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Influence of Water Content on Spectral Reflectance of Leaves in the 3–15- μm Domain

Sophie Fabre, Audrey Lesaignoux, Albert Olioso, and Xavier Briottet

Abstract—This letter describes a laboratory experiment where reflectance signatures of three plant species are measured at a leaf level in the 3–15- μm spectral domain. The leaf samples are progressively dried in order to analyze the behavior of their spectral signature according to the variations in their water content. Our first objective aims to underline leaf water content (LWC) impact on the spectral signatures. This work is a necessary step toward further studies dealing with interpretation of multispectral remote sensing data or estimation of water stress and energy budget. The drying process and measurement method are detailed. This letter deals with dry and fresh leaves (as found in literature) and considers intermediate water content levels as well. For intermediate LWC levels, our analysis outlines some important results: The spectral domain may be divided into two parts, namely, 3–5.5 and 5.5–15 μm , each corresponding to different impacts of LWC variation; both sides of a cherry tree leaf have not the same behavior according to the water content amount; and, in the 8–15- μm , the drying process impacts when the LWC becomes lower than a threshold value (around 30%).

Index Terms—Leaf, optical properties, spectral reflectance, thermal infrared domain, water content.

I. INTRODUCTION

THE IMPACT of leaf water content (LWC) on leaf reflectance has been widely documented in the 0.4–2.5- μm solar spectrum for a long time [1]. It has been shown that the shortwave infrared (1.4–2.5 μm) is strongly influenced by the water in plant tissue, particularly at 1.45 and 1.94 μm . Radiometric measurements in this domain have been suggested for estimating vegetation water content [2].

Conversely, little information is available for larger wavelengths situated in the 3–20 μm range. However, this information can be helpful for remote sensing interpretation or land surface and atmospheric studies (for example, in the 7–15- μm range [3] or around 4.7 μm [4]). Only few measurements of leaf spectral reflectance and emissivity were presented in the past

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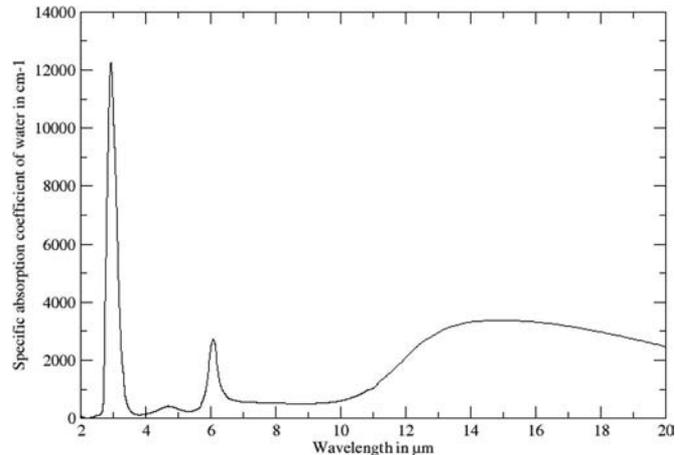


Fig. 1. Specific absorption coefficient of water. Redrawn from [11].

[5]–[10]. Moreover, these measurements considered fresh or fully dried leaves only. Intermediate moisture levels (that means variation of leaf reflectance as a function of water content) were not considered. These measurements showed that the differences between wet and dry leaf reflectances in the 7–15- μm spectral range are limited in comparison to those in the 1.4–2.5- μm range. Similar differences between wet and dry leaf reflectances are expected in the 3–6- μm window [10]. These low differences may be explained by the high absorption characteristics of the other leaf materials which limit the effect of water. As shown in Fig. 1, the absorption coefficient of water is usually very high, which is above 2.5 μm with fundamental molecular vibrations of water located at 2.86, 3.05, and 6.08 μm [11].

Furthermore, active mid-infrared backscatter characteristics of various agricultural crop leaves were measured at different wavelengths in the 9–11- μm spectral domain. Both copolarized and cross-polarized reflectance dependences on leaf moisture were analyzed by Narayanan *et al.* [12]. They pointed out the interest of using this range to study the impact of leaf moisture. However, these works were based on directional active measurements, and their results cannot be transposed to the analysis of remote sensing data which are currently limited to passive acquisitions and which are not obtained in the same geometrical conditions.

