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## REMOTE SENSING OF CONIFEROUS FOREST LEAF AREA<sup>1</sup>

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and K. B. Teuber<sup>2</sup>

Many important ecological questions concern ecosystem processes occurring over large areas. However, our understanding of ecosystem functions is derived primarily from research executed on small, intensively studied sites, and extrapolation to large areas is difficult. For example, it is not known definitively whether the land biota act as a source or a sink in the global carbon cycle, or whether increases in carbon dioxide concentrations and the subsequent predicted global warming would stimulate or suppress land vegetation (Bolin 1977, Woodwell et al. 1983). Much of this indecision results from our inability to directly measure important vegetation properties on large spatial scales. Estimates of the global carbon content of terrestrial plant biomass range from  $450 \times 10^{15}$  to  $1000 \times 10^{15}$  g. These estimates are derived by extrapolation of data from sites of intensive study to the areal coverage of vegetation assumed to be equivalent; hence no direct means of verification exist. As a consequence, no defensible estimate of energy and mass exchange rates is possible for large areas of terrestrial vegetation.

Four recent workshops have evaluated the potential of advanced satellite technology for direct measurement of critical vegetation characteristics over large areas (Botkin 1982, 1985, Goody 1982, Wittwer 1983). Each workshop ultimately identified leaf area index (LAI, the area of leaf over a given area of ground) as the single variable both amenable to measurement by satellite and of greatest importance for quantifying energy and mass exchange by plant canopies over landscapes. Characterizing vegetation in terms of LAI, rather than species composition, is a critical simplification for regional and global comparison of different terrestrial ecosystems. Previous research in crops and grasslands has shown leaf area and biomass to be correlated with reflectance values measured by satellite-based sensors (Wiegand et al. 1979). We report here the first attempt to measure the LAI of coniferous forests using optical scanners of satellite resolution.

### Methods

The coniferous forests of Oregon offer a wide range of LAI values within a relatively small geographic area. Along the Oregon coast and western Cascade Mountains LAI values are among the highest in the world,

reaching a maximum LAI of  $23 \text{ m}^2/\text{m}^2$ , expressed as projected, or one-sided, leaf area (Gholz et al. 1976). Only 300 km inland, the forest LAI declines to  $<1.0 \text{ m}^2/\text{m}^2$ , a result of orographic precipitation and rain shadow patterns from air masses crossing the Coast and Cascade mountain ranges. These forests have been studied extensively, providing quantitative interpretations of environmental influences on forest structure and the allometric equations necessary to estimate LAI (Grier and Running 1977, Waring et al. 1978, Waring and Franklin 1979, Gholz et al. 1979).

A total of 18 plots were selected for this research, based on relocated stands from a previous LAI study (Gholz 1982). Each represented mature, undisturbed coniferous forest. Each of these plots was at least 5 ha in size, to provide an adequate sample of digital image data (or pixel) values. The plots were located in uniform terrain on various aspects but with slopes  $<40\%$ .

Because species-specific allometric equations relating stem diameter to foliage biomass were already available, field sampling included measuring stem diameter at breast height (dbh) and recording the species of each tree on four 0.1-ha subplots randomly located within each 5-ha plot. Understory vegetation was similarly sampled on four 4-m<sup>2</sup> subplots within each 0.1-ha subplot. The allometric equations were constructed through dimensional analysis and were generally of the form  $\ln(Y) = a + b \cdot \ln(X)$ , where  $Y$  is foliage biomass in kilograms and  $X$  is dbh, or basal diameter for many understory species, in centimetres. Foliage biomass was converted to leaf area using surface area/mass conversion factors provided from previous research results (Gholz et al. 1976). Leaf area index was calculated for each subplot by summing the individual leaf areas and dividing by the ground area of the subplot. The average overstory and understory LAI values were combined to produce the total estimated LAI of each 5-ha plot.

