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Suitability of existing and novel spectral indices to remotely detect water stress in *Populus* spp.

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Abstract

Undetected water stress within poplar plantations can result in high economic losses. Although remotely sensed spectral measures associated with variations in plant water status have been developed for non-*Populus* species, little is known about the suitability of such spectral indices to identify water stress in *Populus* species. Our experiments assessed whether such spectral indices acquired at the leaf and canopy level were suitable for detecting water stress in *Populus*. Relationships between four spectral indices and four common measures of plant water status were analyzed for both low to moderate, and highly water stressed trees. The proposed maximum difference water index (MDWI) exhibited significant relationships ($P < 0.001$) with changes in plant water status at both the leaf and canopy levels. At the leaf level, statistically significant, though poorer relationships were obtained between each of the normalized differential water index (NDWI), the red edge inflection point (REIP), the water index (WI), and the plant water status measures. At the canopy level, statistically significant relationships were obtained between MDWI and the measure of relative water content (RWC), and the equivalent water thickness (EWT) ($r^2 > 0.56$, $P < 0.001$), while WI produced reasonable relationships with these water status measures ($r^2 > 0.42$, $P < 0.001$). On exclusion of the highly stressed plants, only MDWI exhibited low sensitivity to RWC ($r^2 = 0.37$, slope = 0.64) and leaf water potential at the canopy level ($r^2 = 0.42$, slope = 9.89) whereas no other indices exhibited sensitivity to changes in plant water status. MDWI, which incorporates short-wave infrared (SWIR, 1300–2500 nm) spectral bands, is more suitable to detect more changes in plant water status as compared to NDWI, REIP, and WI that incorporate near infrared (NIR, 700–1300 nm) spectral bands. These results suggest that such remotely sensed indices are not a viable option to detect low and moderate levels of water stress at a scale of a *Populus* spp. plantation, although further research is warranted to assess the broader applicability of MDWI and other SWIR wavelength incorporating indices to detect water stress in other species.

Keywords: Maximum difference water index (MDWI); Remote sensing; Water stress; NDWI; WI; REIP; *Populus*; Poplar

1. Introduction

Plantations of *Populus* spp. comprise an economically important wood crop in the Pacific Northwest of the USA (Stanton et al., 2002). Suitable climatic and soil conditions, combined with intensive farming practices, have allowed marketable *Populus* to be grown in 5–6-year rotations on approximately 200 km^2 of agricultural land (Zsuffa et al., 1996; Stanton et al., 2002). The principal products of these plantations are fiber for pulp and paper production, as an energy feedstock, for lumber, and as a component of engineered wood products. Furthermore, it has been proposed that *Populus* plantations could serve to treat wastewater (O'Neill and Gordon, 1994; Schultz et al., 1995) and their high carbon sequestration capabilities have been highlighted as exhibiting potential for carbon credit trading (Stanton et al., 2002).

To grow *Populus* in the arid conditions of the Eastern Cascades, such plantations can sustain significant water stress in mid-summer. Irrigation is therefore required (Zsuffa et al., 1996). To ensure sufficient water supply, irrigation scheduling is often based on soil water potential measurements. However, such measurements are difficult and time-consuming on a plantation basis, and as a result such measurements are often acquired at only a limited number of sites. As such, water stress resulting from drip line failures, small-scale variations in soil moisture availability, and/or microclimatic differences have the potential to go undetected unless high water stress is present, which results in visible leaf wilting or discoloration. This is of major concern to

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plantation managers because low levels of water stress are already sufficient to reduce tree growth (Zahner, 1962; Marron et al., 2002) and increase the susceptibility of trees to pathogens and insects (Ragazzi et al., 1999). Hence, undetected water stress can potentially cause high economic losses.

In a variety of non-*Populus* species, the timely collection of plant water status data over large areas has been achieved through remote sensing systems to detect variations in the spectral response of plants to changing levels of plant water status (Penuelas et al., 1997; Ustin et al., 1998; Pu et al., 2003; Stimson et al., 2005). However, although previous findings have indicated that considerable limitations exist when using multispectral satellite sensor imagery to detect changes in plant water status (Hunt and Rock, 1989; Pierce et al., 1990), the application of higher spatial- and spectral-resolution aerial and ground spectrometers may allow the detection of such spectral changes (Goetz et al., 1985).

The ability of field spectrometers and aerial hyperspectral sensors to sample the electromagnetic spectrum in very narrow contiguous bands allows the application of spectral indices that make use of specific wavelengths that are sensitive to changes in plant water status (Horler et al., 1983; Gao, 1996; Penuelas et al., 1993). In many studies, such indices using specific wavelengths in the near infrared (NIR, 700–1300 nm, see Fig. 1) part of the electromagnetic spectrum have shown reasonable relationships to plant water status (Gao, 1996; Penuelas et al., 1997; Serrano et al., 2000; Ceccato et al., 2002; Asner et al., 2003; Pu et al., 2003; Imanishi et al., 2004; Stimson et al., 2005). However, some studies indicated that these relationships decrease with decreasing water stress suggesting that some spectral indices might show limited sensitivity to low and moderate levels of water stress (Carter, 1991; Pu et al., 2003; Stimson et al., 2005; Penuelas et al., 1997). However, the sensitivity of spectral indices to changes in plant water status is often considered species dependant (Sinclair et al., 1971; Penuelas et al., 1997), and thus low sensitivity of indices to low and moderate levels of water stress shown in some studies for non-*Populus* spp. does not necessarily imply that these indices are not sensitive to low and moderate levels of water stress in *Populus* spp.

Several studies have also highlighted that the use of wavelengths in the NIR are less sensitive to changes in plant water status than wavelengths in the short-wave infrared (SWIR, 1300–2500 nm, see Fig. 1) range of the electromagnetic spectrum (Tucker, 1980; Carter, 1991; Danson et al., 1992; Ceccato et al., 2002). Furthermore, the selection of the specific field-based measure of plant water status for comparison with the specific spectral index has been previously demonstrated to affect the strength of the relationships between the measure of water status and the spectral indices (Penuelas et al., 1993; Stimson et al., 2005). In this study, we examined the suitability of both existing and novel spectral indices to help poplar plantation managers detect water stress.

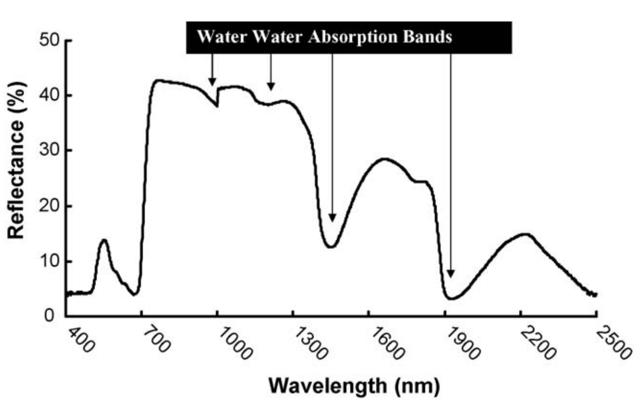

Fig. 1. Spectral response curve for *P. deltoids* × *P. nigra* hybrid. Arrows point to water absorption bands.

2. Background

2.1. Measures of plant water status

Various methods have been used to express plant water status in a physiological relevant way (Slavik, 1974; Turner, 1981). These methods vary in their practical use as well as in the physiological processes measured. Therefore, these differences may be affected by different sources of variability, which may in turn affect the strength of the relationship to spectral indices (Penuelas et al., 1993; Stimson et al., 2005). We used four different measures of plant water status to assess the relationship between a particular measure of plant water status and spectral index-based approaches.

