Remote Detection of Canopy Water Stress in Coniferous Forests Using the NS001 Thematic Mapper Simulator and the Thermal Infrared Multispectral Scanner

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ABSTRACT: Water stress was induced in two coniferous forest stands in West Germany by severing tree sapwood. Leaf water potential (Ψ_L) measurements indicated that maximum, naturally occurring levels of water stress developed in the stressed plots while control plots exhibited natural diurnal trends. Images of each site were obtained with the Thematic Mapper Simulator (NS001) and the Thermal Infrared Multispectral Scanner (TIMS) 12 to 15 days after stress induction. NS001 bands 2 to 6, NS001 indices combining bands 4 and 6, and NS001 and TIMS thermal bands showed significant radiance differences between stressed and control plots when large differences in Ψ_L and relative water content (RWC) existed during the morning overflights at Munich. However, the NS001 and TIMS sensors could not detect the slightly smaller differences in Ψ_L and RWC during the Munich afternoon and Frankfurt overflights. The results suggest that routine detection of canopy water stress under operational conditions is difficult utilizing current sensor technology.

INTRODUCTION

WATER STRESS IN TREES is an important limitation on the growth of temperate conifer forests. "Water stress" is typically manifested as a reduction in leaf water status below levels optimal for growth, and can be a result of a number of biotic and abiotic factors, including climatic drought or attack by insects and disease. Leaf stomata close in response to a reduction in leaf water status, thereby decreasing conductance of CO_2 from the atmosphere into leaf tissues and impeding the tree's ability to assimilate carbon through the photosynthetic process (Schulze and Hall, 1982). Carbon is the primary building block for tree growth and is critically important in maintenance and production of living tissues as well as synthesis of defensive chemical compounds (Waring and Schlesinger, 1985).

Remotely sensed measurements of canopy water status could have a number of advantages over traditional measurement techniques. Regional scale human disturbance such as air pollution or climatic change associated with the greenhouse effect requires an ability to assess forest productivity at large scales. Remote sensing may be able to fulfill this requirement (Thompson and Wehmanen, 1979; Walsh, 1987; Running *et al.*, 1989). Remote sensors may be able to detect water stress conditions before the effects become visible to the human eye, at which point irreversible damage begins to occur.

Two distinct portions of the electromagnetic spectrum have been identified by researchers for detection of water stress in plants; the visible/shortwave infrared region (0.4 to 2.4μm) and the thermal infrared region (8 to 12μm). Gates *et al.* (1965), Knipling (1970), Carlson *et al.* (1971), Thomas *et al.* (1971), and Fox (1977) showed that leaves absorb highly in the red (0.6 to 7μm) and middle infrared (1.3 to 2.7μm) and related this to absorption by chloroplasts and leaf water, respectively. They also found that plants are highly reflective in the near infrared (0.7 to 1.3μm) and related this to internal cellular structure. More recent studies (Kleman, 1985; Ripple, 1986; Hunt *et al.*, 1987a; Westman and Price, 1988) have provided further evidence showing a relationship between leaf water content and a leaf spectrum.

Others have attempted to exploit the reflectance differences between different portions of the spectrum by using various indices. Tucker (1979) used indices of red to infrared reflectance and related these to various vegetation parameters. The Normalized Difference Vegetation Index ($(0.83-0.67\mu m)$ / $(0.83+0.67\mu)$, NDVI), infrared/red ratio (0.83/0.67μm, NS001 4/3), and infrared - red index (0.83−0.67μm, NS001 4-3) were all highly correlated to leaf water content ($R^2 = 0.77-0.83$). Hardisky *et al.* (1983) found that the Normalized Difference Infrared Index ($(0.83-1.65\mu m)$ / $(0.83+1.65\mu m)$, NDII) was related to leaf water content ($R^2 = 0.70$). Rock *et al.* (1986) found that band ratios of NS001 6/5 (1.65/1.23μm) and NS001 6/4 (1.65/0.83μm) were related to forest damage associated with acid rain, and proposed that this relationship is controlled by leaf moisture content and internal cellular structure.

Remotely sensed surface temperatures have also proven to be useful in assessing plant water status (Rhode and Olson, 1970; Heilman and Kanemasu, 1976; Jackson, 1982; Pierce and Congalton, 1988). These studies are based on an energy budget logic which assumes that plants respond to water stress by stomatal closure, thereby decreasing latent heat transfer from the leaf surface to the air and causing an increase in leaf surface temperature. Nemani and Running (1989), based on the logic of Goward *et al.* (1985), calculated the slope of the relationship between surface temperature and the NDVI (σ) and related this to the canopy resistance to water vapor, which is controlled by leaf water status.

Most of the studies discussed above, however, were either executed in labs or with handheld spectrometers where plants were subjected to extreme, often unrealistic, levels of stress. The objective of this study was to determine if broadband sensors representative of current satellite technology could operationally differentiate reflectances between two forest stands of similar structure but markedly different water contents. Specifically, we hypothesized that sub-optimal scene illumination, sensor look angle, atmospheric attenuation, and canopy- rather than leaf-level targets might possibly mask changes in forest reflectance due to changing leaf water content. We monitored radiance with the NS001 Thematic Mapper Simulator (NS001) and temperatures with the Thermal Infrared Multispectral Scanner (TIMS) aircraft-mounted sensors to determine which, if any, of

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 56, No. 5, May 1990, pp. 579-586

0099-1112/90/5605-579$02.25/0

TABLE 1. BANDS AND BAND INDICES TESTED AND THEIR EXPECTED TRENDS IN REFLECTANCE AS LEAF WATER CONTENT DECREASES.

