Indications of Relative Drought Stress in Longleaf Pine from Thematic Mapper Data

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Abstract

Multitemporal Thematic Mapper data indicated that the ratios of reflectances of band 5 to band 4 increased as longleaf pine were subjected to a prolonged drought that began in the fall of 1989 and continued through the fall of 1990. Mean ratios increased from 0.42 preceding the drought to 0.55 during the drought, but the amount of the increase varied from 0.05 to 0.25 among forest stands. Ratios returned to predrought levels once the drought was broken. Tree ring widths in 1990 were significantly smaller than were those for years of average rainfall before the drought, and residual drought stress effects contributed to smaller ring widths in subsequent years. The degree of reduction in ring widths was correlated to the degree of increase in the ratio of band 5 to band 4. The greatest size reductions in ring widths occurred in those stands with the greatest increase in band ratios.

Introduction

The Landsat Thematic Mapper (hereafter, TM) sensor has the potential capacity to measure the water content of vegetation using the relative reflectances of bands 4 and 5 (Tucker, 1980; Mika, 1997). This potential capacity is based on the observations that decreases in leaf water content increase reflectances in the middle infrared spectra while having little effect on reflectances in the near infrared spectra (Gates, 1980; Jensen, 1983; Carter, 1991; Cibula *et al.*, 1992; Aldakheel and Danson, 1997). However, measurement of vegetation water content using these bands is complicated by other factors which affect the reflectances. This is especially the case for forested areas where the reflectances for bands 4 and 5 are also affected by the influences of species composition, forest age, tree density, and tree sizes on canopy structure and leaf abundance (Horler and Ahern, 1986; Leprieur *et al.*, 1988; Ripple *et al.*, 1991; Ekstrand, 1994; Boyd *et al.*, 1996; Jakubauskas, 1996; Steininger, 1996). In particular, the ratios of bands 4 and 5 can be affected by forest growth rates (Cook *et al.*, 1989) and forest ages (Fiorella and Ripple, 1993).

Using these bands to assess canopy water content is further complicated because relatively large reductions in the water content of vegetation may have relatively little effect on reflectances within the range of band 5. Carter (1991) observed that a 50 percent reduction in the water content of pine needles resulted in only a 10 percent increase in middle infrared reflectances. Hunt and Rock (1989) suggested that the minimum detectable change in water content would be greater than the normal range of water content in living leaves. Riggs and Running (1991) observed little difference in reflectances between water stressed and control individuals of white pine (*Pinus strobus*) and suggested that airborne scanners would also have little ability to detect moisture stress in conifers.

Despite the potential problems in applying the relative reflectances in bands 4 and 5 to the detection of water content, Hunt *et al.* (1987) were able to measure changes in leaf water content in individual *Agave deserti* plants using a hand held radiometer that simulated Thematic Mapper data. Their procedure had the advantage of making repeated measurements on the same plants during periods of drought and comparing those measurements to data obtained before the drought when the plants were at full water contents. As long as there was little change in leaf morphologies and leaf abundances, Hunt *et al.* (1987) observed that leaf water contents could be easily assessed. Cibula *et al.* (1992) were also able to relate changes in band 5 reflectance to changes in foliage water content in agricultural plots using a repeated-measures design.

The purpose of the current study was to evaluate a similar repeated-measures procedure using Thematic Mapper data collected from longleaf pine (*Pinus palustris*) plantations before, during, and after a period of intense drought. Spatial variation in changes in canopy reflectances during the drought were assessed for their ability to measure spatial variation in growth reductions related to local variations in rainfall amounts, soil types, tree densities, and tree sizes.

The Study Location, the Species, and the Drought

The study was performed on the U.S. Department of Energy's Savannah River Site (hereafter, SRS) located 35 km southeast of Augusta, Georgia in Aiken, Allendale, and Barnwell Counties in South Carolina (see Cowen *et al.* (1995) for detailed descriptions of the SRS). The SRS was established in 1951, and the United States Forest Service's Savannah River Natural Resource Management and Research Institute (hereafter, USFS) began planting the formerly agricultural area to even-aged pine plantations in 1952 (Langely and Marter, 1973). Much of the > 80,000-ha site has been planted in longleaf pine which occurs throughout the Coastal Plain Region from east Texas to southeastern Virginia on soils that range from mesic flatwoods on the Lower Coastal Plain to the xeric Sandhills soils of the Upper Coastal Plain (Wahlenberg, 1946; Fowells, 1965). On the SRS, longleaf pines occur on relatively xeric soils of the Blanton, Fuquay, Lakeland, and Troup series. These soils occur on relatively flat (i.e., slopes ≤ 6 percent) ridge tops and have upper horizons of ≥ 0.55 m that (1) are composed of sand with ≤ 10 percent clay, (2) have water permeability rates ≥ 0.15 m h^{-1}, and (3) are rated from fair to poor for use in conifer forestry (Rogers, 1990). The moisture content of these soils is dependent upon frequent rainfall events. Although the soils are similar, longleaf pine growth is usually slower on the Lakeland soils (Rogers, 1990).