2.1.1. Relative water content

Relative water content (RWC) has been widely used in the remote sensing literature to determine plant water status (Hunt and Rock, 1989; Penuelas et al., 1993; Serrano et al., 2000; Pu et al., 2003). It provides information about the water content within the leaf by measuring the amount of water in the leaf tissue relative to full saturation. It is obtained by the following equation:

$$\mathrm{RWC} = \frac{\mathrm{FW} - \mathrm{DW}}{\mathrm{TW} - \mathrm{DW}} \tag{1}$$

where FW is the fresh weight of the leaf obtained directly after it is removed from the plant, TW the turgid weight of the leaf after it is rehydrated to full turgidity, and DW is the dry weight measured after all water within the leaf tissue has been removed by drying.

A limitation of RWC is that it does not provide information about soil water status (Kozlowski et al., 1991). Furthermore, the accuracy of RWC measurements is reduced when the full saturation weight of leaves cannot be determined (Bradford and Hsiao, 1982). This uncertainty makes RWC a relatively insensitive index of plant water status. In some cases, low levels of water stress were not detectable with measurements of RWC (Hsiao, 1970).

2.1.2. Equivalent water thickness

The equivalent water thickness (EWT) measures the hypothetical thickness of a single layer of water that would cover the surface of a leaf if water contained in the leaf was uniformly distributed over the entire leaf (Danson et al., 1992). The EWT can be derived from process-based models (Roberts et al., 1997; Dennison et al., 2003) as well as from empirical calculations (Maki et al., 2004). Empirically, EWT can be derived as follows:

$$\mathrm{EWT} = \frac{\mathrm{FW} - \mathrm{DW}}{A} \qquad (2)$$

where FW is the fresh weight, DW the dry weight, and A is the leaf area. Although significant correlations between EWT and spectral indices have been shown (Maki et al., 2004) suggesting its suitability as an indicator of plant water content (Dennison et al., 2003), it does not directly provide information about water stress (Champagne et al., 2003).

2.1.3. Leaf water potential

Differences in water potential in the soil, plant, and atmosphere drive water movement through plants (Kozlowski et al., 1991). Thus, it is not surprising that the leaf water potential (ψ) is most commonly used to characterize plant water status (Turner, 1981). In contrast to RWC and EWT, leaf water potential provides information about the water status of the plant and the soil as an integrated system (Kozlowski et al., 1991). To measure leaf water potential, the pressure chamber technique developed by Scholander et al. (1964) is frequently utilized (Koide et al., 1989). By placing a leaf in a pressure chamber with the cut end of the petiole protruding through a tightly closed seal, the atmospheric pressure in the chamber is increased until sap is just visible on the cut end. At this point, the negative of the atmospheric pressure is equivalent to the hydrostatic pressure of the plant and thus equivalent to the leaf water potential. The point at which sap is just visible, however, is not always easy to determine which can potentially cause erroneous measurements (Koide et al., 1989; Ritchie and Hinckley, 1975).

2.1.4. Soil water potential

Availability of soil water has a major effect on water status of plants (Campbell and Campbell, 1982). If sufficient soil water is available, plants are generally able to replace water loss overnight keeping the plant water status fairly constant. However, if the soil is continuously drying, plants are not able to fully replace the water loss resulting in decreasing plant water status. The energy status of soil water described by the soil water potential is commonly used to obtain information about the availability of soil water. It can be determined by a variety of different methods, like the gravimetric method or devices like tensiometers or neutron probes. A disadvantage associated with measurement of soil water potential is that representative soil samples must be taken which often introduces considerable error due to small-scale variations in soil water and the disruption of natural soil structure (Israelsen and Hansen, 1962).

2.2. General response of plant spectra to changes in plant water status

The spectral response of leaves depends on their surface and internal chemical and structural properties (Sinclair et al., 1971; Horler et al., 1983). Changes in plant water status influence both chemical and structural properties of leaves and thus their spectral response (Sinclair et al., 1971; Hsiao, 1973; Munné-Bosch et al., 2001). Numerous studies have used these chemical and structural changes to evaluate relationships between plant water status and plant spectra (Penuelas et al., 1993, 1997; Pu et al., 2003; Dennison et al., 2005). Unfortunately, the spectral properties of leaves are not only influenced by plant water status but may also by factors such as leaf age (Gausmann et al., 1970), sun versus shade leaf anatomy (Gates et al., 1965), leaf thickness (Ourcival et al., 1999), differences in leaf surface properties (Grant et al., 1993), soil background, and non-water stress related variations in leaf angle, canopy structure (Asner, 1998) and leaf area (Sims and Gamon, 2003). These factors can introduce variation that reduces the correlation between common field measures of plant water status and the spectral response of leaves. To minimize the effect of this variability and to optimize the sensitivity of the spectral response of plants to changes in plant water status, different spectral indices have been proposed.

Our study examined the commonly used normalized differential water index (NDWI), the water index (WI), and the red edge inflection point (REIP) discussed below.

2.3. Spectral indices

Reasonable relationships have been shown between certain spectral indices and plant water status (Gao, 1996; Penuelas et al., 1997; Serrano et al., 2000; Ceccato et al., 2002; Asner et al., 2003; Pu et al., 2003; Imanishi et al., 2004; Stimson et al., 2005). This has prompted their use for detecting water stress causing diseases, like 'Sudden Oak Death' (Pu et al., 2003), to assess live fuel moisture to determine fire danger (Dennison et al., 2003, 2005; Ustin et al., 1998; Chuvieco et al., 2002; Maki et al., 2004) or to determine drought conditions of crops (Strachan et al., 2002) and forests (Asner, 2003).

To detect changes in plant water status, spectral indices, like the WI or the NDWI, utilize simple ratios between the reflectance of a wavelength located within an range of the electromagnetic spectrum strongly absorption by water, described as water absorption bands, and another wavelength located outside the water absorption band typically used as a control (Sims and Gamon, 2003) (Fig. 1). With decreasing plant water status, the decrease in water absorption is more pronounced for wavelengths inside the absorption band resulting in a changing ratio between the reflectance values of these two wavelengths (Fig. 2).

Other indices, like the red edge inflection point (REIP) and the normalized differential vegetation index (NDVI), utilize wavelengths, which are influenced by changes in the leaf pigment content and/or changes in leaf cellular structure (Horler et al., 1983). Thus, unlike the NDWI and the WI, which measure spectral variances directly caused by changes in plant water status, these indices infer spectral variances caused by changes in leaf physiological properties that might be indirectly caused by changes in plant water status.

