REMOTE SENSING OF ENVIRONMENT 19:105–115 (1986)

Analysis of Effective Radiant Temperatures in a Pacific Northwest Forest Using Thermal Infrared Multispectral Scanner Data

STEVEN A. SADER

National Aeronautics and Space Administration, Earth Resources Laboratory – National Space Technology Laboratories, NSTL, Mississippi 39529

Analysis of Thermal Infrared Multispectral Scanner data collected over H. J. Andrews experimental forest in western Oregon indicated that aspect and slope gradient had a greater effect on the thermal emission of younger reforested clearcuts than of older stands. Older forest stands (> 25 years) with greater amounts of green biomass and closed canopies had lower effective radiant temperatures than younger, less dense stands. Aspect and slope had little effect on the effective radiant temperature (ERT) of these older stands. Canopy temperature recorded at approximately 1:30 p.m. local time 29 July 1983 were nearly equal to maximum daily air temperature recorded at eight reference stands. The investigation provided some insights into the utility of the thermal sensor for detecting surface temperature differences related to forest composition and green biomass amounts in mountain terrain.

Introduction

In the late 1960s, interest developed in the use of thermal sensors for previsual detection of insect attacked and diseased trees. Some pine trees under moisture stress and bark beetle attack were shown to have higher canopy temperatures than surrounding healthy trees (Olson, 1972; Weber, 1971). Temperature differences as high as 7 °C were recorded between stressed and control trees, but average temperature differences were only 1°C. These investigations were unable to determine if the temperature differences were attributable to physiological stress within the trees or associated with variation in microclimate, atmospheric perturbations or random noise. Nighttime brightness variations on uncalibrated thermal imagery of coniferous forests were attributed to cold air valley drainage patterns and indicated the potential use of the imagery to infer nocturnal air circulation patterns in mountain terrain (Fritchen et al., 1982; Balick and Wilson, 1980).

Certainly the most successful use of thermal sensors in forestry has been for real time detection of forest fires. Eight years of research and development through the U.S. Forest Service Fire Scan project resulted in an operational system utilizing two detectors (Ge:Hg and InSb) sensitive in 3–4 μm and 8.5–11 μm thermal wave bands (Hirsch et al., 1971). The thermal target created by a forest fire was in high contrast to cooler surrounding surfaces, thus enabling easy detection of the fire in all weather, at night and through dense smoke.

Recent improvements in sensor design and technology may warrant a new look at potential capabilities of thermal remote sensing to investigations in forest physiology, hydrology and climatology. The Thermal Infrared Multispectral Scanner (TIMS) is a six-channel scanner flown in a Lear 23 aircraft operated by the National Aeronautics and Space Administration's

52 Vanderbilt Ave., New York, NY 10017

0034-4257/86/$3.50

National Space Technology Laboratories in Mississippi. Irradiance is measured in the following wavelength regions: (Ch. 1) 8.2–8.6 μm; (Ch. 2) 8.6–9.0 μm; (Ch. 3) 9.0–9.4 μm; (Ch. 4) 9.4–10.2 μm; (Ch. 5) 10.2–11.2 μm; and (Ch. 6) 11.2–12.2 μm. The total angle of look is 76° (38° on each side of nadir). The sensor can resolve temperature variations of the order of 0.2–0.3°C. The increased sensitivity of the TIMS coupled with improvements in atmospheric, terrain, and canopy modeling offer significant advances over the broad band sensors and technology available in earlier studies.

Plant physiological processes such as photosynthesis, respiration, and evapotranspiration are closely linked to temperature. Therefore, air and surface temperatures are necessary components of forest ecosystem studies and models dealing with energy budgets. Measurement of parameters important for estimation of evapotranspiration and the use of plant canopy temperatures to infer water stress and crop yield has created new interest in thermal sensors (Kimes, 1980; Jackson et al., 1977; Idso et al., 1977; Soer, 1980; Gurney, 1978; Heimberg, 1982). However, these investigations have concentrated on homogeneous crop or pasture targets on level terrain excluding more complex forest targets. An important objective of future evapotranspiration research is to develop remote sensing techniques for measuring surface temperature and net radiation in complex canopies and on terrain with variable sun–sensor–surface geometry (Heimberg, 1982).

