ISPRS Journal of Photogrammetry and Remote Sensing 111 (2016) 22–31

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Changes in thermal infrared spectra of plants caused by temperature and water stress

Maria F. Buitrago *, Thomas A. Groen, Christoph A. Hecker, Andrew K. Skidmore

Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, The Netherlands

ARTICLE INFO

Article history:
Received 8 May 2015
Received in revised form 21 October 2015
Accepted 7 November 2015
Available online 8 December 2015

Keywords:
Spectral emissivity
Water stress
Temperature stress
Thermal infrared
Rhododendron cf. catawbiense
Fagus sylvatica

ABSTRACT

Environmental stress causes changes in leaves and the structure of plants. Although physiological adaptations to stress by plants have been explored, the effect of stress on the spectral properties in the thermal part of the electromagnetic spectrum (3–16 μm) has not yet been investigated.

In this research two plant species (European beech, *Fagus sylvatica* and rhododendron, *Rhododendron cf. catawbiense*) that both grow naturally under temperature limited conditions were selected, representing deciduous and evergreen plants respectively. Besides TIR spectra, Leaf Water Content (LWC) and cuticle thickness were measured as possible variables that can explain the changes in TIR spectra.

The results demonstrated that both species, when exposed to either water or temperature stress, showed significant changes in their TIR spectra. The changes in TIR in response to stress were similar within a species, regardless of the stress imposed on them. However, changes in TIR spectra differed between species. For rhododendron emissivity in TIR increased under stress while for beech it decreased. Both species showed depletion of Leaf Water Content (LWC) under stress, ruling LWC out as a main cause for the change in the TIR spectra. Cuticle thickness remained constant for beech, but increased for rhododendron. This suggests that changes in emissivity may be linked to changes in the cuticle thickness and possibly the structure of cuticle. It is known that spectral changes in this region have a close connection with microstructure and biochemistry of leaves. We propose detailed measurements of these changes in the cuticle to analyze the effect of microstructure on TIR spectra.

Published by Elsevier B.V. on behalf of International Society for Photogrammetry and Remote Sensing, Inc. (ISPRS).

1. Introduction

1.1. Plant stress

Stress in plants can be generated from biotic and abiotic factors such as living organisms (bacteria, viruses and parasites), climatic conditions or natural disasters (Rhodes and Nadolska-Orczyk, 2001). Changing climatic conditions such as availability of water, irradiation or extreme temperatures, can create stressing conditions that change the normal growth of the plant and the canopy (Levitt, 1980). There are many known mechanisms to cope with stress, which can be grouped into two classes: (a) fast biochemical responses, followed by (b) microstructural re-arrangement of the cellular space and therefore the leaf structure, in the case of long duration stress or permanent stressors (Levitt, 1980; Rhodes and Nadolska-Orczyk, 2001). Under long duration stress, plants may change not just the microstructure but also the community physiognomy. Long duration and extreme stress conditions such as extreme temperature and water availability are well known evolutionary drivers of phytogeographical diversity and speciation, especially in alpine and desert environments (Charrier et al., 2014; Nevo, 2011).

1.2. Stress detection

Detecting stressors and their impact on vegetation are of importance for agriculture and for ecosystem conservation. Conventional methods of stress detection are based on the observation of physical changes, e.g. color or turgidity, with the risk of being detected only after a critical point of damage has been reached. Other methods focus on detecting early stress symptoms using biochemical and biophysical techniques such as leaf water potential and stomatal conductance (e.g. Hand et al., 1982; Hura et al., 2007; O'Toole

* Corresponding author at: Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands. Tel.: +31 53 4874372.

E-mail addresses: m.f.buitragoacevedo@utwente.nl (M.F. Buitrago), t.a.groen@utwente.nl (T.A. Groen), c.a.hecker@utwente.nl (C.A. Hecker), a.k.skidmore@utwente.nl (A.K. Skidmore).

http://dx.doi.org/10.1016/j.isprsjprs.2015.11.003
0924-2716/Published by Elsevier B.V. on behalf of International Society for Photogrammetry and Remote Sensing, Inc. (ISPRS).

and Cruz, 1980; Zörb et al., 2004) or tracking changes in leaves and canopy temperature or Leaf Water Content (LWC) with thermal cameras and infrared sensors (e.g. Chaerle and Van Der Straeten, 2000; Costa et al., 2013; Mahlein et al., 2012; Oerke and Steiner, 2010). These techniques are time consuming, expensive and not applicable to the large areas observations.