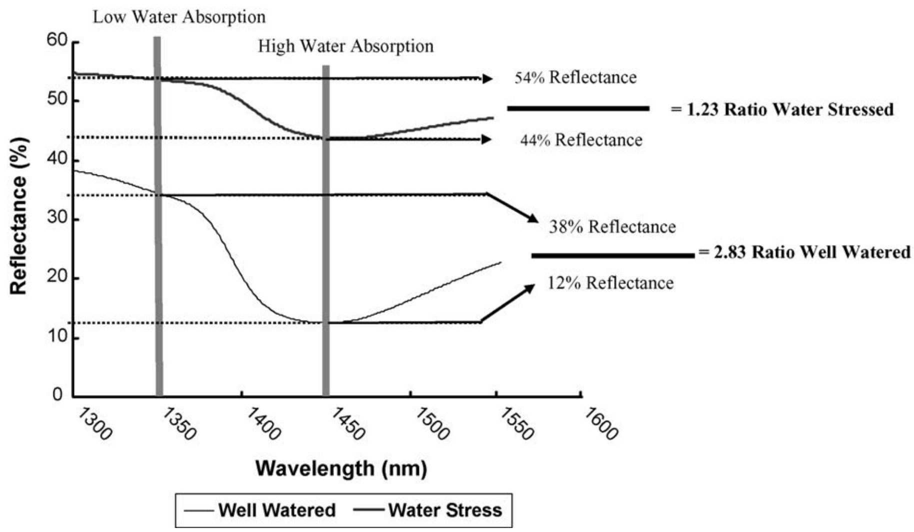

Fig. 2. Ratio between wavelengths with low water absorption and wavelength with high water absorption for well watered and water stressed *P. deltoids* × *P. nigra* hybrid.

2.3.1. Normalized differential water index (NDWI)

The normalized differential water index (NDWI) uses two wavelengths in the NIR located at 860 and 1241 nm and has been shown to be sensitive to leaf water content (Gao, 1996). This index is derived from $(R_{860} - R_{1241})/(R_{860} + R_{1241})$, where R stands for the reflectance at 860 and 1241 nm, respectively. For *Pinus edilus* and other species in chaparral communities, NDWI was significantly correlated ($r^2 = 0.93$ and 0.74) with water content (Stimson et al., 2005; Serrano et al., 2000).

2.3.2. Water index (WI)

The water index (WI) is the ratio between reflectance measured at 900 nm and the reflectance measured at 970 nm. Significant correlations between WI and plant water status have been shown for different Mediterranean tree and shrub species (Penuelas et al., 1997).

2.3.3. Red edge inflection point (REIP)

The ''red edge'' inflection point (REIP), defined as the maximum slope of the prominent increase in reflectance between the red and the NIR spectral range for green vegetation (Horler et al., 1983), may shift when plants exhibit stress. This suggests that REIP can potentially be utilized to detect water stress (Jayaraman and Srivastava, 2002).

Furthermore, it may offer a major advantage over non-derivative-based indices, like the NDWI and WI, because it has been shown that derivative spectra used to calculate the red edge inflection point are less sensitive to background noise, e.g., caused by different soil types (Demetriades-Shah et al., 1990; Danson et al., 1992; Rollin and Milton, 1998).

2.3.4. Limitations of existing spectral water status indices

Ideally, an index for remote detection of water stress in *Populus* spp. should be sensitive enough to detect low and moderate levels of water stress. However, several studies suggest that water stress has to be well developed in order to be detectable (Carter, 1991; Cohen, 1991; Pu et al., 2003; Penuelas et al., 1993, 1997; Asner et al., 2003; Stimson et al., 2005). In the Mediterranean shrub species *Arbutus unedo*, the correlation between RWC and the WI decreased from $r = 0.75$ to 0.37 when plants were exposed to low water stress instead of full dryness (Penuelas et al., 1997). The exclusion of needles from *Pinus edulis* trees undergoing water stress induced mortality from the sample decreased the relationship between the REIP and leaf water potential from $r^2 = 0.51$ to 0.34 (Stimson et al., 2005).

Although these studies suggest that spectral indices are not suitable for detection of low and moderate levels of water stress, such responses may be species specific (Penuelas et al., 1993). The leaf internal structure of some species is more sensitive to changes in plant water status than others, thereby influencing the sensitivity of spectral indices to changes in plant water status.

2.4. Potential spectral water status indices

The use of wavelengths in the short-wave infrared (SWIR, 1300–2500 nm) could improve the sensitivity of spectral indices (Tucker, 1980; Carter, 1991; Danson et al., 1992; Ceccato et al., 2002). Most of the current indices such as NDWI and WI, use wavelengths located in the near infrared (NIR, 700–1300 nm). Although different studies were able to show significant relationships of these indices to plant water status (Penuelas et al., 1997; Serrano et al., 2000; Asner et al., 2003; Pu et al., 2003), others suggest that wavelengths used by these indices are relatively insensitive to changes in plant water status (Tucker, 1980; Carter, 1991; Danson et al., 1992; Ceccato et al., 2002). Selected wavelengths in the NIR can be insensitive to changes in plant water status as compared to wavelengths located in the SWIR (Tucker, 1980). Wavebands in the SWIR located between 1500 and 1750 nm have been suggested to be useful for monitoring plant water status (Tucker, 1980; Ceccato et al., 2002; Chen et al., 2005), life fuel moisture (Chuvieco et al., 2002) as well as for monitoring other plant biochemical variables, like lignin and nitrogen (Serrano et al., 2000) because of the availability of solar irradiance and atmospheric transmission essential for remote sensing (Tucker, 1980; Ceccato et al., 2002). Simulations with the radiative transfer model PROSPECT, a model for leaf reflectance and varying biophysical parameters (Jacquemound and Baret, 1990), suggest that wavelengths located in the 1300–2500 nm range are more sensitive to changes in leaf water content whereas they are relatively insensitive to factors like leaf internal structure and leaf dry matter content (Ceccato et al., 2002). Furthermore, the NIR (700–1300 nm) wavebands showed no or very low sensitivity to detect leaf water content whereas they showed a high sensitivity to other factors such as leaf structural characteristics.

2.5. Objectives

Our primary objectives were to: (1) determine, for selected spectral indices, if statistically significant relationships exist between the index and four different measures of plant water status at both the leaf and canopy level and (2) test the sensitivity of the spectral index measures to low and moderate levels of water stress.

3. Methods

3.1. Plant material and growth conditions

Our study used 180 cuttings of the clone, *Populus deltoides* × *Populus nigra* (OP-367), obtained from the Boise Fiber Farm "Ice Harbor" located near Wallula, Washington, USA. Each cutting was placed in individual 3.79-L pots. The soil medium consisted of a commercially available potting mix (70% sphagnum peat moss, 20% regional fillers), 10% perlite, a wetting agent, and slow release plant nutrients 0.07% nitrogen (N), 0.01% phosphate (P_2O_5), soluble potash (K_2O). During an initial growing period of 8 weeks, each sapling was watered daily to field capacity. After the initial growing period, 90 saplings were randomly selected for a non-water treatment and the remaining 90 saplings served as the control treatment. During the 12-day duration of the experiment, water was withheld from the non-water treatment, whereas each plant of the control group was provided with 0.25 L per day. Throughout the study, pot location was randomized on a regular basis to minimize the effect of microclimatic differences in the glasshouse on plant development. Throughout the experiment, 10 saplings of each treatment were randomly selected every 36 h for spectral measurement and for measurement of plant water status. Upon completion of the measurements, measured saplings were removed from the study population.

3.2. Spectral measurements

Spectral measurements were taken with an ASD FieldSpec® Pro spectroradiometer (Analytical Spectral Devices, Boulder, CO) consisting of two sensors. The first sensor measures reflected light in wavelengths between 350 and 1050 nm by sampling the reflected light every 1.4 nm. The second sensor measures reflected light in wavelengths between 1000 and 2500 nm by sampling the reflected light every 2 nm. Each spectral measurement was preceded by a dark current measurement and a white reference measurement using a white reference panel. Thus, reflectance values could be directly measured and used to compare measurements through time with each other.