Background

All objects with temperatures greater than absolute zero (0°K or −273°C) emit radiation. Amounts and wavelengths of energy emitted from a surface is a function of its absolute temperature and emissivity. Emissivity in the thermal region of the electromagnetic spectrum (8–14 μm) can be considered nearly constant for many vegetation surfaces. Emissivities of vegetated targets are within the range of 0.90–0.98 and are usually greater than 0.95 when the plants are not water stressed (Smith, 1983). Atmospheric effects (atmospheric absorption, scattering and emission from particles and gases) can significantly influence thermal measurements from aircraft or space platforms. Readers interested in detailed reviews of thermal infrared theory, emissivity and effects of the atmosphere on measurements are referred to Smith (1983), Lillisand and Kiefer (1979), and Nunnally (1973).

Land features (including phytomass, soil and soil moisture, rock, plant litter) and the surface mosaic of these features have heat transmission characteristics that influence surface temperature. Common surface materials can have very different albedos. Hungerford (1980) reported albedos of 20–24% for grass, 6–11% for conifer needles, 20–35% for dry clay soils, 25–45% for dry sand soil, and 2% for charcoal. In irregular terrain, the temperature response of the land surface can be influenced by the angle between the sun and surface plane (Lillisand and Kiefer, 1979). Sun angle effects on surface solar loading are more pronounced where soils are exposed or vegetation canopies are open. Surface temperatures in Coram Experimental Forest, Montana were 25° higher in clearcuts than in uncut stands during midsummer and partial cuts were 10–15°C higher than uncut areas (Hungerford, 1980). In mature or closed forest canopies on clear summer days, the temperature of the canopy is generally within a few degrees (±3°C) of air temperature (Smith et al., 1981; Kaufman, 1984). Closed canopy temperatures are influenced by elevation but slope gradient and aspect have almost no effect (Kaufman, 1984; Zobel et al., 1976).

Objective

Thermal Infrared Multispectral Scanner (TIMS) data were analyzed to determine whether temperature differences in reforested clearcuts of various ages and old growth forests could be explained by variations in green leaf biomass. The H. J. Andrews experimental forest was selected as a study site. It is located approximately 50 miles east of Eugene, OR, within the Williamette National Forest–Blue River Ranger District (see Fig. 1).

Methods

The TIMS data were collected at approximately 1:30 p.m. PST, 29 July 1983, corresponding to the time of maximum diurnal surface temperature. Several low altitude lines were flown in a north and south orientation at 7600 ft above mean terrain (ATM). The raw data resulted in a 6-m instantaneous field of view (IFOV) at nadir. As a result of minimum air turbulence and clear atmospheric conditions, the data sets were of high quality.

It was anticipated that differential heating of north and south slopes could have a major influence on the thermal exitance of clearcuts with low biomass and incomplete canopy closures. To test this hypothesis, stands of a variety of ages and canopy densities were selected, and the effects of aspect and slope gradient on ERTs were investigated. Sample stands were also selected representing different forest habitat types along elevation and site gradients within Andrews experimental forest for ERT investigations. Elevation ranged from about 500 to 1600 m (Dryness et al., 1976). Forest vegetation in age classes from recent clearcuts (< 1 year) to old growth Douglas-fir [*Pseudotsuga menziesii* (Mirbel) Franco] exceeding 450 years were selected.

Several computer programs in the Earth Resources Laboratory software package (Graham et al., 1980) were available to process the TIMS data. In order to reduce image registration errors and residual errors that may exist at longer atmospheric path lengths, only data within 30° of nadir were extracted for processing. A series of preprocessing steps were necessary to correct "pixel dropout" values, generate effective radiant temperature (ERT) values, resample, and register the scanner data to a 10-m UTM grid coordinate system. Elevation contour lines were digitized from a 1:15,840 scale topographic map and converted to 10-m raster (grided) aspect and slope images.