NS001 band	TM band	Wavelengths(μm)	Expected Trend
1	1	0.45- 0.52	↑ (1)
2	2	0.52- 0.60	↑ (1)
3	3	0.63- 0.69	↑ (2)
4	4	0.76- 0.90	↑ (2)
5	-	1.12- 1.34	↑ (7)
6	5	1.55- 1.75	↑ (2)
7	7	2.08- 2.35	↑ (4)
8	6	10.4 -12.5	↑ (5)
NS001 index	index name		Expected Trend
4/3	NS001 4/3		↓ (6)
(4 − 3)/(4 + 3)	NDVI		↓ (6)
4 − 3	NS001 4 − 3		↓ (6)
6/5	NS001 6/5		↑ (7)
6/4	NS001 6/4		↑ (3)
(4 − 6)/(4 + 6)	NDII		↓ (8)
8/((4 − 3)/(4 + 3))	σ		↑ (9)
TIMS band		Wavelengths(μm)	Expected Trend
1		8.2- 8.6	↓ (5)
2		8.6- 9.0	↑ (5)
3		9.0- 9.4	↑ (5)
4		9.4-10.2	↑ (5)
5		10.2-11.2	↑ (5)
6		11.2-12.2	↑ (5)

(1) Fox (1977)
(2) Westman and Price (1988)
(3) Hunt *et al.* (1987b)
(4) Ripple (1986)
(5) Jackson (1982)
(6) Tucker (1979)
(7) Rock *et al.* (1986)
(8) Hardisky *et al.* (1983)
(9) Nemani and Running (1989)

the bands or band indices mentioned above (Table 1) were useful for assessing canopy water status across a forested landscape. The capability of high resolution imaging spectrometry to detect canopy water stress using the AIS-2 (Airborne Imaging Spectrometer) was also tested, and is being reported in another paper (Riggs and Running, 1990).

METHODS

STUDY SITES

Changes in canopy structure, such as wilting leaves, are typically associated with decreasing water content in broadleaved plants, leading to a change in reflectance due to leaf angle distribution rather than water content alone. Most conifers, however, do not exhibit wilting under conditions of water stress because of needle morphology, so reflectance differences may be more closely related to leaf water content and internal cellular changes. Two study sites were located within the coniferous forest biome of West Germany; the Munich study site located in the Lauterbacher-Wald approximately 4 km southwest of Seeshaupht in southwest Bayern and the Frankfurt study site located in the Stadtwald Frankfurt A.M. (the Frankfurt City Forest).

In order to minimize the potential variability in reflectance caused by abiotic effects the experimental design consisted of a designated control plot with an immediately adjacent plot in which water stress was induced using the methods of Running (1980a, 1980b). Both plots were of similar overstory and understory structure, thereby neutralizing canopy structure effects on the reflected signal. Due to the immediate proximity of the two plots to one another, each pass of the C-130 aircraft simultaneously imaged both plots, thereby removing atmospheric, look angle, and illumination differences as sources of variance in reflectances.

The Munich site consisted of two 50- by 50-m plots within a stand of Norway spruce (*Picea abies*) with 85 percent crown closure and density of 500 trees/ha, on level ground surrounded by a young reforested clearcut on one side, with roads and Norway spruce forest on the remaining sides (Figure 1). Both plots consisted of trees 30 m in height and 60 cm in diameter with a 5- to 10-cm wide ring of sapwood. One plot was designated the control and used to monitor natural fluctuations in plant water status. On 2 July, trees within the other plot were girdled with chainsaws to a depth of 10 to 13 cm, which was deep enough to completely severe the sapwood (path of water hydraulic conductance from roots to leaves) and induce water stress, yet still maintain the structural support provided by the heartwood (Table 2). Initial measurements of plant water status in the stressed plot showed that water stress had not been successfully induced in some of the girdled trees, so the cuts were deepened on 9 July. Subsequent water stress measurements indicated that all trees in the stressed plot were experiencing severe water stress.

At Frankfurt, two plots were located on level ground in a dense plantation (9000 trees/ha) of white pine (*Pinus strobis*) surrounded by stands of conifer species of various ages dissected with roads (Figure 1). The trees in each plot averaged 7 m in height and 15 to 20 cm in diameter, most of which was sapwood. Crown closure was greater than 90 percent. Again, one plot was designated the control and used to monitor natural fluctuations in leaf water status. On the other plot, the trees were completely severed at 1 m above the ground between 2

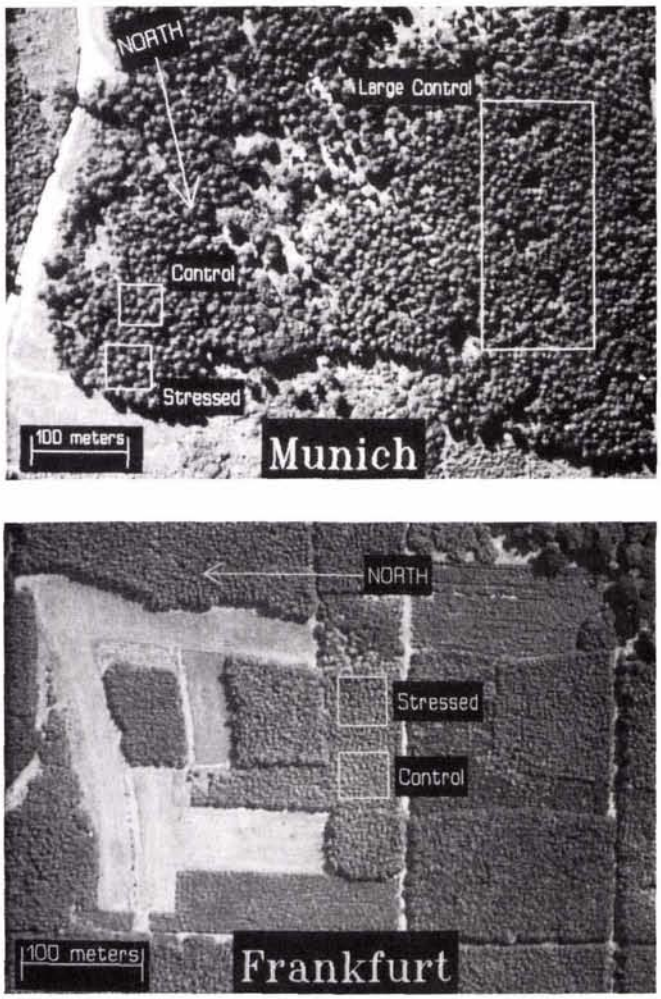

FIG. 1. Black-and-white panchromatic aerial photography showing the stressed (1), control (2), and larger control (3) plots at Munich (top) and the stressed (1) and control (2) plots at Frankfurt (bottom).

