INVESTIGATING THE RELATIONSHIP BETWEEN LIQUID WATER AND LEAF AREA IN CLONAL POPULUS

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1 Introduction

Leaf Area Index (LAI) is one of the most commonly employed biophysical parameters used to characterize vegetation canopies and scale leaf physiological processes to larger scales. For example, LAI is a critical parameter used in regional scale estimates of evapotranspiration, photosynthesis, primary productivity, and carbon cycling (Running et al., 1989; Dorman and Sellers, 1989; Potter et al., 1993). LAI is typically estimated using ratio-based techniques, such as the Normalized Difference Vegetation Index (NDVI: e.g. Tucker 1979; Asrar et al. 1989; Sellers 1985; 1987). The physical basis behind this relationship depends on the high spectral contrast between scattered near-infrared (NIR) and absorbed red radiation in canopies. As the number of leaves present in a canopy increases over a unit area, NIR reflectance increases, while red reflectance decreases, resulting in an increase in the ratio. Through time series and image compositing, NDVI provides an additional temporal measure of how these parameters change, providing a means to monitor fluxes and productivity (Tucker et al., 1983). NDVI, while highly successful for agriculture and grassland ecosystems has been found to be less successful in evergreen chaparral and forested ecosystems (Badhwar et al., 1986; Gamon et al., 1993; Hall et al., 1995). Typically, the relationship between NDVI and LAI becomes progressively more asymptotic at LAI values above three (Sellers, 1985), although linear relationships have been observed in conifers at LAIs as high as 13 for some conifers (Spanner et al., 1990).

In this paper, we explore an alternative approach for estimating LAI for remotely sensed data from AVIRIS based on estimates of canopy liquid water. Our primary objective is to test the hypothesis that the depth of the liquid water bands expressed in canopy reflectance spectra at 960, 1200, 1400 and 1900 nm increases with increasing LAI in canopies. This study builds off of work by Roberts et al. (1997), in which liquid water was shown to increase following a gradient of increasing LAI ranging from grasslands to coniferous forests. In that study, it was observed that forests, which showed little variation in NDVI, showed significant variation in liquid water. In order to test this hypothesis, we analyzed field spectra measured over *Populus* shrubs of known LAI and monitored changes in liquid water in young *Populus* stands as they aged over a four year time span. The study was conducted in south-central Washington, in a clonal *Populus* fiber farm owned and operated by Boise-Cascade near the town of Wallula.