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Precipitation in the area of Augusta and the SRS, which occurs almost entirely as rain, averages approximately 1.1 m per year but can vary among years (Figure 1). Periods of drought may occur either in the growing season for longleaf pine, which extends from April through September, or during the winter period from October through March when pines are less active (Wahlenberg, 1946; Zahner and Grier, 1990). The most severe recent drought began in the winter of 1989 to 1990 and continued throughout the summer months of 1990. This was one of the worst droughts since planting of pines began on the SRS and was especially severe for two reasons. First, the drought began in the winter and continued through the summer. Most other drought periods were restricted to either summer or winter months (Figure 1). Second, infrequent rainfall in the months of April, May, and June was exacerbated by periods of high temperatures in the middle summer (Figure 2). By early July, the rainfall deficit was > 0.20 m, and > 95 percent of South Carolina had deficient levels of soil moisture (NOAA, 1990). Rainfall events in July and August brought temporary recharges of soil moisture but did little to alleviate the long-term precipitation deficit (NOAA, 1990). Moreover, these rainfalls were associated with local, convective storms, and precipitation amounts varied with some areas receiving relatively little rainfall. By the end of the growing season, rainfall deficits were > 0.30 m, and > 80 percent of South Carolina had deficient soil moisture levels (NOAA, 1990). The drought was finally broken in October, 1990 when rainfalls of > 0.30 m occurred in association with tropical systems Klaus and Marco. This rainfall contributed to 1991 being an exceptionally wet year (Figure 1). Rainfalls in 1992 and 1994 were within 0.1 m of the annual mean and had no extensive drought periods during the growing season (NOAA, 1992; NOAA, 1994). Total rainfall in 1993 was also within 0.1 m of the mean, but the winter was wet and the summer ended in an extreme drought with rainfall deficits > 0.30 m (NOAA, 1993).

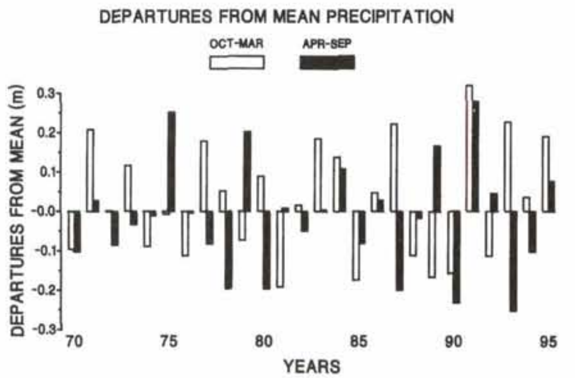

Figure 1. Recent rainfall history for Augusta (compiled from NOAA records). Data are departures from normal precipitation for the growing season of April through September and the period from October through March when pines are less active. Mean precipitation for the growing season is 0.58 m. Mean precipitation for the October to March interval is 0.53 m. Note that the driest year occurred for the period from October 1989 through September 1990 and the wettest year occurred during the period from October 1990 through September 1991.

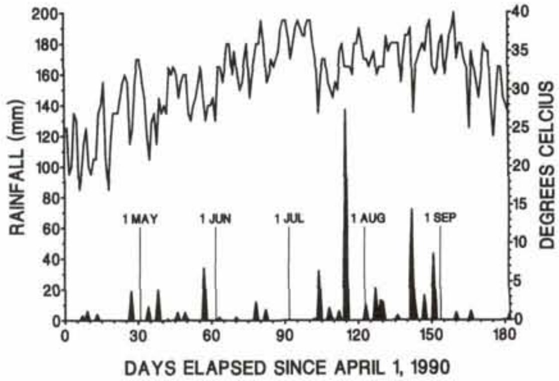

Figure 2. Maximum daily temperatures and daily rainfalls on the Savannah River Site during the growing season of 1990. Precipitation data are means compiled from eight weather stations distributed across the Savannah River Site, and small rainfall amounts likely reflect localized precipitation events due to convective storms.