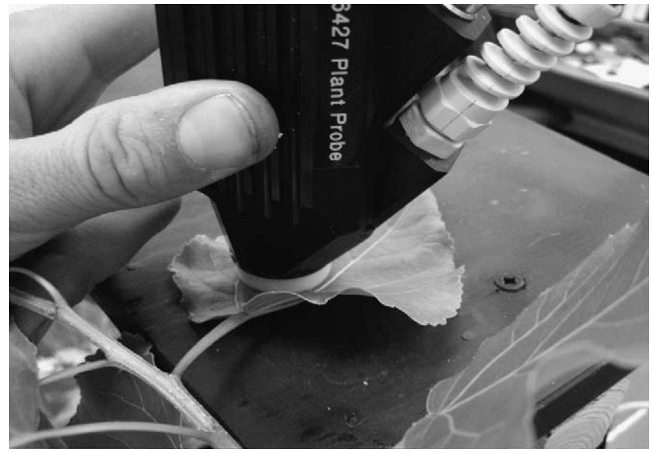

Fig. 3. Spectral measurement at the leaf level by using a cool contact probe designed for leaf spectral measurements.

3.2.1. Acquisition of spectral measures at the leaf level

To obtain spectra at the leaf level, four spectra were taken at the 10–13th leaf counted from the apical meristem (see Fig. 3) and the average of the four spectral measurements was taken. To reduce errors associated with illumination effects a fiber optic contact probe was used. By pressing the contact probe on the leaf surface, the leaf surface was only illuminated by a constant light source inside the contact probe (Contact Probe, Analytical Spectral Devices, Boulder, CO). To minimize differences in background reflectance that could be caused by electromagnetic radiation transmitted through the leaf, a spectrally black surface was put on the underside of the leaf.

3.2.2. Acquisition of spectral measures at the canopy level

For canopy level measurements, the fiber optic probe of the spectroradiometer with a 25° field of view was mounted 0.70 m above the highest point of the sapling canopy (see. Fig. 4). The

Fig. 4. Spectral measurements at the canopy level.

sapling was illuminated by a constant, full spectrum light source (1000 W) from a 30° angle, whereas the distance between the light source and highest point of the canopy was 0.30 m. To ensure a constant background within the field of view, spectrally flat black foam was placed around the base of each tree. For each sapling canopy, four spectra were measured by turning the plant by 90° between each measurement and averaged.

3.2.3. Extraction of spectral indices

To calculate the NDWI and WI, formulae described above were used. For REIP, we calculated the first derivative of the spectrum and determined the wavelength associated with the maximum slope located within the prominent increase in reflectance between the red and the near infrared wavelength ranges. Before extracting the REIP from canopy spectra, potential effects of atmospheric and background noise on the REIP were minimize by applying a moving average approach (Savitzky and Golay, 1964).

3.2.4. Proposed maximum difference water index (MDWI)

Based on the relative depth index (RDI) (Rollin and Milton, 1998), which uses the reflectance minimum between 1120 and 1250 nm,the maximum difference water index (MDWI) was determined by using the following equation:

$$\mathrm{MDWI} = \frac{R_{\max_{1500-1750}} - R_{\min_{1500-1750}}}{R_{\max_{1500-1750}} + R_{\min_{1500-1750}}} \quad (3)$$

where $\max_{1500-1750}$ is the maximum and $\min_{1500-1750}$ is the minimum reflectance located at the atmospheric window between 1500 and 1750 nm.

3.2.5. Sensitivity of spectral indices

To assess the sensitivity of each index for detecting low and moderate levels of water stress, we evaluated the relationship of spectral indices to plant water status both with and without highly stressed trees in the analysis. In this case, water stress was assessed visually. Trees were considered to experience low or moderate water stress if no or minimal signs of wilting were apparent. Trees were considered highly stressed if they showed signs of severe wilting, including desiccation, abscission, discoloration, and rolling of leaves.

3.3. Plant water status

Measurements of soil and leaf water potential, relative water content, and equivalent water thickness were coordinated with the spectral measurements. Soil water potential was measured with a WP4 Dewpoint Potential Meter (Decagon Devices, Inc., Pullman, Washington, USA). The soil sample required by the WP4 was obtained from the base of a 0.07-m soil core. Leaf water potential was measured on the 10th leaf (counted from the apical meristem) with a pressure chamber (PMS Instrument Company, Corvallis, Oregon, USA). For RWC, the fresh weight, turgid weight, and dry weight were determined for 7 cm^2 leaf disks from the 11th and the 12th leave. Turgid weight was determined after each leaf disk was placed in a deionized water bath for 12 h. The final weight reading was done after the leaf sample was placed into a drying oven at 70 °C for 24 h to obtain the dry weight. All three weight measurements were then used to calculate the RWC by using Eq. (1) (Barrs and Weatherley, 1962; Slavik, 1974). The final RWC for each plant was calculated by taking the average of the two RWC measurements determined per sapling. The fresh weight and dry weight measurements of the 11th and 12th leaf were further utilized to empirically determine the equivalent water thickness (EWT) for each leaf disc by using Eq. (2). The final EWT per plant was determined by taking the average EWT of the leaf discs obtained from the 11th and 12th leaf.

3.4. Statistical techniques and accuracy/validation

Linear least squares regression was used to determine the relationship between measures of plant water status and spectral indices. To test the sensitivity of spectral indices to low and moderate levels of water stress, highly stressed trees were excluded from the dataset and a linear least squares regression was determined for measures of plant water status and spectral indices of the remaining datasets. Following prior remote sensing studies (Smith et al., 2002), the coefficient of determination of each spectral index was put into one of five categories describing their sensitivity to changes in plant water status:

- no sensitivity if $r^2 < 0.20$;
- very low sensitivity if $r^2 = 0.20–0.30$;
- low sensitivity if $r^2 = 0.30–0.60$;
- moderate sensitivity if $r^2 = 0.60–0.80$;
- high sensitivity if $r^2 > 0.80$.

Within a category, the index with the maximum slope obtained from the regression model was considered to be the most sensitive.

After linear least square regressions analysis, the validity of each model was assessed based on standard model diagnostics. The root mean square error, the correlation coefficient (r^2), the model equation, and probability value (P-value) were determined for each model. Correlations were considered statistically significant at a probability level of $P < 0.001$.

4. Results

4.1. Relationship of spectral indices to plant water status

4.1.1. Leaf level

A statistically significant correlation ($r^2 > 0.53$, $P < 0.001$) to plant water status could be shown for all indices derived from spectra taken at the leaf level (Table 1). However, the correlation coefficients between measures of plant water status and spectral indices varied considerably amongst indices ($r^2 = 0.53–0.94$). MDWI showed the highest correlation coefficient ($r^2 = 0.94$) to all measures of plant water status, followed by the WI ($r^2 = 0.94$). Substantially lower correlation coefficients could be observed for the REIP ($r^2 = 0.53$).