In order to analyze the impact of LWC on spectral reflectance, we conducted a laboratory experiment. Spectral reflectances were measured over the entire thermal infrared spectral domain between 3 and 15 μm for leaves which were progressively dried. The analysis of these laboratory measurements is provided for the middle infrared (3–5 μm) and the long-wave infrared [(LWIR); 5.5–15 μm] domains.

First, a laboratory measurement method and the acquired spectral reflectance at several water contents are described in Section II. Results are then analyzed in Section III. Discussions will follow in Section IV. Finally, conclusions and perspectives are given in Section V.

II. METHOD AND MEASUREMENTS

A. Overview of the Measurement Sequence and the Drying Process

The effect of water content on leaf optical properties was investigated for three plant species: one monocotyledon, namely, sorghum (*Sorghum bicolor*), and two dicotyledons, namely, sunflower (*Helianthus annuus*) and cherry tree (*Prunus avium*). A preliminary visual analysis showed that their leaves differed by their thickness, color, surface composition (waxes of abaxial leaves of *Prunus* was more visually apparent), and roughness. All samples were collected in agricultural fields near Toulouse (France) during summer 2006. Branch and plants selected for their good health and physiologic conditions were collected and stored in a fresh environment for an efficient conservation. Because of instrumental constraints, a part of leaf was sampled for each species before proceeding to the spectral measurements.

In order to measure the reflectance spectra at different moisture levels, successive LWCs were obtained by progressively drying the leaf samples in a laboratory oven (Sapratin brand). In order to avoid leaf rolling, the oven temperature was set to 60 °C, the drying time was limited to 30 min, and a rigid perforated sheet was put on the sample during the drying (experimental conditions inferred by preliminary tests). Thus, spectral reflectances of each leaf sample were measured at a minimum of five LWC levels. In order to obtain fully dried leaves, the samples were put in the oven for a period of 24 h between the two last spectral measurements. At each drying step, the reflectance spectrum of the leaf sample was measured using a spectrometer operating in the 3–15- μm range. In order to control the leaf moisture variations during the spectral measurements and to provide an accurate moisture assessment, the sample was weighed before and after each acquisition of reflectance data. The spectra were always measured using the same leaf on both sides for each species, as well as the same location on the leaf. The spatial variability within the leaf was not investigated. The dissimilar spectral behaviors are presented in the next paragraph.

B. Measurement of LWC

Leaf weights were measured using a laboratory scale with 100- μg accuracy. The LWC (in percent) was deduced from dry (m_D) and wet (m_W) weights according to the following relation: $LWC = 100 (m_W - m_D)/m_W$. The weight m_D of the fully dried sample was obtained after 24 h of drying (assuming that residual LWC was 2% [13]).

C. Measurement of Spectral Reflectances

In the 3–15- μm domain, spectral reflectances were directly measured with a Fourier transform infrared instrument: Bruker

Equinox 55 spectrometer (<http://www.brukeroptics.com/>). Owing to several mercury–cadmium–telluride detectors, which were cooled with liquid nitrogen (77 K) in order to reduce thermal noise, it made it possible to scan with a waveband of 7000 to 370 cm^{-1} , i.e., from 1.4 to 27 μm , with a standard spectral resolution better than 0.5 cm^{-1} . One measure resulted from the average of 256 acquisitions (scans) done with an 8- cm^{-1} resolution (providing a noise level less than 2% [14]). In order to keep a good signal-to-noise ratio, only the 3–15- μm range was used. The instrument was set using an Infragold integration sphere, with a 127-mm diameter, and measured directional–hemispherical reflectances. The sphere was purged to remove carbon dioxide and water vapor. The angle of the incident beam was 13°. Under this sphere, the sample size had a minimum diameter of 36 mm. Due to the long duration of the measurement sequence, we limited our measures to only one sample per species. The reflectance was obtained by comparing the measurement to an Infragold diffuse reference (annually certified by Labsphere).