Research Methods

The study methodology was composed of three steps. The first step was the analysis of TM data to determine if changes in the reflectances of bands 4 and 5 for longleaf pine in 1990 indicated the presence of drought stress. Drought stress would be indicated by increased reflectances in band 5 and increased band 5 to band 4 ratios. The second step was the analysis of tree ring patterns to determine if the drought had a measurable effect on longleaf tree ring growth rates. Drought stress would be indicated by reduced ring widths in the year of the drought and possible reductions in subsequent years. The third step was the spatial comparison of drought stress indicators and growth reductions to determine if the degree of stress indicated in the TM data was correlated with the degree of stress indicated by reduced growth rates. If either of the first two steps had indicated no measurable drought stress, then proceeding with the third step would not have been warranted.

Thematic Mapper Data

The TM data were obtained from (1) 11 November 1989, after six months of relatively large rainfall (Figure 1); (2) 07 June 1990, at the beginning of the summer; (3) 09 July 1990, after a period of high temperatures (Figure 2); (4) 27 September 1990, after rainfall events in August; and (5) 14 November 1990, after the heavy October rains. The TM data were obtained with nearest-neighbor resampling. Data were corrected for haze effects using the modified dark-body method of Chavez (1988), rectified to UTM coordinates and 30-m pixels using Global Positioning System (hereafter, GPS) coordinates (Cook and Pinder, 1996), and converted to reflectances (Markham and Barker, 1985) using radiometric parameters listed in the associated header files. Because the longleaf plantations were established on relatively flat terrain, no corrections were made for sun incidence angle. Additional TM data were obtained from 19 December 1991 and 20 June 1992 to measure seasonal changes in reflectances during a year of normal precipitation.

The USFS GIS databases of forest management units and soil types were used to develop sampling units composed of polygons of uniform soil type and forest management history. These sampling units were restricted to Blanton, Fuquay, Lakeland, and Troup soil types and to regions where forest management practices such as thinning and burning had not occurred in the 5 years immediately preceding or following the drought. The polygons were converted to raster data, buffered to remove edge effects, and sieved to remove areas ≤ 9 ha. Sampling units affected by cloud and shadow effects in the July images were also deleted. Sampling units were visited to insure (1) that suitably dense stands of longleaf pine were present and (2) that the units were free of major disturbance. Once the sampling units had been selected, statistical analyses of variation among units were performed on a randomly selected sample of non-neighboring pixels.

Sampling Plots

The initial plan of the study envisioned (1) relative uniform measures of drought stress within sampling units and (2) measurements of tree growth effects being obtained from pines sampled along transects across the sampling units. However, preliminary analyses of TM data indicated considerable spatial heterogeneity in drought stress indicators within some sampling units. Therefore, the relationships between drought stress indicators and tree growth were measured using smaller sampling plots within each sampling unit. Sampling plots were 50 m by 100 m. They were positioned by (1) using post-processed pseudoranging GPS data (Wolf and Brinker, 1994) to determine a location on the edge of the unit where satellite reception was not blocked by dense foliage, (2) proceeding ≥ 60 m along a measured compass heading toward the center of the unit to locate the first corner of the plot, and (3) laying out the sample plot with a compass and a measuring wheel. The accuracy of the GPS locations was within 10 m (Cook and Pinder, 1996). Most plots were oriented with the long axis running east and west, but plots were sometimes oriented north and south to accommodate the dimensions of the sampling units. The UTM corner coordinates of the sampling plots were extrapolated from the GPS position at the margin of the sampling unit using the compass bearings and distances used to establish the plots. These coordinates were used to determine the pixels that corresponded to the area encompassed in the sampling plot.

Ten trees were randomly selected from the plot for measurements of height and basal area and the extraction of increment cores in 1996. Height was measured to the nearest 1 m using a clinometer. Basal area was computed to the nearest 0.001 m^2 from measurements of bole diameter at breast height using tapes. Densities of canopy pines in the plots were determined by counting the number of pines whose crowns were in the forest canopy in two 5-m wide by 40-m long belt transects across the narrow axis of the plot. Increment cores were extracted using a 5.15-mm diameter increment borer, air-dried, glued onto wooden blocks, and sanded to clearly expose the ring structure (Phipps, 1985). Ring widths for the years 1983 through 1994 were measured to the nearest 0.01 mm using a Hensen University Increment Measuring Machine with an attached dissecting microscope. Although cores were obtained from all ten trees, problems with core breakage in some sampling units and the statistical constraint for similar numbers of cores from sampling units (Khattree and Naik, 1995) resulted in only the five most intact cores from each plot being analyzed for growth patterns.

