Forest Ecology and Management 351 (2015) 67–77

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Empirical models for tracing seasonal changes in leaf area index in deciduous broadleaf forests by digital hemispherical photography

Zhili Liu [a], Chuankuan Wang [a], Jing M. Chen [b], Xingchang Wang [a], Guangze Jin [a,*]

[a] *Center for Ecological Research, Northeast Forestry University, Harbin 150040, China*
[b] *Department of Geography, University of Toronto, Toronto, ON M5S 3G3, Canada*

ARTICLE INFO

Article history:
Received 13 December 2014
Received in revised form 3 May 2015
Accepted 5 May 2015
Available online 19 May 2015

Keywords:
Leaf area index
Seasonal variations
Digital hemispherical photography (DHP)
Litter collection
Regression
Error sources

ABSTRACT

Accurate estimation of seasonal leaf area index (LAI) variations is essential for predicting forest growth, but rapid and reliable methods for obtaining such estimates have rarely been reported. In this study, direct measurements of LAI seasonal variations in deciduous broadleaf forests in China were made through leaf seasonality observations in the leaf-out season and litter collection in the leaf-fall season. Meanwhile, indirect LAI measurements were made using a digital hemispherical photography (DHP) method. Our objectives were to explore the relationship between direct and indirect LAI measurements and to recommend a rapid and reliable method to determine the seasonal variation of LAI in forests. To achieve these objectives, we first evaluated seasonal variations of the biases due to key factors (woody materials, clumping effects and incorrect automatic exposure) known to influence the estimation of LAI by DHP. The results showed that the biases due to these factors exhibited different seasonal variation patterns, and the total contribution of these factors could explain 72% of the difference between direct LAI and DHP LAI throughout the entire growing season. Second, linear regression models between direct and DHP LAI were first constructed for each 10-day period as well as the entire growing season. Significance tests were made to the differences among the models for different dates, and models for estimating LAI based on DHP in each date were aggregated to 4 periods with R^2 and RMSE values of 0.91 and 0.22, 0.79 and 0.29, 0.81 and 0.14, 0.97 and 0.14, respectively. There was no significant difference between direct LAI and estimated LAI using the four models in each aggregated period ($p < 0.01$). Thus, we confirm that these models can fully simulate the seasonal variations in LAI from the initial leaf emergence to leaf fall in deciduous broadleaf forests.

1. Introduction

Leaf area index (LAI), defined as one half the total green leaf area per unit ground surface area (Chen and Black, 1992), is a central parameter for analyses of forest canopies, which affect the energy, water and carbon fluxes between the canopies and the atmosphere (Asner et al., 2003; Bréda, 2003; Ryu et al., 2012). Furthermore, the seasonal changes in LAI strongly influence the variations in the rates of many forest ecosystem processes such as rain interception, evapotranspiration, photosynthesis and respiration, and LAI has also been used as a predictor for many processes useful for forest management (Arias et al., 2007; Richardson et al., 2011; Sprintsin et al., 2011).

LAI can be obtained directly by destructive sampling, but this method is not only destructive but also unsuitable for forest stands with high and complicated canopies (Chen et al., 1997; Gower et al., 1999; Jonckheere et al., 2004). In contrast, allometric methods are less destructive, and LAI estimates are often based on the development of allometric relationships between LAI and tree data (e.g., diameter at breast height (DBH), sapwood cross-sectional area or basal area) (Gower and Norman, 1991; Jonckheere et al., 2005; Majasalmi et al., 2013). However, these relationships are both species- and site-specific, and these methods cannot be used to monitor the seasonal changes in LAI of a forest stand (Smith et al., 1993; Chen and Cihlar, 1995a; Küßner and Mosandl, 2000). As an alternative to measure LAI directly, the litter collection method has frequently been used in deciduous forests (Neumann et al., 1989; Ishihara and Hiura, 2011). Recently, Nasahara et al. (2008) proposed a method that combines litterfall in the leaf-fall season with leaf seasonality observations in the leaf-out season to monitor the seasonal changes in LAI in a deciduous broadleaf forest. However, the litter collection method used to derive LAI requires multiplying the collected mass of leaves by the specific

---

* Corresponding author. Tel.: +86 451 82191823.
E-mail address: taxus@126.com (G. Jin).

http://dx.doi.org/10.1016/j.foreco.2015.05.005
0378-1127/© 2015 Elsevier B.V. All rights reserved.

leaf area (SLA), which must be determined for each tree species separately (Kalácska et al., 2005; Nouvellon et al., 2010). Meanwhile, litterfall should be collected and sorted by species promptly to avoid leaf decomposition.

Because these direct methods for measuring LAI are time-consuming and labor-intensive for forest canopies, a number of indirect techniques relying on radiative transfer theories have been developed to infer LAI from measurements of the transmission of radiation through a canopy (Ross, 1981). In these techniques, digital hemispherical photography (DHP) and the LAI-2000 plant canopy analyzer (Licor Inc., Lincoln, NE, USA) have usually been used to measure LAI because they can simultaneously measure the canopy gap fraction from several zenith angles. With the development of high-resolution digital cameras, accurate and effective processing of images and permanent preservation of original field data, DHP has been widely accepted as a tool for measuring LAI by forest managers and researchers (Chen et al., 1997; van Gardingen et al., 1999; Gonsamo and Pellikka, 2009; Leblanc and Fournier, 2014). Nevertheless, the accuracy of these indirect LAI estimates should be checked against direct measurements of LAI because of the methods' inherent limitations. For instance, indirect methods cannot fully distinguish woody materials and leaves in the process of calculating the canopy gap fraction and LAI (Chen et al., 1991; Bréda, 2003); they infer LAI under the assumption that the foliage components are distributed randomly in canopies, but most canopies exhibit clumping patterns (Black et al., 1991; Chen et al., 1997). Therefore, this LAI directly derived from indirect methods (i.e., optical methods) is not the true LAI but rather an effective LAI (L_e) (Chen, 1996). Recently, automatic exposure setting has been identified as a large source of error in estimating LAI using DHP because it often causes significant loss of green leaves in the photographs (Zhang et al., 2005; Chianucci and Cutini, 2012; Beckschäfer et al., 2013; Macfarlane et al., 2014).