Digital remote sensing data used in this experiment were collected on 15 August 1983 between 1100 and 1300 Pacific Standard Time by a Daedalus Airborne Thematic Mapper (ATM) aboard an ER-2, a reconnaissance aircraft flying at 20 000 m altitude. The spectral and radiometric characteristics of the ATM are calibrated to be nearly identical to those of the satellite-based Thematic Mapper sensor aboard Landsat 5. The spatial resolution (pixel size) of the ATM data is  $\approx 20$  m at the 20 000 m flight altitude. The ATM has seven spectral bands, three visible and four infrared. The brightness values recorded by the sensors were converted to radiance values (milliwatts per square centimetre per steradian) using published gain settings. Radiance values from  $\approx 125$  pixels were averaged to give mean spectral response for each 5-ha primary sample plot. To correct these radiance values for atmospheric absorption and scattering, near-surface ra-

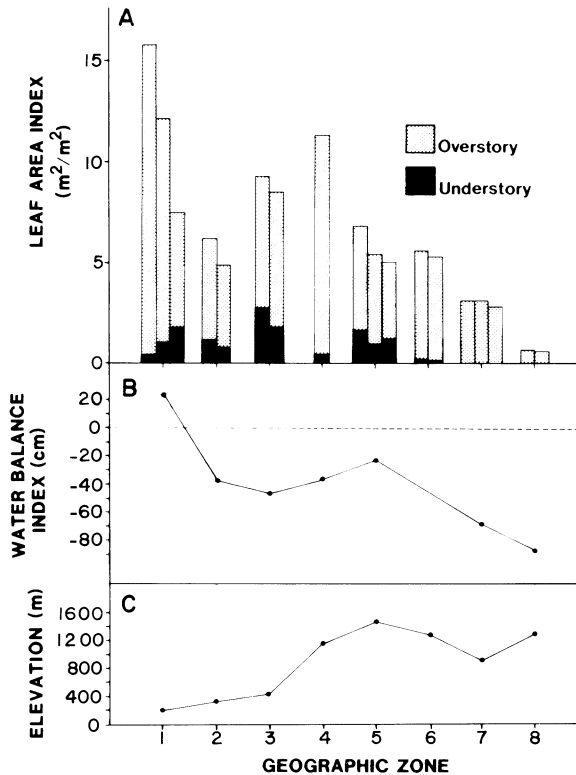


FIG. 1. (A) Leaf area index of the 18 coniferous forest stands sampled in eight vegetation zones in Oregon. Zone 1 = Western Coast Range, Zone 2 = Interior Coast Range, Zone 3 = Low-elevation west Cascade Mountains, Zone 4 = Mid-elevation west Cascade Mountains, Zone 5 = High Cascades summit, Zone 6 = Mid-elevation east Cascade Mountains, Zone 7 = Low-elevation east Cascade Mountains, Zone 8 = Interior high desert. (B) A simple water balance index, derived as summer precipitation plus soil moisture holding capacity minus growing season potential evaporation, has previously been used to quantify this environmental gradient. Two separate studies have correlated leaf area index (LAI) with this water balance index ( $r^2$ : 0.95–0.99; Grier and Running 1977, Gholz 1982). (C) Elevation of the sample plots, illustrating the topography that produces this environmental gradient.

diometric data were acquired concurrently using a Barnes Modular Multiband radiometer mounted on a helicopter hovering 100 m above targets in each geographic zone of the study. Spectral bands and calibration of the Barnes radiometer were set to duplicate the ATM, so a regression of radiance as measured by the radiometer and the ATM was developed for each band to remove atmospheric effects from the ATM data (Spanner et al. 1984).