III. RESULTS: MEASURED SPECTRA AT SEVERAL WATER CONTENTS

A. Fresh Leaf Samples

Fig. 2 shows the spectral reflectances acquired in the 3–15- μm domain for different LWCs. For fresh leaves, the spectral reflectance levels were low and ranged between 0.02 and 0.07. The sunflower leaf sample exhibited weaker spectral reflectance levels than those related to cherry tree and sorghum leaf samples. The behaviors of both leaf sides were dissimilar for the cherry tree leaf sample (see spectral ranges 3–5 and 8–10 μm in Fig. 2).

In the middle infrared domain, i.e., 3–5.5 μm , our measurements were similar to spectra of typical green foliage measured by Salisbury and D’Aria [10], with low reflectance due to intense leaf water absorption [5] (Fig. 1). In this spectral domain, leaf samples had similar global behaviors with two apparent maxima around 4 and 5.2 μm , due to cellulose absorption for dry leaves and water absorption at 4.65 μm for fresh leaves (Fig. 1), and the Reststrahlen bands near 3.43 and 3.51 μm due to the H–C vibration bands [10], [15]. Furthermore, for all the spectra, the strong absorption at 3.05 μm linked to water (Fig. 1) is well noticed.

In the 5.5–15- μm range, the absorption peak linked to water at 6 μm (Fig. 1) is observed for the abaxial cherry, adaxial sunflower, and adaxial sorghum samples.

In the entire spectral domain 3–15 μm , a more detailed analysis showed that the spectral features varied from one species to another. Furthermore, in the case of the cherry leaf sample, both sides of the leaf had dissimilar spectral signatures: In the 3–5.5- μm range, the reflectance level difference between both sides was around 0.02, and double reflectance peaks became less apparent for the adaxial side of the leaf; in the 8–15- μm range, the reflectance peak around 8.7 μm was less pronounced than for the abaxial side of the leaf [Fig. 2(a) \rightarrow 1]. This was in agreement with previously published data [7]–[10], [15] and with the data available in the MODIS (<http://www.>