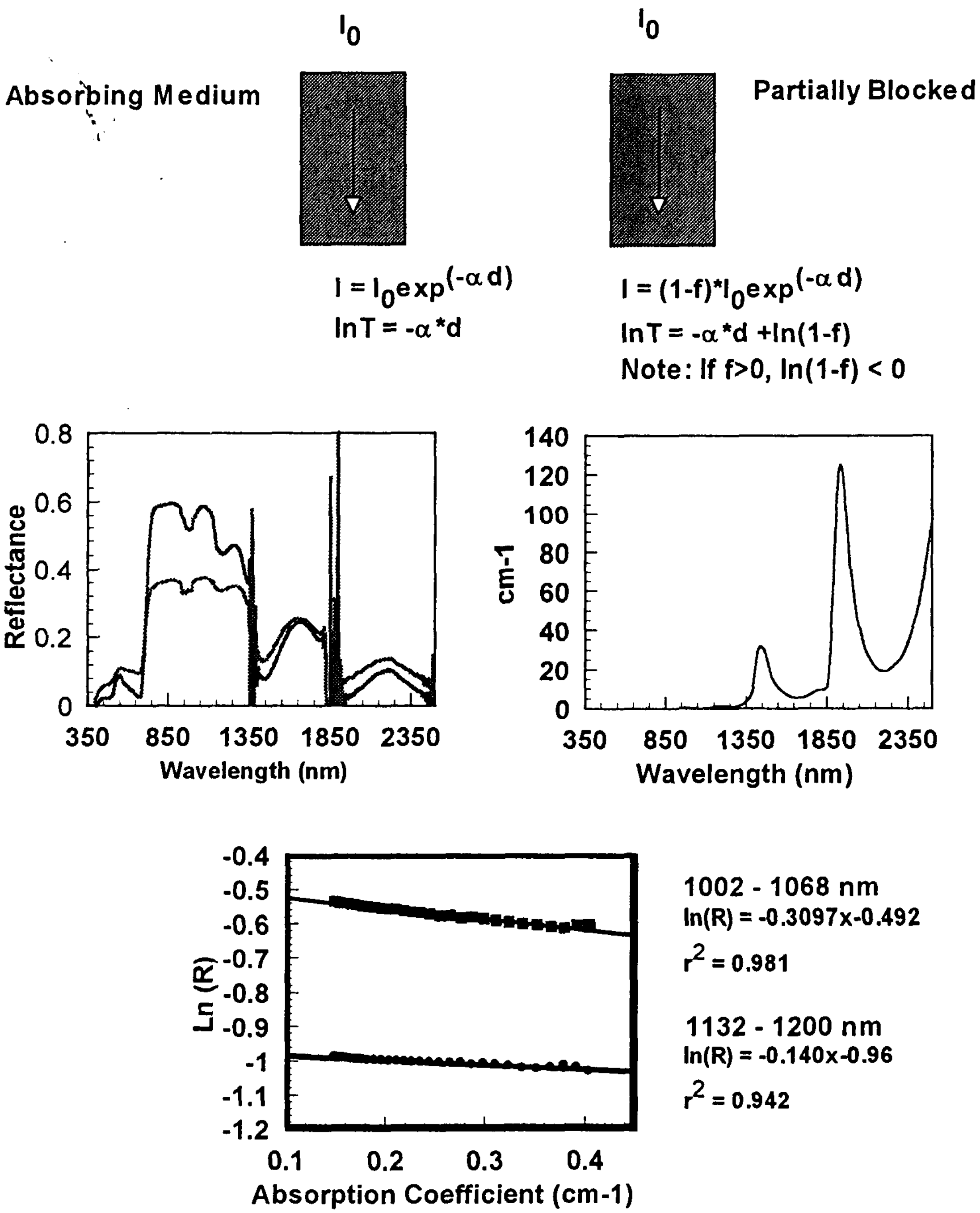
2 Background

2.1 Estimation of Liquid Water in Canopies

Green et al., (1991,1993) developed techniques for retrieving apparent surface reflectance, mapping column water vapor and liquid water from AVIRIS using a modified version of Modtran radiative transfer code. In order to separate water vapor in the atmosphere from liquid water in the landscape, Green et al., (1993) incorporated a simple model for the expression of liquid water in a reflectance spectrum. This model makes the assumption that the depth of the liquid water band across the 865 to 1035 nm region can be approximated using Beer-Lamberts law for exponential extinction in an absorbing or scattering medium. Based on this model, the depth of the water band will vary as a function of the strength of the absorber (described by the absorption coefficient for liquid water) and the pathlength of light within an absorbing/ scattering element. While this simple model was originally developed primarily to improve water vapor retrievals from AVIRIS, recent studies by Roberts et al., (1997) and Ustin et al. (1998) have shown that the liquid water maps that result may be one of the most products available from AVIRIS.

In order to simulate AVIRIS liquid water retrievals in field spectra, a Beer-lambert model was developed that duplicates the approach used in AVIRIS. This approach is shown schematically in Figure 1. In the upper two frames, two formulations of the Beer-Lambert law are presented, one that models light attenuated as it passes through an absorbing (or scattering) medium, and one in which part of the light is partially blocked. In the example shown on the left, the natural log of transmittance (or reflectance) can be modeled as linear function that passes through the origin and has a slope equal to the pathlength. Addition of a blocking factor adds an intercept to the equation. In the central frames, two leaf reflectance spectra are shown on the left, with a plot of the absorption coefficient of liquid water on the right. The lowest frame shows a plot of ln(R) against the absorption coefficient for two wavelength regions. Liquid water thickness would be reported as the slope of the line.