Results

Field and TM data were obtained for 30 sampling units. The number of sampling units for Blanton, Fuquay, Lakeland, and Troup soils was 15, 7, 3, and 5, respectively. Although tree sizes showed relatively little variation within the even-age plantations, the densities and sizes of trees showed considerable variability among sampling units due to variations in the ages and management histories of the plantations (Table 1). Tree densities ranged from 1.1 to 9.7 per 100 m^2, but there was no statistically significant difference among soil types (One-Way Analysis of Variance; $P > 0.05$; $df = 3, 26$; SAS Institute, 1989). Tree heights varied significantly among soil types ($F = 7.19$; $df = 3, 26$; $P < 0.01$) and among sampling units within soil types ($F = 4.48$; $df = 26, 269$; $P < 0.01$). Similar, statistically significant differences in basal area were also observed among soil types and among sampling units. Trees of shorter stature and smaller basal areas occurred on Lakeland soils, but this difference was more related to the age of the plantations than to the effects of soil type on tree growth rates.

Thematic Mapper Data

Reflectances for bands 4 and 5 showed different temporal patterns (Table 2). There was little change in the reflectances for band 4 throughout the year, whereas the reflectances for band 5 were greater in the months of June, July, and September. Repeated-measures analysis of variance (hereafter, RM-ANOVA; Milliken and Johnson, 1984; Khattree and Naik, 1995) on the data from randomly selected pixels indicated (1) significant differences in reflectances among soil types ($F = 7.46$; $df = 3, 26$; $P < 0.01$); (2) significant differences among sampling units within soil types ($F = 8.28$; $df = 26, 756$; $P < 0.01$); and (3) significant differences among times ($F = 16.92$; $df = 1, 26$; $P < 0.01$; note that the *df*s for time comparisons have been adjusted using Box's Conservative Correction to account for the lack of compound symmetrical error matrices; Milliken and Johnson, 1984). Comparisons of means indicated significantly increased reflectances in band 5 for June ($F = 195.2$; $df = 1, 26$; $P < 0.01$), July ($F = 233.0$; $df = 1, 26$, $P < 0.01$), and September ($F = 372.6$; $df = 1, 26$; $P < 0.01$). Reflectance data for band 4 also showed significant variation among sampling units ($F = 27.8$; $df = 26, 756$; $P < 0.01$) but no significant variation among soil types.

The greater reflectances for band 5 for June, July, and September resulted in greater ratios of band 5 to band 4 (Figure 3). The RM-ANOVA on band ratios indicated that the ratios for June ($F = 48.6$; $df = 1, 26$; $P < 0.01$), July ($F = 126.4$; $df = 1, 26$; $P < 0.01$), and September ($F = 146.9$; $df = 1, 26$; $P < 0.01$) were greater than those for November 1989 but that the ratio for November 1990 was not significantly different from that for November 1989 ($F = 0.01$; $df = 1, 26$; $P > 0.05$). Thus, ratios increased during the

TABLE 1. VARIATIONS IN FOREST STRUCTURE AMONG SAMPLING UNITS EXPRESSED AS THE MEAN DENSITY OF PINE TREES (EXPRESSED AS THE NUMBER OF TREES PER 100 M^2), MEAN TREE HEIGHTS (m), AND MEAN TREE BASAL AREA (m^2) FOR THE 30 SAMPLING PLOTS.

Variable	Mean of all Sampling Units	Range among Sampling Units	
		Minimum	Maximum
Density	4.5	1.1	9.7
Height	21.8	16.3	26.7
Basal Area	0.483	0.213	0.780

TABLE 2. MEAN (± STANDARD DEVIATION) REFLECTANCES FOR THEMATIC MAPPER BANDS 4 AND 5 FROM LONGLEAF PINE PLANTATIONS. DATA ARE MEANS OF 786 RANDOMLY SELECTED PIXELS FROM 30 SAMPLING UNITS THAT REPRESENTED POLYGONS OF UNIFORM SOIL TYPE AND FOREST MANAGEMENT.