The six-thermal channels were highly correlated, indicating that little would be gained by processing all channels. Channel 3 was chosen for further processing. Through the use of computer software that applied the calibration data available at the time of the mission, the raw data were converted to data representing effective radiant temperature (ERT) for each pixel in the data set. The resulting data were matched to table look-up values which provided the ERT in 0.5°C increments.

A map of forest unit boundaries, old growth reference stands and remote thermograph stations was used to select the sample stands representative of the age classes and topographic variation present. Twenty-two stands were selected in

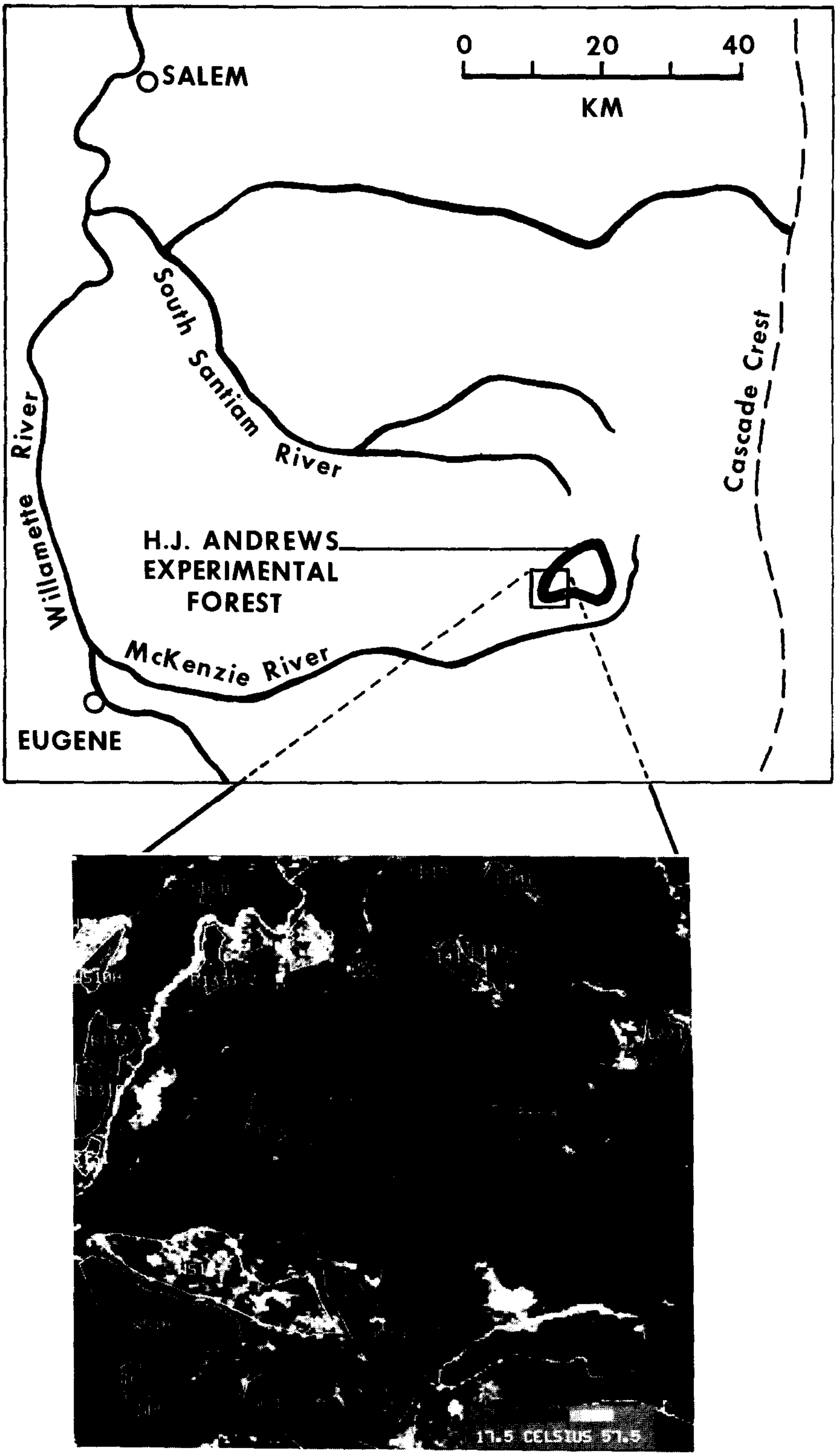


FIGURE 1. Location of H. J. Andrews experimental forest (a) in western Oregon (after Zobel et al., 1976) and sample areas superimposed on thermal scanner data (b).

watersheds where the rasterized slope and aspect data were available.