Methodology: Modified Beer-Lambert



3 Methods

3.1 Study Site

The study was conducted in the vicinity of Wallula, Washington (46° 4' N, 118° 54' W), located several km southeast of the confluence of the Snake and Columbia Rivers. The area has a semi-arid, steppe climate, characterized by minimum monthly temperatures slightly below freezing between the months of December and February and peak summer temperatures above 30° C in July and August (Environmental Data Service, 1994;1996). Total annual precipitation ranges between 200 and 350 mm, falling primarily between November and February, but extending through all months except July and August. The dominant natural vegetation is sagebrush scrub (*Artemisia tridentata*), although the region has extensive agricultural development growing potatoes, corn, and other agricultural crops. Field research and image analysis concentrated at the Boise-Cascade Wallula fiber farm, a plantation consisting primarily of *Populus trichocarpa, nigra* and *deltoides* clones (Fig. 2). *Populus* clones in the area begin to leaf out in April, reach peak leaf display by June then senesce by October, varying slightly each year depending on annual temperature. Spectral differences between *trichocarpa-deltoides* (TxD) and *deltoides-nigra* (DXN) can be attributed primarily to architectural differences between TxD with more horizontally oriented leaves and DxN with more vertical leaf displays (Roberts et al., 1995; Hielman et al., 1996).

3.2 Field Study

The field study was designed to test the LAI/liquid water hypothesis using field spectra of DxN clones at the Wallula fiber farm. Field work was conducted at the farm between July 20th and July 25th, 1997 during the time of an AVIRIS overflight. Seventy six young stump sprouting plants, ranging between 10 and 60 cm in height were located and flagged in a 6 year old stand that had been recently harvested. Reflectance spectra were measured of each plant using an Analytical Spectral Devices (ASD) full range instrument on loan from JPL (Analytical Spectral Devices, Boulder, CO). Field spectra were standardized to spectralon (Labsphere, Inc. North Sutton, NH) measured at approximately 10 minute intervals. At least three replicates were measured for each plant. One to four sets of spectra were measured at each plant depending on the size of the shrub at a height of 0.5 m above the canopies.

For destructive harvesting the plants were stratified into five height classes: < 19 cm, 20-29 cm, 30-37 cm, 38-48 cm and 48-60 cm. Five plants were randomly sampled from each height class for detailed analysis. Measurements of plant height, and diameter along the major and minor axes were collected for each of the sampled plants for later determination of ground area and plant volume. In order to determine leaf area of each of the sample plants, every stem was destructively harvested then measured with calipers to determine stem diameter. In order to develop a linear equation that relates leaf area to stem diameter, one of every ten stems was stored in a plastic bag and cooled for later laboratory analysis. In the laboratory, leaves from each stem were harvested, measured for leaf area then regressed against stem diameter. Once this relationship had been developed, it was combined with the shrub stem data to calculate total leaf area for each shrub, then divided by the areal projection of each shrub (in meters) to determine LAI. An example for plant 6-7 (row 6, 7th plant), which consisted of 353 stems is shown in Figure 3.

Liquid water was determined from leaf spectra using the approach described in the background section, modified to account for differences between AVIRIS spectra and the field spectra. The most notable difference occurs in the transition between the VNIR and SWIR1 detectors in the instrument used in the field. Instrumental problems between the VNIR (350-1000 nm) and SWIR1 (1000-1800 nm) regions, tend to create a discontinuity between the two detectors in reflectance spectra (Fig. 1). As a result, it was not possible to apply the same wavelength range as used in AVIRIS to the field spectra. As a solution, the liquid water fits were restricted to the long-wavelength end of the liquid water band, ranging from 1002-1068 nm rather than the 865 to 1065 nm region used in AVIRIS. To test whether AVIRIS and ASD data gave similar results in a wavelength region that did not have instrumental artifacts, fits were also extended to the 1132-1200nm and applied to both field and AVIRIS reflectance spectra.

