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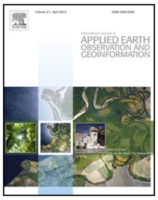

Measuring the response of canopy emissivity spectra to leaf area index variation using thermal hyperspectral data

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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.

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

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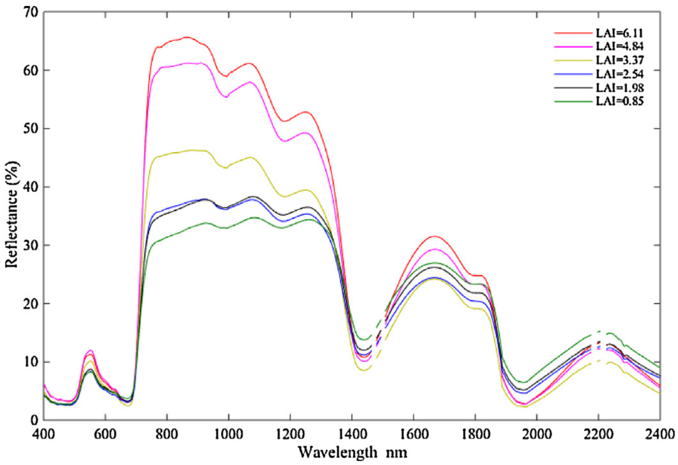

Fig. 1. Canopy spectral reflectance of *Asplenium nidus* in visible, NIR and SWIR regions corresponding to LAI values between 0.87 and 6.11.
(Source: Darvishzadeh et al. (2009)).

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 lab temperature to 10 °C in order to generate a suitable thermal contrast with the plants, which were at a higher room temperature. For this, plants were kept outside the laboratory at an ambient room temperature of 20 °C, and were briefly individually transfered to the cool room in order to make the thermal measurements, and then were returned to normal room termperature. In this experiment, the background soil was covered with black plastic of known emissivity to minimize possible effects of soil. We measured the emissivity spectra of the black plastic using a BRUKER Vertex 70 laboratory FTIR spectrometer. The black plastic had a very low emissivity so could be assumed to cause minimal interference with the thermal radiance measurements of the samples.

2.3. Canopy spectroscopic measurment

2.3.1. Thermal infrared emission spectroscopy

The radiance spectra were measured using a portable MIDAC FTIR spectrometer (Model M4401-F; MIDAC Corporation, CA, USA). The MIDAC configuration enables the measurement of radiance spectra within the spectral range of 2.5–20 μm with an adjustable spectral resolution of 32–0.5 cm^{-1} (Eisele et al., 2015). The MIDAC has a liquid-nitrogen-cooled Mercury-Cadmium-Telluride (MCT) detector and customized foreoptics that consist of a flat folding mirror on a rotational axis, which allows measurements of two blackbodies (hot and cold), for calibrating and measuring each sample. The MIDAC's folding mirror was kept at nadir position above the samples. The MIDAC's field of view (using a cut-off of 5% of the maximum responsivity) has a starting diameter of 53 mm at the folding mirror and spreads with about 18 mrad. Since the amount of thermal emission varies according to the distance between the sample and the sensor (Ribeiro da Luz and Crowley, 2007), and also to reduce atmospheric attenuation (Korb et al., 1996), measurements were made with a fixed vertical distance between sensor and sample (600 mm), resulting in a sampling spot with a diameter of 330 mm..

2.3.1.1. Radiometric calibration and downwelling radiance measurements. The emissivity spectra of plant canopies were obtained using a series of FTIR measurements performed in the following order: radiance measurements of the hot blackbody, radiance measurement of the cold blackbody, radiance measurement of the sample (i.e., the plant canopy), and finally, radiance measurements of a highly diffuse reflecting gold plate (Infragold®). For instrument radiance calibration, two individual blackbodies were used. The temperatures of the hot and cold blackbodies were regularly checked between measurements of each sample. The cold blackbody temperature was set just below the ambient temperature, at 5 °C (Korb et al., 1996). The hot blackbody temperature was set above the sample temperature, at 30 °C (Hori et al., 2006; Salvaggio and Miller, 2001). Details of the radiometric calibration that was applied to the measurements of these blackbodies radiances can be found in Hook and Kahle (1996). A diffuse reflecting gold plate with an emissivity of ~0.04 was used to measure downwelling radiance (DWR) in order to correct radiance measurements and determine any significant influence of laboratory background emissions (Eisele et al., 2015). The infragold plate was placed directly under the MIDAC sensor at the same distance as the sample. The temperatures of the sample, infragold plate, and lab were frequently monitored before and after each measurement, using thermistors (FLUKE 51 II Thermometer and Precision IR Thermometer) to detect any possible changes in temperature that could affect the measurements, as such changes in temperature could disturb the thermal contrast and result in over- or underestimation of the emissivity values. The measurement series were taken within five minutes to minimize possible temperature drift of the instrument, physiological changes in the plants, and fluctuations in laboratory temperature (Hori et al., 2006).