Date	Band 4	Band 5
11 Nov 1989	0.18 ± 0.02	0.074 ± 0.016
07 Jun 1990	0.18 ± 0.02	0.097 ± 0.014
09 Jul 1990	0.18 ± 0.02	0.10 ± 0.016
27 Sep 1990	0.17 ± 0.02	0.092 ± 0.015
14 Nov 1990	0.19 ± 0.02	0.079 ± 0.011

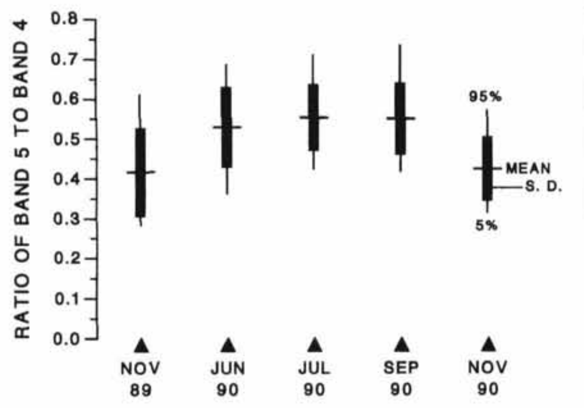

Figure 3. Ratios of reflectances in band 5 to band 4 for the time periods from November 1989 through November 1990. Data are means, standard deviations, and the range from the 5th to the 95th percentile of data from 785 randomly selected pixels. The 5th and 95th percentiles are reported rather than the minimum and maximum because of the occurrence of unusually small and unusually large ratios for some time periods.

drought months, but declined once the drought had been broken. There was little indication that the July and August rains affected the band ratios because the mean ratio for September, 0.544, was similar to the mean of 0.552 measured in July before the rains. Ratios differed significantly among soil types ($F = 4.77$; $df = 3, 26$; $P < 0.01$) and sampling units ($F = 11.67$; $df = 26, 756$; $P < 0.01$). There was also a significant interaction between time effects and the effects of sampling unit ($F = 5.14$; $df = 26, 756$; $P < 0.01$). This interaction is important because it indicates that the ratios changed more in some sampling units than in others.

The ratios of band 5 to band 4 for November 1989 varied among soils and among sampling units (Figure 4). Mean ratios for sampling units ranged from a minimum of 0.307 to a maximum of 0.584, a range of approximately two-fold. Rather than representing a two-fold difference in drought stress after a wet year, this variability more likely reflects the effects of differences in tree sizes and densities on canopy structure and reflectances in bands 4 and 5. Although there were significant differences in ratios among soil types and sampling units, most of the variation in ratios occurred among pixels within sampling units. Variation within sampling units accounted for 63.5 percent of the total variation in November 1989 and 71.8 percent of the total variation in September 1990.

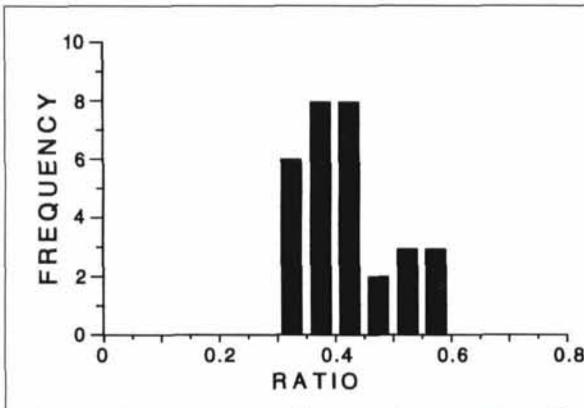

Figure 4. Frequency distribution of mean ratios of band 5 to band 4 in November 1989 for the 30 sampling units.

TABLE 3. MEAN (± STANDARD DEVIATION) REFLECTANCES FOR THEMATIC MAPPER BANDS 4 AND 5 AND THE RATIO OF BAND 5 TO BAND 4 FROM LONGLEAF PINE PLANTATIONS. DATA ARE MEANS OF 565 RANDOMLY SELECTED PIXELS FROM 18 SAMPLING UNITS THAT REPRESENTED POLYGONS OF UNIFORM SOIL TYPE AND FOREST MANAGEMENT.

Date	Band 4	Band 5	Ratio
11 Nov 1989	0.18 ± 0.02	0.075 ± 0.016	0.43 ± 0.11
27 Sep 1990	0.17 ± 0.02	0.094 ± 0.015	0.55 ± 0.10
19 Dec 1991	0.17 ± 0.02	0.070 ± 0.014	0.43 ± 0.12
20 Jun 1992	0.17 ± 0.02	0.080 ± 0.014	0.47 ± 0.10

Changes in reflectances in band 5 and changes in band ratios between winter and summer months in the drought year of 1990 were greater than those observed in the more normal year of 1992 (Table 3). The band ratios observed in December 1991 did not differ significantly from those observed for the same pixels in November 1989 ($F = 0.06$; $df = 1, 14$; $P > 0.05$), and the increase in mean band ratios from November 1991 to June 1992 was only one-third as large as that observed from November 1989 to the summer months of 1990. Because of clouds in the June 1992 image, the data from 1992 were limited to only 18 of the original 30 sampling units.

