Int J Appl Earth Obs Geoinformation 74 (2019) 120–129

Contents lists available at ScienceDirect

Int J Appl Earth Obs Geoinformation

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

Estimation of forest leaf water content through inversion of a radiative transfer model from LiDAR and hyperspectral data

Xi Zhu[a,*], Andrew K. Skidmore[a,b], Roshanak Darvishzadeh[a], Tiejun Wang[a]

[a] Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, P.O. Box 217, 7500 AE Enschede, the Netherlands
[b] Department of Environmental Science, Macquarie University, NSW 2109, Australia

ARTICLE INFO

Keywords:
Leaf water content
INFORM
Prior information
Canopy cover

ABSTRACT

The accurate estimation of leaf water content (LWC) and knowledge about its spatial variation are important for forest and agricultural management since LWC provides key information for evaluating plant physiology. Hyperspectral data have been widely used to estimate LWC. However, the canopy reflectance can be affected by canopy structure, thereby introducing error to the retrieval of LWC from hyperspectral data alone. Radiative transfer models (RTM) provide a robust approach to combine LiDAR and hyperspectral data in order to address the confounding effects caused by the variation of canopy structure. In this study, the INFORM model was adjusted to retrieve LWC from airborne hyperspectral and LiDAR data. Two structural parameters (i.e. stem density and crown diameter) in the input of the INFORM model that affect canopy reflectance most were replaced by canopy cover which could be directly obtained from LiDAR data. The LiDAR-derived canopy cover was used to constrain in the inversion procedure to alleviate the ill-posed problem. The models were validated against field measurements obtained from 26 forest plots and then used to map LWC in the southern part of the Bavarian Forest National Park in Germany. The results show that with the introduction of prior information of canopy cover obtained from LiDAR data, LWC could be retrieved with a good accuracy (R^2 = 0.87, RMSE = 0.0022 g/cm^2, nRMSE = 0.13). The adjustment of the INFORM model facilitated the introduction of prior information over a large extent, as the estimation of canopy cover can be achieved from airborne LiDAR data.

1. Introduction

Leaf water is an essential component of plant leaves which plays a key role in many physiological processes such as plant growth, photosynthesis, transpiration, and thermal regulation (de Jong et al., 2014; Running and Gower, 1991; Ullah et al., 2013) and is a major driver in predicting the susceptibility to fire (Chuvieco et al., 2004). Leaf water content (LWC) is also important as an essential biodiversity variable, having relevance for ecosystem function and ecosystem structure (Skidmore et al., 2015). The quantification of LWC and knowledge about its spatial variation can provide crucial information for assessing forest drought conditions and predicting future forest change associated with climate change (Anderson et al., 1976; Asner et al., 2011).

Remote sensing data can be used to retrieve leaf properties, including LWC, across a wide range of spatial and temporal scales (Zarco-Tejada et al., 2003). A number of studies have successfully demonstrated the feasibility of retrieving leaf biochemical variables from passive remote sensing data through empirical approaches as well as the inversion of radiative transfer models (RTM) (Ceccato et al., 2001; Cheng et al., 2012, 2006; Colombo et al., 2008; Mirzaie et al. 2014). Empirical models are usually established by correlating leaf biochemical variables with reflectance using spectral indices (Seelig et al., 2008; Tong and He, 2017), artificial neural networks (Dawson et al., 1999; Mutanga and Skidmore, 2004), or partial least square regression (Asner et al., 2015; Atzberger et al., 2010). The main disadvantage of empirical approaches is that the established model may be highly dependent on site, sampling conditions and time (Cheng et al., 2012; Darvishzadeh et al., 2012). In contrast, RTMs simulate physical processes describing the interaction of photons and vegetation components, and their inversion allows the retrieval of vegetation biochemical and biophysical variables, thus offering potential advantages in terms of transferability compared to empirical models (Colombo et al., 2008; Darvishzadeh et al., 2008b; Houborg et al., 2009; Liu et al., 2015).

