

## Reflectance indices indicative of changes in water and pigment contents of peanut and wheat leaves

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### Abstract

Measurements of reflectance in visible and near-infrared spectral regions were made on detached leaves of two crop species of different leaf morphology, structure, and water content (peanut and wheat) throughout progressive desiccation. Relative water content (RWC) was well correlated with water index (WI) but even better with the ratio of WI and normalized difference vegetation index. RWC was also significantly correlated with structural independent pigment index indicative of carotenoids/chlorophyll ratio. New indication is thus provided to assess leaf water content and apply simple and fast radiometric techniques for plant water stress management.

*Additional key words:* *Arachis*; leaf desiccation; normalized difference vegetation index; relative water content; structural independent pigment index; *Triticum*; water index.

### Introduction

Quantitative and rapid methods for evaluating leaf water status are required for plant water stress management in agriculture, horticulture, forestry, and fire risk assessment (Chandler *et al.* 1983, Inoue *et al.* 1993). Because of this, one of the main goals of remote sensing has been the detection of plant water content (for references see Bowman 1989, Peñuelas *et al.* 1993, Shibayama *et al.* 1993, Peñuelas and Filella 1998). Several indices using the near-infrared region have been proposed as water stress indices with varying results depending on the species (Carter 1991, Peñuelas *et al.* 1996). At long middle-infrared water-absorption wavelengths such as 1430 and 1900 nm there is a strong absorption by the atmosphere, and irradiance is too low. Therefore they are not very practical for leaf and plant water assessment in the field. Instead, the changes in a reflectance trough at 950-970 nm corresponding to a weak

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water absorption band are effective at plant and canopy levels. Peñuelas *et al.* (1993, 1996, 1997) showed that the ratio between the reflectance at a reference wavelength, 900 nm, and the reflectance at 970 nm (WI, water index) closely tracked the changes in plant and canopy RWC in several species of trees, shrubs, crops, and grasses. The reference wavelength of 900 nm has no absorption by water but is subjected to the same changes in sample structure as 970 nm. The plant and canopy sensitivity is linked to higher irradiance penetration into the canopy at these wavelengths than at longer wavelengths (Bull 1991). However, at the leaf level the signal seems weaker and it is not yet clear whether it will be useful. There are also other possible changes in the visible region linked to progressive pigment degradation under desiccation. Reflectance indices such as structural independent pigment index (SIPI), a pigment index related to the ratio between carotenoids and chlorophyll, may be useful to assess these pigment changes (Peñuelas *et al.* 1995).

We aimed to study (1) the performance of WI as an indicator of water content at the leaf level, and (2) the performance of SIPI under progressive desiccation of leaves. We compared the response of these spectral indices in peanut and wheat leaves, *i.e.*, in two species with very different foliar morphology and water content. Finally, (3) we also tested the possibility of improving WI as leaf RWC indicator by dividing by NDVI (WI/NDVI) with the aim of standardizing by different specific and desiccation leaf structural traits.

## Materials and methods

Leaves of wheat (*Triticum aestivum* L.) and peanut (*Arachis hypogea* L.) were sampled from field grown plants. They were placed in water under a photosynthetic flux density (PFD) of 10  $\mu\text{mol m}^{-2} \text{s}^{-1}$  for 2 to 4 h until no further biomass increase occurred. The saturated masses (SM) were assumed to be at full turgor. Then the reflectance was measured on the adaxial surface of each leaf using a spectroradiometer with an integrating sphere and a tungsten lamp (Beckman, UV5240). The spectral range was from 400 to 2500 nm and the resolution was 2 nm for the visible region and 4 nm for the infrared region. Reflectance was measured several times concurrently with the measurement of leaf fresh mass (FM) as leaves gradually dried in glass containers. After several consecutive spectral and mass measurements, leaves were oven dried at 80 °C to determine dry mass (DM). RWC was calculated as  $100 \times (FM - DM) / (SM - DM)$  and WC (water content) as  $(FM - DM) / A$ . Leaf area (A) was measured for each leaf at full turgor. These measurements were conducted on five leaves for peanut and ten leaves for wheat.

The following radiometric indices were computed:

- (1)  $WI = R_{900} / R_{970}$
- (2)  $NDVI = (R_{900} - R_{680}) / (R_{900} + R_{680})$
- (3)  $WI/NDVI$
- (4)  $SIPI = (R_{800} - R_{445}) / (R_{800} - R_{680})$

where R indicates reflectance and numbers indicate nanometers.

Statistical analyses, mainly consisting in correlation and regression, were done by using the *Statview 4.5* program package (*Abacus Concepts*, Berkeley, CA, USA).

