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A new technique for extracting the red edge position from hyperspectral data: The linear extrapolation method

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Abstract

The position of the inflexion point in the red edge region (680 to 780 nm) of the spectral reflectance signature, termed the red edge position (REP), is affected by biochemical and biophysical parameters and has been used as a means to estimate foliar chlorophyll or nitrogen content. In this paper, we report on a new technique for extracting the REP from hyperspectral data that aims to mitigate the discontinuity in the relationship between the REP and the nitrogen content caused by the existence of a double-peak feature on the derivative spectrum. It is based on a linear extrapolation of straight lines on the far-red (680 to 700 nm) and NIR (725 to 760 nm) flanks of the first derivative reflectance spectrum. The REP is then defined by the wavelength value at the intersection of the two lines. The output is a REP equation, $REP = -(c_1 - c_2)/(m_1 - m_2)$, where c_1 and c_2, and m_1 and m_2 represent the intercepts and slopes of the far-red and NIR lines, respectively. Far-red wavebands at 679.65 and 694.30 nm in combination with NIR wavebands at 732.46 and 760.41 nm or at 723.64 and 760.41 nm were identified as the optimal combinations for calculating nitrogen-sensitive REPs for three spectral data sets (rye canopy, and maize leaf and mixed grass/herb leaf stack spectra). REPs extracted using this new technique (linear extrapolation method) showed high correlations with a wide range of foliar nitrogen concentrations for both narrow and wider bandwidth spectra, being comparable with results obtained using the traditional linear interpolation, polynomial and inverted Gaussian fitting techniques. In addition, the new technique is simple as is the case with the linear interpolation method, but performed better than the latter method in the case of maize leaves at different developmental stages and mixed grass/herb leaves with a low nitrogen concentration.

Keywords: Hyperspectral data; Red edge position; Linear extrapolation technique; Foliar nitrogen concentration

1. Introduction

The region of the red-near infrared (NIR) transition has been shown to have high information content for vegetation spectra (Collins, 1978; Collins et al., 1977; Horler et al., 1983). This region is generally referred to as the "red edge". It represents the region of abrupt change in leaf reflectance between 680 and 780 nm caused by the combined effects of strong chlorophyll absorption in the red wavelengths and high reflectance in the NIR wavelengths due to leaf internal scattering (Gates et al., 1965; Horler et al., 1983). Increases in the amount of chlorophyll, for example, results in a broadening of the major chlorophyll absorption feature centred around 680 nm (Buschmann & Nagel, 1993; Dawson & Curran, 1998), causing a shift in the red edge slope and wavelength of maximum slope (or inflection point) towards longer wavelengths (Boochs et al., 1990; Clevers et al., 2002; Collins et al., 1977; Gates et al., 1965; Hare et al., 1984; Horler et al., 1980, 1983). The latter is termed the red edge position (REP). Shifts in the REP to longer or shorter wavelengths has been used as a means to estimate changes in foliar chlorophyll content and also as an indicator of vegetation stress (Chang & Collins, 1983; Clevers et al., 2002; Curran et al., 1995; Horler et al., 1983; Lamb et al., 2002; Smith et al., 2004).

Since the REP is defined as the inflection point of the red-NIR slope, an accurate determination of the REP requires a number of spectral measurements in narrow bands in this region (Clevers et al., 2002). Fortunately, recent developments in imaging spectrometry have provided additional bands (contiguous spectra of less than 10 nm bandwidths) within the red edge region compared to broadband imagery such as

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Landsat Thematic Mapper (Asner, 1998). Subsequently, the REP is defined by the maximum first derivative of the reflectance spectrum. However, the limitation of this approach is that the maximum first derivatives of contiguous spectra have been well documented to occur within two principal spectral regions (around 700 and 725 nm) causing a bimodal distribution of REP data around 700 and 725 nm and a discontinuity in the REP/chlorophyll relationship (Horler et al., 1983). Several other studies have revealed the existence of this double-peak feature in the first derivative of contiguous spectra. Boochs et al. (1990) identified two peaks in winter wheat at 703 and 735 nm. Smith et al. (2004) also found peaks in canopy spectra of grass near 702 and 725 nm. Clevers et al. (2004) used the Analytical Spectral Devices (ASD) FieldSpec FR spectroradiometer with a 1 nm spectral resolution and observed two peaks in canopy spectra of grass near 700 and 720 nm. Zarco-Tejada et al. (2003) observed the double-peak feature at 690–710 nm and found out that it is a function of natural fluorescence emission at 690 and 730 nm.