The selection of sample stands was conducted in an interactive mode. The sample areas were located on a computer display screen, and a moving cursor was used to draw the polygonal boundaries of each area. This information was filed for subsequent computation. Within each designated forest unit, the sample area was selected in a manner to be as "homogeneous" as possible in forest composition and stand density. Atypical areas were excluded in an attempt to reduce variation within sample stands. Figure 1(b) shows the sample areas selected within one flight line in the western portion of the H. J. Andrews forest.

The thermal data for sample stands were statistically analyzed to determine effects of age class, aspect, and slope on the ERTs. Ages (years since clearcut–reforestation) were grouped into four classes: 1) 0–12; 2) 13–25; 3) 26–33; and 4) old growth (relatively undisturbed virgin forest). Aspects (azimuths) were grouped as: 1) north 316–45°; 2) east 46–135°; 3) south 136–225°; and 4) west 225–315°. Also, four slope classes were defined; 1) 0–15; 2) 16–30; 3) 31–45; 4) 46–60; 5) > 60%. Figures 2(a) and (b) depict the distribution of aspect and slope classes on the H. J. Andrew experimental forest.

Results and Discussion

Air temperatures recorded at thermograph sites at H. J. Andrews on 29 July were compared to ERTs of sample areas

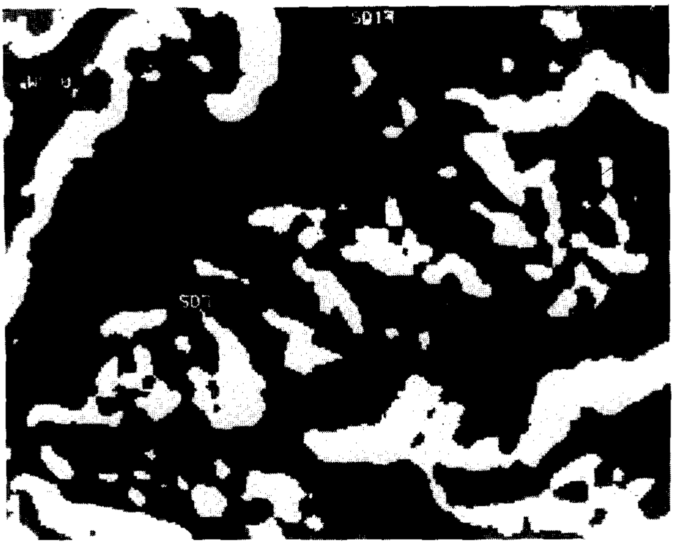


FIGURE 2. Rasterized aspect (a) and slope percent (b) classes derived from a digitized elevation contour map.

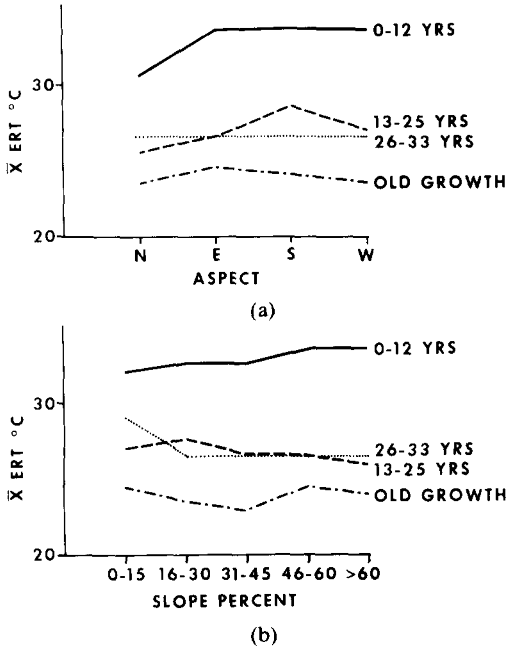
FIGURE 2b.

that encompassed the thermograph sites (Table 1). The 1:30 p.m. ERTs at these eight locations were nearly equal to the maximum air temperature recorded by the thermographs at the respective sites on this day.