Because band ratios varied among soil types and sampling units at the beginning of the drought (Figure 4), because changes in band ratios during the drought varied among sampling units, and because changes in band ratios differed between dry and normal years (Table 3), the appropriate measure of probable drought stress becomes the changes in band ratios observed during the drought. This change expresses the degree of drought effect within each sampling unit. To assess drought effects in subsequent computations, the band ratio for November 1989 will be subtracted from that for September 1990 on a pixel-by-pixel basis. This linear difference of ratios is a measure of the change in reflectance patterns and should be more indicative of changes in moisture content than the simple ratio at any single time period. The ratio data for September were used because (1) they express the condition of the canopy near the end of the drought and (2) there is little difference among the ratios for June, July, and September (Figure 3).

Tree Ring Data

The width of tree rings varied among years for the period from 1983 through 1994 (Figure 5). The largest mean widths of > 3 mm occurred in 1984 and 1989 when annual precipitation exceeded 1.2 m. The smallest mean widths of < 1.9 mm occurred in 1992 and 1993 following the drought.

Ring widths in the years preceding the drought (i.e., 1983 through 1989) did not show patterns of decrease across tree ages associated with increasing bole diameter (Schweingruber, 1988; $F = 0.14$; $df = 1, 26$; $P > 0.05$; RM-ANOVA test of the first-order polynomial contrast; Khattree and Naik, 1995). Instead, the ring widths in the years 1983 through 1989 were positively correlated with annual precipitation (Figure 6), which indicates that yearly variation in precipitation has a greater effect on ring width patterns than does age. Similar dependencies of ring widths on precipitation have been noted for longleaf (Lodewick, 1930; Schumacher and Day, 1939; Zahner and Grier, 1990) and other southern pines

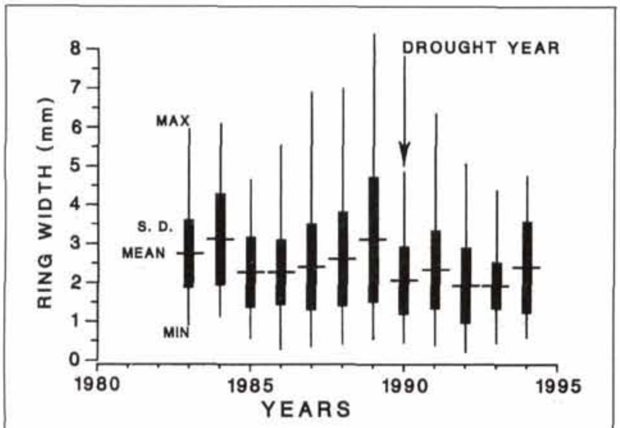

Figure 5. Tree ring widths (mm) for the years 1983 through 1994. Data are means, standard deviations, minimums, and maximums for 145 longleaf pines from 50- by 100-m plots located within 30 sampling units of uniform soil type and forest management.

(Grissino-Mayer *et al.*, 1989; Zahner and Grier, 1990; Grissino-Mayer and Butler, 1993).

To analyze the effects of the drought on tree ring widths, the ring widths observed for an individual in the drought year of 1990 and the subsequent years of 1991, 1992, 1993, and 1994 were compared to a mean ring width computed for that individual for the years 1986, 1987, and 1988. These were consecutive years of near normal precipitation (Figure 1), and growth during these years should be indicative of average performance for an individual. Growth in the drought year of 1990 and the years following the drought were compared to the mean for 1986 through 1988 using RM-ANOVA.

Tree ring growth during the drought in 1990 and in several subsequent years was significantly less than that observed before the drought (Figure 5). Significantly lower growth was observed in 1990 ($F = 26.53$; $df = 1, 26$; $P < 0.01$), 1992 ($F = 39.72$; $df = 1, 26$; $P < 0.01$), and 1993 ($F = 38.80$; $df = 1, 26$; $P < 0.01$). Mean growth increments in 1990, 1992, and 1993 were, respectively, 81 percent, 76 percent, and 77 percent of those observed before the drought. The reductions in ring widths for 1990, 1992, and 1993 did not differ significantly among soils but did differ significantly among sampling units ($F = 3.38$; $df = 26, 115$; $P < 0.01$). Significant differences among sampling units indicates that drought effects were not uniform but were greater in some units than others. There was also a significant interaction between years and sampling unit ($F = 1.92$; $df = 26, 115$; $P < 0.05$) which indicated that the effects of time were not constant among sampling units.