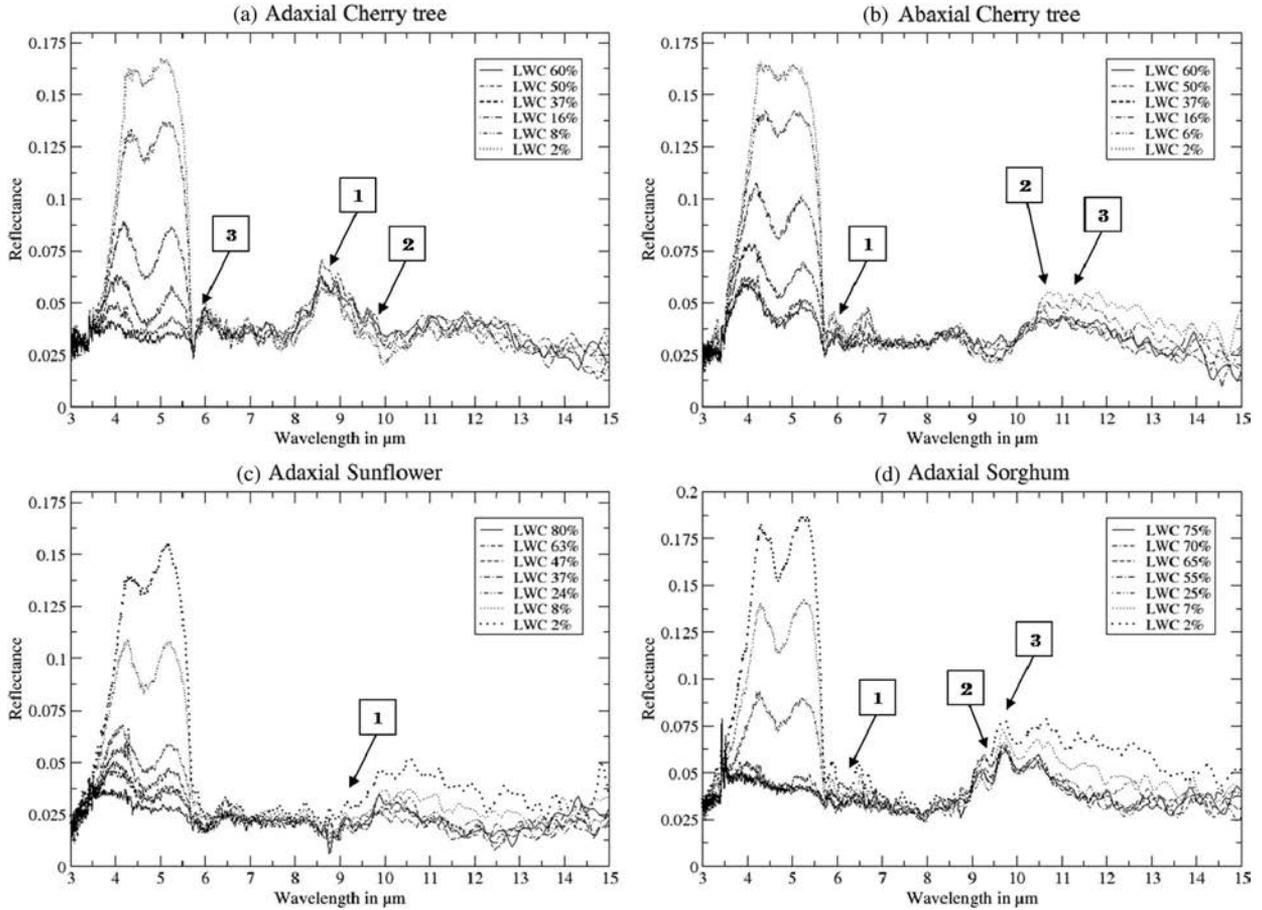


Fig. 2. Spectral reflectances of leaves for several water contents in the thermal domain. (a) Adaxial and (b) abaxial sides of cherry tree, (c) adaxial side of sunflower, and (d) sorghum leaf samples. Arrow labels locate a specific behavior, detailed in the document.

icess.ucsb.edu/modis/EMIS/html/em.html) spectral library. Indeed, the spectral signatures of abaxial and adaxial side leaves of green cherry (*Prunus serotina*) presented in [8] and those of *Prunus serotina* measured by Ribeiro da Luz [15] were in good agreement with our measurements: the maximum of reflectance at $5.94 \mu\text{m}$ [Fig. 2(b) \rightarrow 1] and at $9.67 \mu\text{m}$ [Fig. 2(a) \rightarrow 2] due to the absorption of triterpenes existing in resin, absorption peaks at $5.75 \mu\text{m}$ [Fig. 2(a) \rightarrow 3] due to the C–O double bond, and between 8.7 - and 9.7 - μm [Fig. 2(a) \rightarrow 1] reflectance peaks due to leaf compounds other than cellulose. In fact, the very subtle reflectance maxima of cellulose in this range are normally accompanied by high transparency between 10.5 and $12 \mu\text{m}$ [Fig. 2(b) \rightarrow 2] and by a volume scattering feature at $11.15 \mu\text{m}$ [Fig. 2(b) \rightarrow 3] [5], [7].

The sunflower leaf sample had similar spectral signature as the one of *Red oak* leaf in [9] and was close to those of *Heliantus annuus* and *Cucurbita pepo* in [15]. For the *Heliantus annuus* variety, the only difference was related to the absorption peak near $9 \mu\text{m}$ [Fig. 2(c) \rightarrow 1].

The sorghum spectral signature looked like *Indiangrass blades* in [9] and *Zea mays* in [7], [15]: absorption peaks near $6 \mu\text{m}$ [Fig. 2(d) \rightarrow 1] due to water [Fig. 1] and $9.5 \mu\text{m}$ [Fig. 2(d) \rightarrow 2], the maximum of reflectance at $9.62 \mu\text{m}$ [Fig. 2(d) \rightarrow 3] *a priori* related to COH bending, and the presence of hemicellulose.