Effective radiant temperatures were plotted for each age class against aspect and slope gradient (Fig. 3). Mean ERT decreased as age class increased and was independent of aspect and slope. There were only minor temperature variations between the 13–25 and 26–33 year age classes, but the sparse, young canopies (0–12 year age class) were 8–9° warmer than the old growth stands when averaged over all aspect and slope positions. The actual ages of the forest stands in the 0–12 age class were 7 and 11 years. Although canopy closure was at or near

TABLE 1 Comparison of Effective Radiant Temperature and Maximum Daily Air Temperatures Recorded 29 July 1983 at Eight Remote Thermograph Stations, H. J. Andrews Experimental Forest

STATION	MAXIMUM AIR TEMP (°C)	TIMS ERT (°C)
Reference Stand 1	25.3	22.5
Reference Stand 2	25.4	24.5
Reference Stand 3	26.1	22.5
Reference Stand 17	26.2	24.5
Reference Stand 20	23.9	24.0
Reference Stand 26	22.2	23.0
Watershed 6	27.8	24.0
Watershed (North) 10	29.4	30.0
	$\bar{x}_A = 25.8$	$\bar{x}_T = 24.4$
	S.D. = 2.2	$r = 0.68$



(a)

(b)

FIGURE 3. Mean effective radiant temperature of forest age classes by aspect (a) and slope gradient classes (b).

100% in many of the 25–33-year-old stands, the tree heights and structure of these forests were more homogeneous as compared to old growth forests. Old growth forests were heterogeneous in structure; coefficients of variation in tree size and understory patchiness was greater and leaf area indices in old growth were higher also (Franklin et al., 1981). Old growth forests were approximately 2.5 °C cooler than the 25–33 year old forests. Figure 3(a) revealed that:

1. Stands on north aspects were coolest for all age classes. Temperatures of the 0–12 year age class were approximately 3 °C cooler on north aspects.
2. For the 13–25 year age class, the south aspect had a higher mean ERT.
3. Aspect had little effect on mean ERT for the 26–33 and old growth age classes.

Trends in temperature differences by slope classes were less apparent [Figure 3(b)]. Mean ERT for 13–25 and 26–33 year age classes were nearly identical on all slopes greater than 31%. The 0–15% and 16–30% slopes exhibited 2 °C and 1 °C differences, respectively.

As anticipated, not all aspect-slope-age class combinations were equally represented. Missing data were evident in age classes 3 and 4. In age class 3 there were no data available for east facing aspects. Also, three out of 20 possible cases did not exist in age class 4. For the purposes of performing the analysis of variance, missing data were replaced by average values. The replacement value for the east aspect on 0–15% slopes (age class 3) was derived by computing the overall mean of the 0–15% slopes on north, south, and west aspects. The missing value for the east aspect on the 16–30%, 31–45%, 46–60%, and > 60% slopes were derived in the same manner. For each of the three missing values in age class 4, the value was derived by computing the overall mean of all other slope classes on the same aspect and all other aspect classes on the same slope.