Table 1
Summary statistics of the leaf area index (LAI) measurements for four plant species (n = 144).

Species name	LAI (m^2 m^{-2})			
	2 Mean	Max	Min	Sample size
Azalea japonica	1.57	3.35	0.60	30
Buxus sempervirens	4.54	9.80	1.17	40
Euonymus japonicus	3.28	7.43	1.25	44
Ficus benjamina	3.60	8.36	1.04	30
Total	3.25	9.80	0.60	144

2.3.1.2. Canopy radiance measurements. The radiance spectra of the plant canopies were measured between wavelengths of 2.5–20 μm with a resolution of 2 cm^{-1}. An average of 32 scans was observed for each sample (measurement). The canopy emissivity measurements included 279 wavebands between 8 and 14 μm regions. Measurements outside this range had very low signal strength and therefore were excluded from further analysis. After each set of measurements, the canopy was rotated 90° clockwise. The final corresponding canopy emissivity spectra of each sample (for a particular LAI value), was then calculated from the average of four sets of measurements (covering 360°). The position of the MIDAC sensor above the canopy was kept constant. In total, 576 (4*144) canopy radiance measurements were obtained for the four plant species (Table 1).

2.4. Data processing and analysis

Spectral emissivity of the plants was calculated from their absolute radiance using the following equation (Korb et al., 1996),

$$\epsilon_{\mathrm{sam}}\left(\lambda\right) = \frac{L_{\mathrm{sam}}\left(\lambda\right) - L_{\mathrm{LWR}}\left(\lambda\right)}{B\left(\lambda, T_{\mathrm{sam}}\right) - L_{\mathrm{DWR}}\left(\lambda\right)} \tag{1}$$

where $\varepsilon_{\mathrm{sam}}(\lambda)$ denotes the directional emissivity of the sample at the wavelength λ, $L_{\mathrm{sam}}\left(\lambda\right)$ is spectral radiance from the target, T_{sam} is the actual physical temperature of the sample, $B\left(\lambda, T_{\mathrm{sam}}\right)$ is the Planck function at the wavelength λ and sample temperature, and $L_{\mathrm{DWR}}\left(\lambda\right)$ is total spectral DWR from the hemisphere above the sample. To retrieve canopy surface emissivity, the information regarding precise surface temperature (T_{sam}) at the time of the measurement is essential. Therefore, in spite of measuring canopy temperature before and after each measurement, the blackbody fit method was used to estimate the exact sample temperature value at the time of measurement. The details about the blackbody fit method can be found in Kahle and Alley (1992) and Salvaggio and Miller (2001).

A Savitzky–Golay filter with a frame size of 15 data points and second- degree polynomial was used to reduce the noise of the canopy emissivity spectra (Savitzky and Golay, 1964). Data were analyzed and processed using MATLAB R2013b (Mathwork, Inc).