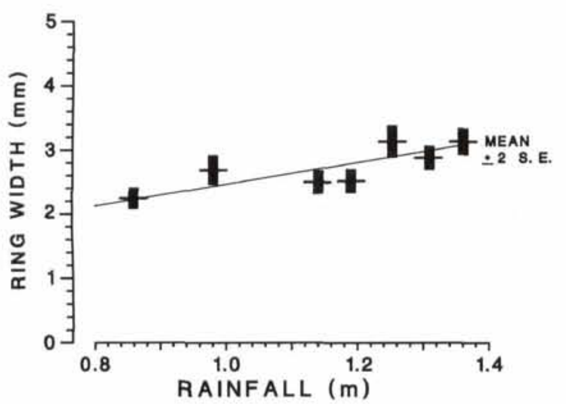

Figure 6. The relationship between tree ring width and rainfall in the years from 1983 through 1989.

Not all of the post-drought years showed significantly less growth than the pre-drought average. Mean ring widths for 1991, which was the wettest year since 1951, were not significantly different from those for 1986 through 1988 ($F = 0.02$; $df = 1, 26$; $P > 0.05$). Ring widths for 1994, which was a year of near normal precipitation, were also not significantly different ($F = 0.31$; $df = 1, 26$; $P > 0.05$) from those for 1986 through 1988.

The smaller ring widths in 1990 clearly express the effects of the drought, and the smaller widths in 1992, which was a year of more typical annual precipitation, suggest that the 1990 drought had residual effects on growth in subsequent years. Residual effects of climate in one year on growth in subsequent years is a common occurrence in the analysis of tree ring widths for most tree species (Fritts, 1976; Waring, 1983; Schweingruber, 1988) and has been previously observed for longleaf pine (Schumacker and Day, 1939). The smaller ring widths in 1993 may have resulted from residual effects of the 1990 drought or may have been caused by the low rainfalls (Figure 1) and extreme drought that occurred during July, August, and September of 1993 (NOAA, 1993).

The lack of significant differences in ring widths for 1991 probably reflects the exceptionally large precipitation during that year. Although the 1991 growth was not less than that for average years preceding the drought, it was less than that which should be expected given the relationship between annual precipitation and ring widths observed for the years 1983 through 1989 (Figure 6). Mean ring widths > 3.0 mm were observed in years of high precipitation before the drought, and a mean ring width of approximately 3.6 mm would be expected for the annual precipitation of 1.81 m for 1991. The observed mean (± S.D.) of 2.41 ± 1.00 mm is only 67 percent of this expected value and suggests that residual effects of the drought stress reduced the ability of the trees to respond to the large precipitation.

Relationships between Thematic Mapper Data and Tree Ring Data

The level of drought stress indicated by the difference in band ratios between September 1990 and November 1989 was significantly correlated to the reductions in tree ring widths observed for years 1990 and 1992 (Figure 7). Although the correlations for 1991 and 1993 were not statistically significant, they were also negative. Similar correlations between TM and tree ring data were also observed using Spearman Rank correlations which are not affected by possible departures from the assumptions of normally distributed data (Conover, 1971).

It is important to note that the difference in band ratios was not significantly correlated with tree density, tree heights, or tree basal areas, and statistically significant correlations between the difference in September and November band ratios and tree ring widths persisted after adjusting for the effects of tree densities and tree sizes. The adjusted correlations between ratio differences and growth effects for 1990 and 1992 were -0.42 ($df = 25$; $P < 0.05$) and -0.55 ($df = 25$; $P < 0.01$), respectively. The persistence of these significant correlations after adjustment indicates that the correlations between the differences in ratios and growth effects presented in Figure 7 are not merely artifacts of their mutual correlation with measures of canopy structure. It is also im-