Analysis of variance (ANOVA) with a randomized complete block design was used to test the null hypothesis that no temperature differences occur between age classes, aspects, or slope gradients. Age classes were used as blocks. F tests revealed that age class and aspect were highly significant ($\alpha = 0.01$), but slope and aspect-slope interaction were nonsignificant (Table 2). Response surfaces of aspect versus slope class (Fig. 4) for each age class indicated that age class 1 (0–12 years) and age class 2 (13–25 years) were contributing most of the variability in ERT related to terrain. Terrain had little

TABLE 2 Watershed 1, 2, 3-Randomized Complete Block ANOVA (Forest Age Class = Blocks)

	Degree of Freedom	Sum of Square	Mean Square	*F*
Age	3	3365.37	1121.79	121.80[a]
Aspect	3	121.29	40.43	4.39[a]
Slope	4	32.17	8.04	0.87
Aspect-slope	12	53.96	4.50	0.49
Error	57	525.11	9.21	

[a] Significance at $\alpha = 0.01$.

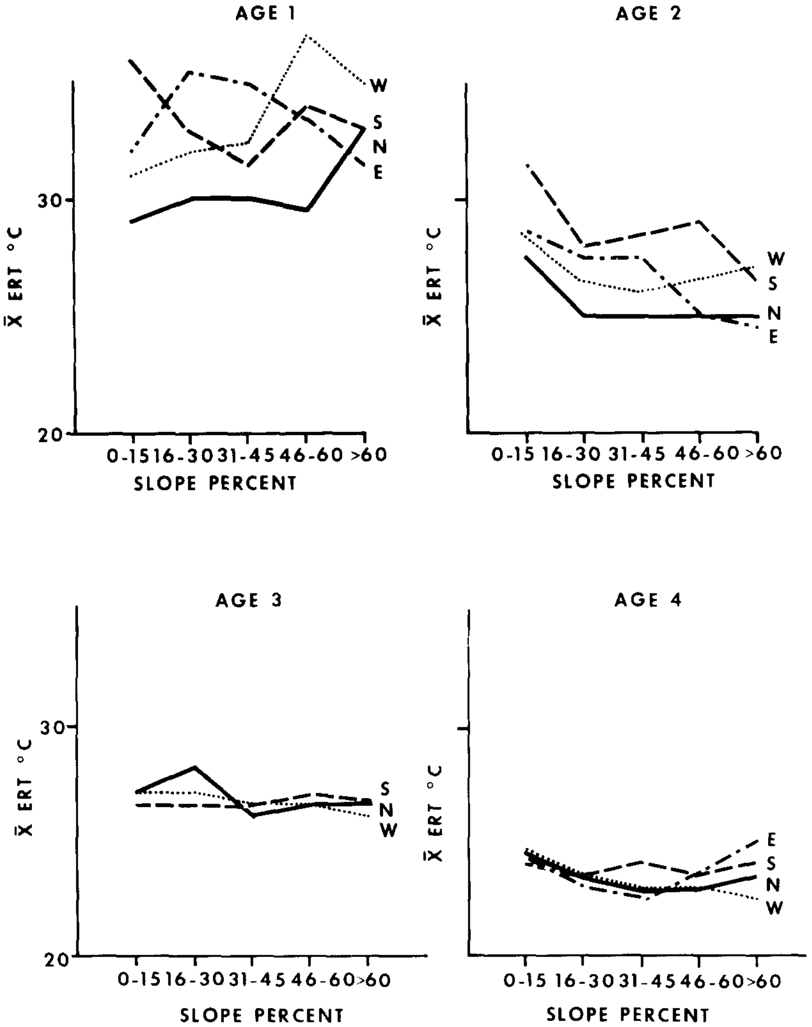


FIGURE 4. Mean effective radiant temperature of aspect class by slope gradient for each forest age class.

effect on ERT for age class 3 (26–33 years) and 4 (old growth). The effects of aspect within age classes 1 and 2 were tested using single degrees of freedom for each aspect sum of squares. For age class 1, the north aspect had highly significantly different mean ERT as compared to the east, south, and west aspects. The south aspect in age class 2 was highly significant, and north, east, and west aspects were nonsignificant. It is possible that significant differences in ERT may have been undetected as the result of missing data in age class 3 and 4.

These data were compared to a second data set from stands approximately 1000 ft higher elevation in the transition zone of Western Hemlock [*Tsuga heterophylla* (Raf.) Sarg.] and Pacific Silver Fir [*Abies amabilis* (Dougl) Forbes]. Mean ERT of each age, slope, and aspect class were lower in the higher elevation data set (Sader, 1984). The greatest difference in ERT recorded between the two data sets was in the 0–12 year age class which were 4–5° cooler over all aspects and slopes at higher elevation.

