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Research Paper

Modeling seasonal surface temperature variations in secondary tropical dry forests

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ABSTRACT

Secondary tropical dry forests (TDFs) provide important ecosystem services such as carbon sequestration, biodiversity conservation, and nutrient cycle regulation. However, their biogeophysical processes at the canopy-atmosphere interface remain unknown, limiting our understanding of how this endangered ecosystem influences, and responds to the ongoing global warming. To facilitate future development of conservation policies, this study characterized the seasonal land surface temperature (LST) behavior of three successional stages (early, intermediate, and late) of a TDF, at the Santa Rosa National Park (SRNP), Costa Rica. A total of 38 Landsat-8 Thermal Infrared Sensor (TIRS) data and the Surface Reflectance (SR) product were utilized to model LST time series from July 2013 to July 2016 using a radiative transfer equation (RTE) algorithm. We further related the LST time series to seven vegetation indices which reflect different properties of TDFs, and soil moisture data obtained from a Wireless Sensor Network (WSN). Results showed that the LST in the dry season was 15–20 K higher than in the wet season at SRNP. We found that the early successional stages were about 6–8 K warmer than the intermediate successional stages and were 9–10 K warmer than the late successional stages in the middle of the dry season; meanwhile, a minimum LST difference (0–1 K) was observed at the end of the wet season. Leaf phenology and canopy architecture explained most LST variations in both dry and wet seasons. However, our analysis revealed that it is precipitation that ultimately determines the LST variations through both biogeochemical (leaf phenology) and biogeophysical processes (evapotranspiration) of the plants. Results of this study could help physiological modeling studies in secondary TDFs.

1. Introduction

Land cover change in tropical forests due to deforestation, afforestation, and forest regeneration provides important climate forcings and feedbacks that can amplify or diminish the ongoing climate change (Bonan, 2008; Denman et al., 2007), and in turn affect physical and physiological processes of the plant (Fischlin and Midgley, 2007). Whereas the climate impacts of tropical deforestation and afforestation are relatively well documented (Achard et al., 2014; Baccini et al., 2012), the impacts of forest regeneration tend to be ignored despite of their huge potential (Bongers et al., 2015; International Tropical Timber Organization, 2002; Chazdon et al., 2009; Pan et al., 2011). One hotspot of forest regeneration occurs in tropical dry forests (TDFs). TDFs are more vulnerable to human disturbances than any other tropical forests as a result of their tremendous agricultural potential and climatic conditions favorable for human settlement (Calvo-Alvarado et al., 2009; Murphy and Lugo, 1986; Powers et al., 2009; Gillespie et al., 2000). To date, nearly half of TDFs have been already converted to other land use at the global level (Hoekstra et al., 2005), and more than 65% of TDFs have disappeared in Americas (Portillo-Quintero and Sanchez-Azofeifa, 2010). The remnants are mostly complex landscapes of forest patches in different stages of ecological succession (Sanchez-Azofeifa et al., 2005). These successional stages can be characterized as early (21 years since its last disturbance), intermediate (32 years), and late (50+ years) by their horizontal and vertical structure, leaf area index (LAI), green canopy cover density, and species composition (Cao et al., 2015; Arroyo-Mora et al., 2005; Kalacska et al., 2004).

Tropical forest regeneration can influence climate through biogeochemical and biogeophysical processes (Bonan, 2008). For the climate-related biogeochemical processes, great efforts have been made in the greenhouse gas (atmospheric CO_2) uptake (e.g., Phillips and Lewis, 2014; Anderson-Teixeira et al., 2016). It has been shown that carbon sequestration in regenerating forests is stronger than in intact forests, and offsets more than one half carbon emissions from tropical deforestation (Pan et al., 2011). In secondary TDFs, the intermediate successional stage has a higher aboveground net primary productivity

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(ANPP) (8.90 Mg C ha^{-1} $year^{-1}$) than the late successional stages (7.59 Mg C ha^{-1} $year^{-1}$) (Cao et al., 2016). Biogeophysical processes, on the other hand, are far less well understood in tropical forests due to the complex forest-atmosphere interactions (Alkama and Cescatti, 2016). The biogeophysical impact of forest regeneration depends on the trade-off between surface albedo and evapotranspiration (Alkama and Cescatti, 2016). Tropical forests can warm climate by their low albedo and cool climate by their strong evapotranspiration (Bonan, 2008), producing locally cooler and wetter climate year round (Feddema et al., 2005).

A critical variable to quantify the climate impact of biogeophysical processes is land surface temperature (LST). LST drives water and energy exchange at the forest surface-atmosphere interface, and determines a range of physical and physiological processes between the forest canopy and the atmosphere such as photosynthesis, respiration, and evapotranspiration (Wang et al., 1995; Wang, 1996; Kalma et al., 2008; Quattrochi and Luvall, 1999). LST is generally quantified by taking advantage of aircraft-mounted or satellite-based thermal infrared (TIR) data. The basic idea is that every physical object as a single thermodynamic system continuously emits electromagnetic radiation at all wavelengths which could be captured by remote sensors (Becker and Li, 1995). The amount of emitted radiation can be mostly described by Planck's law, but also relies on the effectiveness of the physical object in emitting thermal radiation (referred as "emissivity") and the instantaneous atmosphere conditions through which thermal radiation reaches the sensors (Quattrochi and Luvall, 1999).