July and 7 July. The stems were dropped to the ground in a vertical position and strapped to their stumps with steel banning in order to maintain a canopy structure similar to that of the control plot.

GROUND MEASUREMENTS OF PLANT WATER STATUS

At both sites, water status of the stressed and control plots was measured using a pressure chamber (Ritchie and Hinckley, 1975) to obtain measurements of leaf water potential (Ψ_L). Briefly, a clipped branch tip approximately 10 cm in length was placed inside the pressure chamber so that the cut end of the branch protruded through a small rubber seal at the top of the chamber. The chamber was then pressurized with nitrogen gas until a droplet of water began to exude from the cut branch. The pressure within the chamber at this point is equal to the Ψ_L and is a measure of the free energy status of water within the plant (Tyree and Hammel, 1972; Turner, 1981), expressed in units of pressure (MPa).

Under non-stressed conditions, Ψ_L fluctuates on a diurnal basis (Hinckley *et al.*, 1978), and is highest during the pre-dawn hours due to water uptake from the soil with little water loss from leaves, and lowest in the afternoon due to transpiration rates exceeding the rate of water uptake (Figure 2). The control plot would be expected to follow this trend given conditions of low evaporative demand and abundant soil moisture. Ψ_L of the stressed plots did not follow this pattern because water uptake

TABLE 2. SCHEDULE OF EXPERIMENTAL EVENTS AT MUNICH AND FRANKFURT SITES.

Event	Munich	Frankfurt
Sapwood severed	2,9 July	2-7 July
Ψ_L measured	4,8,9,14,15 July	3,4,17 July
NS001 overflights	15 July	16,22 July
TIMS overflights	15 July	16 July

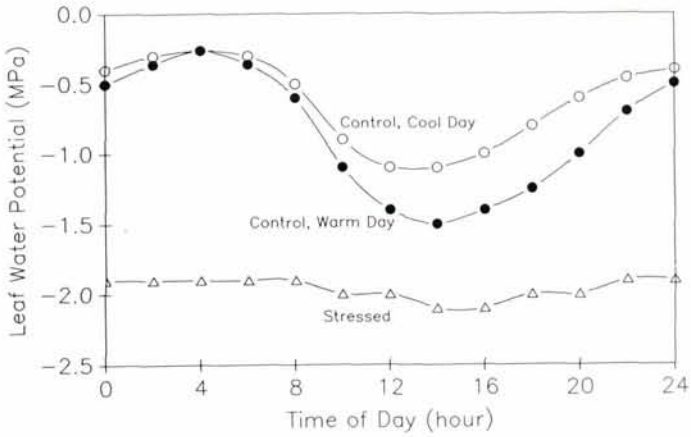

FIG. 2. Idealized diurnal cycle of leaf water potential for the stressed and control plots. The differences in Ψ_L between stressed and control plots are influenced by air temperature and humidity. See Running (1980a, 1980b) for similar field data.

from the soil was prevented. Instead, transpiration would be expected to reduce Ψ_L to approximately −2.0 MPa, at which point Ψ_L would stabilize in response to stomatal closure (Running, 1980a, 1980b).

Relative water content (RWC) is another measurement of plant water status, which may be more appropriate for comparison to reflectance (Hunt *et al.*, 1987a). RWC is a measure of leaf water content (percent) relative to the leaf water content of that species at full turgor (100 percent), and is defined as

$$\text{RWC} = ((\text{field weight} - \text{dry weight}) / (\text{turgid weight} - \text{dry weight})) * 100 \quad (1)$$

The dry weight was obtained by oven-drying the cut stem sample at 75°C for 24 hours and recording the weight. The turgid weight was obtained by soaking the cut stem sample in water for 24 hours and recording the weight.

RWC was estimated for each plot by means of a pressure-volume (P-V) relationship developed in the laboratory by measuring RWC across a range of Ψ_L. The P-V relationship can be site- as well as species-dependent. Plant samples were collected separately in both the stressed and control plots for the white pine at Frankfurt. The pressure-volume data for Norway spruce was collected at Hoglwald (B.N. Rock, unpublished data, 1986), nearby the Munich stand. Two second-order polynomial regression equations were used to predict RWC from Ψ_L measurements for each Frankfurt stressed and control plot. A third-order polynomial regression equation was fitted to the Hoglwald data and used to predict RWC from Ψ_L measurements for both the stressed and control plots at Munich (Figure 3). Both the measurements of Ψ_L and estimates of RWC were used in the analysis of spectral data because the P-V relationship for Munich was not site-specific.