Summary and Conclusions

Mean ERT decreased as age class increased and the relationship was independent of aspect and slope positions. Age class was used as an indicator of relative crown closure, forest structure and amount of green leaf area because reforestation (primarily replanting of Douglas fir) was practiced on all of the sites (33 years and younger age classes). Old growth forests which existed prior to the period when accurate records were kept were considered to be of similar age and structural development as the result of wildfires that occurred in the past.

ERT differences corresponding to aspect and slope variation in age classes 1 and 2 may be attributable to low amounts of green leaf area and less than complete canopy closure present in the sensor field of view. Differential heating and cooling related to sun–surface geometry had a greater influence on ERTs when forest canopies were not completely closed. Highly significant differences in ERT on north slopes (0–12 age class) and on south slopes (13–25 age class) were detected through analysis of variance. As forests matured and canopy closure and green leaf area approached maximum levels, the influence of surface emittance from below the canopy contributed less to the total return. This may explain why aspect and slope appeared to have little effect on ERT of the older age classes.

Some problems were encountered in interpreting the influence of aspect and slope on ERT in older age classes as a result of missing data that were replaced by average values. However, the number of observations available to detect temperature differences among age classes (major effects) was sufficient (several hundred samples) to have confidence in the results. Significant differences in temperature between age classes were detected in another thermal data set located in a higher elevation zone. Variability within age class stratum was unavoidable because not all forest units of similar age were completely homogeneous in composition, structure, stocking, and other physical characteristics which likely had some influence on the thermal return. Also, it should be noted that results were for one point in time and temperature variations, especially in open canopies, can be affected by sun–surface geometry and meteorologic conditions that existed at the time of thermal data acquisition. Little is known (quantitatively) about these effects but they may limit the generality of some of the results.

The Thermal Infrared Multispectral Scanner appears to be capable of detecting temperature differences related to relative differences in canopy closure and green leaf area; however, calibration techniques are needed to correct for emissivity differences and atmospheric effects. Research at H. J. Andrews experimental forest is underway to develop and test a mathematical model capable of predicting irradiance measured by the TIMS in forest canopies of various compositions and topographic positions. Data used to support the research will include physical relationships, results of field experiments, ground measurements and radiosonde data (to develop atmospheric corrections), and measurements collected by the TIMS sensor at night and near solar noon. A capability of remote measurement of surface temperatures will have important applications in ecosystem level and landscape scale studies of evapotranspiration, plant–water stress, and energy budgets and partitioning.

References

Anderson, J. E. (1983), Mid/thermal IR remote sensing, FY82 RTOP #677-21-21 Summary Report, NASA/NSTL/ERL Report No. 214, 45 pp.

Balick, L. K., and Wilson, S. K. (1980), Appearance of irregular tree canopies in nighttime high-resolution thermal infrared imagery, *Remote Sens. Environ.* 10:299–305.

Dryness, C. T., Franklin, J. F., and Moir, W. H. (1974), A preliminary classification of forest communities in the central portion of the western cascades in Oregon, U.S.I.B.P.—coniferous forest biome, Bull. No. 4, 123 pp.

Franklin, J. F., Cromack, K., Jr., Denison, W., McKee, A., Maser, C., Sedell, J., Swanson, F., and Juday, G. (1981), Ecological characteristics of old-growth Douglas-fir forests, USDA Forest Service, PNW For. and Range Expt. Sta., Gen. Tech. Rep. PNW-118, 48 pp.

Fritchen, L. J., Balick, L. K., and Smith, J. A. (1982), Interpretation of nighttime imagery of a forested canopy, *J. Appl. Meterol.* 21:730–734.

Graham, M. H., Junkin, B. G., Kalcic, M. T., Pearson, R. W., and Seyfarth, B. R. (1980), ELAS—Earth Resources Laboratory Applications Software, revised Jan. 1984, NASA/NSTL/ERL Report No. 183.