### Results and Discussion

The range in LAI values of the 18 sample plots was 0.6 to 15.9 m<sup>2</sup>/m<sup>2</sup>, with a relatively even distribution

of intermediate values (Fig. 1). The wet, mild-temperature coastal forests of *Tsuga heterophylla* (Raf.) Sarg., *Picea sitchensis* (Bong.) Carr., and *Pseudotsuga menziesii* (Mirb.) Franco supported the higher LAI values, while the cool, high-elevation mountain stands of *P. menziesii*, *Tsuga mertensiana* (Bong.) Carr., *Abies lasiocarpa* (Hook.) Nutt., and *Pinus contorta* Dougl. ex Loud. produced midrange LAI values. Arid stands of the eastside Cascade Mountains, typified by *Pinus ponderosa* Dougl. ex Loud. and *Juniperus occidentalis* Hook., produced LAI values ranging from 3.2 to the low of 0.6 m<sup>2</sup>/m<sup>2</sup>. The coefficient of variation of LAI measured on the four subplots averaged 25% of the mean LAI for each sample plot. Twelve species of coniferous trees contributed to the LAI measured across the transect.

Digital image data were correlated with LAI in the form of various ratios of red and infrared (IR) wavelength bands. Previous research has established significant correlations of IR/red combinations with photosynthetically active biomass in plant canopies (Tucker 1979). A linear regression between LAI and a ratio of IR/red wavelengths, as measured by ATM band 4 (or ATM4, 0.76–0.90  $\mu\text{m}$ , and band 3 (ATM3, 0.63–0.69  $\mu\text{m}$ ), provided an  $r^2$  value of 0.76 with a standard error of 0.380. Another, less successful combination includ-

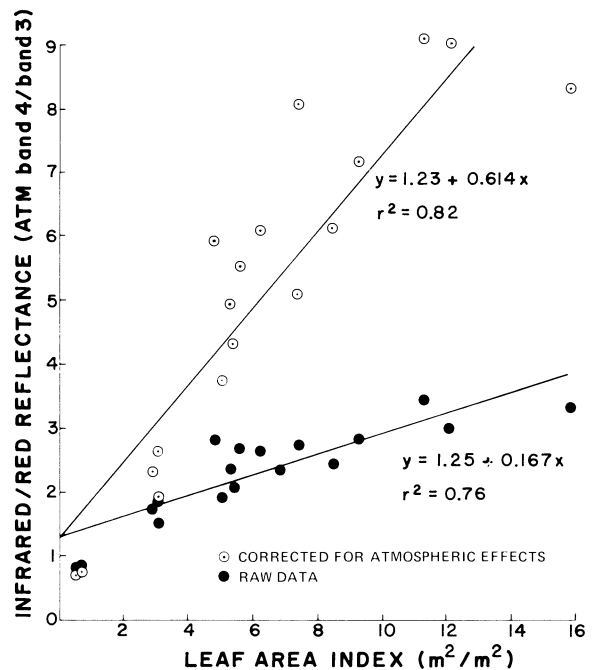


FIG. 2. The relationship between reflectance ( $y$ ), measured as the ratio of Airborne Thematic Mapper (ATM) band 4 (0.76–0.90  $\mu\text{m}$ ) to band 3 (0.63–0.69  $\mu\text{m}$ ), and leaf area index (LAI,  $x$ ) for each of the 18 coniferous forest stands sampled.

ed a ratio known as the normalized difference vegetation index ( $[ATM4 - ATM3]/[ATM4 + ATM3]$ ), with  $r^2 = 0.55$  and a standard error of 0.132. When corrections for atmospheric effects were applied to the raw ATM data, the variance accounted for by the relation between LAI and the ATM4/ATM3 ratio changed to  $r^2 = 0.82$ , with a standard error of 1.187 (Fig. 2). This coefficient of determination was not significantly different from that obtained with the uncorrected ATM data; however, the slope of the regression line increased from 0.167 to 0.614, producing a greater sensor sensitivity to LAI (Spanner et al. 1984).

The correlation of LAI with the IR/red ratio was first established on a tropical rain forest canopy using transmitted light measured on the forest floor (Jordan 1969). More recent studies have observed correlations between LAI values of grass and crop canopies with IR/red ratios from airborne and satellite sensors (Wiegand et al. 1979, Wardley and Curran 1984). The chlorophyll pigments in green leaves absorb radiation in the red (0.63–0.69  $\mu\text{m}$ ) wavelengths. Red reflectance is thus inversely related to the quantity of chlorophyll present in the canopy. Near-infrared radiation (0.76–0.90  $\mu\text{m}$ ) is scattered by internal leaf structure, and is then either reflected or transmitted, allowing multiple layers of leaves to influence overall infrared reflectance (Knippling 1970). In addition, IR/red ratios partially compensate for variations in illumination, view angle, and topography (Tarpley et al. 1984).