Table 1
Linear regression results between four different measures of plant water status and four different indices derived from spectra taken at the leaf level

Index	Water metric	Entire dataset						Excluding highly water stressed trees						
		RMSE	r^2	Intercept	Slope	P	N	RMSE	r^2	Intercept	Slope	P	N	Sensitivity[a]
MDWI	RWC	0.061	0.94	0.030	3.607	<0.001	90	0.030	0.05	0.723	0.870	0.087	59	No
	EWT	0.001	0.92	0.000	0.049	<0.001	90	0.001	0.18	0.002	0.040	<0.001	59	No
	LWP	0.472	0.34	−7.486	26.055	<0.001	67	0.432	0.08	−4.817	15.592	0.035	59	No
	SWP	6.519	0.39	−22.766	83.021	<0.001	80	3.922	0.02	−19.365	69.167	0.359	49	No
NDWI	RWC	0.104	0.78	−0.066	25.923	<0.001	90	0.031	0.00	0.949	−0.207	0.909	59	No
	EWT	0.002	0.75	−0.001	0.344	<0.001	90	0.001	0.00	0.012	0.003	0.949	59	No
	LWP	0.557	0.00	−0.927	−2.867	0.926	67	0.448	0.01	−0.296	−16.368	0.538	59	No
	SWP	6.674	0.35	−25.608	608.845	<0.001	80	3.955	0.00	−4.564	65.671	0.802	49	No
REIP	RWC	0.154	0.53	16.941	−0.021	<0.001	90	0.030	0.05	−0.799	0.002	0.089	59	No
	EWT	0.002	0.49	0.221	0.000	<0.001	90	0.001	0.06	−0.036	0.000	0.055	59	No
	LWP	0.519	0.13	−54.813	0.071	0.003	67	0.406	0.18	−49.817	0.065	<0.001	59	No
	SWP	7.211	0.24	377.208	−0.503	<0.001	80	3.955	0.00	39.894	−0.055	0.792	49	No
WI	RWC	0.069	0.90	−29.139	28.468	<0.001	90	0.031	0.00	−0.782	1.632	0.653	59	No
	EWT	0.001	0.88	−0.390	0.381	<0.001	90	0.001	0.01	−0.052	0.061	0.498	59	No
	LWP	0.515	0.15	−160.275	150.830	<0.001	67	0.449	0.00	−25.712	23.488	0.658	59	No
	SWP	6.621	0.36	−677.183	639.045	<0.001	80	3.912	0.02	−674.607	636.836	0.298	49	No

[a] Sensitivity: no ($r^2 < 0.20$); very low ($r^2 = 0.20$–0.30); low ($r^2 = 0.30$–0.60); moderate ($r^2 = 0.60$–0.80); high ($r^2 > 0.80$).

4.1.2. Canopy level

A statistically significant correlation ($r^2 > 0.18$, $P < 0.001$) to plant water status could also be observed for all indices derived from spectra taken at the canopy level (Table 2). The highest correlation coefficient could be shown between MDWI and RWC ($r^2 = 0.60$) and the lowest between NDWI to RWC ($r^2 = 0.18$).

4.2. Sensitivity of spectral indices to low and moderate water stress

Correlation coefficients of $r^2 < 0.18$ were shown at the leaf level if highly stressed trees were excluded from the analysis (Table 1). The highest correlation coefficient could be shown between REIP and leaf water potential ($r^2 = 0.18$, slope = 0.04) and MDWI and EWT ($r^2 = 0.18$, slope = 0.07). No correlation ($r^2 = 0.00$) was shown between NDWI and RWC, EWT, and leaf water potential, between REIP and SWP, and between WI and RWC and EWT. At the canopy level, correlation coefficients of $r^2 < 0.42$ were shown if highly stressed trees were excluded from the analysis (Table 2). The highest correlation coefficient could be shown between MDWI and leaf water potential ($r^2 = 0.42$, slope = 9.89) whereas no correlation ($r^2 = 0.00$, slope = 7.95) could be shown between NDWI and SWP.

The decreasing correlations between spectral indices and measures of plant water status indicated by our results was less

Table 2
Linear regression results between four different measures of plant water status and four different indices derived from spectra taken at the canopy level

Index	Water metric	Entire dataset						Excluding highly water stressed trees						
		RMSE	r^2	Intercept	Slope	P	N	RMSE	r^2	Intercept	Slope	P	N	Sensitivity[a]
MDWI	RWC	0.153	0.60	−0.079	3.004	<0.001	90	0.025	0.37	0.736	0.635	<0.001	59	Low
	EWT	0.002	0.56	−0.001	0.040	<0.001	90	0.001	0.16	0.009	0.010	0.002	59	No
	LWP	0.491	0.32	−4.477	10.768	<0.001	67	0.390	0.42	−4.095	9.888	<0.001	59	Low
	SWP	7.454	0.25	−25.826	71.183	<0.001	80	3.921	0.07	−13.373	35.573	0.074	49	No
NDWI	RWC	0.203	0.18	0.597	3.347	<0.001	90	0.028	0.19	0.907	0.482	<0.001	59	No
	EWT	0.003	0.16	0.008	0.043	<0.001	90	0.001	0.05	0.012	0.006	0.097	59	No
	LWP	0.535	0.08	−1.433	5.701	0.023	67	0.421	0.12	−1.317	5.761	0.006	59	No
	SWP	7.938	0.08	−10.576	88.254	<0.010	80	3.953	0.00	−2.629	7.950	0.726	49	No
REIP	RWC	0.200	0.21	7.359	−0.008	<0.001	90	0.030	0.03	1.268	0.000	0.202	59	No
	EWT	0.003	0.18	0.093	0.000	<0.001	90	0.001	0.01	0.008	0.000	0.540	59	No
	LWP	0.534	0.08	9.066	−0.013	0.020	67	0.441	0.04	4.440	−0.007	0.152	59	No
	SWP	8.087	0.05	123.679	−0.164	0.050	80	3.840	0.06	−67.558	0.083	0.093	49	No
WI	RWC	0.169	0.43	−8.266	7.925	<0.001	90	0.029	0.13	0.042	0.780	0.005	59	No
	EWT	0.002	0.42	−0.111	0.106	<0.001	90	0.001	0.07	−0.004	0.014	0.045	59	No
	LWP	0.518	0.14	−17.370	14.188	0.002	67	0.430	0.08	−11.446	9.140	0.025	59	No
	SWP	7.524	0.18	−224.978	192.092	<0.001	80	3.904	0.03	−61.637	51.665	0.258	49	No

[a] Sensitivity: no ($r^2 < 0.20$); very low ($r^2 = 0.20$–0.30); low ($r^2 = 0.30$–0.60); moderate ($r^2 = 0.60$–0.80); high ($r^2 > 0.80$).

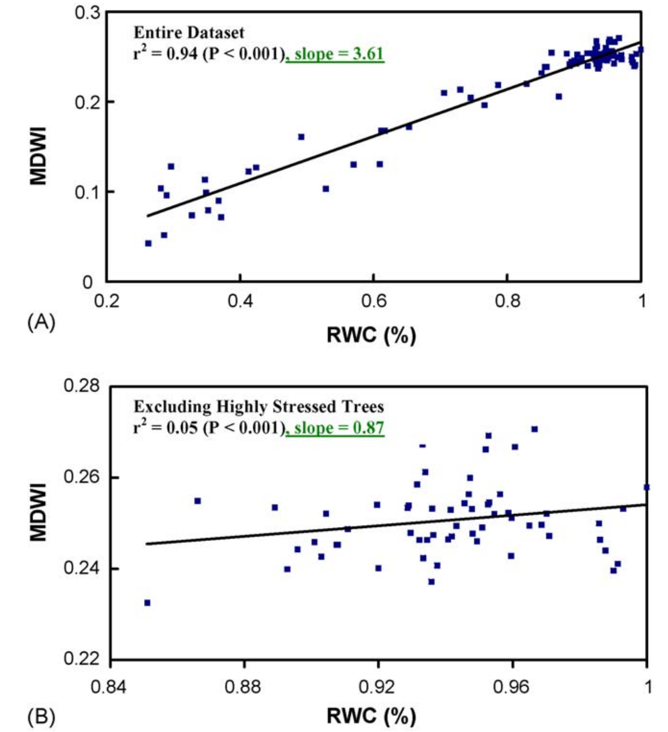

Fig. 5. Regression of relative water content (RWC) to maximum difference water index (MDWI) at the leaf level for *P. deltoides* × *P. nigra*: (A) entire dataset and (B) excluding highly stressed trees.