To the best of our knowledge, rapid and accurate monitoring of the seasonal changes in LAI based on field measurements in a forest stand could most likely be accomplished in two ways: 1, based on the indirect LAI, we could estimate the direct LAI by constructing relationships between indirect and direct LAI in different seasons; or 2, we could correct the indirect LAI estimates by accounting for factors that influence the accuracy of LAI estimation (e.g., woody materials or clumping effects) in different seasons. However, consensus methods for quantifying these factors have not been developed. Even if we obtained the corrected indirect LAI in different seasons, its accuracy would still need to be checked against direct estimates of LAI. In contrast, the first way of monitoring the seasonal changes in LAI is more practical and effective, as reported by many previous studies. For instance, Chason et al. (1991) estimated the seasonal dynamics of LAI using LAI-2000 and litter collection measurements in a mixed deciduous broadleaf forest and found that $\mathrm{LAI}_{litter} = 1.86 \times \mathrm{LAI}_{\text{LAI-2000}}$ with $R^2 = 0.97$; Kalácska et al. (2005) reported the seasonal changes in LAI derived from optical (e.g., LAI-2000) and litter collection methods in a tropical dry forest and constructed a relationship of $\mathrm{LAI}_{litter} = 2.12 \times \mathrm{LAI}_{\text{LAI-2000}} - 1.55$ ($R^2 = 0.78$). However, whether a single model is useful across different seasons has not been assessed in most of these studies. Qi et al. (2013) constructed the relationship between the effective LAI from DHP and direct LAI in the leaf-fall season in a mixed broadleaved-Korean pine forest in China, but detail for the leaf-out season is lacking. Up to now, few studies have constructed a time-dependent relationship between direct LAI and indirect LAI from initial leaf-out to the leaf-fall season in a forest stand.

This study aims to develop accurate but less labor-intensive empirical models to determine the seasonal changes in LAI using the indirect DHP method in deciduous broadleaf forests. To achieve this aim, we (1) evaluated the seasonal variations of the biases due to error sources of LAI measurement by DHP (e.g., woody materials, clumping effects or photographic exposure); (2) directly measured the seasonal changes in LAI (defined as direct LAI) by combining leaf seasonality observations in the leaf-out season with litter collection in the leaf-fall season; and (3) constructed an empirical model based on the correlation between direct LAI and indirect LAI in each 10-day period and explored how to integrate these models in all dates.

2. Materials and methods

2.1. Site description and sample design

The study site is at the Maoershan Ecosystem Research Station of Northeast Forestry University in northeastern China (127°30′–34′E, 45°20′–25′N). It represents typical deciduous forest in northeastern China, with an average altitude of 300 m above sea level and an average slope of 10°–15°. The mean (1989–2009) annual precipitation is 629 mm, of which ~50% falls between June and August. The mean annual air temperature is 3.1 °C. The frost-free period spans between 120 d and 140 d, with an early frost in September and a late frost in May (Wang et al., 2013). The study was conducted using four 20 m × 30 m permanent plots of mixed deciduous broadleaf plants, the basic characteristics of which are summarized in Table 1. We randomly installed five litter traps in each plot (i.e., a total of 20 l traps). Each trap had a square aperture of 1 m^2 and a base approximately 0.5 m above the ground. Observations were recorded from May 1 to October 21 of 2012, and there were nearly no leaves on trees before May 1 and after October 21, i.e., the LAIs in these two dates were zero. Therefore, the entire growing season in this study area contains leaf-out seasons and leaf-fall seasons, and the leaf-out season is from May 12 to mid-July when the annual maximum LAI, $\mathrm{LAI}_{\max}$ occurred, and the leaf-fall season is from August 1 to October 11.

2.2. Indirect LAI estimation

We used a DHP technique (with a Nikon Coolpix 4500 digital camera with a 180° fish-eye lens) to estimate LAI on the same dates as the leaf seasonality observations and litter collection dates. All of the hemispherical photographs of sample points were taken 1.3 m above the ground using a tripod, and the sample points were located near litter traps. The photographs were obtained near sunrise (or sunset) under uniform sky conditions. We chose the following settings for the camera: (1) aperture priority mode with

Table 1
General characteristics and species composition of the four deciduous broadleaf forest plots under investigation.

Forest plots	Major species	Density trees (ha^{-1})	Mean DBH (cm)	Basal area ($\mathrm{m}^2\,\mathrm{ha}^{-1}$)	Height (m)
1	*Ulmus japonica* (64.8%), *Fraxinus mandshurica* (15.8%)	1840	7.73	19.59	20
2	*Betula platyphylla* (47.9%), *Ulmus japonica* (20.3%)	2140	8.01	19.64	18
3	*Betula platyphylla* (50.8%), *Acer mono* (7.3%)	5067	6.29	23.25	16
4	*Fraxinus mandshurica* (49.5%), *Ulmus japonica* (32.5%)	2167	9.09	35.94	21

Values in parentheses are dominance (i.e., the proportion of the total basal area of all species in the plot represented by the basal area of major species) of species; DBH stands for diameter at breast height. Height is a canopy height of the dominant species in each plot.