Detection of moisture stress in Eucalyptus Camaldulensis using leaf-level spectral reflectance: implications for remote sensing

Laurie A. Chisholm

University of Wollongong, lauriec@uow.edu.au
Detection of moisture stress in Eucalyptus Camaldulensis using leaf-level spectral reflectance: implications for remote sensing

Abstract
Foliage moisture stress may be detectable by remote sensing using high resolution spectral data, but meaningful diagnosis requires that plant water status be assessed on the ground under controlled conditions. Design parameters of an experimental plantation of E. camaldulensis (River red gum), were used to examine tree-level responses to moisture stress, as measured by xylem water potential, and relationships to physiological parameters including spectral reflectance, chlorophyll fluorescence, and chlorophyll across a range of stress categories.

Keywords
Detection, moisture, stress, Eucalyptus, Camaldulensis, using, leaf, level, spectral, reflectance, implications, for, remote, sensing

Disciplines
Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

Publication Details

This journal article is available at Research Online: http://ro.uow.edu.au/scipapers/1181
Detection of Moisture Stress in *Eucalyptus Camaldulensis* Using Leaf-Level Spectral Reflectance: Implications for Remote Sensing

L. A. Chisholm
GeoQUEST Research Centre
School of Earth and Environmental Sciences, University of Wollongong, Wollongong, NSW, 2522, Australia
Tel: +61 2 4221 3765, Fax: +61 2 4221 4250, E-mail: lauriec@uow.edu.au

Abstract

Foliage moisture stress may be detectable by remote sensing using high resolution spectral data, but meaningful diagnosis requires that plant water status be assessed on the ground under controlled conditions. Design parameters of an experimental plantation of *E. camaldulensis* (River red gum), were used to examine tree-level responses to moisture stress, as measured by xylem water potential, and relationships to physiological parameters including spectral reflectance, chlorophyll fluorescence, and chlorophyll across a range of stress categories. Detailed leaf-level measurements revealed discrimination between stress categories. Statistical analysis, including a new pair-wise moving t-test comparing mean spectral reflectance curves of each stress category, served to determine gross spectral regions discriminate of moisture stress. Distinct biophysical differences were found between healthy and moisture-stressed trees which were detectable by high resolution remote sensing suggesting the potential for remote sensing to significantly contribute to forestry management practices.

1. Introduction

It is well established that for most vegetation species, the reflectance of leaves increases with moisture stress at all wavelengths over the 400 – 2500nm ranges (Knippling 1970, Gauman 1974, Carter 1991, Goetz and Boardman 1995, Aldakheel and Danson 1997). However, inconsistent spectral responses among leaf samples have been reported where factors such as leaf age and species account for the inconsistencies. Upon closer inspection these studies have largely been conducted on agricultural crops which have quite different physiological responses to moisture stress than woody plants and therefore elicit non-conformal spectral behaviour to the general rule, or on trees where leaf age cohorts have not been taken into account.

For those trees in which moisture stress causes an increase in reflectance at all wavelengths from 450 – 2500nm, there are varying reports of the portions of the spectrum that are affected and which portion provides first detection of stress. Knippling (1970) and Tucker (1980) found the primary response of moisture stress in the water absorption region of the spectrum (1350 – 2500nm); in contrast to Weber and Olson (1967), Hoffer and Johannsen (1969), and Sinclair et al (1971) where the entire leaf reflectance spectrum was affected due to changes in cell structure and chemistry that accompanied moisture stress. More recently, Carter (1993, 1994) and Carter and
Knapp (2001) found that increased reflectance is consistently detected more often in the visible wavelengths (450 – 720nm) than in the remainder of the spectrum (730 – 2500nm). Thus, research attempting to define wavebands most discriminate of moisture stress are not definitive.

However, it is clear that wavebands which are sensitive to changes in leaf chlorophyll content and/or leaf water content tend to be narrow (Carter 1994; Treitz and Howarth 1999; Sampson et al., 2001), making narrowband optical data a necessity for quantitative assessment of biophysical parameters indicative of moisture stress. In addition, successful use of remote sensing methods for these means is dependent on the comparison of remote sensing data from healthy trees with data from those under stress, preferably under controlled conditions (Roberts et al., 1998) and using ancillary measures of plant function (Sampson et al., 2001). The monitoring of fluorescence is a useful tool in the detection of various stress responses in plants (Zarco-Tejada et al., 2000) with the ability to examine the effects of water stress on PS II photochemistry (Lu and Zhang 1998).