2.5. Statistical analyses

Three statistical tests were used in this study: one-way ANOVA, two-way ANOVA, and principal component analysis (PCA). A two-way analysis of variance (ANOVA) was performed to ascertain the effects of 1. variation in LAI values and the wavelength values across 8–14 μm (independent variables) and 2. the interaction between these independent variables, on canopy emissivity (the continuous dependent variable). For all species, LAI values were binned in three common classes of 1.5, 2.5 and 3.5 (m^2 m^{-2}). Also, wavelengths from 8 to 14 μm were binned into six categories ranging from 8 to 8.99 μm, 9–9.99 μm, 10–10.99 μm, 11–11.99 μm, 12–12.99 μm, and 13–13.99 μm. We examined whether the mean emissivity at different LAI values or waveband ranges were statistically different and whether there was an interaction between these variables (i.e. LAI and wavelength). In addition, a one-way ANOVA was used to explore whether the mean emissivity of different species with the same LAI value is significantly different. Tukey's honestly significant difference (HSD) test was used as a post-hoc test, to determine the statistical significance of differences between pairs of species and to examine whether mean emissivity in different species with the same LAI value is statistically different. In addition, Principal Component Analysis (PCA) was used as data reduction technique to determine the significant wavebands for discriminating between plant species with similar LAI values among the 279 wavebands in the TIR region that were studied. PCA is a popular multivariate statistical technique introduced by Pearson (1901) and refined by Hotelling (1933). It has been successfully used in many remote sensing studies as a data reduction approach (Chen et al., 2014; Du and Fowler, 2007; Hirosawa et al., 1996; Holden and LeDrew, 1998; Tsai et al., 2007). In our analysis, wavebands that have the highest factor loadings on the selected principal components (PC_s) have the greatest variation in emissivity between species with similar LAI values and have high information content, due to the significant contribution to the selected PCs.

3. Results

3.1. Statistical analysis

The experimental setup ensured a broad range of emissivity spectra at the canopy level and a large range of LAI values. In total, 144 samples were studied, with LAI values varying between 0.60 ($m^2\,m^{-2}$) in *Azalea japonica* and 9.80 ($m^2\,m^{-2}$) in *Buxus sempervirens* (Table 1).

In Fig. 2, canopy emissivity spectra of various plant species are plotted separately, based on different LAI values. It can be seen that LAI and thermal emissivity are positively correlated, in agreement with the positive correlations found between LAI and emissivity. As can be seen from Fig. 2, for all species the emissivity increases in all wavelengths across 8–14 μm parts of the electromagnetic spectrum. However, this increment is more pronounced above 9 μm, and the wavelength in the 8–9 μm portion of the electromagnetic spectrum, which is moderately responsive to LAI increases. Three of the measured species, namely, *Buxus sempervirens*, *Euonymus japonicas*, and *Ficus benjamina*, had high LAI values, with maxima above 3.5. Therefore, we further investigated how the change in emissivity spectra responded to higher LAI values. Plots of the emissivity spectra for these species for higher values (Fig. 2b–d) show that the difference in emissivity spectra of LAI values between 1.0 and 3.5 ($m^2\,m^{-2}$) is quite distinct for all four species.

For the LAI values larger than 4.0 ($m^2\,m^{-2}$), the differences in canopy emissivity spectra value become less pronounced and at some wavelengths seem to be saturated. The canopy emissivity spectra at several wavelengths reached saturation at different level, depending on the plant species. For instance, emissivity reaches saturation level in *Euonymus japonicus* and *Buxus sempervirens* when LAI exceeds 4.5 and 4 ($m^2\,m^{-2}$) respectively, while in *Ficus benjamina*, at wavelengths between 8 and 9 μm saturation is only observed when LAI exceeds 6.5 ($m^2\,m^{-2}$).

The two-way ANOVA results are presented in Table 2. The results showed that there was an interaction between wavelength and LAI values for all species. In other words, it seems that the effect on the canopy emissivity spectra of changing LAI values depends on the specific part of the spectrum.

Table 2
Summary statistics of Two-way ANOVA analyzing canopy emissivity spectra for different species, wavelength, and LAI value. The mean difference is significant at the 0.05 level.

Species	Source	*F* statistics	*p*-value
Azalea japonica	LAI	79.39	**<0.001**
	Wavelength	217.27	**<0.001**
	LAI × Wavelength	4.420	**<0.001**
Buxus sempervirens	LAI	76.07	**<0.001**
	Wavelength	218.26	**<0.001**
	LAI × Wavelength	4.54	**0.004**
Euonymus japonicus	LAI	51.73	**<0.001**
	Wavelength	236.90	**<0.001**
	LAI × Wavelength	9.26	**<0.001**
Ficus benjamina	LAI	134.05	**<0.001**
	Wavelength	128.39	**<0.001**
	LAI × Wavelength	25.38	**<0.001**

Table 3
Summary statistics from One-way ANOVA with Post-hoc Tukey's HSD test of canopy emissivity spectra for four plant species with LAI value binned around 1.5, 2.5 and 3.5 ($m^2\,m^{-2}$). The mean difference is significant at the 0.05 level.