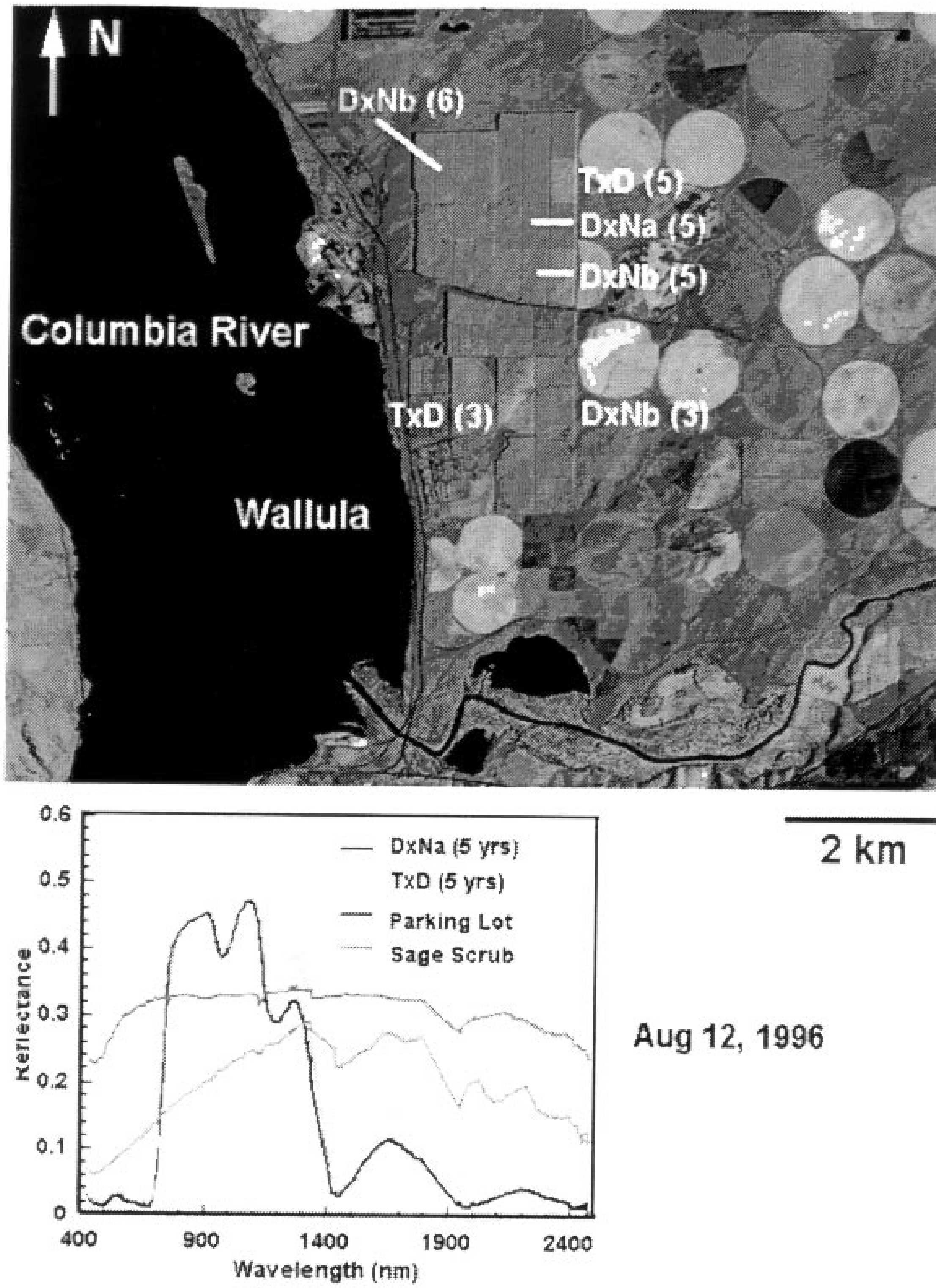


Figure 2. Index map of Wallula fiber farm. Reflectance spectra are displayed for DXN, TXD clones, sage scrub and a parking lot, which was used as a temporally invariant for calibration.