REMOTE SENSING OF PLANT WATER STATUS

The NS001 and TIMS broadband sensors were used to collect reflected and emitted energy for comparison to canopy water

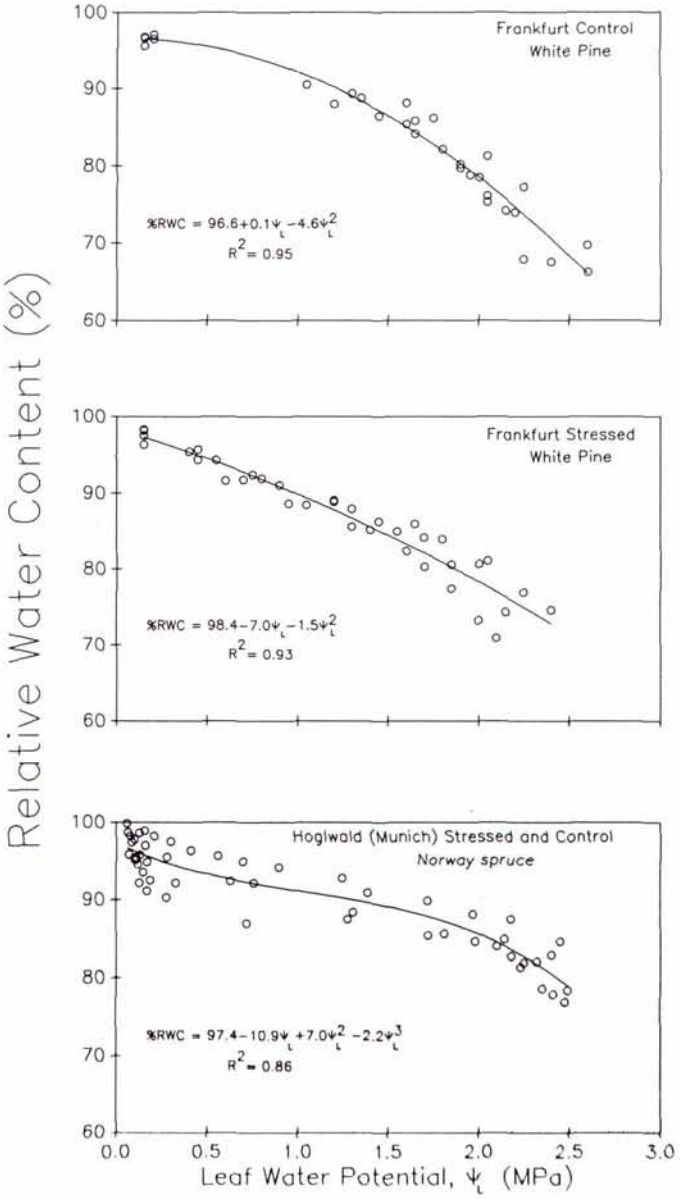

FIG. 3. Pressure-volume (*P-V*) curves for white pine control (top) and stressed (middle) plots at Frankfurt and a Norway spruce plot (bottom) at Hoglwald. Comparison of the *P-V* curves at Frankfurt indicate the relationship can be unique to site as well as species.

status. The NS001 sensor is similar in spectral resolution to the Landsat Thematic Mapper but has an added band in the 1.12- to 1.34-μm portion of the spectrum (Table 1). The TIMS records emitted energy in the thermal infrared portion of the spectrum using six adjacent channels ranging from 8.2 to 12.2μm. Both sensors are flown aboard the National Aeronautic and Space Administration (NASA) Ames Research Center U-2 or ER-2 high altitude research aircraft and have a spatial resolution at nadir 30 metres when flown at an altitude of 20,000 metres above terrain. In this study, both sensors were mounted in the NASA Ames C-130 research aircraft along with the AIS-2 and color infrared and black-and-white large format cameras. The C-130 was flown at 3000 metres above terrain (an altitude optimal for the AIS-2), providing a spatial resolution of approximately 7 metres at nadir for both the NS001 and TIMS sensors.

On 15 July 1986, six NS001 and TIMS images were recorded at Munich; three in the morning (0912, 0925, 0938 solar time) and three in the afternoon (1210, 1219, 1240 solar time). At Frankfurt, three NS001 and TIMS images were recorded on 16 July 1986 (1017, 1031, 1041 solar time) and an additional NS001 image was recorded on 22 July 1986 at 1101 solar time. Both study sites were located within 10° of nadir on all images. Due to the slow groundspeed of the C-130 relative to the sensor scan rates, both NS001 and TIMS images were overscanned. T-tests indicated that the means of the overscanned imagery were not significantly different from the means of the corrected imagery. Additionally, the overscanned imagery provided us with more degrees of freedom due to twice the number of pixels, which increased the confidence of our estimates of mean reflectance within each band.

Digital numbers of pixels within polygons denoting the stressed and control plots at each site were extracted using the ERDAS 1024 PC-based image processing system at the University of Montana. The polygon boundaries were carefully delineated to include only pixels within each plot by sampling an area slightly smaller than the actual plot boundaries, insuring a signal not contaminated by border pixels. Digital counts were converted to radiance (mW cm^{-2} μm^{-1} sr^{-1}) using published calibration values from the NASA Ames Flight Summary Reports for each NS001 flightline. Extremely variable calibration values for NS001 band 7 during all overflights precluded its use in this study. For the NS001 thermal and TIMS bands, digital counts were converted to emitted temperature using the low- and high-temperature blackbody count-to-temperature conversion located in the housekeeping information at the beginning of each scanline. Because of the adjacency of the stressed plot to the control, no atmospheric correction was applied to the radiance or temperature values. Arithmetic means and variances were calculated for each band and band index for both stressed and control plots and compared by an analysis of variance.

RESULTS AND DISCUSSION

GROUND WATER STATUS MEASUREMENTS

As expected, the severed trees at both sites became water stressed to approximately −2 MPa (Table 3), typically the maximum naturally occurring level of water stress found in coniferous forests (Hinckley *et al.*, 1978). At Munich, numerous precipitation events from the time the trees were girdled to the day prior to overflight provided abundant moisture for the control plot, which remained at high Ψ_L. The level of stress in the girdled trees developed rapidly so that a very large difference in Ψ_L (1.2 MPa) existed between the stressed and control plots at the time of the morning overflights. This difference was somewhat reduced in the afternoon due to transpirational demands placed on the control plot. Similar, but smaller than expected, differences also occurred in RWC during the morning (7 percent) and afternoon (4 percent), as estimated from the Hoglwald Norway spruce data.

