where $f_s(x) = 1$ indicates no environmental limitation on heating temperature accumulation and $f_s(x) = 0$ indicates no heating temperature accumulation due to strong environmental stresses on vegetation growth. The scalar factors are often multiplied in sequence as indicated by the product operator Π and formulated differently in various models. Note that all symbols are defined in Table A1 in the appendix.

The French scientist De Réaumur (1735) first proposed the GDD model in its simplest form, in which temperature accumulation is assumed to not be limited by other environmental factors (i.e., $\prod f(T_i) = 1$). The leaf-out event is predicted to occur when heating accumulation, starting from a fixed date, reaches a certain heating forcing. Chuine et al. (1998) reviewed several derivative GDD models, of which the Sequential model uses a binary function and the Parallel model uses a weighted function of chilling temperature to constrain the accumulation of heating temperature. Acknowledging the importance of photoperiod in regulating plant leaf onset, Melaas et al. (2013) modified the GDD model by adding a photoperiod trigger (a binary function based on photoperiod) to improve model predictions for woody plants. Xin et al. (2015b) further introduced the scalar factors of vapor pressure deficit and soil moisture, which are indicative to surface water availability, and made predictions of grassland green-up dates. Some models use soil temperature or daily minimum air temperature instead of daily mean air temperature in the GDD models (Baldocchi et al., 2005; Jolly et al., 2005). Complex ecosystem models use a system of equations to trigger leaf onsets for different plant functional types and for stressed and non-stressed vegetation (Oleson et al., 2013; White et al., 1997). In addition to the GDD model family, efforts have been made to develop complicated models to account for vegetation spring onset (Arora and Boer, 2005; Choler et al., 2010). While these efforts have found varying degrees of success in predicting leaf onset when evaluated against in-situ observations, the temperature-based models could have difficulties in capturing the long-term variability of spring onset timing derived from large-scale satellite observations (Fisher et al., 2007). Furthermore, the temperature-based spring onset models have empirical formulations and are thus limited in global climate change studies.

There is a current need for developing a leaf-out model that synthesizes all environmental factors and has explicit biological explanations. Plants in an ecosystem compete for natural resources such as light, water, nitrogen, and mineral nutrients to assimilate carbon through photosynthesis for maintenance and survival (Menzel, 2002). The optimization theory suggests that plants have evolved traits and functioning to maximize carbon gain while minimizing water loss (Dawson et al., 2007; Eagleson, 2002; Field, 1983; Givnish, 1986). Leaf phenology, including the phenomena of foliation and defoliation, is essentially a strategy that plants adopt to invest materials in their leaves in response to climate variation (Bonan, 2002). One fundamental tradeoff underlying the plant strategy of earlier leaf allocation arises from the inevitable conflict between greater productivity and higher risk of hazard damages such as frost and drought. Therefore, a plausible leafing model may have to account for both the risk and the benefit associated with plant functions, of which plant photosynthetic productivity is the first-order control in such a tradeoff.

The goals of this study are to: (1) develop a sophisticated model of spring onset that accounts for the tradeoff underlying vegetation leafing strategies, and (2) evaluate the model performance against vegetation spring onsets derived from in-situ observations, flux tower measurements, and satellite data.

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