B. Drying Leaf Samples

For fully dried leaves (Fig. 2; a residual LWC of 2%), the spectral reflectance levels increased and ranged between 0.02 and 0.18. The spectral reflectance signature of cherry tree sample was in good agreement with dried cherry leaf in [8]. Dried sorghum and dried sunflower spectra were similar to senescent foliage of *rye grass* in [9] and [10] with weaker reflectance levels, particularly in the 3 – 5 - μm domain. Furthermore, our measurements tallied with the spectra of dry plant materials in [1]. For example, the signature due to the mixture of holocellulose and lignin was well observed with a maximum around 4 – $5.5 \mu\text{m}$.

In complement to the spectra in Fig. 2, the impact of leaf drying is shown for two specific wavelengths in Fig. 3. For our data set, the water had more impact in the 3 – $5 \mu\text{m}$ domain. Indeed, the spectral reflectance increased when the water content decreased, and the levels between fresh and dry spectra differed from 0.1 to 0.14 [Figs. 2 and 3(a)]. Furthermore, the reflectance levels were more influenced when LWC varied below 30% to 40% (in relation to the high absorption by water). In Fig. 3(a), the reflectance at $4.1 \mu\text{m}$ increased with LWC, as an exponential function. There were few spectral variations in the 5.5 – 10 - μm spectral domain due to the strong absorption of cellulose.

The impact of water content increased beyond $10 \mu\text{m}$. This increase is underlined in particular for low LWC (LWC < 20%),

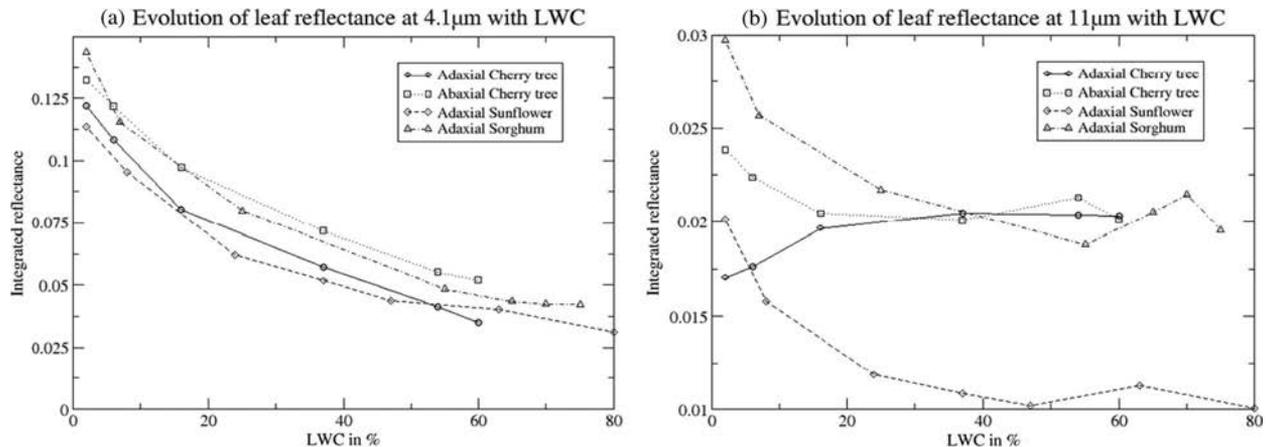


Fig. 3. Leaf reflectances at (a) 4.1 and (b) 11 μm as a function of LWC (wavelengths chosen in atmospheric window only).

with variations of reflectances between 0.03 and 0.01 at 11 μm [Fig. 3(b)]. This behavior was not observed for the abaxial side of the cherry tree, and the drying impact was different on both sides of the cherry tree leaf. This might be due to dissimilar leaf compounds and textures on the two sides of the leaf.

IV. DISCUSSION

Works conducted in [5], [7]–[10], and [15] provide information for the interpretation of fresh and dry leaf spectra and allow one to validate our measurements by comparison. The leaf spectra behavior might be then defined, owing to its specific components (see, for example, the spectral impact of wax on cherry tree sample or of hemicellulose on sorghum sample). For fresh and dry conditions, some differences in terms of spectral reflectance level appeared in comparison to [8]–[10], [7], and [15] data. For example, sorghum spectra had similar levels as those of *Indian grass* [10], *Zea Mays* [15], and *Rye grass* [10] in the 8–15- μm range, but lower levels at shorter wavelengths. In the case of sunflower, the reflectance levels were always different from those found in the literature. These differences might be explained by variations in the chemical composition of leaves, particularly in the surface layers, and/or by variations in the structure of the leaves. Such changes might be related to differences in plant cultivar, as well as differences in leaf age and growth conditions.

