Measuring the response of canopy emissivity spectra to leaf area index variation using thermal hyperspectral data

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ABSTRACT

One of the plant biophysical factors affecting the canopy spectral reflectance of plants in the optical domain to receive research attention in recent decades is leaf area index (LAI). Although it is expected that the value of LAI affects the emission of radiation, it not known how. To our knowledge, the effect of LAI on plant canopy emissivity spectra has not yet been investigated in the thermal infrared region (TIR 8–14 μm). The overall aim of this study was to demonstrate the effect of LAI on canopy emissivity spectra of different species at the nadir position. The 279 spectral wavebands in the TIR domain were measured under controlled laboratory condition using a MIDAC spectrometer for four plant species. The corresponding LAI of each measurement was destructively calculated. We found a positive correlation between canopy emissivity spectra at various LAI values, indicating that emissivity increases concomitantly with LAI value. The canopy emissivity spectra of the four species were found to be statistically different at various wavebands even when the LAI values of the species were similar. It seems that other biophysical or biochemical factors also contribute to canopy emissivity spectra: this merits further investigation. We not only quantify the role of LAI on canopy emissivity spectra for the first time, but also demonstrate the potential of using hyperspectral thermal data to estimate LAI of plant species.

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1. Introduction

In recent decades, vegetation reflectance spectra and their features in the visible/near–infrared (VNIR 0.35–1.0 μm) and short–wave infrared (SWIR 1.0–2.5 μm) regions of the electromagnetic spectrum have been widely investigated. Consequently, meaningful relationships have been established between reflectance spectra and vegetation biophysical, and biochemical properties at leaf, canopy, and landscape levels (Asner, 1998). Despite the growing importance of remote sensing for vegetation studies, it is not fully understood how the emissivity spectra interact with biophysical and biochemical properties of vegetation in the thermal infrared region (TIR 8–14 μm). TIR hyperspectral data is important for earth observation such as geological remote sensing studies, due to the strong response of minerals (e.g., quartz) in this domain (Van der Meer et al., 2012). Additionally, TIR data is particularly important for investigating vegetation phenomena in which temperature plays a critical role (e.g., photosynthesis, and transpiration) (Lindroth et al., 2008).

Leaf area index (LAI) is a dimensionless variable, defined as the one-sided leaf area (m^2) per unit of horizontal surface area (m^2) (Watson, 1947), and it is a critical input for climate and large-scale ecosystem models (Zheng and Moskal, 2009). In addition, the LAI is an important biophysical parameter of vegetation that exhibits a primary control on the plant energy balance, transpiration, respiration, and gas exchanges (e.g., uptake of CO_2 and H_2O by the canopy) (Running and Coughlan, 1988). Previous studies have revealed the importance of LAI in ecological and remote sensing studies. For instance, process-based ecosystem simulations are often required to produce quantitative analyses of productivity; in this regard, LAI is a key input parameter to such models (Liu et al., 1999, 1997; Matsushita et al., 2004). Also, LAI is indispensable for scaling between leaf and canopy measurements of biochemical variables (e.g., water vapor, CO_2 conductance and flux) at global scale (Asner et al., 2003). In addition, long-term monitoring of LAI can provide critical information on climate impacts on ecosystems (Zheng and Moskal, 2009). LAI can explain the differences between photosynthesis and respiration in different ecosystems as well as how photosynthesis varies under different light levels and leaf
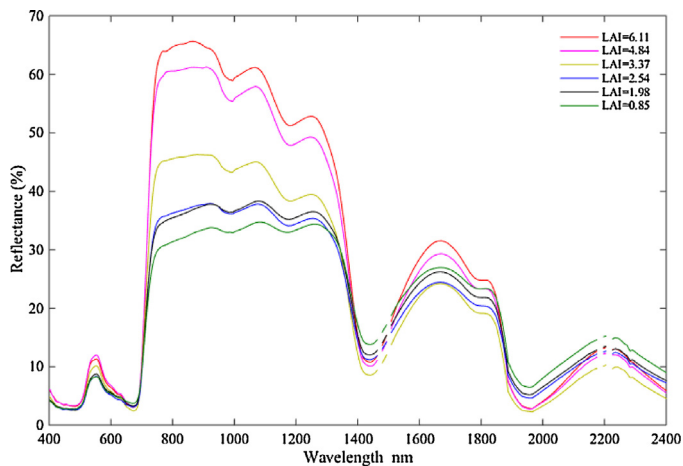
Fig. 1. Canopy spectral reflectance of *Asplenium nidus* in visible, NIR and SWIR regions corresponding to LAI values between 0.87 and 6.11.
(Source: Darvishzadeh et al. (2009)).

nitrogen concentrations in the area of low and high LAI respectively (Boegh et al., 2002).