High spectral resolution spectral reflectance studies carried out on Eucalypts in Australia is increasing, however, all of these studies examined relatively healthy leaves. This paper presents the first evaluation of high spectral resolution leaf spectra to characterize and discriminate moisture stress in a single species E. camaldulensis (River red gum), a unique and significant component of Australian floodplain forests. The study focused on the assessment of moisture stress in terms of stress, strain and damage, not vegetation water content per se.

2. Methodology

2.1 Study area

In 1991 the NSW Forestry Commission established the largest irrigated river red gum plantation in Australia to study the precise water requirements, fertiliser needs and effects of various planting intensities of the species to determine the overall effect of flooding regime on forest health (Bren 1998). Management of the trial required a specified flooding regime to be artificially applied to areas within the trial. At the time of construction nine separate bays were established within the plantation (Figure 1). An irrigation canal network enables each bay to receive varying watering regimes based on increments of pan evaporation. Ground cover and soils are consistent throughout the plantation (Bren 1998). The nine bays shown in Figure 1 consist of two that receive no additional irrigation (Natural), two that receive irrigation when 450mm of pan evaporation occurs (bays 1 and 6), three that receive irrigation after 300mm of pan evaporation occurs (bays 3, 4 and 8) and two that are irrigated after 150mm pan evaporation occurs (bays 2 and 9). These four different flooding treatments are applied when measured pan evaporation reaches the required depth (150mm, 300mm, 450mm). The natural bays only receive natural rainfall and therefore serve as controls. The experimental design layout within each of the bays is based on four planting spacings (3m x 1.5m, 3m x 3m, 3m x 4.5m, and 3m x 6m); four levels of nitrogen (N) (0g, 25g, 50g, 100g) and four levels of phosphorus (P) (0g, 10g, 20g, 50g) applied per tree, each coded from 1 through 4 respectively. The irrigation bays are replicated (total of 512 plots in nine irrigation bays) with each treatment plot consisting of twenty-five trees numbered to enable re-measurement; all plots have the same basic layout (Figure 2). Nine central trees are measured in each plot annually for height and diameter at breast height with the surrounding sixteen trees acting as a buffer.

2.2 Moisture stress category selection

Irrigation treatments implemented at the site were used to establish categories representing contrasting rates of stress development for sampling. The 300mm and 150mm treatments were selected as “healthy” categories as determined by George
Figure 1 Study area and experimental plan of the NAP plantation site.

Figure 2 Schematic diagram of bay 7 (natural/controls) representative of each bay in the plantation where each '+' denotes an individually numbered tree located by row and column. Variations in tree spacing can readily be seen; nitrogen and phosphorus applications vary for each plot.
(1998) as these trees receive more frequent watering. The 450mm treatment (mid-range category based on infrequent watering) and the controls (natural rainfall only) were also selected for measurement to provide a range of stress categories and contrast with the "healthy" categories. Two replicate plots were randomly selected for each stress category using the experimental design code of '442' to control for fertilizer application rate and planting spacing.

2.3 Foliage measurements

Three trees within each replicate plot were randomly selected to obtain foliage for assessing tree water status and condition. Foliage was obtained by shooting down small branches with a 0.22 caliber rifle with telescopic sights and a spotlight for pre-dawn sample collection. For each tree, two small branches were sampled at mid-crown height with only mature, even-age leaves measured. Twenty leaves (Demarez et al., 1999, Stone 1999) were randomly selected from each branch, a total of forty leaves, for subsequent foliar measurements of pre-dawn xylem water potential, spectral reflectance, chlorophyll fluorescence and SPAD chlorophyll. Leaf xylem water potentials were used as the physiological measure of stress similar to Carter and Miller (1994) and Peñuelas et al., (1993). The water status of the trees was assessed from the mean value of the xylem water potential measured immediately prior to dawn on twigs < 2mm stem diameter, using a Scholander pressure bomb (Scholander et al., 1964; Ritchie and Hinckley 1975). The branches were then immediately transported to a nearby field office for further measurements completed within 2 hours after detachment.