At Frankfurt, the stressed plot also developed severe water stress to a level similar to that found at Munich (Table 3). However, the control plot was under a greater degree of water stress than the Munich control, probably due to a combination of transpirational demands, reduced soil moisture, and plot density. Precipitation did not supply the Frankfurt site with abundant soil moisture prior to the overflights. Differences in Ψ_L of only 0.27 MPa and RWC of 6 percent were recorded on 17 July at 1030 solar time, the same time as the overflights on the previous day. No measurements of Ψ_L were gathered for the 22 July flight as it was unplanned but graciously collected by the C-130 crew enroute to another study site. However, meteorological records indicate that no significant precipitation fell on the Frankfurt site between 16 and 22 July so that the difference in RWC between stressed and control plots on 22 July was probably similar to that found on 17 July.

TABLE 3. LEAF WATER POTENTIAL MEASUREMENTS TAKEN AFTER CUTTING OF SAPWOOD FOR SEVERED AND CONTROL PLOTS AT MUNICH AND FRANKFURT. VALUES SHOWN ARE THE AVERAGE OF FIVE TO SEVEN MEASUREMENTS WITH THE 1 STANDARD DEVIATION FROM THE MEAN IN PARENTHESES.

Site: Munich spruce	Species: Norway							
			mean Ψ_L (MPa)			estimated RWC (%)		
Date	Solar Time	Days after cutting	stressed(SD)	control(SD)	diff.	stressed	control	diff.
4 July	1200	2	−1.27(0.08)	−0.99(0.15)	0.28	90	91	1
8 July	1400	6	−1.13(0.19)	−0.45(0.05)	0.68	91	94	3
9 July	1400	7	−2.18(0.17)	−1.66(0.38)	0.52	84	89	5
14 July	0900	12	−2.30(0.13)	−0.82(0.13)	1.48	83	92	9
	1200		−1.88(0.23)	−1.19(0.17)	0.69	87	91	4
15 July	0900	13	−2.10(0.29)	−0.91(0.14)	1.19	85	92	7
	1200		−2.04(0.22)	−1.32(0.21)	0.72	86	90	4
Site: Frankfurt	Species: white pine							
3 July	0930	2	−1.82(0.04)	−1.53(0.06)	0.29	81	86	5
4 July	0730	3	−1.82(0.08)	−1.20(0.13)	0.62	81	90	9
17 July	0900	15	−1.95(0.14)	−1.33(0.10)	0.62	79	89	10
	1030		−1.80(0.08)	−1.53(0.18)	0.27	81	86	5
	1230		−1.87(0.11)	−1.47(0.05)	0.40	80	87	7

REMOTELY SENSED MEASUREMENTS

Radiance and temperature differences between stressed and control plots (as a proportion of the average difference between the pooled standard deviations) were calculated for bands and band indices for all overflights at Munich (Figure 4) and Frankfurt (Figure 5). The relative difference (RD) in radiance between stressed and control plots was calculated according to

$$\mathrm{RD} = (S_m - C_m) / (((S_{max} - S_{min}) + (C_{max} - C_{min})) / 2) \quad (2)$$

where S_m and C_m are stressed and control plot mean radiance, respectively. S_{max} and C_{max} are plus 2 standard deviations from the mean and S_{min} and C_{min} are minus 2 standard deviations from the mean reflectance for stressed and control plots, respectively. The relative difference was calculated so that we could approximate the lines of significance in Figures 4 and 5.

At Munich, NS001 bands 2, 3, and 6 displayed significant reflectance differences ($p = 0.01$) between stressed and control plots for the 0912 and 0925 flights. NS001 bands 4 and 5 were significant at a level of $p = 0.05$ for these same two flights. For the 0938 flight, bands 2,4, and 5 showed significant differences ($p = 0.05$). For the afternoon flights, only band 3 significantly tracked expected trends in reflectance of the stressed plot for the 1210 ($p = 0.01$) and 1240 ($p = 0.05$) flights.

Indices comprised of NS001 bands 4 and 6 (TM 4 and 5) were useful in properly distinguishing between stressed and control plots, significant ($p = 0.05$) for the 0912 and 0925 morning flights. No indices were significant for the 0938 flight, while large Ψ_L differences still existed between stressed and control plots. For the afternoon flights, the NS001 4/3 ratio and NDVI appeared to show significantly decreased values in the stressed plot during the 1210 ($p = 0.01$) and 1219 ($p = 0.05$) flights. This occurred because NS001 band 4 reflectance shifted downward slightly in the stressed plot while NS001 band 3 reflectance increased, causing artificial decreases in these indices. Bands 3 and 4 should both increase in reflectance within the stressed plot under moderate water stress, although band 3 reflectance increased a greater amount relative to band 4, thereby driving the NS001 4/3 ratio and NDVI downward (Table 1).

It is possible under severe water stress that changes in the internal cellular structure of leaf would cause band 4 reflectance to decrease, driving down the NS001 4/3 ratio and the NDVI (Rock *et al.*, 1986; Westman and Price, 1988). Westman and Price (1988) found that these changes in cellular structure took place only upon removal of free water. Running (1980a) showed that conifer needles maintained high amounts of free water 30 days and more after the sapwood was severed at ground level by recharging from water stored in the bole sapwood. Based on this finding, we would have to conclude that the water stress at Munich and Frankfurt was probably not severe enough to cause changes in internal leaf structure, so that band 4 reflectance should always be greater in the stressed plot.

For the 1240 flight, the NS001 6/5 ratio increased and was significant at a level of $p = 0.05$, but not for the expected reasons because NS001 bands 5 and 6 decreased in reflectance in the stressed plot, band 5 decreasing more relative to band 6. Reflectance of bands 5 and 6 should increase within the stressed plot, band 6 increasing more relative to band 5, causing the NS001 6/5 ratio to increase (Table 1).

The TIMS bands mimicked NS001 band 8 for all flights at Munich, showing that the stressed plot was significantly ($p = 0.05$) warmer during the 0912 and 0925 flights, but significantly ($p = 0.01$) cooler for the 0938 morning flight and all afternoon flights. Cooling of needle surfaces due to a greater degree of wind exposure at the stressed plot (located on the edge of the Norway spruce stand) could cause this plot to become cooler than the more interior control, although this is only speculation. Unfortunately, without extensive micrometeorological data, there is no way for us to further analyze these curious results.