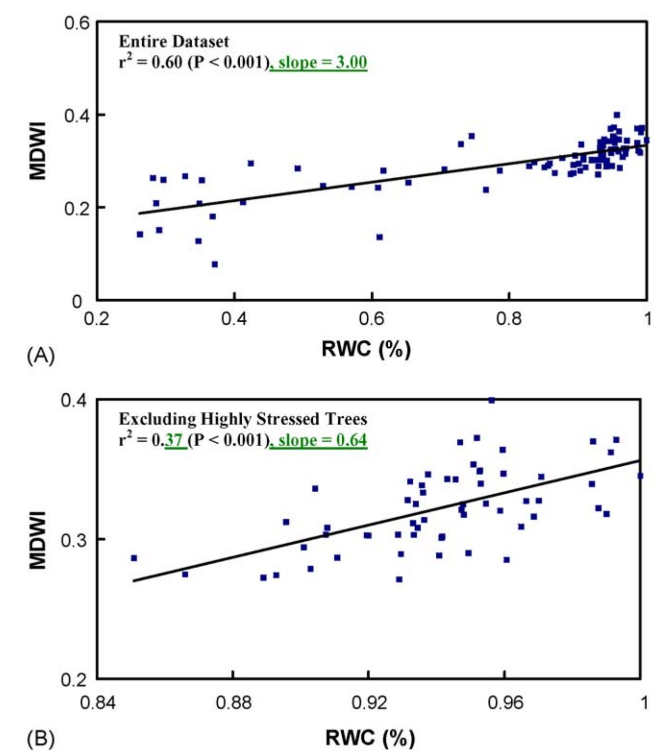

Fig. 6. Regression of relative water content (RWC) to maximum difference water index (MDWI) at the canopy level for *P. deltoides* × *P. nigra*: (A) entire dataset and (B) excluding highly stressed trees.

pronounced at the canopy level than it was at the leaf level (see Figs. 5 and 6 and Tables 1 and 2). For example, the exclusion of highly stressed trees changed the correlation coefficient between RWC and MDWI from $r^2 = 0.94$ to 0.05 at the leaf level and from $r^2 = 0.60$ to 0.37 at the canopy level.

By excluding highly stressed trees from the analysis, correlation coefficients between measures of plant water status and spectral indices were in general higher for indices extracted from canopy scale measurements compared to indices extracted from leaf scale measurements (see Tables 1 and 2). The highest correlation coefficient between measures of plant water status and spectral indices derived from canopy scale measurements could be observed between leaf water potential and MDWI ($r^2 = 0.42$, slope = 9.89) and RWC and MDWI ($r^2 = 0.37$, slope = 0.635) compared to the highest correlation coefficient for spectral indices derived from leaf scale measurements between leaf water potential and REIP ($r^2 = 0.18$, slope = 0.065) and EWT and MDWI ($r^2 = 0.18$, slope = 0.04).

5. Discussion

5.1. Relationship of spectral indices to plant water status

5.1.1. Leaf level

Although leaf level measurements are not practical from a management perspective because it is difficult to acquire timely information over larger areas with frequency, they provide insights about changes in leaf spectral properties accompanied by changes in plant water status. In our study, MDWI, NDWI, and WI extracted from reflectance spectra taken at the leaf level showed a statistically significant correlation of $r^2 > 0.75$ to RWC and EWT if highly water stressed trees were included (Table 1). This result reinforces findings by other studies suggesting that there is an existing relationship between plant water status and the spectral response of plants (Penuelas et al., 1993, 1997; Stimson et al., 2005). The advantage of taking spectra at the leaf level is that the relationship between plant water status and spectral indices is not affected by background variables or atmospheric noise. Thus, we can assume that variations of spectral index are purely caused by leaf properties. However, leaf property variations are influenced by more than just plant water status and these factors complicate the development of a direct relationship between plant water status and spectral indices.

Changes in leaf morphology and biochemical properties that are independent of plant water status are able to influence photon scattering and thus present potential sources of variability (Sinclair et al., 1971; Curran, 1989). Differences in leaf biochemical properties, such as lignin, cellulose or sugar content independent of plant water status may generate spectral variability. Curran (1989) showed that a wide variety of absorption features could be related to biochemical properties of leaves. Besides biochemical properties of leaves, differences in leaf morphology can strongly influence the reflectance properties of leaves and thus can be responsible for some variability (Sinclair et al., 1971; Ceccato et al., 2002). Differences in leaf morphology may be caused by genetic variations between individuals (Van Volkenburgh and Taylor, 1996). However, considering that a single poplar clone was used in this study, variability caused by genetic variations can be assumed to be negligible. Differences in leaf anatomical properties on the other hand, which can be caused by differences in light conditions and the developmental stage of leaves may cause variability (Gates et al., 1965; Gausmann et al., 1970; Grant et al., 1993; Ourcival et al., 1999; Xie and Xianshi, 2003). During leaf development, anatomical changes take place potentially altering the spectral response of leaves (Gausmann et al., 1970; Bauer et al., 1983). Thus, although spectral measurements were taken at the same node positions, leaf developmental stages were not necessarily the same.

Furthermore, differences in light conditions could have introduced some variation. In order to optimize photosynthesis, leaves acclimate their anatomical properties to varying light conditions. Some of these acclimations, including, for example, the thickness of the cuticle layer or the palisade and spongy mesophyll cells, are known to influence the reflectance properties of leaves and thus could have caused some variation in our study (Gates et al., 1965; Grant et al., 1993; van Gardingen, 1996; Ourcival et al., 1999; Xie and Xianshi, 2003).

5.1.2. Canopy level

Measurements at the canopy level are of greater interest to land managers because it more closely represents what remote sensing instruments would “see” when flown over a poplar plantation. Thus, results obtained from canopy scale measurements enable better inferences of how a certain spectral index may perform if it is extracted from spectra acquired by an airborne sensor. Our study showed that the relationship between plant water status and spectral indices decreased by moving from the leaf to canopy level if highly stressed trees were included (Table 2). This could be because of a variety of broader scale factors, including variations in background, leaf display, and leaf area. Variations of background and leaf display, however, can be assumed to be negligible in this study. A constant background was ensured by placing a spectrally flat black foam around the base of the tree and variations in leaf display can be assumed to be fairly small because significant species and clonal differences in leaf display were eliminated by the use of a single clone. In contrast, differences in leaf area were most likely responsible for some of the spectral variations in this study. The influence of leaf area on the spectral response of leaves can be considerable (Goward and Huemmerich, 1992; Asner, 1998; Roberts et al., 1998). Water absorption features located at around 1000 and 1200 nm used to calculate WI and NDWI become deeper with increasing leaf area (Asner, 1998). The strong influence of changes in leaf area on the spectral response is especially pronounced for lower leaf area (Asner and Wessman, 1997; Ceccato et al., 2002). This suggests that due to the low leaf area in our study, changes of LAI between sampled trees may have had a strong effect on spectral indices. However, although relationships between indices and measures of plant water status decreased by going from the leaf to the canopy level, the relationship between MDWI and RWC ($r^2 = 0.60$) and to EWT ($r^2 = 0.56$) was still reasonably high. This suggests that MDWI may allow a better mapping of water stressed poplars. From these maps, plantation managers would be able to obtain current information about the location of poplars experiencing water stress and thus allow them to take appropriate management actions against otherwise undetected trees experiencing water stress.

