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# Assimilating leaf area index of three typical types of subtropical forest in China from MODIS time series data based on the integrated ensemble Kalman filter and PROSAIL model

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Subtropical forest ecosystems play essential roles in the global carbon cycle and in carbon sequestration functions, which challenge the traditional understanding of the main functional areas of carbon sequestration in the temperate forests of Europe and America. The leaf area index (LAI) is an important biological parameter in the spatiotemporal simulation of the carbon cycle, and it has considerable significance in carbon cycle research. Dynamic retrieval based on remote sensing data is an important method with which to obtain large-scale high-accuracy assessments of LAI. This study developed an algorithm for assimilating LAI dynamics based on an integrated ensemble Kalman filter using MODIS LAI data, MODIS reflectance data, and canopy reflectance data modeled by PROSAIL, for three typical types of subtropical forest (Moso bamboo forest, Lei bamboo forest, and evergreen and deciduous broadleaf forest) in China during 2014–2015. There were some errors of assimilation in winter, because of the bad data quality of the MODIS product. Overall, the assimilated LAI well matched the observed LAI, with $R^2$ of 0.82, 0.93, and 0.87, RMSE of 0.73, 0.49, and 0.42, and aBIAS of 0.50, 0.23, and 0.03 for Moso bamboo forest, Lei bamboo forest, and evergreen and deciduous broadleaf forest, respectively. The algorithm greatly decreased the uncertainty of the MODIS LAI in the growing season and it improved the accuracy of the MODIS LAI. The advantage of the algorithm is its use of biophysical parameters (e.g., measured LAI) in the LAI assimilation, which makes it possible to assimilate long-term MODIS LAI time series data, and to provide high-accuracy LAI data for the study of carbon cycle characteristics in subtropical forest ecosystems.



## 1. Introduction

The leaf area index (LAI), which is defined as one-half of the total area of the plant (Chen et al., 2002), is one of the most important physiological parameters of terrestrial vegetation. LAI has a close relationship with photosynthesis, transpiration, water use, and the formation of ecosystem productivity, and it is always considered an important parameter and indicator in research focusing on carbon and water cycling and on the energy exchange of terrestrial ecosystems (Jonckheere et al., 2004). Furthermore, the trend of LAI time series data can be used to monitor the growth status of vegetation, which has great significance in studies of the characteristics of the terrestrial ecosystem carbon cycle.

Using LAI derived from remote sensing data as input data to drive ecosystem carbon cycle models, which can achieve cross-scale simulation of the carbon cycle process and reflect the spatial distribution and dynamics of the carbon budget on a regional (or even global) scale, has been at the forefront of research into the estimation of the carbon cycle of forest ecosystems (Brown, 2002; Cao et al., 2005; Chen and Cihlar, 1996; Liu et al., 2015; Ma et al., 2014; Plummer, 2000; Qing et al., 2002; Zhao et al., 2011). However, because of the impact of cloud cover, aerosols, snow cover, and sensor failure, many existing satellite-based LAI

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products are characterized by high noise, low accuracy, and large fluctuations in time the series, which cannot correctly reflect the process of plant growth continuity, thereby constraining the global application of LAI products (Heinsch et al., 2006; Xiao et al., 2008). Data assimilation methods, which are used widely in remote sensing, meteorological, soil, ecological, and hydrological studies, can improve the accuracy of the observed data (Gu et al., 2009; Li et al., 2014b; McLaughlin, 2002; Moradkhani et al., 2005). They can incorporate data from multiple sources, with consideration of error information and inconsistencies in the spatiotemporal resolution of the observed data, into a dynamic model to determine an optimal solution between a model simulation and the observations, thereby improving the accuracy of the observational data.

Data assimilation methods can be considered either sequential or variational methods. The ensemble Kalman filter (EnKF) is a classical algorithm of the sequential group of data assimilation methods that analyzes model errors according to the Monte Carlo theory and statistical methods (Evensen, 1994). The EnKF is an important method with which to assimilate LAI products to obtain high-accuracy time series LAIs (Li et al., 2014a). Xiao et al. (2011) assimilated real-time LAIs using EnKF techniques coupled with a Markov chain reflectance model and an LAI dynamic model, which was found to improve the accuracy of MODIS-derived LAI products significantly. Zhao et al. (2013) simulated maize yields by coupling MODIS-derived LAIs and the PyWOFOST crop model with EnKF. They found the simulated yields correlated strongly with statistical yields. Zhang et al. (2013) found considerable improvement in accuracy when they assimilated measured LAIs and remote sensing LAIs into the BIOME-BGC model using an EnKF algorithm to simulate the water and carbon fluxes in the Harvard forest area. Quaife et al. (2008) used EnKF to assimilate canopy reflectance data into an ecosystem model, which reduced the uncertainty of both the estimated gross primary production and the net ecosystem productivity significantly.