Leaf reflectance measurements were made using a FieldSpec FR Spectroradiometer (Analytical Spectral Devices, Inc, Boulder, USA) with 1.4 nm (350-1050 nm) and 2 nm (1000-2500 nm) spectral sampling. A Spectralon white reference panel (Labsphere, Inc., North Sutton, USA) was measured between each reflectance measurement. Three 150w halogen bulbs on stands powered by a stable DC power supply were used to illuminate the leaves and the reference standard. Leaves were stacked six layers thick covering an area of approximately 15cm × 15cm on the target platform (Datt 1999; Stone et al., 2001). The pre-processed spectra were imported into S-Plus 6.2 for Windows (Insightful Corporation: Seattle, USA) for further processing and plotting. All measured spectra from 350 to 2500 nm were converted to reflectance (Reflectance = light emitted from sample / light emitted from white reference) and averaged to obtain mean reflectance spectra. Reflectance means of the spectral reflectance data were determined for each tree. Statistical analysis using a 5-point moving t-test determined whether significant differences between the averaged spectra for different categories existed. This method applies a t-test for every set of five wavelengths between two spectral reflectance curves, subsequently plotting the p values of the t-test back against wavelength on a log scale, with regions of significant difference shown beneath the critical threshold line (p<0.05). This method enables gross determination of significant regions of spectral difference between two spectral reflectance curves, where for this case, each spectra represents a different date. This "pairwise" moving t-test was computed for each pair of mean spectra representing the health categories and compared.

For the same leaves, measurements of Fv/Fm ratio of variable to maximum chlorophyll fluorescence were made using a portable chlorophyll fluorometer (Fluorescence Induction Monitor 1500: Analytical Development Company Ltd., Herts, UK) as per Stone et al., 1999, 2003. For the same leaves, a SPAD™ meter (Minolta Co., Ltd., Model 502, Japan) was used to obtain a measure of total chlorophyll concentration as per Stone et al., 2001, 2003.
2.4 Weather data

Daily rainfall and evaporation were obtained from the Tocumwal weather station, approximately 10 km from the study site to determine seasonal patterns of rainfall and evaporation by the 20-year means (Data not shown). The autumn seasonal break in weather pattern came early in 1999, distinctly marked by relatively high rainfall in March. Overall the evaporation rates for 1999 closely followed the twenty-year means. In contrast, the precipitation rates for 1999 were erratic in comparison to the respective twenty-year means. January 1999 was marked by higher than usual evaporation. Evaporation substantially reduced in February and March. In February precipitation was distinctly lower than the twenty-year mean. More importantly, the summer to autumn transition is well marked by an unusual amount of precipitation that occurred in March, well above long-term averages.

3. Results

Pre-dawn water potential varied considerably between the controls and all other categories (Figure 3a). The high (more negative) mean for the controls of -1.47 MPa, indicates the poorest water status and is well separated from the other three categories. The 450mm, 300mm and 150 mm pan evaporation categories are clearly of better water status than the controls with lower (less negative) values of water potential indicating less water deficit and superior health than the controls. The 150mm pan evaporation category was the least water deficit with a mean of -0.28 MPa. The 300mm and 450mm pan evaporation categories are similar in water status with the 300mm category (-0.48) of slightly better water status than the 450mm category (-0.52). Figure 3b illustrates comparative values of the sample means of the chlorophyll fluorescence (Fv/Fm) data for each category. The 300mm and 150mm categories have distinctly higher mean values (0.821 and 0.818 respectively) than either the 450mm pan evaporation or control categories. The 450mm pan evaporation category presents an intermediate mean value (0.80) and the controls have the lowest mean value (0.796). The controls clearly have the least photosynthetic efficiency of all categories whereas the 300mm and 150mm pan evaporation categories have the highest photosynthetic efficiency. The 450mm pan evaporation category falls just above the mean for all categories at 0.810 indicating that photosynthetic efficiency is good. Figure 3c illustrates comparative values of the sample means of the SPAD chlorophyll data for each category. The low mean value (39.5) for the controls clearly indicates lower leaf chlorophyll concentration than the other categories. The 300mm and 150mm pan evaporation categories reveal similar chlorophyll means of 43.9 and 44.0 respectively. The 450mm pan evaporation category presents the highest chlorophyll mean of the data indicating that this bay contains values among the highest of the leaf chlorophyll concentrations.