To our knowledge, our study is the first one to report the impact of leaf drying on reflectance in the 3–15- μm range. A previous study at canopy level by Olioso *et al.* [3] suggested the impact of such drying but no direct evidence was given at leaf level. This letter showed that the drying impact may be different according to species, spectral domain, and LWC level. The first evidence in our results was that the investigated domain could be split into two parts: one above and the other below 5.5 μm . All samples had the same spectral behavior in the 3–5.5- μm range, whereas it changed according to species in the 8–15- μm range. For all leaf samples, the reflectance at a given wavelength in 3–5.5 μm had an exponential behavior according to water content decrease. A quite similar behavior was noticed for most of the samples in the 8–15 μm , except for the adaxial side cherry tree leaf which was almost unaffected by

drying. In this last range, the observed changes in reflectance were limited and occurred mostly for LWC lower than 30%. At higher LWC, reflectances were almost unaffected, while in the 3–5.5- μm range, reflectance changes were continuous.

Only measurements of leaf directional–hemispherical reflectances were presented in this letter, and no attempt was done for deriving leaf emissivity. If the validity of the Kirchhoff law is not challenged, the derivation of leaf spectral emissivities would require the measurement of leaf directional–hemispherical transmittance in order to derive the absorptance of directional radiation. Indeed, the works in [16] and [17] highlighted that drying leaves might not be opaque in the thermal infrared domain (in particular, in the spectral domains characterized by high leaf reflectances).

Our study was the first step for considering the impact of vegetation water content on spectral properties in the mid- and thermal-infrared domains. It only considered the leaf level and could not be used per se for the direct interpretation of land surface spectral properties and satellite signal. Many other factors would have to be accounted for, such as sensor performances, geometry of acquisition, vegetation architecture, soil optical properties, atmospheric properties, and the relative contributions of reflected radiations (solar and atmospheric) and of emitted radiations according to wavelength. The assessment of all these factors would require the integration of various specific models, including atmospheric radiative transfer models, sensor models, and vegetation canopy radiative transfer models. These last ones have to be used for analyzing the impact of geometry of acquisition, vegetation architecture (Leaf Area Index, leaf angle distribution, etc.), and soil spectral properties on land surface spectral emissivities or spectral radiances [10], [14], [17], [18]. It is important to notice that coherent modeling of directional radiances requires solving leaf and soil energy balances in order to account for the distribution of surface temperatures inside the canopy and at the soil surface, which also require the knowledge of leaf optical properties over the whole spectral range. Another point to consider in the future concerns the differences between drying conditions in the laboratory and *in vivo*. This drying process difference might affect the relationship between LWC and spectral properties.

V. CONCLUSION

We have presented the laboratory measurements of spectral directional-hemispherical reflectances acquired on leaf samples in the 3–15- μm domain. Three species have been investigated. Our measurements were in good agreement with existing data published in literature for fresh and fully dried leaves (even if the reflectance levels differ). The originality of our work consists not only in measuring spectral signatures for fresh and dry samples but also for intermediate LWCs. Our measurement analysis has led to the following significant points.

- 1) The investigated spectral domain might be divided into two parts: 3–5.5 and 5.5–15 μm . In the first domain (mid-wave infrared), the reflectance was very sensitive to LWC, whereas in the LWIR domain, this dependence remains very weak for wavelengths higher than 10 μm .
- 2) The considered species and leaf side had a different behavior according to the water content amount.

In future laboratory experiments, these measurements will be completed by increasing the set of leaf samples in order to validate our first results. Moreover, it will be interesting to measure both reflectance and transmittance in order to describe the complete optical property behavior, including emissivity, according to water content amount. The experiment measurement geometry and observation conditions were not representative of those related to remote sensing observations. Further analyses are in progress for including the impact of other factors such as atmospheric conditions, canopy architecture [19], or soil water content [18].

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