Generally, radiance spectra depends on leaf surface temperature (Becker and Li, 1990) and are part of the radiation term in the energy budget of the leaves (Gates, 2012). The temperature of a canopy surface depends on the balance between incoming solar energy and energy loss. Leaves absorb a certain fraction of the incident radiation with this energy, dividing it over three outgoing streams: re-radiation, convective heat exchange with the air, and evaporation or transpiration (Gates, 2012). A large proportion of these outgoing streams is devoted to convective heat exchange with the air. In other words, most of the incoming solar energy in plants is transformed and lost as heat (McKinney and Schoch, 2003). It has been shown that in terms of physiology and ecology, plants are able to regulate their energy balance through their leaf surfaces (Delrot et al., 2010). It has been demonstrated by Drake et al. (1970) that transpiration has an important role to stabilization of the leaf temperature, particularly at high environmental temperature through the cooling role of transpiration. In this respect, Vertessy et al. (1995) showed that the relation between transpiration and leaf area is almost linear. Further, LAI is related to the efficiency of canopy evaporation value (van den Hurk et al., 2003). Brutsaert (2013) has demonstrated that high LAI values are strongly correlated to the efficiency of canopy evaporation and account for the majority of the existent energy, applied for evapotranspiration. Therefore, it can be realized that LAI variability affects canopy evaporation and transpiration.

Previous studies have investigated the effect of varying LAI values on canopy reflectance and have demonstrated that with rising LAI the canopy reflectance spectra increases in particular in NIR region (Asner, 1998; Darvishzadeh et al., 2009). As can be observed from Fig. 1, the variation of LAI has an influence on canopy reflectance signatures, with the most pronounced impact in the NIR domain (750 nm–1350 nm). Moreover, as LAI rises within a canopy, an obvious deepening of the two water absorption features within the NIR region located at 1000 nm and 1200 nm can be observed in the reflectance spectra. To date, our knowledge regarding the canopy emissivity spectra and its relation to LAI in the TIR region has been limited by mainly technical problems (Ribeiro da Luz and Crowley, 2007).

Recently, thermal hyperspectral devices have improved: new thermal infrared sensors discern TIR spectral features at higher spectral resolution (e.g., the MIDAC illuminator Fourier Transform Infrared (FTIR) spectrometer). Reviewing the literature revealed that most vegetation studies using TIR hyperspectral data have focused at the leaf level (Buitrago et al., 2016; Ullah et al., 2013, 2014), and only a few studies have addressed TIR hyperspectral data at canopy level (Ribeiro da Luz and Crowley, 2010; Sepulcre-Cantó et al., 2006). In preliminary studies, Salisbury and Milton (1988) were among the first to use thermal data to investigate the reflectance spectra of different plant species at leaf level in the 2.5–13.5 μm region. They showed that deciduous species have unique reflectance features. Recently, Ullah et al. (2012) studied the leaf emissivity spectra for different species and demonstrated that vegetation has specific characteristic emissivity signatures at leaf level.

The above literature revealed that leaves are not opaque and featureless in the TIR domain and that hyperspectral thermal remotely sensing of vegetation is an area in which there is still much to explore. No studies have focused on the biophysical properties of vegetation and their influence on emissivity spectra of canopies. Here, for the first time, we use TIR hyperspectral data to evaluate changes in emissivity spectral measurements under different values of LAI measured for structurally different species and under controlled laboratory conditions. Our study had two principal objectives: (1) to measure the response of canopy emissivity spectra to LAI variation and (2) to explore the canopy emissivity spectra of different plant species with the same LAI.

2. Materials and methods

2.1. LAI measurements

In the present study, four different plant species were selected: *Azalea japonica*, an evergreen flowering shrub with ovate leaves about 2–3 cm long (n = 10); *Buxus sempervirens*, an evergreen shrub with oval leaves about 1.5–3 cm long and 0.5–1.3 cm wide (n = 10); *Euonymus japonicus*, an evergreen shrub with oval leaves about 3 cm to 7 cm long, with finely serrated margins (n = 11); and *Ficus benjamina*, which has glossy, oval leaves about 6–13 cm long, with an acuminate tip (n = 6).

To create variation in LAI and corresponding emissivity measurements, leaves from different layers and on the inner side of the canopy were randomly removed in 3–4 consecutive steps (depending on the plant size), hence after each removal phase, the total LAI value of the canopy were lowered. These harvesting steps were carried out on each sample species within a few hours to minimize possible changes in the plants physiological status such as stomatal conductance and to exclude the possible interference of any physiological processes. The areas of harvested leaves were measured using the LI-3000C portable leaf area meter (LICOR, NE, USA) that was regularly calibrated. To calculate the LAI ($m^2\,m^{-2}$), the measured surface areas of the leaves (m^2) were divided by the corresponding ground area of the canopy (m^2). The dataset includes 37 plants, resulting in 144 LAI measurements, as the plants were destructively sampled for LAI.

2.2. Laboratory condition

To create optimal measurement conditions, and reduce any possible sources of error due to the changes in atmospheric conditions or temperature, the measurements were carried out under controlled laboratory condition where the walls, ceiling, and ground were coated with a black material (Avis Aqua Blackboard Black) and plastic of known emissivity. The traditional procedure when measuring emissivity is to heat samples (e.g. geological samples) to a temperature above ambient condition to create a thermal contrast (Ribeiro da Luz and Crowley, 2007; Salisbury, 1998). However, such treatment stresses plant samples, so instead we reduced the