At the canopy level, the link between leaf biochemical variables and reflected radiation is often complicated by canopy structure (e.g. canopy cover, leaf area index (LAI)) (Colombo et al., 2008; Niemann et al., 2012; Ollinger, 2011; Wang et al., 2017). According to Fourty and Baret (1998), a large variation in LAI may weaken the relationship

* Corresponding author.
E-mail address: x.zhu@utwente.nl (X. Zhu).

https://doi.org/10.1016/j.jag.2018.09.008
Received 1 June 2018; Received in revised form 7 September 2018; Accepted 10 September 2018
0303-2434/

between LWC and spectral reflectance. Zarco-Tejada et al. (2003) demonstrated the dependency of water-related optical indices on LAI. Cheng et al. (2006) showed that the retrieval of LWC using RTMs was significantly affected by vegetation canopy architecture causing over or under estimations.

A common challenge when using RTMs is the ill-posed problem in the model inversion, as is well documented in a number of studies (Combal et al., 2003; Koetz et al., 2005). The ill-posed problem is mainly caused by the under-determined nature of the modeling schemes (Jacquemoud et al., 2009), whereby different parameter combinations may yield almost the same spectral signatures (Darvishzadeh et al., 2008a; Jacquemoud, 1993). The use of prior knowledge of the model input parameters may help overcome this problem during inversion and improve the estimation of vegetation variables (Combal et al., 2002; Darvishzadeh et al., 2008b). Darvishzadeh et al. (2008a) examined the effect of soil background brightness on LAI retrieval and suggested that using prior knowledge about soil background was important when estimating vegetation variables. Dasgupta et al. (2009) showed that the use of prior information improved the accuracy of fuel moisture content estimation by 18–27 % in a grassland when employing the PROSAIL model. Xiao et al. (2014) indicated that the use of prior knowledge of canopy structure when inverting an RTM was key to accurately estimating leaf biochemical variables, especially with sparse canopy cover.

The integration of LiDAR and hyperspectral data offers the potential to solve key issues related to the effects of canopy structure on the canopy reflectance and the inversion of RTMs by providing prior information (Niemann et al., 2012). Koetz et al. (2007) showed that the introduction of prior information derived from LiDAR data in RTM inversion significantly improved the estimation accuracy of canopy cover compared to an estimation based solely on spectral information. Cao et al. (2012) decomposed the reflectance of spectral scene components using LiDAR. The result was then used as an input in a simplified Li–Strahler geometric-optical model (Li et al., 1995). Ma et al. (2014) estimated canopy height using LiDAR data to parameterize a geometric-optical mutual-shadowing (GOMS) model for the retrieval of LAI in a natural forest.

Four main categories of canopy reflectance models can be distinguished (Schlerf and Atzberger, 2006): (1) Turbid medium models (1-D radiative transfer models) such as SAILH (Verhoef, 1984) characterize the forest canopy layer as horizontally homogeneous and infinitely extended, which is unsuited for the sparse forest that is horizontally heterogeneous. (2) Geometric models such as the Li-Strahler GO model (Li and Strahler, 1986) assume that the canopy consists of a series of regular geometric shapes, placed on the ground surface in a prescribed manner (Liang 2005). Consequently, crown transparency is assumed to be zero. That transmissivity of tree crowns ignored introduces a fundamental weakness of these models (Atzberger, 2000). (3) Ray-tracing models such as the FLIGHT model (North, 1996) can accurately compute the radiation distribution over a complex canopy configuration. However, due to the complex structure and a large number of input parameters required, these models are computationally expensive and difficult to invert (Schlerf and Atzberger, 2006). (4) Hybrid models such as GeoSail (Huemmrich, 2001) are combinations of geometric and turbid medium models. These types of models provide a compromise between the realism of simulation of canopy and invertibility (Schlerf and Atzberger, 2006). The invertible forest reflectance model INFORM (Atzberger, 2000) is a hybrid model which has successfully estimated plant biophysical and biochemical variables (Ali et al., 2016b; Wang et al., 2018). In order to solve the ill-posed problem, it is of key importance to use prior information on canopy structure for the model inversion. However, structural variables that most affect canopy reflectance in INFORM (viz. stem density and crown diameter) (Ali et al., 2016a) are not easy to measure by fieldwork based on visual judgements or remote sensing techniques due to the complex forest structure (Bechtold et al., 2002), especially when tree crowns are irregular and overlapped (Maltamo et al., 2004). In addition, ground surveys of stem density and crown diameter are costly and time consuming that is not feasible for remote areas. In this study, stem density and crown diameter in the INFORM model were replaced by canopy cover which can be directly retrieved from LiDAR with a good accuracy (Armston et al., 2013; Korhonen et al., 2011). Consequently, prior information of canopy cover was used to restrain the inversion procedure. Therefore, the aim of this study is to determine if introducing LiDAR-derived prior information of canopy cover into the INFORM model could improve the estimation accuracy of LWC from hyperspectral data.