Experimental studies have shown that low leaf chlorophyll concentration is associated with REP values near 700 nm, while high chlorophyll concentration in combination with leaf internal scattering influence REP values near 725 nm (Boochs et al., 1990; Horler et al., 1980; Lamb et al., 2002). Model fitting techniques such as the simple linear four-point interpolation method (Guyot & Baret, 1988) and computational complex procedures including fitting a high-order polynomial function (Pu et al., 2003) or an inverted Gaussian function (Bonham-Carter, 1988) to the reflectance spectrum somewhat generate continuous REP data (Clevers et al., 2002). In other words, these techniques mitigate the discontinuity in REP data caused by the double-peak feature. But the first question we pose is whether these techniques adequately track variations in spectral reflectance near the low and high chlorophyll sensitive peaks (near 700 and 725 nm). Dawson and Curran (1998) proposed a three-point Lagrangian interpolation approach. But Clevers et al. (2002) argue that this approach is suitable for coarsely sampled spectra and is not capable of resolving the destabilising effect of the double-peak feature when determining the REP. In this study, we hypothesise that first, the discontinuity in the REP/chlorophyll relationship caused by the existence of a double-peak feature on the derivative spectrum could be mitigated and secondly, spectral changes near the low and high chlorophyll sensitive peaks could be adequately tracked if the REP is determined as an intersection of two straight lines extrapolated through two points on the far-red (680 to 700 nm) and two points on the NIR (725 to 760 nm) flanks of the first derivative reflectance spectrum. The second research question is whether the proposed linear extrapolation method yields similar results to conventional methods such as the linear four-point interpolation, high-order polynomial and inverted Gaussian fitting techniques in explaining variations in foliar nitrogen concentration.

Plant nitrogen status is often related to chlorophyll content (Boochs et al., 1990; Everitt et al., 1985; Yoder & Pettigrew-Crosby, 1995). But such a relationship depends on the physiological status of the plant (Boochs et al., 1990; Mooney, 1986), e.g. changing from low to high positive correlations with increasing leaf age (Wenjiang et al., 2004). Nitrogen is used for the formation of components such as chlorophyll, the carbon fixing enzyme ribulose biphosphate carboxylase (Rubisco) and inert structural components in cell tissue (Jongschaap & Booij, 2004; Mooney, 1986). Reflectance measurements in the visible and red edge wavelengths (400–700 nm) have been used to determine foliar nitrogen concentration (Bausch & Duke, 1996; Sullivan et al., 2004; Thomas & Oerther, 1972). But the results rely on the close correlation between nitrogen and chlorophyll pigments (Haboudane et al., 2004; Hansen & Schjoerring, 2003; Yoder & Pettigrew-Crosby, 1995) because pigments (chlorophyll, carotenoids and xanthophylls) predominantly determine most spectral features between 400 and 700 nm (Blackburn, 1998; Carter & Knapp, 2001; Gates et al., 1965; Gausman, 1977; Merzlyak et al., 2003; Yoder & Pettigrew-Crosby, 1995). Therefore, the estimation of foliar nitrogen concentration based on the REP as the predictor (Jongschaap & Booij, 2004; Lamb et al., 2002) indirectly depends on shifts in the REP mainly attributed to changes in chlorophyll concentration.

Thus, the objectives of this study were to (i) define a simple technique for extracting the REP from hyperspectral data in order to first, mitigate the discontinuity in the REP/nitrogen relationship caused by the double-peak feature on the first derivative spectrum and secondly, track variations in spectral reflectance near the dominant peaks (700 and 725 nm) and (ii) compare the performance of the REPs retrieved by the new technique with REPs located by the maximum first derivatives and model fitting techniques such as the linear four-point interpolation, high-order polynomial fitting, and inverted Gaussian fitting methods in explaining variations in foliar nitrogen concentration.

2. Experiments and data sets

Three spectral data sets were used in this study. First, greenhouse experiments were carried out to assess the performance of REPs extracted by the proposed linear extrapolation technique for predicting leaf nitrogen concentration with regard to spectral reflectance at (i) leaf scale for maize leaves and (ii) canopy scale for rye grass canopies. Secondly, leaf specimens were collected in the field at the Majella National Park in Italy for applying the same analysis on a stack of mixed grass/herb leaves.

2.1. Experimental design

2.1.1. Greenhouse experiment

Maize (*Zea mays*, L.) and rye (*Lolium perenne*, L.) were separately grown in 5-l pots in a greenhouse chamber for ten weeks. Three soil nitrogen treatments (low, medium and high) were used in order to create different foliar nitrogen concentration levels. The low nitrogen treatment consisted of potting soil. In the medium and high nitrogen treatments,