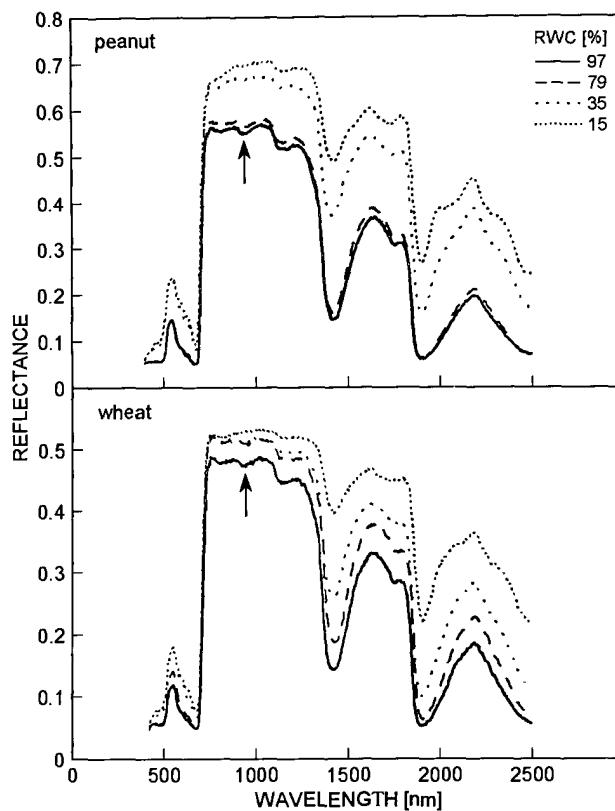


Fig. 1. Spectral reflectance of peanut and wheat leaves under progressive desiccation from RWC 97 % to 15 and 27 %, respectively.

## Results and discussion

In both peanut and wheat leaves, reflectance increased at all wavelengths with decreasing leaf water content from fully turgid to dry state (Fig. 1). There were strong reflectance troughs, due to strong absorption by water at 1430 and 1950 nm, that tended to disappear with progressive desiccation. However, indices based on such wavelengths are not measurable in nature (Inoue *et al.* 1993). In contrast, the 970 nm trough of the reflectance spectra was measurable in field conditions, and it also disappeared with progressive desiccation. Therefore, RWC was well correlated with WI ( $R_{900}/R_{970}$ ) ( $r = 0.92$  for peanut and  $r = 0.6$  for wheat,  $p < 0.001$ ). However, whereas WI started to decrease with first water losses in wheat, it did not start to decrease until 60 % RWC in peanut leaves, which had about twice as large water content than wheat leaves (Fig. 2). No common regression for both species was thus obtained. The difference in equations must be due to the structural and water content

differences of their leaves. WI also changes with structural leaf characteristics such as cell wall elasticity (Peñuelas *et al.* 1996). As the NDVI follows structural and colour changes (loss of pigments) in the drying leaves, the ratioing of WI by NDVI was a better indicator of RWC than the WI itself in both species (Fig. 3, *top*). These results at the leaf level agree with similar results reported at plant and canopy levels for many other species (Peñuelas *et al.* 1997).

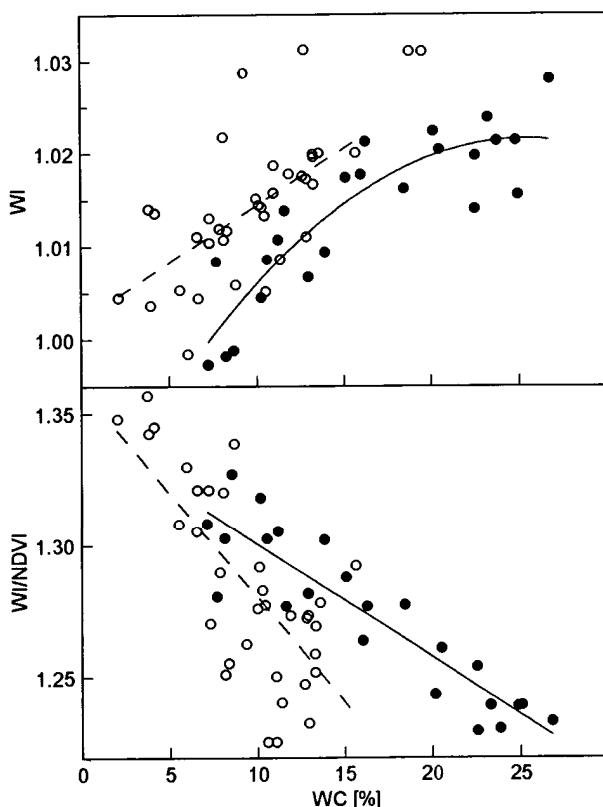


Fig. 2. Water index (WI,  $R_{900}/R_{970}$ ) relationships with water content (WC) in peanut (O) and wheat (●) leaves under progressive desiccation.

The pigment index SIPI was also very strongly correlated with RWC (Fig. 3, *bottom*) indicating a possible progressive increase in the ratio between carotenoids and chlorophyll, likely because of chlorophyll degradation under desiccation (Young and Britton 1990, Peñuelas *et al.* 1995). It adds new possibilities of indirectly assessing progressive leaf water stress.