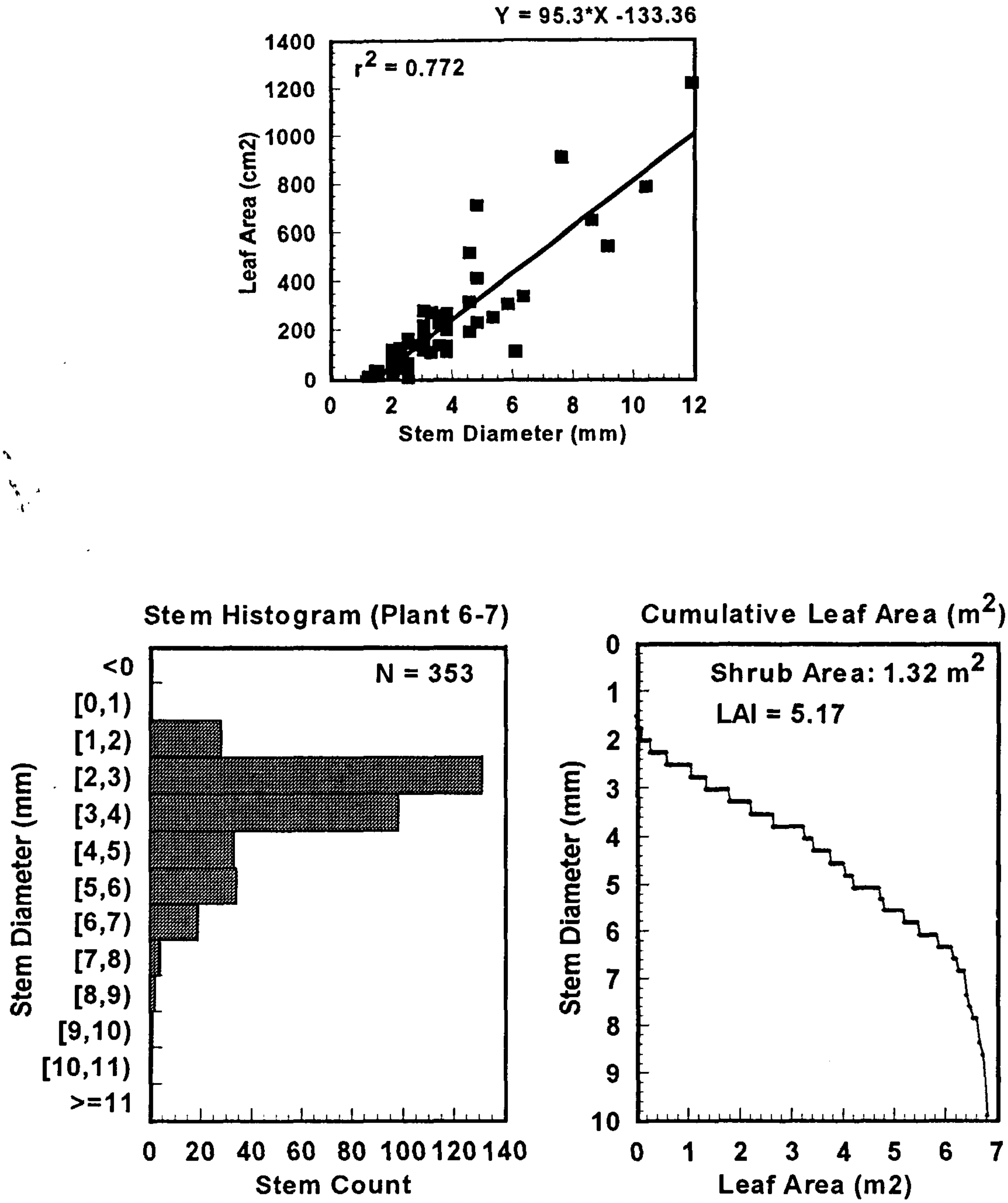


Figure 3. Stem diameter, leaf area relationship. An example calculation is shown for Plant 6-7.

3.3 AVIRIS Processing

An alternate approach, based off of multitemporal AVIRIS data was used to determine whether changes in canopy liquid water matched expected patterns in leaf area development as stands aged. In order to test this hypothesis, five AVIRIS scenes were analyzed over the study site, acquired primarily within a seasonal window after full leaf area development in early June and prior to senescence in October. Data sets acquired during this window included September 22, 1994, June 12 and August 18, 1996 and July 23 1997. A late season data set, acquired on October 18, 1995, showed early signs of senescence in most of the clones.

Once acquired, reflectance was retrieved and liquid water and water vapor mapped for each scene using the modified Modtran-2 radiative-transfer approach described by Green et al., (1993) and Roberts et al. (1997). Field spectral data from two bare soil transects measured in 1997 were used to correct for radiometric and wavelength discrepancies between AVIRIS and modtran. After correcting the 1997 data, a temporally invariant target was located in the scene and used to improve reflectance retrieval for the remaining scenes from 1994, 1995 and 1996. Example spectra for Aug 12, 1996 are shown in Figure 2.