Gurney, R. J. (1978), Estimation of soil moisture content and actual evapotranspiration using thermal infrared remote sensing, *Proc. Remote Sens. Soc.*:101–109.

Heimberg, K. F. (1982), Evapotranspiration estimates based on surface temperature and net radiation: development of remote sensing methods, Water Resoures Res. Ctr., Publ. No. 66, University of Florida, Gainesville, 210 pp.

Hirsch, S. N., Kruckeberg, R. F., and Madden, F. H. (1971), The bi-spectral forest fire detection system, in Proc. 9th Symp. Remote Sensing of Environment, Mich. Inst. Science and Tech., University of Mich., Ann Arbor, pp. 2253–2272.

Hungerford, R. D. (1980), Microenvironmental response to harvesting and residue management, in Proc. of Environmental Consequences of Timber Harvesting in Rocky Mountain Coniferous Forests, 11–13 Sept. 1979, USDA-Forest Service Gen. Tech. Rep. Int.-90, Ogden, UT, pp. 37–73.

Idso, S. B., Jackson, R. D., and Reginato, R. J. (1977), Remote sensing of crop yields, *Science* 189:1012–1013.

Jackson, R. D., Reginato, R. J., and Idso, S. B. (1977), Wheat canopy temperature: a practical tool for evaluating water requirements, *Water Resources Res.* 13:651–656.

Kaufmann, M. R. (1984), Effects of weather and physiographic conditions on temperature and humidity in subalpine watersheds of the Fraser Experimental Forest, USDA-Forest Service, Rocky Mtn. For. and Range Exp. Sta. Res. Paper RM-251, 9 pp.

Kimes, D. S. (1980), Effects of vegetation canopy structure on remotely sensed canopy temperatures, *Remote Sens. Environ.* 10:165–174.

Lillisand, T. M., and Kiefer, R. W. (1979), *Remote Sensing and Image Interpretation*, Wiley, New York, 612 pp.

Nunnally, N. R. (1973), Introduction to remote sensing: the physics of electromagnetic radiation, in *The Surveillant Science —Remote Sensing of the Environment* (R. K. Holz, Ed.) Houghton Mifflin, Boston, pp. 18–27.

Olson, C. E. (1972), Remote sensing of changes in morphology and physiology of trees under stress, Final Report for Earth Resource Surv. Program., Off. Space Science and Applications/NASA, Prep. by School of Nat. Resources, University of Michigan, 33 pp.

Sader, S. A. (1984), Thermal differences in reforested clearcuts and old growth forest on mountainous terrain using thermal infrared multispectral scanner data, NASA-National Space Technology Laboratories, Report 229, 34 pp.

Smith, J. A. (1983), Matter–energy interaction in the optical region, in *ASP Manual of Remote Sensing*, 2nd ed., Falls Church, VA, Chap. 3.

Smith, J. A., Ranson, K. J., Nguyen, D., and Balick, L. (1981), Thermal vegetation canopy model studies, *Remote Sens. Environ.* 11:311–326.

Soer, G. J. R. (1980), Estimation of regional evapotranspiration and soil moisture conditions using remotely sensed crop surface temperatures, *Remote Sens. Environ.* 9:27–45.

Weber, F. P. (1971), The use of airborne spectrometers and multispectral scanners for previsual detection of Ponderosa pine trees under stress from insects and disease, in *Monitoring Forest Land from High Altitude and from Space*, Office Space Sci. and Appl., NASA, Houston, TX, pp. 94–104.

Weber, F. P., and Olson, C. E. (1967), Remote sensing implications of changes in physiological structure and function of tree seedlings under moisture stress, Ann. Prog. Rep. Nat. Resource Program Office of Space Science and Application, NASA, 61 pp.

Zobel, D. B., McKee, A., and Hawk, G. M. (1976), Relationships of environment to composition, structure and diversity of forest communities of the Central Western Cascades of Oregon, *Ecol. Monographs* 46(2):135–156.

Received 28 May 1985; revised 10 September 1985.