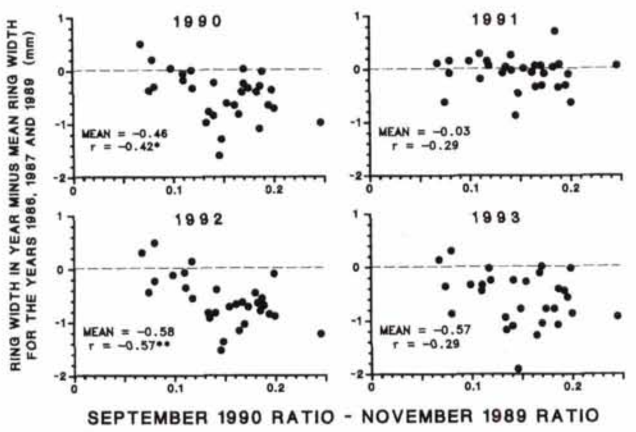

Figure 7. The relationship between the change in band ratios from November 1989 to September 1990 and drought effects on ring width increments. r = Pearson correlation coefficients. $df = 28$. * = $P < 0.05$. ** = $P < 0.01$.

portant to note that the reductions in ring widths were not significantly correlated with either the band ratios for November 1989 or September 1990. They were only correlated with the differences between these ratios.

Thus, repeated measures of TM data were able to detect changes in reflectance patterns that were related to growth effects in the year of the drought as well as reductions in growth expressed in subsequent years.

Discussion

Although the TM data were able to detect changes in reflectances that were correlated with drought stress effects on growth, questions remain concerning the practical application of these correlations. Their practical application is limited by the following four factors: (1) the small value of the correlation coefficients, (2) the complex nature of multi-year effects of drought on growth, (3) the combination of extreme drought stress with marginal soils, and (4) uncertainties concerning what is being measured by the increases in the reflectances for band 5.

The correlations between the differences in ratios and the growth reductions are between 0.4 and 0.6, which indicates that they predict from 16 percent (i.e., $= r^2 \times 100$ percent) to 36 percent of the variation in the reduction in tree ring widths. The low proportion of the variance predicted implies that the benefits of this analysis may not exceed the costs (Draeger *et al.*, 1997) of acquiring the multiple dates of TM data required to compute changes in band ratios. Where the TM data may be obtained at reduced costs for U.S. Government purposes (Draeger *et al.*, 1997), the procedure may be more economically feasible.

The residual effects of climate on tree ring widths in subsequent years implies that estimating growth reductions from changes in band ratios may become a complicated procedure, especially where rainfall varies considerably among successive years. For example, the growth in 1991 was less than that expected for a year of unusually large precipitation, but the changes in band ratios in 1990 provided no estimate of the spatial variation in growth reductions. Measures of TM data may need to be integrated into models of ring width formation (e.g., Zahner and Grier, 1990; Luxmore *et al.*, 1990) to obtain more accurate predictions.

The correlations observed in this study occurred when a severe drought was applied to a species growing along the edge of its natural range on marginally suitable soils. Longleaf pine occurs naturally on these soils, but its occurrence is more a reflection of fire tolerance than drought resistance (Wahlenberg, 1946). As an extreme example of drought effects, the correlations between the TM data and growth data observed in this study may not be typical of those to be expected for this species or other species subjected to less severe droughts on more favorable soils. In less extreme cases, lower correlations may be anticipated which will further reduce the benefit to cost ratio of the procedure.

The increases in reflectances for band 5 during the summer months of 1990 are approximately 35 percent. This is a relatively large increase compared to that observed for pine needles under more controlled conditions. Carter (1991) observed increases in middle infrared reflectances of > 20 percent only when dried needles had lost 85 percent of their initial water content. Some species such as *Agave deserti* (Hunt *et al.*, 1987) and *Nuphar luteum* (Carter, 1991) may show large increases in band 5 reflectances as leaf water contents decline, but pines and other conifers show relatively small increases (Carter, 1991; Riggs and Running, 1991). To obtain the 35 percent increases in reflectances observed in this study would appear to require the death and desiccation of almost all pine needles. This did not occur. Trees maintained living needles at the end of the summer that persisted through the winter. Thus, it is probable that the increases in reflectances in band 5 were due to factors other than the loss of canopy water content. The factors causing the large changes in reflectances remain to be identified, but, whatever these factors are, they are apparently temporary because reflectances in band 5 returned to pre-drought levels in November 1990.

Despite these potential limitations in using changes in ratios of band 5 to band 4 to assess drought effects on growth, the procedure does not require any field measurements during the year of the drought. Although the study would have benefitted from measures of leaf water content taken concurrently with the TM data, these measures were not required to relate TM data to growth depressions. Thus, the procedure may be employed in a retroactive manner to consider drought effects in any year where TM data have been collected and where measures of tree growth may still be extracted from tree cores or other records of tree growth.

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