4 Results

4.1 Field Study

LAI for the 25 study plants ranged between 1.8 for one of the smallest shrubs to 8.75 for one of the largest, with most of the shrubs ranging between 4 and 6.5 (Fig. 4). Liquid water fits ranged between 0.05 and 0.38 cm in the 1002-1068 nm region and 0.025 and 0.23 cm in the 1132-1200 nm region. Lower liquid water estimates at the longer wavelength are consistent with the fact that the 1132-1200 nm water band is a stronger absorption feature and thus scattered NIR light will penetrate to a shallower depth within the crown. When plotted against liquid water, estimated from the spectral data, LAI and liquid water proved to have a positive, linear relationship with r^2 values of 0.646 and 0.721 in the 1002-1068 and 1132-1200 nm liquid water absorptions (Fig. 4). Differences in the slopes of these linear relationships can also be attributed to the greater strength of the 1132-1200 nm water band.

The validity of the LAI-liquid water relationship is supported by analysis using more standard approaches such as the NDVI (NIR-red)/(NIR+red) and VI (NIR/red). For example, the plot of NDVI against LAI demonstrates that the NDVI becomes progressively more asymptotic with increasing LAI, matching most published observations. The VI, in contrast, shows a much more linear relationship, showing only slightly lower fits than liquid water. In both cases, liquid water provides the superior estimate and shows a linear relationship even to the highest value observed in the shrubs.

4.2 AVIRIS Multitemporal Study

Based on prior work with the clonal *Populus*, leaf area would be expected to reach peak development in June, sustain a high level throughout the summer, then begin to senesce in the Fall, during October. As a result, with the exception of the 1995 data, differences in LAI observed from 1994 to 1997 should be a product of long term differences in stand age, not phenological changes. Between 1994 and 1997, stand age varied between less than one year to over six years. Over this period of time, LAI would be expected to show yearly increases for the first three years, followed by slight declines over the remaining three years (Heilman et al., 1996).

In order to test whether the expected patterns were observed in liquid water, four stands (plus replicates) were located in the study site, two stands that were originally planted in 1992 and two planted during April, 1994. In order to determine whether leaf angles had an impact on the liquid water retrievals, stands were selected both from the clone with more horizontally oriented leaves, TXD and the more vertically oriented DxN. Temporal patterns in liquid water were also compared to the NDVI, to determine whether similar patterns were observed in that measure.

Temporal analysis of the older stands (Fig. 5, top left) demonstrated few changes in liquid water from 1994 to 1997. The only major temporal change was observed in 1995, in which the TxD showed a marked decrease in liquid water and the DxN a slightly lower decrease, attributed to late season senescence and a loss of leaf area. In all cases, the TxD showed a slightly lower liquid water than the DXN, which can be attributed to either lower leaf area, or the effect of differences in leaf angles. In comparison, the NDVI showed little temporal variation (Fig. 5, row 2). Calculation of liquid water directly from AVIRIS reflectance, using the same program used for the field data, yielded similar results to those produced from the reflectance retrieval. Comparison of field data to AVIRIS spectra, demonstrated higher liquid water estimates for full stands relative to small shrubs, equal to close to 1 mm of water.

Analysis of changes in liquid water in the younger stands demonstrated a uniform increase in liquid water over the first three years, followed by a slight decline in the fourth year (Fig. 5, top right). Unlike observations in the older stands, NDVI showed marked changes, dramatically increasing in the first two years followed by little change in the third year. The VI was not calculated because it proved too sensitive to minor atmospheric correction problems in the red wavelengths.

Patterns in the liquid water matched expected patterns based on stand age and seasonality. In comparison, the NDVI shows little variation except in very young stands.