In general, all mean reflectance spectra look very similar (Figure 4), with absorption features in very similar positions. This similarity is to be expected as the spectra are of the same species. However, the controls are different in the near to mid-infrared (800 – 1300 nm) range and show the greatest reflectance in this region. The controls also show an increase in reflectance in the 450 – 550nm and 1700 – 1900nm ranges. There are differences, albeit relatively minor, in terms of absolute reflectance, depths of the absorption features and the relative position of change in terms of the wavelength across all categories. Overall the visual differences between controls and the 150mm pan evaporation categories suggest good discrimination between extreme health categories. Visually there would appear to be association between decreased relative moisture of the leaves and increased leaf reflectance in the 450 – 2500 nm range. These reflectance patterns are similar to other studies of water-stressed plants (Gausman 1974, Goetz and Boardman 1995) and others. However, the visual differences between the 450
Figure 3. Sample means per category (n=24)
mm, 300mm and 150mm categories appear relatively small. In comparison to all other categories, spectral reflectance of the controls increase throughout the spectral range 400 - 2500 nm and remains high until 1300 nm where it rapidly decreased and merged with the reflectance curves of the other categories. The reflectance of all categories reached a low point at 1400 nm and 1900, both liquid water absorption bands. The greatest visual change occurred in the near-infrared region followed by the mid-infrared and visible.

There is an increase in reflectance across all wavelengths with an increase in stress. This reflectance pattern is similar to other studies of water-stressed plants (Knipling 1970, Woolley 1971, Gausman 1974, Carter 1991, Goetz and Boardman 1995, Aldakheel and Danson 1997). This suggests a reduced moisture content of the controls and therefore a greater refractive index due to an increase of air cavities between the cells. Given the trend for increasing reflectance in the near-infrared region, the spectral reflectance curves for the controls versus all other categories exhibit the classic manifestations of water stress. However, the reflectance curves for all categories virtually merge at the water absorption bands at 1450nm and 1930 nm suggesting that all bays are not overly dry. Woolley (1971) and Carter (1994) stated that only large changes in leaf water content, such as drying, would significantly affect reflectance in the far-infrared region. The spectral reflectance results further suggest that stress levels in all categories were not extreme due to the March rainfall and seasonal break.

Not all results of the pairwise moving t-tests can be shown due to space limitations. No significant differences were found between the mean reflectance curves of the 300mm and 150mm pan evaporation categories (Figures 5a, b). In contrast, significant differences (p < 0.05) were found between the controls and all other categories, as represented by Figure 6a and b. Spectral

![Figure 4: Stacked plot of mean spectral reflectance curves by category.](image-url)
regions most different between these categories were consistent within the 750 – 1570 nm (near-to mid-infrared) region and near 1850nm. In addition there were significant differences in the 500 – 550nm (green) between the controls and the 150mm category (Figures 6a, b). Significant differences were found in the 1170 – 1880nm and 1985 – 2500nm spectral regions between the 450 mm and 150mm categories and in the 900 – 1440 nm regions between the 450 and 300mm categories (data not shown).

4. Discussion

While the water potential measurements for the 450mm, 300mm, and 150mm pan evaporation categories were more positive than the controls, even the highest (more negative) readings for the controls of –1.5 MPa would not be considered severe water deficit (Heinrich 1990, Lu and Zhang 1998, McEvoy 1992). The lowest (less negative) minimum pre-dawn water potential (~0.2 MPa) was recorded in the 150mm pan evaporation category. Values of this order have been observed in this and other eucalypt species after significant rainfall (Sinclair 1970 and others). The 150mm category received irrigation treatments in January, February and March based upon the 150mm pan evaporation measure, thus could be considered to be particularly well watered through the hot summer. When combined with the March rainfall and associated reduction in evapotranspiration, the pre-dawn water potential reached the ~0.2 MPa value. The 150mm category was clearly of better water status than the 300mm and 450mm categories due to these effects. As a general comparison to the controls, the water status of the 450mm, 300mm and 150mm pan evaporation categories could be regarded as relatively similar, within the range of ~1.55 to ~0.29, indicating a range from well-watered to mildly stressed trees. The 450mm pan evaporation category, the intermediate health class, was quite comparable in water status to the 300mm category.