At Frankfurt, the NS001 bands which showed significant reflectance differences between the stressed and control plots (4, 5, and 6 at 1017 on 16 July 4 and 5 on 22 July) all moved opposite to expected trends, reflectance decreasing within the stressed plot (Table 1). The contrary reflectance shifts caused indices containing NS001 band 4 to artificially follow expected trends in the stressed plot for the 1017 flight on 16 July. NS001 indices comprised of band 6 also artificially followed expected trends and showed significant ($p = 0.05$) reflectance differences at 1031 but not at 1017 or 1041 on the 16 July overflights, because reflectance of NS001 bands 4 and 5 decreased, while band 6 reflectance increased within the stressed plot (Table 1).

All NS001 indices for the 22 July flight followed expected trends and showed strong differences in reflectance at a level of significance of $p = 0.01$. However, this is an artifact of reflectances of NS001 bands 3 and 6 remaining similar between stressed and control plots, while reflectances of NS001 band 4 and 5 within the stressed plot were significantly ($p = 0.05$) lower, opposite to expected trends (Table 1). The contrary reflectance shifts of NS001 bands 4 and 5 caused indices comprised of NS001 band 3 and 4 to decrease, the NS001 6/5 and 6/4 ratios to increase, and the NDVI to decrease artificially, suggesting that something other than leaf moisture was dominating reflectance patterns.

For the TIMS flights over Frankfurt, only bands 3 and 5 showed that the stressed plot was significantly ($p = 0.05$) warmer than

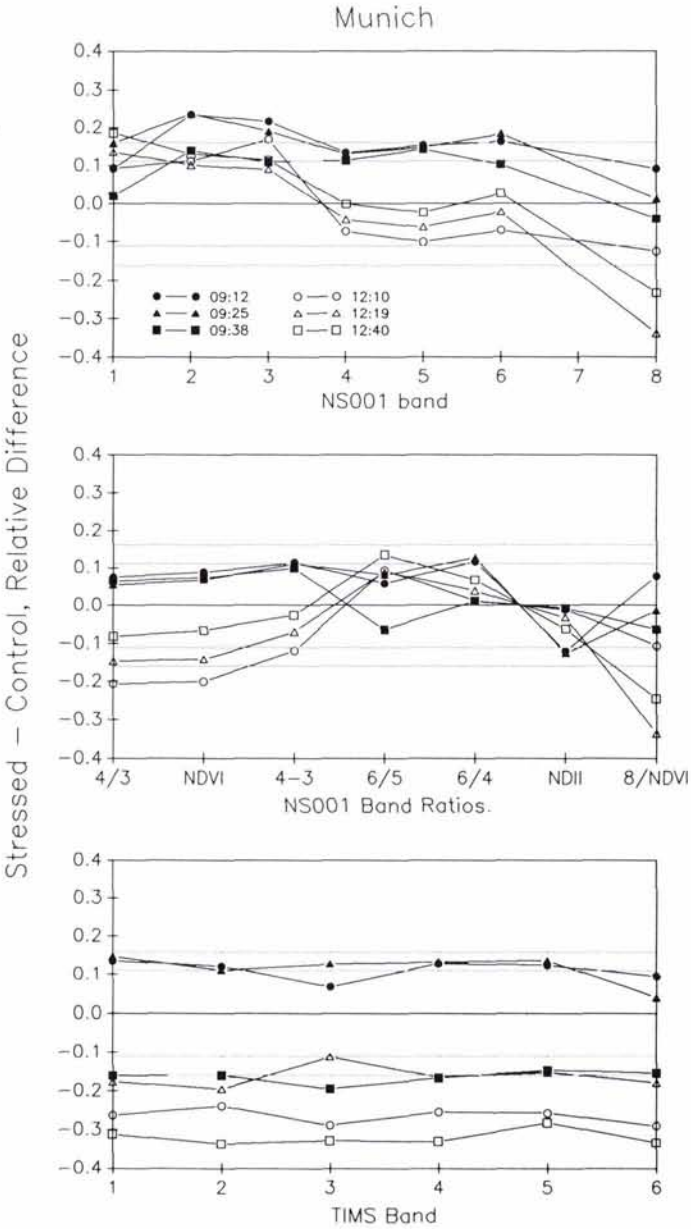

FIG. 4. Relative difference in reflectance between stressed and control plots for all overflights at Munich as a proportion of the pooled standard deviations for NS001 bands 1 through 6 and 8, NS001 band indices, and TIMS bands 1 through 6. Levels of significance are represented by the dotted lines at 0.11 and −0.11 (p = 0.05) and 0.16 and −0.16 (p = 0.01).