LAI Compared to Liquid Water

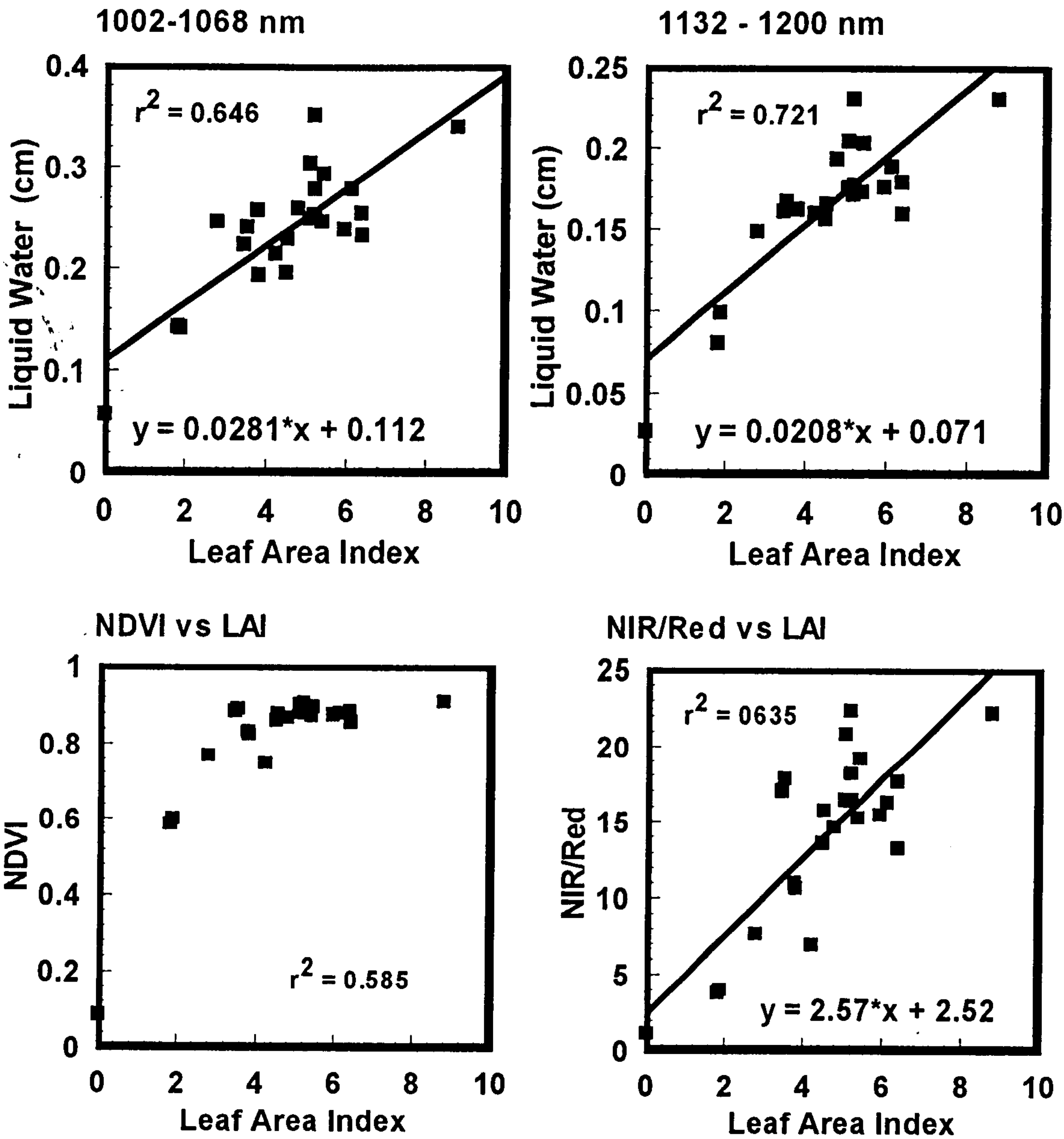


Figure 4. Comparison of LAI to liquid water thickness, NDVI and VI.