5.2. Sensitivity of spectral indices to light and moderate water stress

It is important for plantation managers to know how sensitive spectral indices are to low and moderate levels of water stress because reduced tree growth occurs at low levels of water stress (Bradford and Hsiao, 1982). Hence, earlier water stress detection may reduce economic loss. Although our results indicate that it is possible to map water stress by using spectral indices, plantation managers need to know how sensitive these measures are to low and moderate levels of water stress to evaluate their suitability. We examined this by excluding highly stressed trees from our analysis and demonstrated that no current index is sufficiently sensitive to detect light to moderate water stress in *P. deltoids* × *P. nigra* hybrids at the leaf level ($r^2 \leq 0.18$) (see Table 1). This suggests that the analyzed indices are not suitable to detect light to moderate water stress in *P. deltoides* × *P. nigra* hybrids at the leaf level.

At the canopy level, low sensitivity of indices to changing measures of plant water status was shown between MDWI and leaf water potential ($r^2 = 0.37$, slope = 0.64) and RWC ($r^2 = 0.42$, slope = 9.89) (see Table 2) whereas the REIP, WI, and NDWI showed no sensitivity to measures of plant water status ($r^2 < 0.19$). This indicates that MDWI performs considerably better in detecting moderate levels of water stress than REIP, WI, and NDWI and thus could allow plantation managers to take appropriate management actions in an earlier stage of water stress than by using the REIP, WI, or NDWI. Although the results suggest that MDWI is most sensitive to changes in plant water status, the low sensitivity shown for MDWI is unlikely to be sufficient to remotely detect low and moderate water stress in *Populus* spp.

No or low sensitivity of spectral indices to low and moderate water stress suggests that major changes of leaf properties did not occur until the plants were highly stressed, and thus were not detectable by spectral measurements. In order to spectrally separate non-water deficient from water deficient plants, water deficiency has to be well developed (Cohen, 1991). Spectral variation in reflectance among leaves at the same plant water status can be higher than the spectral changes due to increasing water deficiency (Cohen, 1991; Pu et al., 2003). Although statistical significant relationships between the leaf RWC of *Quercus agrifolia* to the depth of water absorption features at 975 and 1200 nm has been observed (Pu et al., 2003) if RWC ranged between 0.45% and 57.94%, the correlation would have been considerably lower if one would exclude trees with RWC between 0.45% and 40% from the analysis. These findings are further supported by Hoffer and Johannsen (1969) who reported that in order to detect an increase in reflectance due to water deficiency in corn leaves between 500 and 2300 nm, RWC has to decrease below 66%. Considering that wilting in corn occurs at RWC < 80%, Hoffer and Johannsen (1969) concluded that slight to moderate levels of water stress in corn are not detectable from remotely sensed data. Besides these findings, Carter (1991) showed that by reducing the RWC to 75%, the difference in reflectance between associated wavelengths was 5% or less compared to the reflectance of full turgid leaves. By reducing the RWC to 50%, the difference in reflectance between associated wavelengths increases to 10% or less compared to the reflectance of full turgid leaves. Based on these observations, Carter (1991) concludes that RWC must be highly reduced to result in spectrally detectable changes. Our research suggests these findings also apply to *Populus*.

The insensitivity of indices extracted at the leaf level to slight or moderate water stress in *P. deltoides* × *P. nigra* hybrids could be explained by observations by Sinclair et al. (1971). They observed that the reflectance of wavelengths in the NIR increased only slightly for soybeans by decreasing the RWC to 75%. At the same time they observed that the leaf internal structure of soybean leaves did not change by decreasing the RWC to 75%. However, by reducing the RWC of leaves to about 50% RWC, leaf internal structure collapsed resulting in a strong increase in reflectance in the near infrared. From this observation, Sinclair et al. (1971) concluded that changes in leaf internal structure associated with water stress are mainly responsible for spectral changes. However, RWC values ranging between 75% and 85% RWC represent the wilting point in most plant species (Bradford and Hsiao, 1982). Hence, RWC values of 50% at which strong spectral changes in soybeans took place represent high levels of water stress. The same seemed to be true for *P. deltoides* × *P. nigra* hybrids. There was virtually no relationship between RWC and spectral indices between RWC 1 and 0.85 (Fig. 5A), which could have been caused by no or very little change of leaf internal structure. However, after RWC dropped below around 0.80, obvious spectral changes, most likely caused by the onset of leaf internal changes, started to become obvious and could be related to changes in plant water status (Fig. 5A).

5.3. Suitability of spectral indices to detect changes in plant water status

In this study the strongest relationship between a spectral index and measures of plant water status was between MDWI and RWC at the leaf ($r^2 = 0.94$) and canopy level ($r^2 = 0.60$). MDWI exhibited low sensitivity to changes in leaf water potential ($r^2 = 0.42$, slope = 9.89) and RWC ($r^2 = 0.37$, slope = 0.64) at the canopy level compared to no sensitivity shown for all other indices. The superior relationship and sensitivity of MDWI to plant water status compared to the other analyzed indices may be explained by the use of adjustable wavelengths. The MDWI, WI, and NDWI all employ ratios between wavelengths, which are weakly and strongly absorbed by water. This optimizes the sensitivity of the index to changes in plant water status: the lower the impact of water absorption on one wavelength and the higher on the other, the greater the change of the ratio between these two wavelengths due to changes in plant water status. The selection of wavelengths weakly and strongly absorbed by water is therefore critical for the sensitivity of the index to changes in plant water status. However, the WI utilizes fixed reference wavelengths at 900 and 970 nm, which may not always be the greatest and least affected by water absorption within this wavelength region, respectively (Pu et al., 2003). The NDWI utilizes the reflectance at 1241 nm located at the water absorption band edge and is less affected by water absorption than a wavelength located at the center of the water absorption feature.

In contrast, MDWI extracts the local minimum and maximum reflectance between 1500 and 1750 nm and therefore always presents the ratio between the wavelengths least and strongest affected by water absorption within this wavelength. This may maximize its sensitivity to changes in plant water status since the ratio change between these two wavelengths always represents the maximum change in ratio between wavelengths located between 1500 and 1750 nm caused by changes in plant water status.

MDWI also uses longer wavelengths located in the SWIR, whereas all other studied indices use wavelengths in the NIR.

Wavelengths within the SWIR penetrate less far into the canopy in comparison to NIR wavelengths (Sims and Gamon, 2003) making SWIR wavelengths less sensitive to changes in leaf area compared to NIR wavelengths (Ceccato et al., 2002). The lower sensitivity of SWIR wavelengths to changes in leaf area may therefore result in less variation and thus a stronger relationship between MDWI and measures of plant water status.