We expected two potential complications to the LAI vs. IR/red relationship: the diversity of species covered by the study and the topographic diversity among the different plots. The high correlation found despite these complications suggests that a similar relationship may be possible in a variety of coniferous forests. We do not suggest that this specific relationship be extrapolated to other vegetation types.

Vegetation has been mapped regionally at 1–4 km resolution using the normalized difference vegetation index calculated from data provided by the AVHRR (Advanced Very High Resolution Radiometer) sensor aboard the National Oceanic and Atmospheric Administration's NOAA-7 meteorological satellite (Tarpley et al. 1984, Tucker et al. 1985). The AVHRR data have a more coarse 1.1 km spatial resolution and spectral bands of 0.73–1.1  $\mu\text{m}$  and 0.58–0.68  $\mu\text{m}$ , for near-infrared and red wavelengths, respectively, somewhat wider than the Thematic Mapper bands used in this study. While this vegetation index is currently being used to qualitatively monitor vegetation dynamics and indicate productivity, we expect that it will also correlate with LAI.

Satellite-derived measures of vegetation cover type and LAI may be used to provide more direct estimates of the carbon content and exchange rates of global

vegetation than are possible with current data. Satellite data can also provide a methodology for the quantitative study of large-scale vegetation disturbances such as desertification of the Sahara region or tropical deforestation in the Amazon basin (Tucker et al. 1984, Woodwell et al. 1984). These capabilities will be critical in future global ecological research.

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## HERBIVORE-LIMITED ESTABLISHMENT OF A SONORAN DESERT TREE, *CERCIDIUM MICROPHYLLUM*<sup>1</sup>

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Knowledge of factors limiting the establishment of long-lived perennial plants in desert communities is required for a better understanding of species distributions, abundances, and diversity within these communities. In this paper I document factors limiting the establishment and distribution of a common Sonoran Desert tree, the foothill paloverde (*Cercidium microphyllum*). This species is a conspicuous part of the vegetation in mid- and upper-bajada habitats as well as in rocky uplands throughout the Sonoran Desert, contributing up to 30% of the plant cover in some habitats (MacMahon and Schimpf 1981). I suggest that consumption of *Cercidium* seedlings by herbivores limits successful establishment of this tree species to refuges provided by canopies of other established perennial plants.

### Materials and Methods

Fieldwork was conducted in 1983 and 1984 at three Sonoran Desert sites in bajada habitat with slopes of <2% and soils primarily of gravel and sand. (1) Saguaro National Monument West (SNMW): A 200 × 500 m study area was located directly north of the northwest corner boundary of the Tucson Mountain Unit at the intersection of Rudasill and Sandario Roads (32.3° N, 111.2° W). (2) Organ Pipe Cactus National Monument (ORPI): A 4000 × 300 m study area paralleled highway 85; its northern boundary was 1 km south of the National Park Service visitors' center (31.9° N, 112.8° W). (3) Kino Bay (KINO): Located at Punta Arenas, 40 km north of Bahia Kino, Sonora, Mexico, along the coastal road towards Puerto Libertad; the 300 × 100 m study site was situated 1.5 km from the Gulf of California (29.2° N, 112.2° W). At an additional site located on the southeast-facing slope of Twin Peaks in Organ Pipe Cactus National Monument, 2 km north of the visitors' center, the distribution of *Cercidium* saplings was examined in rocky upland habitat of ≈20–30% slopes with substrate composed entirely of massive igneous rock (trachyandesite) and boulders.

At the study areas, each *Cercidium microphyllum* sapling with basal trunk diameter between 1 and 7.5 cm (at SNMW and ORPI) or between 1 and 5 cm (at KINO) was recorded, and any association with a perennial plant was noted. An association was scored if