LAI ($m^2\,m^{-2}$)	Variable		Mean Difference (I–J)	p-value
	(I)	(J)		
1.5	1*	2	−0.013*	**<0.001**
		3	0.005*	**0.008**
		4	−0.005*	**0.007**
	2	3	0.018*	**<0.001**
		4	0.007*	**<0.001**
	3	4	−0.010*	**<0.001**
2.5	1	2	−0.010*	**<0.001**
		3	0.004*	**0.011**
		4	−0.000	0.905
	2	3	0.014*	**<0.001**
		4	0.009*	**<0.001**
	3	4	−0.004*	**0.007**
3.5	1	2	−0.006*	**<0.001**
		3	0.001	0.212
		4	−0.002*	**0.024**
	2	3	0.008*	**<0.001**
		4	0.004*	**0.003**
	3	4	−0.004*	**0.003**

*Where (1) is *Azalea japonica*, (2) is *Buxus sempervirens*, (3) is *Ficus benjamina*, (4) is *Euonymus japonicas.*

As can be seen from Fig. 3, the emissivity spectra and absorption features vary between plant species with similar LAI values. The one-way ANOVA shows significant differences at $p < 0.05$ among all species ([LAI = 1.5, $F_{(3,1112)} = 44.63$, MSE = 0.01, p-value = 0.00], [LAI = 2.5, $F_{(3,1112)} = 36.29$, MSE = 0.01, p-value = 0.00], and [LAI = 3.5, $F_{(3,1112)} = 18.82$, MSE = 0.00, p-value = 0.00]), showing that the mean emissivity of at least one pair of species was statistically different from the others. In addition, the results show that at a similar LAI, the emissivity spectra of the different plant species are mainly different between wavelengths 9–11 μm (Fig. 3). The Tukey's HSD test (Table 3) for the six possible pair combinations for the four species showed that the mean canopy emissivity spectra of all species with a similar LAI of 1.5 ($m^2\,m^{-2}$) was significantly different at the $P < 0.05$ level. However, not all comparisons were statistically significant for LAI values of 2.5 and 3.5 ($m^2\,m^{-2}$). At an LAI value of 2.5 ($m^2\,m^{-2}$) there was no statistically significant difference between *Azalea japonica* and *Euonymus japonicus* in the mean score for the canopy emissivity spectra. Neither were there significant differences between *Azalea japonica* and *Ficus benjamina* with a LAI value of 3.5 ($m^2\,m^{-2}$).