These reflectance indices should be effective for estimating leaf RWC or WC in the respective crops by using reflectance simple techniques. It is thus feasible to develop a compact portable instrument for field measurement of leaf water content. For example, a simple radiometer that only measures reflectance at 680, 900, and 970 nm can instantly calculate the NDVI and the WI, and by using appropriate calibration functions estimate plant water content in seconds.

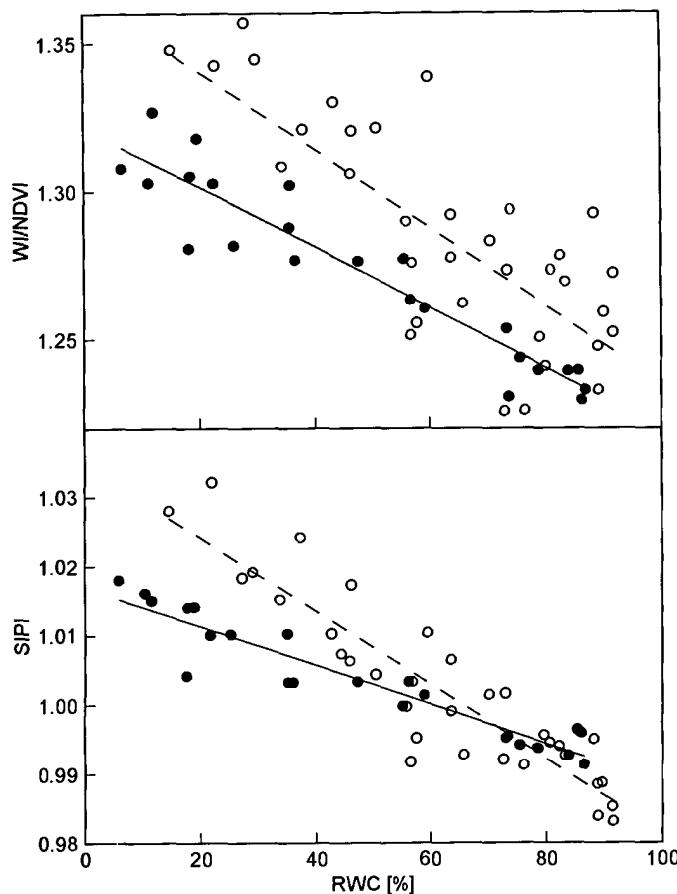


Fig. 3. Relationships of WI/NDVI (top) and SIPI (bottom) with RWC for peanut (O) and wheat (●) leaves under progressive desiccation.

## References

- Bowman, W.D.: The relationship between leaf water status, gas exchange, and spectral reflectance in cotton leaves. - *Remote Sens. Environ.* **30**: 249-255, 1989.
- Bull, C.R.: Wavelength selection for near-infrared reflectance moisture meters. - *J. agr. Eng. Res.* **49**: 113-125, 1991.
- Carter, G.A.: Primary and secondary effects of water content on the spectral reflectance of leaves. - *Amer. J. Bot.* **78**: 916-924, 1991.
- Chandler, C., Cheney, P., Thomas, P., Trabaud, L., Williams, D.: *Fire in Forestry. Vol. I. Forest Fire Behaviour and Effects.* - J. Wiley & Sons, New York 1983.
- Inoue, Y., Morinaga, S., Shibayama, M.: Non-destructive estimation of water status of intact crop leaves based on spectral reflectance measurements. - *Jap. J. Crop Sci.* **62**: 462-469, 1993.
- Peñuelas, J., Baret, F., Filella, I.: Semiempirical indices to assess carotenoids/chlorophyll *a* ratio from leaf spectral reflectance. - *Photosynthetica* **31**: 221-230, 1995.
- Peñuelas, J., Filella, I.: Visible and near-infrared reflectance techniques for diagnosing plant physiological status. - *Trends Plant Sci.* **3**: 151-156, 1998.

- Peñuelas, J., Filella, I., Biel, C., Serrano, L., Savé, R.: The reflectance at the 950-970 nm region as an indicator of plant water status. - *Int. J. Remote Sens.* **14**: 1887-1905, 1993.
- Peñuelas, J., Filella, I., Serrano, L., Savé, R.: Cell wall elasticity and Water Index (R970 nm/R900 nm) in wheat under different nitrogen availabilities. - *Int. J. Remote Sens.* **17**: 373-382, 1996.
- Peñuelas, J., Piñol, J., Ogaya, R., Filella, I.: Estimation of plant water content by the reflectance water index WI (R900/R970). - *Int. J. Remote Sens.* **18**: 2869-287, 1997.
- Shibayama, M., Takahashi, W., Morinaga, S., Akiyama, T.: Canopy water deficit detection in paddy rice using a high resolution field spectroradiometer. - *Remote Sens. Environ.* **45**: 117-126, 1993.
- Young, A., Britton, G.: Carotenoids and stress in stress responses. - In: Alscher, R.G., Cumming, J.R. (ed.): *Plants: Adaptation and Acclimation Mechanisms*. Pp. 87-112. Wiley-Liss, New York 1990.