Furthermore, different studies have shown that wavelengths in the SWIR are more suitable to detect changes in plant water status than wavelengths in NIR (Tucker, 1980; Carter, 1991; Danson et al., 1992; Ceccato et al., 2002). Ceccato et al. (2002) showed that wavelengths in the SWIR are more sensitive to changes in plant water status and are less susceptible to noise caused by leaf internal structure. They also suggested that NIR wavelengths show no or very low sensitivity to leaf water content whereas they show a high sensitivity to other factors, like leaf internal structure. These findings are in broad agreement with results by Carter (1991) and Danson et al. (1992). Carter (1991) indicated that wavelengths located between the NIR are not sensitive to changes in the RWC and that wavelengths located at around 1450, 1920 and 2500 nm show the highest sensitivity to changes in RWC independent of the plant species. Danson et al. (1992) observed that leave reflectance at wavelengths located at 1450, 1650, and 2250 nm was correlated to specific water density (SWD) at a $\alpha = 0.05$ significance level whereas there was no relationship between leaf reflectance and specific water density at 975 and 1175 nm. Thus, these findings by other authors showing that SWIR wavelengths are more suitable to detect changes in plant water status than NIR wavelengths is further corroborated by this study.

The study showed further that the observed spectral indices were generally stronger correlated to RWC and EWT than to LWP and SWP. An explanation for this could be that RWC and EWT both provide information solely about water contained within leaves which are directly “seen” by the spectro-radiometer. In contrast, LWP gives also information about the water content of other plant parts, like the stem and root system (Kozlowski et al., 1991), which are not directly "seen" by the spectroradiometer. The same is true for soil used to measure SWP, which was not visible for the spectroradiometer because it was covered by black foam in this study. Thus, considering that the water content of other plant parts and the soil can be significantly higher than indicated by the water content of leaves (Kozlowski et al., 1991; Bradford and Hsiao, 1982), the spectroradiometer would only see the low water content of leaves even though there are different amounts of water contained in other plant tissues or the soil. Consequently, although LWP or SWP might not indicate any water stress, spectral indices might indicate water stress because leaf water content is low weakening the correlation between LWP and SWP to spectral indices.

5.4. Potential limitations of study results

5.4.1. Applicability of study results for larger plants and field grown P. deltoides × P. nigra hybrids

The presented results are based on measurements solely conducted on saplings and thus the results might be different if the same study would have been conduced on larger trees. Saplings differ from larger trees in their leaf area and canopy architecture which both strongly influence canopy reflectance properties (Asner, 1998; Ceccato et al., 2002; Sims and Gamon, 2003). These differences in canopy reflectance properties might affect the relationship and sensitivity of spectral indices to measures of plant water status. To properly evaluate the effect of plant size on the relationship and sensitivity of spectral indices to plant water status further study is needed.

The results of this study suggest that spectral indices are not suitable to detect low to moderate levels of water stress in greenhouse grown *P. deltoides* × *P. nigra* hybrids. This may not be true for trees cultivated under field conditions. The drying process in the field is likely to be slower than it was in the greenhouse giving the trees in the field the opportunity to adjust to lower water availability (Ludlow et al., 1985). These adjustments to drought could be spectrally detectable. One of the adjustments found in *Populus* spp. that might be detectable is the lowering of the osmotic potential. By lowering their osmotic potential, biochemical properties influencing the spectral response of leaves might change and help to detect spectral changes associated with water stress. For *P. deltoides* × *P. nigra* hybrids it has been shown that the osmotic adjustment causes an increase in the concentration of soluble sugars (Tschaplinski and Blake, 1985). This increase in concentration of sugars might cause spectral changes (Curran, 1989) that could help to detect light and moderate levels of water stress.

Furthermore, low water stress over a longer period of time is sufficient to notably decrease leaf area (Bradford and Hsiao, 1982) that might be spectrally detectable (Asner, 1998). Roden et al. (1990) showed for *Populus trichocarpa* and *P. deltoides* that non-irrigated poplars had a smaller leaf area than irrigated poplars. Thus, less radiation is intercepted by trees exposed to water stress than by non-water stressed trees causing spectral differences that might be useful for mapping water stress. However, reduction in leaf area might not only be caused by water stress but also by other stress factors such as nutrient deficiency and may be more suitable as a general indicator of stress.

5.4.2. Determination of high water stress levels

We separated high levels of water stress from low and moderate levels solely by visual signs. Although visual signs have been acknowledged as an indirect technique to determine water status of plants (Turner, 1981; Siemens and Zwiazek, 2003), the onset of wilting is species dependant and physiological changes may occur before visual signs become apparent (Hsiao, 1973). Thus, their usefulness as an estimator of water stress is limited and may not be sensitive to low and moderate levels of water stress. However, our ability to visually separate highly stressed from low and moderate stressed trees is shown by leaf water potential and RWC values measured for trees that were excluded from the study. All trees that were excluded from the analysis had leaf water potential values below −1.6 MPa and RWC values below 0.85 except one sample with a RWC 0.89. Considering that values below leaf water potential of −1.5 MPa and RWC of 0.85 are generally assumed to indicate high levels of water stress, trees that were exposed to a high level of water stress based on their visual signs were also highly stressed based on published measures of plant water status (Hsiao, 1973; Bradford and Hsiao, 1982; Blake et al., 1996).

5.4.3. Applicability of study results on other Populus genotypes and hybrids

The results of this study are limited to *P. deltoides* × *P. nigra* hybrids and may not be applicable to other *Populus* genotypes and hybrids due to biophysical differences between genotypes and hybrids that could cause different spectral responses to changes in plant water status (Sinclair et al., 1971; Van Volkenburgh and Taylor, 1996; Asner, 1998). Distinct anatomical differences between genotypes within *Populus* spp. can for example be shown between *P. trichocarpa* and *P. deltoides*. *P. trichocarpa* leaves contain large intercellular air spaces whereas they are missing in *P. deltoides* leaves. Futhermore, differences in the thickness of cuticle waxes and leaf display can exist between genotypes and hybrids within the *Populus* spp. (Ceulemans and Isebrands, 1996; Cameron et al., 2002).

6. Conclusions

The analysis of plant spectra taken at the leaf and canopy level to evaluate their suitability to detect water stress in *P. deltoides* × *P. nigra* hybrids provided some new insights about the potential use of remotely sensed spectral information to provide plantation managers with information or maps about plant water status in *Populus* spp. The new spectral index MDWI showed a consistently stronger relationship and sensitivity to changes in plant water status at both leaf and canopy levels than NDWI, WI, and REIP. Furthermore, on exclusion of highly stressed plants from the regression analysis, MDWI was the only index that exhibited low sensitivity to low and moderate levels of water stress compared to no sensitivity shown for all other indices. This confirmed that SWIR wavelengths used by MDWI in contrast to NIR wavelengths used by NDWI, WI, and REIP are more sensitive to changes in plant water status. Consequently, MDWI and other SWIR incorporating indices could considerably improve the ability to detect water stress at earlier stages in *Populus* spp. from multi- and hyperspectral remote sensing data compared to NIR-based indices. The higher sensitivity of MDWI may allow earlier detection of water stress assisting plantation managers in their decision-making.

However, although MDWI showed a higher sensitivity to plant water status than the other indices, the strength of the relationship between plant water status and spectral indices decreased considerably if highly stressed trees were excluded from the analysis revealing no or low sensitivity of spectral indices to low and moderate levels of water stress. These results suggest that current spectral indices are not suitable to remotely detect low and moderate water stress in *Populus* spp., but that further research is warranted to assess the broader applicability of MDWI and other SWIR incorporating indices to detect water stress in other species. Biophysical differences between greenhouse and field grown *P. deltoides* × *P. nigra* hybrids and between genotypes within the *Populus* spp. may influence the sensitivity of the spectral response to changes in plant water status. Therefore, further research is necessary to evaluate the use of spectral indices to detect water stress in other *Populus* spp. and in natural settings to further understand their suitability to detect water stress in *Populus* spp.

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