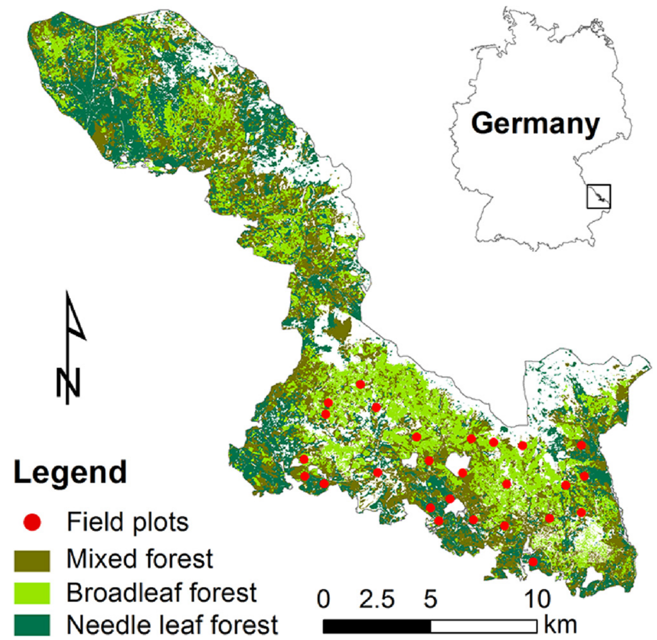

Fig. 1. The location of the study area in Germany and the distribution of sample plots in the southern part of the Bavarian Forest National Park.

2. Data set

2.1. Study area

The study area is located in the Bavarian Forest National Park in southeastern Germany and covers an area of 24,250 ha of forest (Fig. 1). The elevation ranges from 600 to 1453 m. The natural forest ecosystems of the Bavarian Forest National Park vary according to altitude: there are alluvial spruce forests in the valleys, mixed mountain forests on the hillsides and mountain spruce forests in the high areas. Dominant tree species are Norway spruce (*Picea abies*) (67%) and European beech (*Fagus sylvatica*) (24.5%), with some white fir (*Abies alba*) (2.6%), sycamore maples (*Acer psudoplatanus*) (1.2%) and mountain ash (*Sorbus aucuparia*) (3.1%) (Heurich et al., 2010).

2.2. Field data collection and laboratory analysis

The fieldwork was carried out between July 11 and August 23, 2013, using a stratified random sampling design. A land cover map with the classification of broadleaf, needle leaf and mixed forest including stand age (i.e. mature, medium and young) was provided by the Bavarian Forest National Park for analysis. To incorporate the heterogeneity and variation in canopy structure, 26 plots (7 broadleaf, 6 needle leaf, and 13 mixed stands) were selected. Each plot was 30*30 m in size. Within each plot, leaf samples were taken from the branches of one to three dominant tree species depending on the homogeneity. Leaves were firstly scanned by an image scanner. The one-sided area of each leaf sample was computed by multiplying the number of leaf