The generally overall low water potential for the controls indicate that the trees in this category were experiencing moderate moisture stress, at most, at the time of sampling. The relatively low (less negative) water potential readings for all categories reflect the high precipitation in March 1999 combined with the lower demand of the trees for water in the autumn season. The autumn break occurred early in 1999 marked by higher precipitation rates than the 20-year average. It is therefore assumed that in April 1999 the trees within the plantation were of a closer water status in terms of overall range than might be the case if the typical summer conditions of low precipitation and high evaporation had prevailed. This also explains why the trees in the 450mm category were closer in water status to the 300mm and 150mm pan evaporation categories than to the controls and well above the overall mean.

Leaf-level reflectance spectra gave good discrimination between the 150mm and 300mm pan evaporation versus control categories. Results from the chlorophyll fluorescence parameter (Fv/ Fm) and SPAD chlorophyll were significantly lower for the controls than the other categories and serve to confirm that the controls have poorer function and decreased leaf chlorophyll concentration levels. These parameters enable a distinction between major stress categories (controls vs healthy).

Leaf xylem water potentials observed during this sampling period were representative of tree condition after a climatic break from summer to autumn (Heinrich 1990, McEvoy 1992). The moderate xylem water potential readings for the control category, confirmed by the chlorophyll fluorescence and SPAD chlorophyll measurements, indicate that while they were distinctly separable from the healthy categories, they were not experiencing severe water deficit. Similarly, xylem water potential means for all categories were of low variance suggesting relatively constant stress conditions during this sample period.
Figure 5 (a) Mean spectral curves for 300mm (healthy) and 150mm (healthy) pan evaporation categories. (b) Moving t-test plot of 300mm (healthy) versus 150mm (healthy) categories. No significant differences were detected at the $p < .05$ level.
Figure 6 (a) Mean spectral reflectance curves for controls and 150mm (healthy) pan evaporation categories.
(b) Moving t-test plot of controls versus 150mm (healthy) pan evaporation category. Significant differences (p<0.05) are plotted below the blue line and occur in virtually all spectral regions: 500 – 590nm, 640 – 710nm, and from 750 – 2500nm.
crease in reflectance for an increase in moisture stress category, the changes in response within the mid-infrared were relatively shallow, further indicating relatively mild water deficit (Woolley 1971).

It is interesting to note that the 450mm pan evaporation category was more similar to the healthy categories than the controls during the time period sampled. Similarly the spectral reflectance for the 450mm category would be considered intermediary between the controls and healthy categories. It is likely that the 450mm pan evaporation category staged a degree of recovery from the March rainfall than what would otherwise have been expected under summer conditions. The water potential readings support this premise as the 450mm category was shown to be close in water status to the 300mm category. The 300mm category had not been irrigated as frequently as the 150mm category during the hot summer (Irrigated on 1 February 1999 only) thus its physiological status is closer to the 450mm category than the 150mm category. This goes some way towards explaining the high variance in the SPAD chlorophyll measurements and spread when plotted against chlorophyll fluorescence. SPAD chlorophyll values indicate the 450mm category exhibits a wide range of chlorophyll content, reflecting a category which contains healthy and relatively non-healthy samples related to the climatic influence of summer and autumn conditions, eg in the summer with less than adequate rainfall for optimum growth, the trees are less healthy; in the winter with increased rainfall, they are healthier overall. Given potential confusion with healthy categories, inclusion of the 450mm pan evaporation category is of no particular benefit if one is attempting to discriminate between extreme stress classes, and in fact, could be a disadvantage. An important trend was the greater variability of the controls and 450mm pan evaporation category for nearly all leaf traits measured compared to foliage from healthy categories.

Moving t-tests demonstrated that reflectance means for the controls and the healthiest treatment category (150mm) were separable across most of the spectral region between 450 – 2500 nm. Similar tests for other combinations of categories in which the stress differential was less also indicated separability, however, the most significant regions of change occurred in the shortwave infrared (750 – 2500nm). This infers that more severe stress is manifested as changes not only in leaf structure and water content as shown in the near infrared and SWIR, but also in chlorophyll content within the visible region, thus affecting the majority of the leaf reflectance spectrum (Weber and Olson 1967, Hoffer and Johannsen 1969, Sinclair et al 1971). It would appear that any differences in chlorophyll content due to stress in the intermediate stress categories were not present, indiscernible by the moving t-test, or that leaf chlorophyll levels were relatively similar between these categories. Previous results have indicated that stress conditions were not at a maximum at the time of sampling.