1.3. Remote sensing

Remote sensing (RS) provides methods for early detection of plant stress based on changes in the reflection of different regions of the electromagnetic spectrum. The early availability of multispectral bands from air and spaceborne sensors promoted the development of spectral indices in the Visible (VIS), Near Infrared (NIR) and the Short Wave Infrared (SWIR) parts of the spectrum. More recently, the development of new technologies and remote hyperspectral sensors, have promoted the development of a new generation of more accurate hyperspectral indices which can detect a high variety of stressors. The electromagnetic spectrum can be divided in regions according to the interaction between energy and leaves, especially with the outer surface of leaves and their composition. The VIS–NIR is known for the strong interaction of light with pigment concentrations in the VIS and the strong reflectance and transmittance by the leaf in the NIR, which can be analyzed with different methods. The ultraviolet induced florescence in the VIS–NIR is used to detect the concentration of antioxidants and Reactive Oxygen Species (ROS), which are the initial responses to water and temperature stress (Chaerle et al., 2007; Frohnmeyer and Staiger, 2003). The VIS–NIR fluorescence can additionally be used to detect changes in pigments as a response to the reduction in the photosynthetic activity (Belasque et al., 2008; Lang et al., 1996; Lichtenthaler, 1996; Zarco-Tejada et al., 2009, 2002). Reflectance methods in the VIS–NIR allow the detection of leaf pigments, and their variations due to stress conditions (e.g. Carter, 1993; Cozzolino, 2014; Dobrowski et al., 2005; Eitel et al., 2006; Gao, 1996; Peñuelas and Filella, 1998; Peñuelas et al., 1997; Seelig et al., 2008). Changes in other biochemicals can also be detected in the VIS–NIR such as nitrogen, lignin and cellulose (Kokaly and Clark, 1999; Li et al., 2007; Martin and Aber, 1997; Serrano et al., 2002). The strong absorption features of water in the SWIR have been widely used for assessing water stress, by formulating water stress indices (e.g. Ceccato et al., 2002; Ceccato et al., 2001; Eitel et al., 2006; Feng et al., 2013; Fensholt and Sandholt, 2003; Seelig et al., 2008). While the Thermal Infrared (Karlson et al., 2004) range is conventionally used for detecting early signs of stress by observing canopy temperatures (e.g. Calderón et al., 2013; François et al., 1997; Grant et al., 2007; Jones et al., 2009; Leinonen and Jones, 2004).

1.4. Thermal infrared

TIR is the region of the electromagnetic spectrum where the radiation emitted by objects due to their thermal state is more intense than the reflected solar radiation (Prakash, 2000). Sensors working in this region detect mainly the long-wave radiation of materials. The most explored regions in the TIR are the Mid-Wave Infrared (MWIR: 3–6 μm) and the Long-Wave Infrared (LWIR: 6–16 μm) which contain relevant information for the analysis of plant properties (Ribeiro da Luz and Crowley, 2007; Ullah et al., 2012b). Longer wavelengths, above 16 μm, have not been used for plant studies.

Hyperspectral variations in the TIR region have so far been studied mainly for geological purposes, due to the strong spectral responses of minerals in this region (Van der Meer et al., 2012). Other scientific fields such as ecology and plant science have used this region less due to a lack of sufficiently accurate laboratory and field instruments to detect the subtle spectral differences in the TIR that can be found in plants (Ribeiro da Luz and Crowley, 2007). Nevertheless, in the last decades the accessibility to new laboratory and field work equipment, as well as new airborne and satellite sensors with hyperspectral TIR detection capacity, is creating a need for further research in this field.

While the VIS, NIR and SWIR are dominated by the reflectance of the solar energy, longer wavelengths in the MWIR and especially the LWIR operate independently from reflected sunlight. The emissivity, *i.e.*, the ratio of the energy radiated from a material's surface to that radiated from a blackbody (a perfect emitter) according to the Planck function at the same temperature and wavelength, is one of the most important factors in the variation of energy recorded in the TIR.

Thus emissivity is not the result of the interaction between solar energy and pigments like in shorter wavelengths, but is the effectiveness in emitting thermal radiation by the surface of the leaf. This means that the thermal radiation in the TIR can potentially contain information about the biochemistry and microstructure of single leaves and plants (Ribeiro da Luz, 2006; Ribeiro da Luz and Crowley, 2007, 2010). For instance, some researchers have found that single plant species can have a different 'spectral finger print' in the LWIR which could be used as a key for species identification (Ribeiro da Luz, 2006; Ribeiro da Luz and Crowley, 2010; Salisbury, 1986; Ullah et al., 2012a). Similarly some regions in the MWIR have a clear response to LWC (Ullah et al., 2012b), and the LWIR could be associated to biochemistry and microstructure of the leaves (Elvidge, 1988; Ribeiro da Luz and Crowley, 2007). This may be linked to physiological changes of plants and may be associated with responses to stressors.

Despite early efforts with exploring the TIR (e.g. Fensholt and Sandholt, 2003; Hunt and Rock, 1989; Ullah et al., 2013), the changes caused by water and temperature stress in the whole TIR has not yet been explored.

2. Materials and methods

2.1. Species

When selecting the species for this study, species which can grow up to the tree line in mountains (the line above which trees do not grow any more due to temperature limitations) were chosen, due to their differential plasticity and their capacity to cope with extreme conditions such as low temperatures and water depletion. These plants are, therefore, expected to have different mechanisms to cope with stressful conditions, such as structural changes in their leaves, when stress conditions continue for a long period (Prasad, 2001).

Rhododendron spp. are in general evergreen species whose leaves resist winter temperatures without senescence, and is found as a continuous tree line in Asia, Europe and America. *Fagus sylvatica* (beech) is a European deciduous species with a wide distribution in the mountains, where it forms tree lines in some localities. As a deciduous species, it loses its leaves seasonally when temperatures become colder. For this reason the low temperature treatment (see below) was not applied to beech, to avoid inducing premature senescence.

2.2. Experiment

A factorial experiment was established with two factors: temperature stress and water stress (Fig. 1). Temperature stress was defined as low or chilling temperatures between 1 and 10 °C, which can have a negative impact on the metabolism of plants, especially during the growing season (Bracale and Coragio, 2003;