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Retrieval of forest fuel moisture content using a coupled radiative transfer model

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A B S T R A C T

Forest fuel moisture content (FMC) dynamics are paramount to assessing the forest wildfire risk and its behavior. This variable can be retrieved from remotely sensed data using a radiative transfer model (RTM). However, previous studies generally treated the background of forest canopy as soil surface while ignored the fact that the soil may be covered by grass canopy. In this study, we focused on retrieving FMC of such forestry structure by coupling two RTMs: PROSAIL and PRO-GeoSail. The spectra of lower grass canopy were firstly simulated by the PROSAIL model, which was then coupled into the PRO-GeoSail model. The results showed that the accuracy level of retrieved FMC using this coupled model was better than that when the PRO-GeoSail model used alone. Further analysis revealed that low FMC condition fostered by fire weather condition had an important influence on the breakout of a fire during the study period.

Software and/or data availability section

Software ENVI (version 5.2), ArcGIS (version 10.1), Origin (version 8.0) and Office EXCEL (version 2013).
Hardware Computer with 4 CPU nodes and 16 GB memory.
Dataset Field measurements, Landsat 8 OLI products and MODIS LAI products (MOD15A2).

Program language
(i) Fortran: for the forward modeling of the forest spectra using the coupled RTM (PROSAIL + PRO-GeoSail).
(ii) Matlab (version: 2015a): Used for the backward inversion based on the built LUT and observed spectra.

1. Introduction

Wildfire is a natural agent of many ecosystems since fire impacts nutrient cycles, vegetation succession patterns and resistance to insect plagues (Kilgore, 1973). However, it also has a wide range of negative impacts on soil erosion and degradation, destruction of vegetation water conservation function, emissions of atmospheric greenhouse gases, as well as human life and welfare (Boerner et al., 2009; Rieman et al., 2003; van der Werf et al., 2009; van der Werf et al., 2006). Three major forces are essential for understanding forest fire risk and its behavior: weather, fuel and topography (Pyne et al., 1996). In this context, fuel moisture content (FMC), defined as the proportion of water content over dry mass, is one of the key factors for wildfire risk assessment since it affects both fire ignition and spread (Bowyer and Danson, 2004; Chuvieco et al., 2004a, 2004b; Chuvieco et al., 2009; Danson and Bowyer., 2004; Dennison and Moritz, 2009; Dennison et al., 2008; Nolan et al., 2016; Page et al., 2013; Sharples et al., 2009; Sullivan and Matthews, 2013; Wang et al., 2013). Accurate, robust and timely estimations of FMC at landscape are vital for forest fire risk assessment, and to date, the remote sensing technique is the unique way to that end due to its high temporal and spatial resolution image of large landscape observation (Casas et al., 2014; Dasgupta et al., 2007; Jurdao et al., 2013; Qi et al., 2014; Riaño

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et al., 2005; Yebra et al., 2013).

Two main remote sensing-based techniques have been used for the estimation of FMC and/or other vegetation biophysical variables: statistical methods and the inversion of radiative transfer models (RTMs) (Yebra et al., 2013). The former techniques are known to use statistical formulas based on field measurements of the target parameters and reflectance or vegetation indices derived from remote sensing images. These statistical approaches are simple and have a known accuracy, but they have the drawbacks of being sensor-specific and site-dependent, and therefore lack generality (Al-Moustafa et al., 2012; Broge and Mortensen, 2002; Colombo et al., 2003; Fang et al., 2003; Gitelson et al., 2005; Houborg et al., 2009; Tucker, 1980; Yebra et al., 2013). The techniques based on the inversion of RTMs have proven to be promising and reproducible for vegetation variables retrievals because RTMs are built based on physical laws that provide explicit connections between those parameters and leaf and/or canopy spectra (Darvishzadeh et al., 2008; Houborg et al., 2007; Huang et al., 2016; Meroni et al., 2004). Furthermore, RTMs are robust, not site-specific and easier to generalize. Nevertheless, these methods heavily rely on a proper model selection and parameterization to make the final simulated spectra as close as possible to the spectra that might be observed from a satellite over the study area (Jurdao et al., 2014; Yebra et al., 2013).