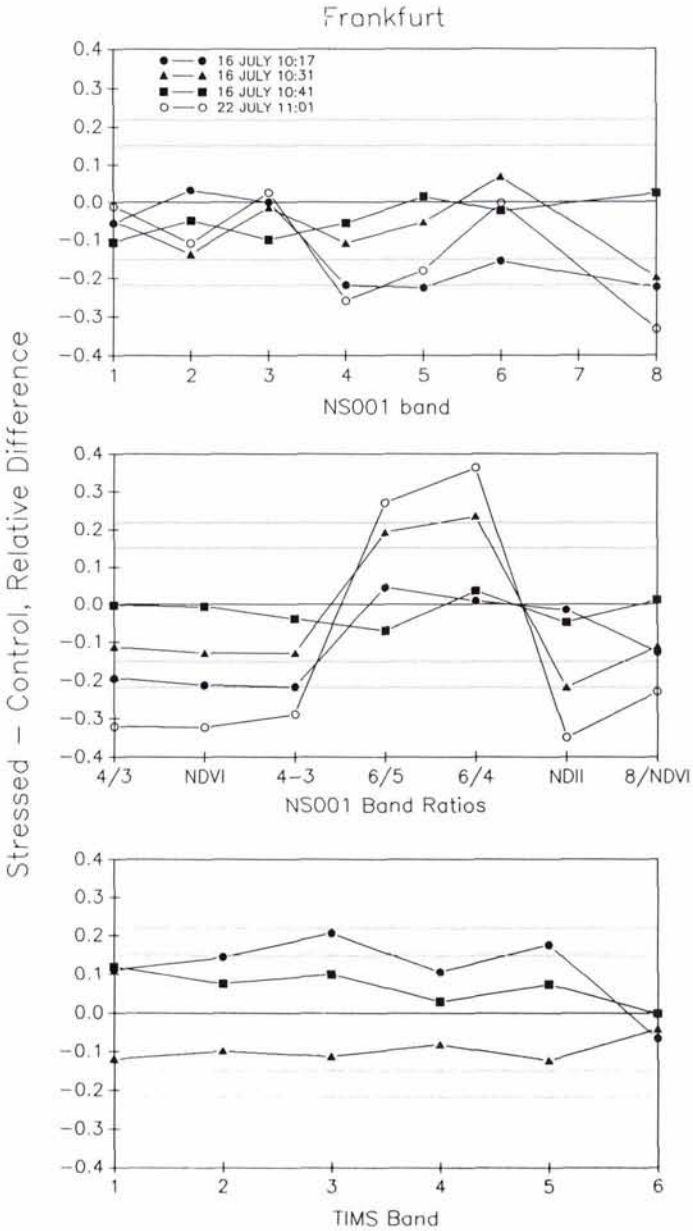

FIG. 5. Relative difference in reflectance between stressed and control plots for all overflights at Frankfurt as a proportion of the pooled standard deviations for NS001 bands 1 through 6 and 8, NS001 band indices, and TIMS bands 1 through 6. Levels of significance are represented by the dotted lines at 0.15 and −0.15 (p = 0.05) and 0.21 and −0.21 (p = 0.01).

the control during the 1017 flight. Conversely, the stressed plot was significantly cooler (p = 0.05) than the control for NS001 thermal band 8 data during the 1017 flight. None of the other TIMS bands or flights were significant. The TIMS was not flown at Frankfurt on 22 July. The lack of consistent results between the thermal bands at Frankfurt would indicate that the slight, if any, temperature differences occurring between the cut and control plots could not be detected by the TIMS or NS001 sensors.

The bands and band indices for the NS001 and TIMS sensors tested in this study are only sensitive to the largest differences in plant water status of Norway spruce which occurred during the morning overflights at Munich (Table 3). Specifically, NS001 bands 2 through 6 and indices comparing NS001 bands 4 and 6 were useful in detecting water stress during the morning flights. Images from the afternoon flights at Munich were not useful in detecting the only slightly smaller differences in Ψ_L (0.72) or RWC (4 percent) of Norway spruce occurring between the stressed and control plots at that time (Table 3). These data corroborate the study by Olson (1987), who also found that the NS001 sensor could not detect differences in Ψ_L of 0.9 MPa between stressed and control plots of red pine (*Pinus resinosa*). The NS001 bands and band indices were also not sensitive enough to detect the small differences in Ψ_L or RWC between the stressed and control plots of white pine at Frankfurt (Table 3). The σ index was not useful for detecting water status at this small scale as the calculation of σ requires a larger range in NDVI to accurately define the slope of the NDVI-to-temperature relationship.

Prior knowledge of plot locations allowed us to extract our

polygon statistics in such a way as to maximize any differences in radiance between the stressed and control plots. This process allowed creation of special enhancements that highlight the stressed plot at Munich, even though the stressed plot was not evident in the unenhanced image (Figure 6). In practice, we would not have prior knowledge about the location of stressed plots, so that even larger differences in Ψ_L would be necessary before water stress could be delineated operationally using special enhancements (Figure 7). Rohde and Olson (1970) had parallel results, suggesting that stressed plots could not be delineated on thermal imagery without prior knowledge of location. Figure 7 attempts to show that, within the same Norway spruce stand at Munich, the stressed plot could not be visually separated from the larger control stand on an operational basis. The enormous range of NS001 band 6 reflectance values within the larger control stand conceal the slight increase in reflectance (<2 digital numbers) from the stressed stand.

Change detection techniques may be more appropriate for detection of water stress given a lack of prior knowledge about stressed plot locations. However, the large changes in Ψ_L or RWC mentioned above must still occur before change detection can become an appropriate method for detecting water stress. Attempts to remotely assess water status using change detection techniques within this small scale study were unsuccessful because registration inaccuracies of 1.5 pixels overshadowed any reflectance differences caused by water content changes in the stressed plots. Inherent registration inaccuracies of this magnitude are common and lead to inclusion of some border pixels when calculating the stressed stand mean reflectance, causing reflectance changes which cannot be attributed to water status alone. Therefore, change detection techniques can only be applied to larger scale studies.