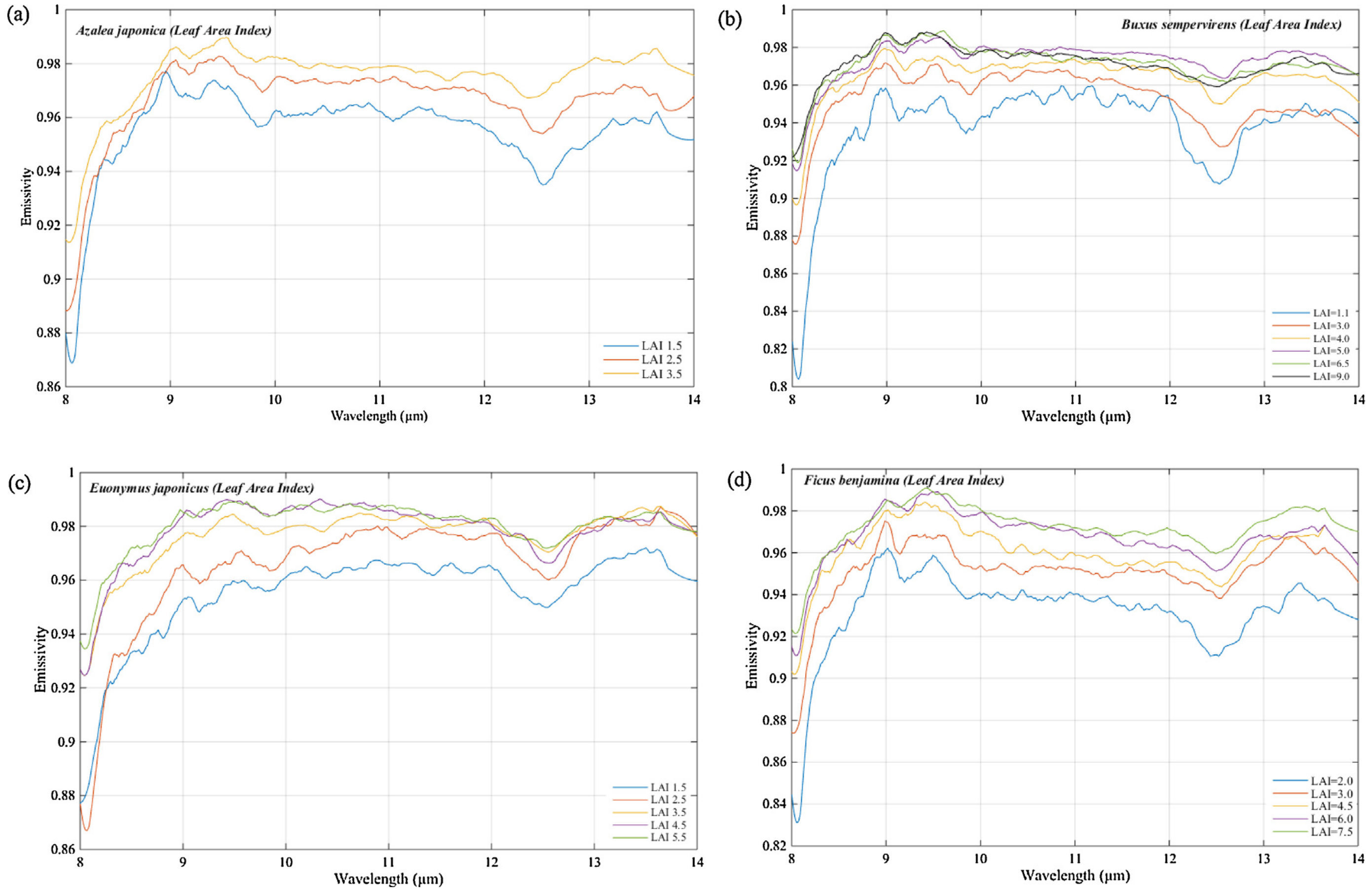

Fig. 2. The canopy emissivity spectra in *Azalea japonica* (a), *Buxus sempervirens* (b), *Euonymus japonicus* (c), and *Ficus benjamina* (d). Changes in canopy emissivity spectra become smaller when LAI values exceed 4.0 ($m^2\,m^{-2}$).

3.2. Principal componant analysis

The PCA analysis revealed that the proportion of the total variance between plant species that was explained by the first principal component (PC_1) was 97.28% for species with an LAI around 1.5 ($m^2\,m^{-2}$), 93.43% for species with an LAI value around 2.5 ($m^2\,m^{-2}$), and 94.07% for species with an LAI around 3.5 ($m^2\,m^{-2}$). The second principal component (PC_2) explained only 1.69%, 4.15% and 5% of the variance for LAI values of 1.5, 2.5 and 3.5 ($m^2\,m^{-2}$) respectively. Therefore, only PC_1 was selected for determining the wavebands for which the canopy emissivity spectra of different species with similar LAI values were highly variable. The waveband regions that provided the highest factor loadings were similar for all species with LAI 1.5, 2.5, and 3.5 ($m^2\,m^{-2}$), and were located in 8–10 μm part of the electromagnetic spectrum; they included the 8.0–8.3 μm, 8.8–9.1 μm, 9.4–9.6 μm, and 9.9–10.1 μm regions.

4. Discussion

Earlier studies using TIR hyperspectral data focused mainly on leaf scale measurements and their related properties (e.g. water content, and leaf chemical constituents) (Buitrago et al., 2016; Ribeiro da Luz and Crowley, 2010); to our knowledge, to date there have been no studies on the biophysical properties at canopy scale in the TIR domain. We believe our study is the first to use thermal hyperspectral data in order to understand the canopy emissivity spectral response to variation in LAI. Further, it explored whether canopy emissivity spectra of different plant species can be discriminated while their LAI is constant. The analysis of the canopy emissivity spectra of the four plant species revealed discrepancies due to dissimilarities between species in the absolute value of emissivity at different spectral wavebands. The finding demonstrates the potential of TIR hyperspectral data measured at the canopy level for discriminating between various plant species when their LAI is similar.