Many authors (eg Rigg and Running 1991) have found that water stress may not be detectable in the relatively small reflectance differences involved. Others such as Cohen (1991a, 1991b) also state that results from leaf reflectance-water stress studies have only limited applicability to the remote sensing of plant canopy water stress because of the limited reflectance variation among different leaves in a sample at the same level of water stress. Although these and other works (eg Bowman 1989) indicate there are limitations to the use of spectral reflectance to estimate leaf moisture stress, the results described here suggest that high spectral resolution may be useful in detecting moisture stress in E. camaldulensis at the leaf level. Given that this study was able to detect the higher variation in the 450mm pan evaporation category, an intermediary stress level, suggests that determining adequate sampling numbers under controlled conditions is instru-
mental to successfully establishing relationships amongst trees suffering from moisture stress. Under similar conditions Peñuelas et al., (1993) found significant correlations between spectral indices in the near-infrared range with xylem water potential and other leaf water status variables that were considered physiologically meaningful, however, the best results were obtained when moisture stress was well developed. The results of this study indicate that considerable sampling at the leaf level can produce meaningful results which enable differentiation between degrees of stress.

5. Conclusion

Leaf-level measurements of xylem water potential, chlorophyll fluorescence and SPAD chlorophyll were measured concurrently with high resolution spectral reflectance for four anticipated stress classes of *E. camaldulensis*. All measurements confirmed the expected “health” status of the categories despite stress maxima being relatively low due to rainfall and a seasonal climatic break. The results show that chlorophyll fluorescence and SPAD chlorophyll are useful for assessing tree condition as ground-based measurements to support remotely-sensed methods. However, SPAD chlorophyll appears to provide an indicator of a physical response in the canopy architecture while chlorophyll fluorescence serves as an indicator of physiological status, thus, it should not be anticipated that the relative health status ranking should necessarily be the same for these parameters. Statistical analysis used to compare mean spectral reflectance curves of each category was successful in identifying gross spectral regions which may be discriminative of moisture stress in *E. camaldulensis*.

The primary implication of this study is that moisture stress in *E. camaldulensis* can be detected using laboratory-based high resolution spectral reflectance data obtained at the leaf level. Given that there were measurable and detectable differences between categories despite a low range of stress levels, this presents four implications: (i) the threshold is relatively low for discrimination and previsial changes are detectable; (ii) various levels of moisture stress might be discriminated given more extreme conditions; (iii) there are spectral reflectance regions which may be developed as indicators of moisture stress in *E. camaldulensis*; and (iv) there is scope to examine the response time of spectral reflectance for the detection of response to stress recovery.

Acknowledgements

This research was conducted with the support and advice of NSW State Forests, Western Region, Deniliquin District, with particular acknowledgement given to Mr B. George and Mr G. Haegney.

References


Sampson, P.H., Mohammed, G.H., Zarco-Tejada, P.J., Miller, J.R., Noland, T.L., Irving, D., Treitz,


Stone, C., 1999; Assessment and monitoring of decline and dieback of forest eucalypts in relation to ecologically sustainable forest management: a review with a case study. Australian Forestry, 62, 55-63.


Dr. Laurie Chisholm received the BSc degree in geology and MA degree in geography from the University of Oklahoma, USA, and the PhD degree in remote sensing from the University of New South Wales, NSW, Australia. For her PhD, Laurie used hyperspectral data to investigate the spectral characteristics of a single floodplain forest species, E. camaldulensis (river red gum), to changes in a single stressor, moisture stress, including predictive modeling for stress detection at the airborne level. She was Associate Director of the Centre for Image Analysis at Charles Sturt University, Wagga Wagga, NSW, Australia in 1997-98, and a GIS consultant to the UN FAO from 1994 – 1997. Currently Laurie is a Senior Lecturer in the School of Earth and Environmental Sciences at the University of Wollongong, NSW, Australia where she lectures in Biogeography and Environmental Change, and Remote Sensing of the Environment. She is a member of the GeoQuEST Research Centre with research interests in biogeography, landscape ecology, and disturbance ecology for sustainable resource management. Currently she is undertaking several projects which combine field studies with remotely-sensed data (airborne, satellite, LiDAR) and simulation modeling at multiple spatial and temporal scales.