To this end, previous studies have generally coupled a single leaf optical model such as PROSPECT (Jacquemoud and Baret, 1990) or LIBERTY (Leaf Incorporating Biochemistry Exhibiting Reflectance and Transmittance Yields) (Dawson et al., 1998) with a canopy level RTM such as SAIL (scattering by arbitrarily inclined leaves) (Verhoef, 1984, 1985), Kuusk's RTMs (Kuusk, 1994, 1995a, 1995b, 2001; Nilson and Kuusk, 1989), and GeoSail (Huemmrich, 2001) (Fang et al., 2003; Jurdao et al., 2013; Quan et al., 2015b; Riaño et al., 2005; Yebra and Chuvieco, 2009a, 2009b; Yebra et al., 2008; Yebra et al., 2013; Zarco-Tejada et al., 2003). The PROSPECT model describes a leaf as a stack of plates with absorbing and diffusing constituents and is usually used to calculate reflectance and transmittance of broadleaves from 400 nm to 2500 nm (Jacquemoud and Baret, 1990). LIBERTY is used to simulate needle reflectance and transmittance also from 400 to 2500 nm by assuming that a needle structure is composed of roughly spherical cells, which are separated by air spaces (Dawson et al., 1998). The SAIL model is a 1D turbid medium RTM, which solves the scattering and extinction of four upward/downward fluxes within the canopy to predict the bidirectional reflectance of homogeneous and continuous plant canopies (Verhoef, 1984, 1985; Jacquemoud et al., 2006; Jacquemoud et al., 2009). SAIL was later modified by Kuusk (1991) to take into account the hot spot effect and then evolved into SAILH model. SAILH describes the canopy structure in a simple way and requires several input parameters, which makes the inversion process convenient. The Kuusk's MCRM (Markov chain reflectance model) incorporates the Markov properties of stand geometry into an analytical multispectral RTM (Kuusk, 1995b). The GeoSail model combines a geometric model that calculates the amount of shadowed and illuminated components in a scene with the SAIL turbid medium model that simulates the reflectance and transmittance of the tree crowns. It is designed to use optical properties of the canopy components, tree shape, solar zenith angle and canopy cover to calculate scene reflectance and the fraction of absorbed or intercepted photosynthetically active radiation for forest stands (Huemmrich, 2001). However, these models, obviously, are not suitable to resemble spectra of some forest ecosystems which are characterized by the two-layered canopy (i.e., upper tree canopy layer and lower grass canopy layer). Therefore, it led to the development of more complex two-layered RTM such as the Kuusk's two-layered canopy reflectance model (also called as ACRM) (Kuusk, 2001) which has also been used to retrieve biophysical and biochemical variables of crops or grassland (He et al., 2013; Houborg et al., 2007, 2009; Houborg and Boegh, 2008; Ma et al., 2013; Quan et al., 2014) and to simulate the post-fire spectral or derived spectral indices for the estimation of burn severity (Chuvieco et al. 2006, 2007). ACRM assumes the vegetation canopy consists of a main homogeneous and continuous canopy layer and a geometrically thin layer of vegetation on the ground surface. Both vegetation layers are characterized by a similar set of input parameters that control the optical properties of the leaves (Kuusk, 2001). However, the ACRM is not suitable for the retrieval of FMC in the two-layered forest area because the tree canopy layer is not continuous but discontinuous.

We proposed a new method to address this problem and accurately and robustly retrieved FMC in a two-layered forest study area. The method consisted in coupling PROSAIL (PROSPECT + SAIL), which modeled the spectra of continuous lower grass canopy layer, and PRO-GeoSail (PROSPECT + GeoSail), which modeled the spectra of the discontinuous upper tree canopy layer. Our hypothesis was that this coupled RTM would better represent the two-layered forest configuration in the study area, and therefore its performance would be superior to that using one canopy RTM alone. A subsequent objective of this study was to analyze the relations between the forest FMC maps, meteorological data (temperature, relative humidity and accumulated rainfall) and fire occurrence in the study area in order to understand how the forest FMC responses to local weather change.

2. Materials and methods

2.1. Study area

The study area is the Sichuan province, China (Fig. 1). The main geomorphic types of this area are mountains, hills, plains and plateaus, accounting for 74.2%, 10.3%, 8.2%, and 7.3% of the total area, respectively (http://www.sc.gov.cn/10462/10778/10876/2013/3/27/10253724.html). The climate in this province differs from the northwest to southeast due to a more than 2000 m difference in altitude. The northwest of the province is cold (mean and maximum annual temperature for the period 1961 to 2010 were 8.2 °C and 15.5 °C, respectively), receiving abundant sunshine, and its rainfall is concentrated from June to September. The southwest area also receives abundant sunshine but presents a strong rainfall pattern with dry winters and springs (e.g., high wildfire risk during this period) whereas the southeast plain area is cloudy and foggy. The major vegetation types in the study area are forests (about 35.51%, from the Statistical Yearbook of Sichuan Province 2014 (SYSP 2014), http://www.sc.stats.gov.cn/tjcbw/tjnj/2014/index.htm), grasslands (about 43.72%) (Wen, 2008) and wetlands (about 8.64%, http://www.wetwonder.org/news_show.asp?id=14428). The forests are distributed in the mountainous areas and can be roughly classified to the spruce-fir forest, evergreen broad-leaf forest, broadleaved deciduous forest, evergreen pine-oaks forest and Masson pine forest. Due to the subtropical monsoon climate and particular geographic location, the forest ecosystem in this region presents two canopy layers: an upper tree canopy layer and a lower grass canopy layer. The natural resources in the area are abundant. Numerous natural reserves of endangered animals (giant pandas, golden monkeys, etc.) and plants (*Cathaya*, *Argyrophylla*, *Davidia*, etc.) are protected here. However, according to the data given by the SYSP 2014, this province (mostly in southwestern part) has suffered from about 4472 forest fires, affecting a total of 11345.5 ha in the period from 2000 to 2013 and causing large damage to the environment.

Four study sites distributed in forested areas in this province