It is well known that LAI variability affects reflectance signatures in the VNIR portion of the spectrum. Here, we demonstrate that canopy emissivity spectra are also influenced by increasing LAI values in the 8–12 μm region. For LAI values greater than 4.0 ($m^2\,m^{-2}$), the changes in canopy emissivity spectra were less pronounced (Fig. 2). This suggests that other biophysical (such as leaf angle) and biochemical properties contribute to canopy emissivity spectra; this merits further investigation. In our study, it was observed that the small changes in LAI values (i.e. <0.5 ($m^2\,m^{-2}$)) are not readily detectable via canopy emissivity spectra. Our results confirmed earlier results obtained by Ullah (2013) that plants have relatively high emissivity and only small and subtle features in the TIR region, and this also applies to measurements made at canopy level.

Plant canopy temperature exerts strong control over respiration and transpiration. LAI is the critical parameter in canopy evaporation (van den Hurk et al., 2003) and transpiration: its variability affects biophysical and biochemical processes through its impact on heat and water fluxes between vegetation and the atmosphere. Moreover, canopy photosynthesis varies according to change in LAI value and the arrangement of the angular distribution of leaves

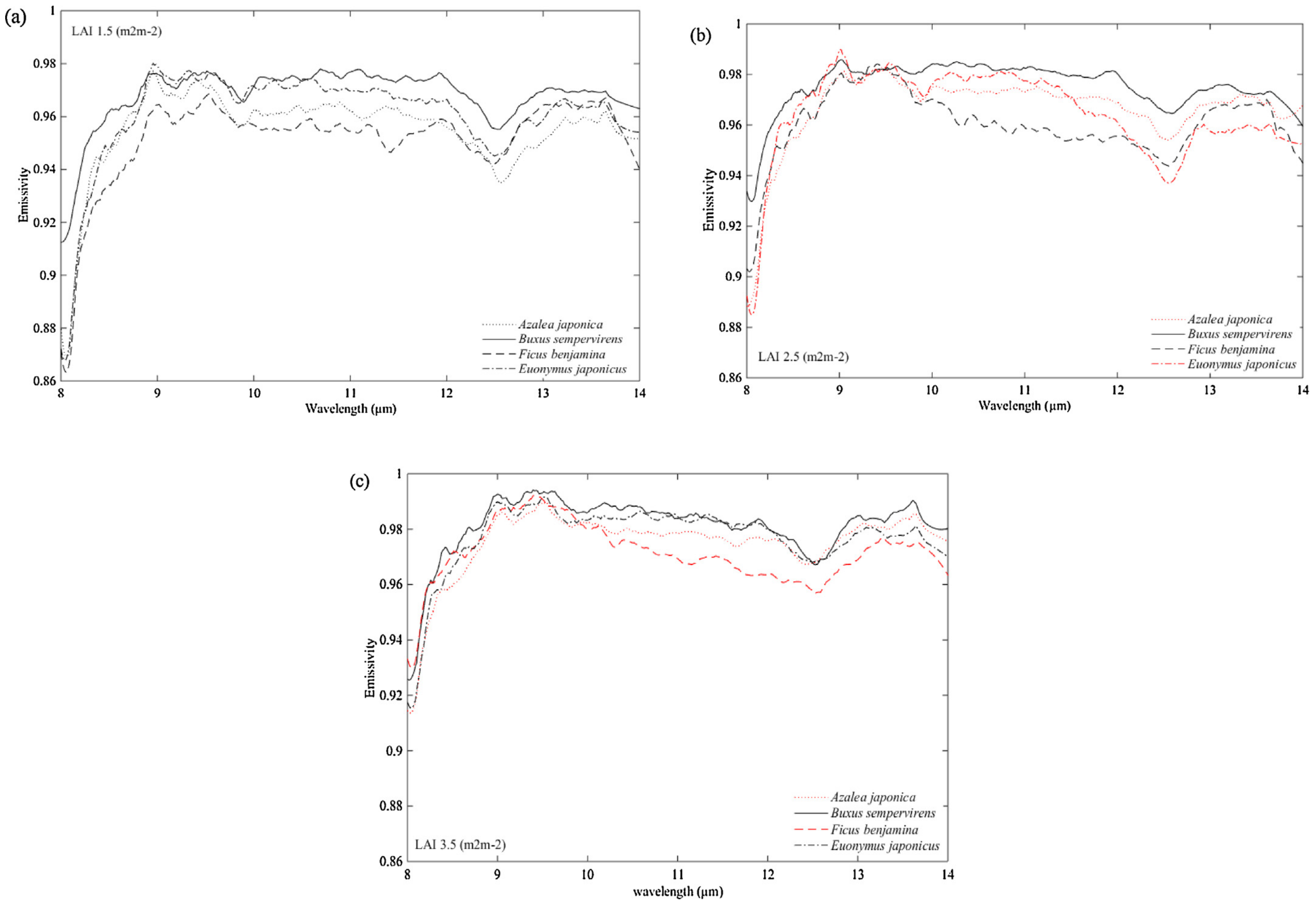

Fig. 3. The mean canopy emissivity spectra of different plant species with similar LAI value of (a) 1.5 (m^2 m^{-2}), (b) 2.5 (m^2 m^{-2}), and (c) 3.5 (m^2 m^{-2}). Plant species that are not statistically significant from each other are shown in red.

(Peri, 2005). In addition, as the LAI of a canopy increases, solar absorption increases because more leaves are present to absorb photons. The effects of the changes in leaf solar absorptance are significant in terms of affecting leaf temperature. In other words, changes in LAI values can determine the interception of solar radiation by plants. Therefore, it seems raising the LAI increases the absolute value of emissivity.

Many researchers have investigated the retrieval of LAI from reflectance spectra using optical remote sensing. Our finding is in agreement with previous findings by Darvishzadeh et al. (2008) who demonstrated that plant species with similar LAI values have different canopy reflectance spectra in the VNIR and SWIR regions. The finding that the canopy emissivity spectra of various plant species with the same LAI value were quite distinct (Fig. 3) suggests that LAI is probably not the sole factor affecting the canopy emissivity spectra. We know that at leaf level there are factors that affect emissivity (Buitrago et al., 2016; Ullah et al., 2013, 2014) but probably other canopy structural parameters also contribute to the variation of the canopy emissivity spectra. This might be attributed to the differences in canopy architecture (Pinter et al., 