Since the 1970s, there have been a number of remote sensing based LST retrieval methods and applications (McMillin, 1975; Li et al., 2013), but few of them focused on forests. The LST in forests is typically considered driven by evapotranspiration, among others (Bonan, 2008). Holbo and Luvall (1989) used airborne Thermal Infrared Multispectral Scanner (TIMS) to investigate daytime and nighttime LST frequency distributions in coniferous forests of different forest landscapes. They found that LSTs at forest sites with more developed canopies tended to be more stable (Holbo and Luvall, 1989). Hais and Kucera (2009) proposed that topography was another important factor that controls the LST in forests. Their estimated LST in homogeneous forests decreased with elevation and increased with higher values of insolation regardless of which kind of sensors were used (Landsat TM, Landsat ETM+, or TERRA ASTER) (Hais and Kucera, 2009). Ermida et al. (2014) underscored the impact of viewing and illumination geometries on LST at a woodland landscape and proposed a model to correct LST errors related to those geometric effects.

Remote sensing based LST has frequently been used for evaluating forest properties and status. One popular LST product is derived from TIR bands of Moderate Resolution Imaging Spectroradiometer (MODIS) (Wan, 1997). Applications of MODIS LST product include fire risk evaluation (Guangmeng and Mei, 2004), forest cover estimation (Van Leeuwen et al., 2011), and forest phenology modeling (Liu et al., 2016). However, other studies pointed out that the MODIS LST product could fail to monitor tropical forests due to extensive cloudiness (Gao et al., 2008; Gao et al., 2016). Instead, microwave datasets for instance collected by Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) (Calvet et al., 1994), Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) (Gao et al., 2008), and Special Sensor Microwave Imager Sounder (SSMIS) (Gao et al., 2016) could be better choices despite of their coarse spatial resolutions.

Thermal remote sensing has also been applied in TDFs. Southworth (2004) documented that the canopy structure in TDFs effectively regulated the LST. At Yucatan, Mexico, she demonstrated that Landsat TM thermal band acquired in the dry season outperformed other spectral bands in differentiating successional stages of secondary TDFs (Southworth, 2004). However, her study has been largely biased to thermal band information of Landsat TM rather than the LST in TDFs, and her conclusions could hardly hold in the wet season or other dates of the dry season because the TDF canopy structure is highly dynamic. In-depth analysis of biogeophysical mechanisms of thermal differences across successional stages was also lacking.

In this context, the objective of this study is to investigate seasonal and successional LST patterns in secondary TDFs. Of the most popular thermal sensors, we select Thermal Infrared Sensor (TIRS) onboard Landsat-8 which was launched on February 11, 2013. Landsat satellites (Landsat TM/ETM+) have been commonly used in LST modeling because of their long time archive and relatively high spatial resolution compared to other sensors such as AVHRR and MODIS (e.g., Sobrino et al., 2004; Jimenez-Munoz et al., 2009; Weng and Fu, 2014; Quintano et al., 2015; Vlassova and Pérez-Cabello, 2016). Based on the thermal band of Landsat TM/ETM+, different single-channel algorithms for LST retrieval have been proposed and successfully applied (Sobrino et al., 2004). Compared with its predecessors, the new Landsat-8 TIRS provides a higher data quality (signal to noise ratio) and radiometric quantization (12-bits), opening opportunities to derive more reliable LST results. Landsat-8 TIRS has two thermal bands (band 10 and band 11) located in wavelength between 10 μm and 12 μm, rather than only one as in Landsat TM/ETM+ (Irons et al., 2012). This designation of Landsat-8 TIRS enables the application of split-window (SW) algorithms which are only available for multi-channel sensors (Atitar and Sobrino, 2009; Sobrino et al., 1994; Jimenez-Munoz et al., 2014; Rozenstein et al., 2014), but later analysis by the U.S. Geological Survey (USGS) has reported a large calibration uncertainty associated with TIRS band 11 caused by stray light. It is suggested that SW algorithms which rely on band 11 are unreliable for LST estimation. As such, this study applies a single-channel algorithm to estimate LSTs from July 2013 to July 2016 using time series of Landsat-8 TIR band 10 data. A combination of spectral vegetation indices (VIs) which reflect different aspects of land surface properties (canopy structure, canopy moisture, and biomass), precipitation data, and soil moisture data acquired from a Wireless Sensor Network (WSN) are also used in this study to explore the intrinsic mechanisms that produce LST variation of TDFs.

2. Methodology

2.1. Study area and data

The study was conducted within Santa Rosa National Park (SRNP; 10°50'N, 85°37'W), in the Pacific coast of northwestern Costa Rica (Fig. 1a). The terrain is relative flat with an average slope of 7% (Sanchez-Azofeifa et al., 2013). SRNP has a typical tropical dry climate, characterized by a six-month dry season extending from the middle of December to early May when precipitation is extremely scarce and a majority of the vegetation is drought deciduous. Mean annual precipitation is 1390 mm. Air temperature that ranges from 26 °C in the wet season to 29 °C in the dry season, are relative stable across the years. SRNP was a cattle ranch for almost 200 years until it became protected parkland in 1972. It is home to one of the most important TDF remnants in Central America (Kalacska et al., 2004). Current landscape at SRNP, denominated "agro-landscape", consists of pastures and secondary TDFs in various stages of regeneration as a result of different land use histories, land use intensities, discrete anthropogenic events (Kalacska et al., 2004) as well as different regeneration mechanisms during the past 40 years (Castillo et al., 2011; Sanchez-Azofeifa et al., 2017).

Three successional stages at SRNP: early, intermediate, and late are classified by their horizontal and vertical structures and species compositions (Fig. 2b) (Kalacska et al., 2004; Arroyo-Mora et al., 2005). The early stage has only one single canopy layer (6 m average height) and is considered as a heterogeneous mixture of woody vegetation, shrubs, pastures, and small trees. The intermediate stage presents two canopy layers (15 m average height): fast growing species and lianas infestations. The late successional stage has two canopy layers of vegetation (30 m average height) including dominant canopy trees and understory species (Arroyo-Mora et al., 2005). In the wet season, canopies of three