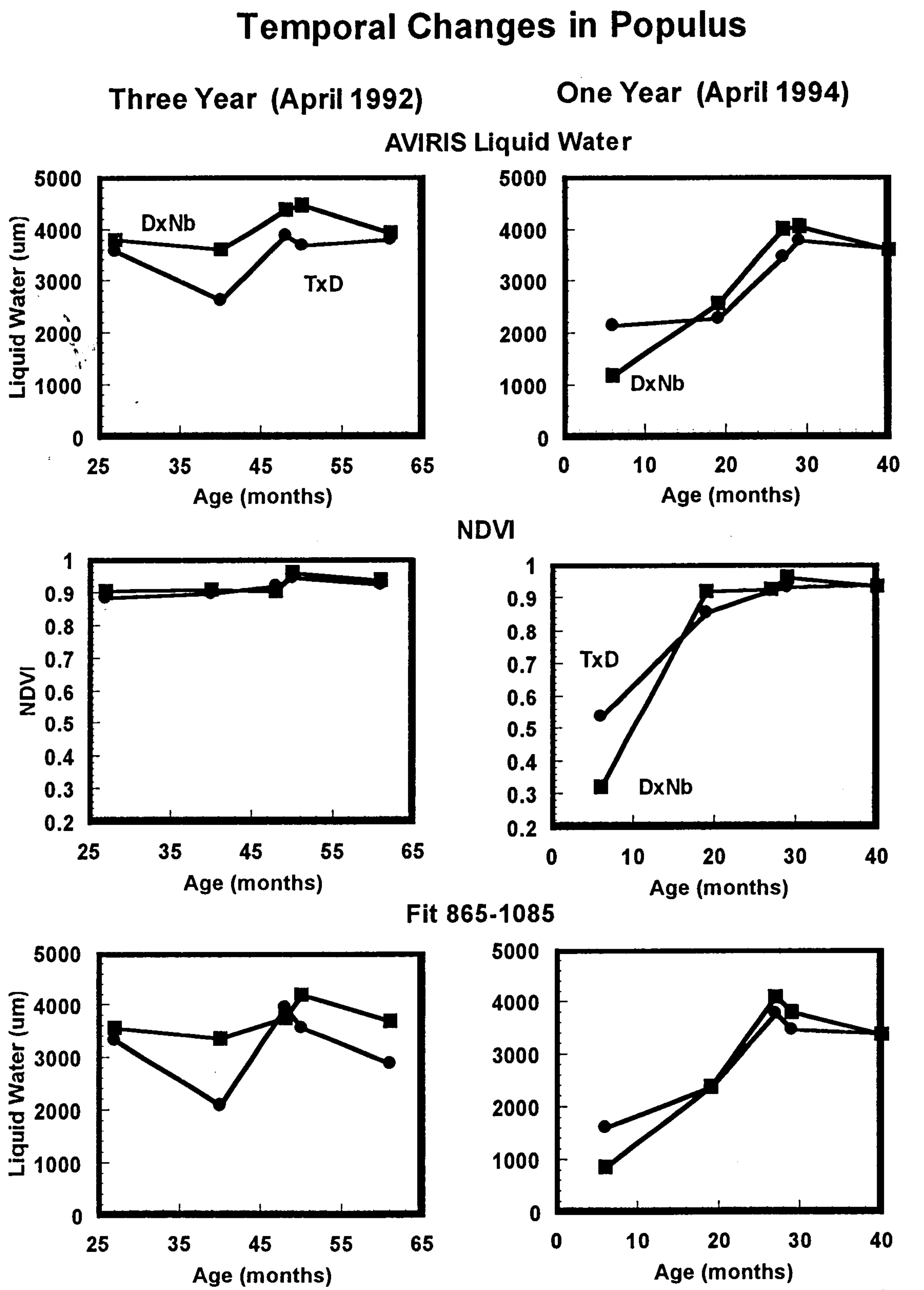


Figure 5. Temporal changes in liquid water and NDVI for select Populus stands from 1994 to 1997. Plots to the left show results for stands planted in 1992, plots on the right show stands planted in 1994.

5. 0 Summary

In this study we tested the hypothesis that LAI is linearly related to liquid water. There were two components of the study, a field study using reflectance measurements of *Populus* shrubs which were harvested to determine LAI and a temporal study of AVIRIS data that tracked changes in liquid water as stands aged over a four year period. The field study demonstrated that LAI and liquid water are linearly correlated up to LAI 8.75. In comparison, the NDVI/LAI relationship showed the expected asymptotic relationship which saturated near an LAI of 3.0. The VI showed a surprisingly good linear relationship.

AVIRIS analysis showed temporal patterns in the liquid water which matched expected patterns based on stand age and seasonality. In this instances, the only significant pattern in the older stands was due to senescence in the October, 1995 data set. In the younger stands, liquid water increased for the first three years followed by a decline in the fourth year. In comparsion, the NDVI showed little variation except in very young stands.

These results suggest that liquid water retrieved from AVIRIS may form a new, potentially powerful technique for mapping stand structure. However, there remain several important research directions that should be pursued. These include sensitivity analysis to determine how relationship varies between very different types of vegetation (e.g. shrubs, conifers) and how it varies seasonally with water status (as in chaparral). Furthermore, methods should be explored that avoid the use of correlative relationships between field data and remotely sensed measures of liquid water.

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