1985), leaves (i.e., size and orientation), canopy gap size (Ribeiro da Luz and Crowley, 2010), and concentrations of biochemical factors (Curran et al., 2001) or interactions among these factors. Moreover, the outermost layers of the leaf (i.e., plant cuticle) are claimed to be a principal cause of emissivity spectral features for different plant species in the TIR region (Ribeiro da Luz and Crowley, 2007). The external walls of plant epidermal cells are unique for every plant species (Glover, 2000). Therefore, the differentiation observed in emissivity spectral for various plant species with similar LAI value might be due to differences in the composition of the external walls of plant epidermal cells. As can be seen from Fig. 2 canopy emissivity spectra reached saturated at different levels for the different species. A possible explanation is that leaf biophysical variables such as internal leaf structure and leaf orientation as well as pigments are different within the studied species (Baret and Guyot, 1991; Yoder and Waring, 1994). Additionally, our results are partly in line with the findings of Ullah et al. (2012), who determined the important wavebands for discriminating between plant species at leaf level. We too found that waveband 9.4 µm is one of the most important wavebands, as it yields sufficient information to discriminate between plant species with similar LAI value at canopy level.

Finally, it should be noted that variation in LAI affects the emissivity of the canopy and could potentially affect plant strategies to cope with environmental conditions in cases where a plant needs to regulate energy. However, further research is essential to understand the impact of other biophysical and biochemical variables on canopy emissivity spectra in the TIR region.

5. Conclusions

This study demonstrated the feasibility of using TIR hyperspectral data to explore the influence of LAI on high-resolution emissivity spectra with rising LAI values, the canopy emissivity spectra increased. Further, the results also demonstrated that different plant species had different canopy emissivity spectra even when LAI values were similar. The ability to utilize laboratory spectral measurements to analyze the TIR hyperspectral data at canopy level is also an encouraging result, and the first in its kind. General knowledge on the possible relation between vegetation properties and emissivity spectral variation for plant species is still limited. Therefore, efforts should be devoted to exploring the advantages and limitations of TIR hyperspectral data for vegetation studies, especially at the canopy level. This study proved that under controlled laboratory conditions, measurements could also be made at canopy level, and it has shown that hyperspectral TIR remote sensing data are worthwhile analyzing in order to study vegetation.

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