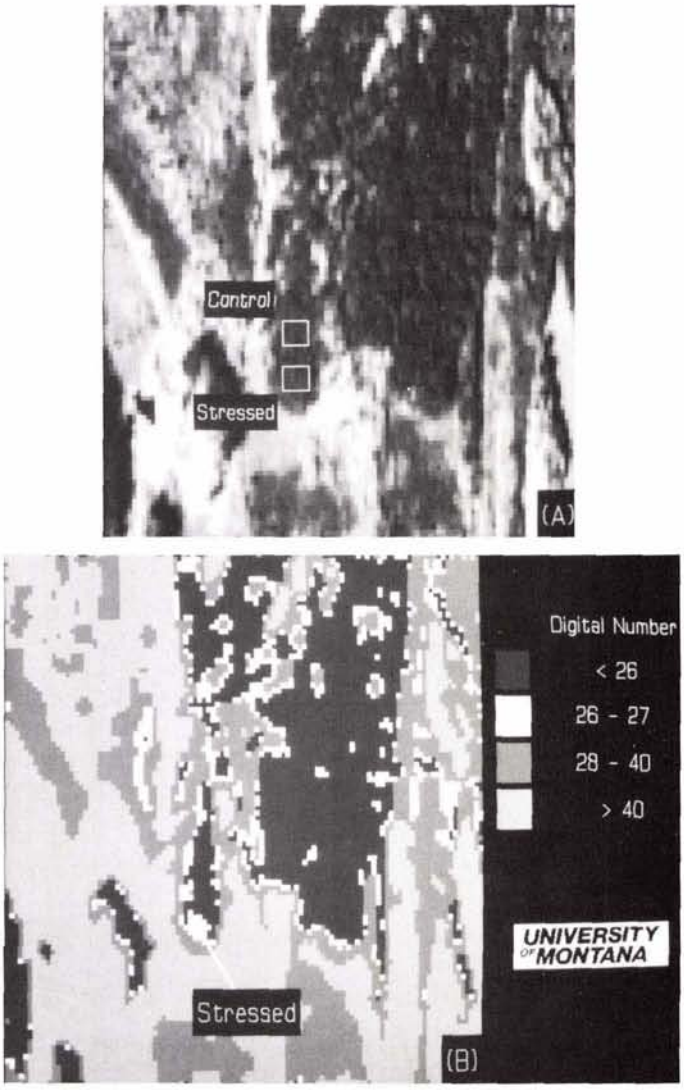

FIG. 6. Images of histogram equalized NS001 band 6 (A) and histogram equalized, smoothed (3 by 3 low pass filter), and enhanced NS001 band 6 (B) of the Munich site during the 0925 overflight. Special enhancements based on statistics developed from prior knowledge of stressed plot location can successfully delineate the stressed plot in image (B) as compared with image (A).

CONCLUSIONS

This experiment tested the NS001 TMS and TIMS sensors across a near-complete range of normal, reversible physiological water stress in trees (Hinckley *et al.*, 1978). Given that we achieved conditions optimal for detection of water stress, we were able to utilize the NS001 and TIMS sensors to detect extreme differences in canopy water content. Specifically, NS001 bands 2 through 6, NS001 indices combining bands 4 and 6, and NS001 and TIMS thermal bands were useful in detecting the maximum, naturally occurring differences in canopy water status between the stressed and control plots during the morning overflights at Munich, when environmental conditions for detection were ideal. Slightly smaller differences in canopy water status (yet significant in terms of growth reduction) could not be discriminated on imagery from these same broadband sensors at Munich in the afternoon, or at Frankfurt. Riggs and Running (1989) also had similarly confounding results at even higher spectral resolutions in attempting to remotely determine canopy water status differences at the Munich and Frankfurt sites using the AIS-2. These inconsistent results obtained using low-altitude aircraft imagery force us to conclude that trends of reversible canopy water status in forest trees cannot be operationally detected using current satellite technology.

It is possible that a forest subjected to exceptional stress conditions brought about by acute disturbance may develop Ψ_L of -3.0 to -4.0 MPa, corresponding to an RWC of <60 percent. Stress conditions of this magnitude can probably be sensed re-

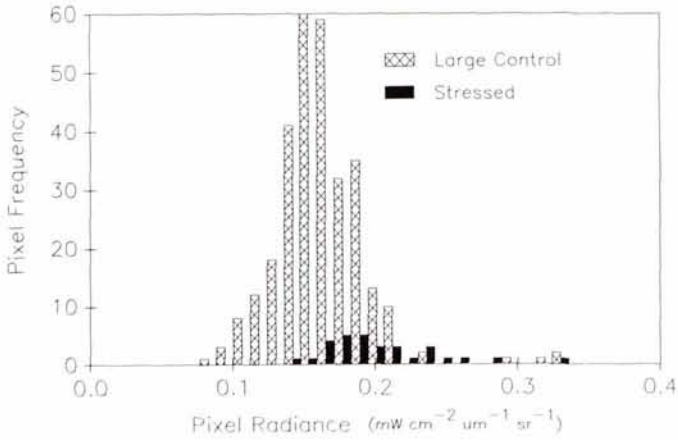

FIG. 7. A comparison of band 6 pixel frequency distributions between a larger control plot representative of the whole stand at Munich and the stressed plot at Munich during the 0925 overflight, for which large and significant differences ($p = 0.01$) occurred between the stressed and control plots. Without prior knowledge of the stressed plot location, the statistics representing the spectral response of the stressed plot would be difficult to generate. Hence, we conclude that the stressed plot could not be detected operationally.

motely. However, these extreme conditions are almost always irreversible, and forest trees are visibly dead within a short time. Other vegetation types, such as desert or chaparral shrubs, can endure reversible water stress to <60 percent RWC which may be remotely sensed using broadband spectrometers (Hunt and Rock, 1990). Across forested landscapes, however, longer term changes in canopy structure associated with chronic water stress, such as changes in internal leaf structure or reductions in canopy leaf area, are more appropriate for application of remote sensing to the detection of stress.

ACKNOWLEDGMENTS

We wish to thank Dr. Barry Rock, Dr. Manfred Schramm, Martin Lamberty, Dr. Barbara Koch, Dr. George Kritikos, and their associated forestry crews for all their hospitality and help in Germany as well as the 1986 NASA-Acems C-130 European Expedition for collecting imagery of our study sites. We also wish to thank Dr. E. Raymond Hunt, Jr. for his helpful discussions and review of this manuscript as well as his development of the *P-V* relationship for the Hoglwald data. Funding was provided by the National Aeronautics and Space Administration (NASA) Graduate Student Researchers Program, NASA Grant No. NAGW-829, and NASA-Ames Research Center Joint Research Interchange No. NCA2-252.

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(Received 5 July 1989; accepted 5 October 1989; revised 14 December 1989)