A radiative transfer model simulates canopy reflectance by modeling the absorption, bidirectional reflectance, and transmission of solar radiation using the inputs of measured LAI, chlorophyll, and other parameters. Coupling an LAI dynamic model and a radiative transfer model with EnKF, and updating the modeled LAI based on the difference between the modeled reflectance and MODIS reflectance using EnKF methods, can provide high-accuracy LAIs. The PROSAIL model, which is a coupling of the PROSPECT and SAIL models, is an advanced radiative transfer model used for simulating canopy reflectance (Jacquemoud, 1993; Jacquemoud et al., 2009). The PROSPECT model is an improvement of the Allen plane model for simulating leaf reflectance and transmittance in the wavelength range 400–2500 nm (Jacquemoud and Baret, 1990). The SAIL model is based on the SUITS model, developed to simulate the height of the sun and the canopy reflectance in the viewing direction using environmental and biochemical parameters (Verhoef, 1984). Feret et al. (2008) succeeded in separating plant pigment contributions to chlorophylls and carotenoids using leaf biochemical and optical properties, which improved significantly the value of using remote sensing data for estimating photosynthetic rates and providing more accurate monitoring of vegetation stress. Nilson and Kuusk (1989) developed the SAIL model by adding the canopy hot spot effect into the model, and Verhoef and Bach (2007) introduced the 4SAIL model with improved applicability and performance. Therefore, the coupling of the PROSPECT 5 model with the 4SAIL model can be used to simulate forest canopy reflectance with high accuracy.

There are various types of subtropical forest that have strong photosynthetic capacity and year-round growth, which play an important role in both the global carbon cycle and the carbon sequestration function (Fang et al., 2015; Piao et al., 2009; Yan et al., 2006). The gross primary productivity and carbon sink of subtropical forests account for 40% of the global total (Beer et al., 2010; Pan et al., 2011; Tan et al., 2011; Zhou et al., 2006), and the net ecosystem productivity, which in the East Asian monsoon region is 720 million Mg C year$^{-1}$, accounts for 8% of the global total (Fang et al., 2015; Piao et al., 2009; Yan et al., 2006). China has an important proportion of the subtropical forest in East Asia. Bamboo forests (especially Moso bamboo forests), which are widely distributed in subtropical regions of China, have high capacity for carbon sequestration (>1300 Tg of carbon storage potential), and they provide a carbon sink that has a prominent role regarding global climate change (Han et al., 2013; Li et al., 2015; Lou et al., 2010; Zhou et al., 2013). However, subtropical forests are extremely complex and the various forest types have markedly different carbon cycle characteristics and spatiotemporal distributions. The MODIS LAI product cannot distinguish specific forest types and therefore, it cannot provide high-accuracy parameters for simulating the carbon cycles of the various types of subtropical forest. This study developed an algorithm for assimilating LAI dynamics based on an integrated EnKF using MODIS LAI data, MODIS reflectance data, and canopy reflectance data modeled by the PROSAIL (PROSPECT 5 + 4SAIL) model, for three typical types of subtropical forest (Moso bamboo forest, MBF; Lei bamboo forest, LBF; and evergreen and deciduous broadleaf forest, EDBF) in China during 2014–2015. The objective was to provide high-accuracy LAI data for modeling and predicting the spatiotemporal dynamics of the carbon cycle in a subtropical forest ecosystem.

## 2. Methods

### 2.1. Study area

Three flux stations located in the study area of Zhejiang Province were selected for ground verification of the assimilated LAI. The details of the three sites (Anji County, the town of Taihuyuan, and on Tianmu Mountain) are shown in Table 1.

The MBF flux measurement site is located in Anji County, in the northwest of Zhejiang Province. This area has a subtropical monsoon climate with distinct seasons and abundant rainfall; the average January temperature is 2.5 °C, average July temperature is 27.8 °C, and the average annual precipitation is 1400 mm. MBF is distributed widely across Anji County, covering an area of 335,484 ha, which accounts for about 45% of the total forested area. The area (1 × 1 km) around the flux tower comprises MBF. The average diameter at breast height of the bamboo is 9.3 cm and the canopy height is 12–18 m with a sparse understory of shrubs and herbs.

The LBF measurement site is located in the town of Taihuyuan, Lin'an, which is one of the well-known "Hometown of Bamboos" in China. Lin'an has a warm and moist subtropical monsoon climate; the annual average temperature is 16 °C and the average annual precipitation is 1700 mm. The bamboo forest is this area covers 39,052 ha, of which LBF accounts for 19,020 ha. The LBF around the flux tower is mainly 2–3 years old and it has an average height of 4.5 m, with few shrubs distributed in the understory.

The EDBF flux measurement site is located on West Tianmu Mountain in Lin'an County. The West Tianmu Mountain region is influenced by an oceanic warm and wet climate that is characteristic of a subtropical to northern subtropical region. The mild and rainy climate is responsible for the complex forest ecology (Tang et al., 2007). The annual average temperature is 12 °C and the average annual precipitation is 1630 mm. The elevation of the flux tower site is about 1000 m above sea level. The flux tower is surrounded by EBDF comprising mainly *Cyclobalanopis myrsinaefolia* and *Daphniphyllum macropodum*.