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REMOTE SENSING OF THE LEAF AREA INDEX OF TEMPORATE CONIFEROUS FORESTS

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ABSTRACT

An empirical model was developed to estimate the one sided leaf area index (LAI) of temperate coniferous forests using Daedalus Airborne Thematic Mapper data. The relationship between the ratio of Thematic Mapper bands 4 (.76-90 um) and 3 (.63-69 um) and leaf area index was investigated for closed canopy or fully stocked forest stands along an environmental gradient across west-central Oregon. Preliminary results show that a good relationship exists between near IR/red reflectance and the leaf area index of conifers. An asymptotic relationship between IR/red reflectance and LAI was observed, with radiometric near-saturation occurring at an LAI of approximately 7-8. The reflectance/LAI relationships appeared to be species independent for conifers. Atmospheric and topographic effects may degrade the relationship between LAI and reflectance. Techniques for the reduction of the influence of these effects are under investigation.

I. INTRODUCTION

Of the many structural variables that can be measured in forest ecosystems, possibly the most useful for quantitative ecosystem analysis are leaf area and foliage biomass. Leaf surface area is functionally related to the exchange of carbon dioxide, water and oxygen; and strongly correlated to the rate of photosynthesis, evapotranspiration, and respiration (Gholz, 1982). Leaves also represent the surface medium for the biogenic emmission of hydrocarbon gas species and for the interception of rainfall and radiation (Peterson et al., 1983). The interaction of solar radiation with the plant canopy is important for capturing energy to drive these functional processes. The manner in which solar radiation interacts with the plant canopy also provides a means to measure leaf area. The penetration of light into the canopy and the consequent reflectance and scattering properties are potentially measurable by remote sensing instruments, such as the Thematic Mapper aboard Landsat 4 and 5. Reliable estimates of leaf area, or leaf area index (LAI) (leaf area per unit of ground area), are required as input for proposed biogeochemical cycling, photosynthesis and net primary productivity models that will be linked to environmental driving forces at satellite resolutions (Rambler et al., 1983; Wittmer et al., 1983; Peterson and Mouat, 1984; Botkin and Running, 1984).

This paper describes preliminary results from research involving the remote sensing estimation of the leaf area index of temperate coniferous forests using data acquired from the Daedalus Airborne Thematic Mapper (referred to as Thematic Mapper Simulator for the purposes of this paper). The study area for this research follows an environmental gradient across west-central Oregon, where leaf development varies in response to temperature and moisture. Leaf area indices along the transect range from 1-20 m^2/m^2 (one sided-LAI) (Gholz, 1982). The relationship between the ratio of Thematic Mapper Simulator (TMS) channels four (.76-.90 um) and three (.63-69 um) and the leaf area index for selected closed canopy or fully stocked forest stands along this gradient was analyzed and is reported here. Results from this study will be used to relate the structural variable, LAI, to aboveground net primary production (ANPP) and to nitrogen cycle processes.

II. BACKGROUND

A. Oregon Transect Study Area

A transect across Oregon (Figure 1) was selected as the study area for this research because of the existence of a

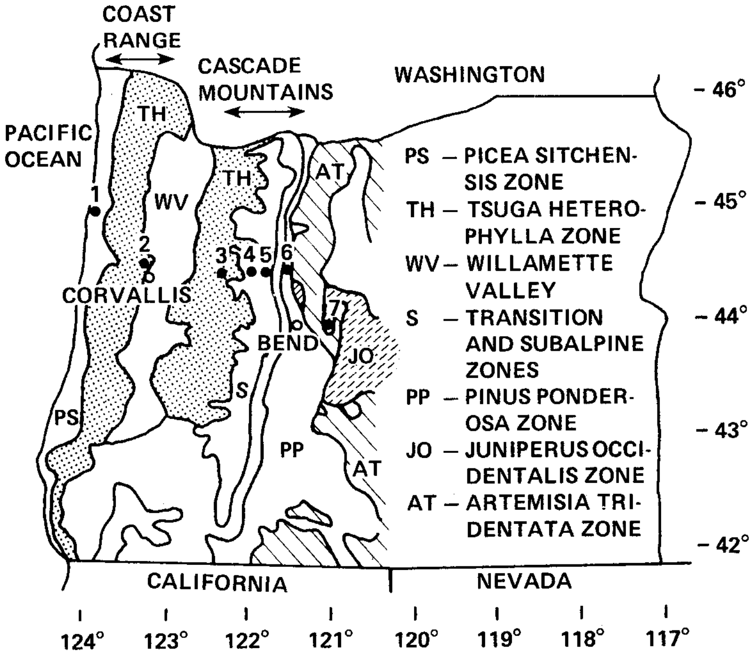


Figure 1. Location of transect and vegetation zones in Oregon. The numbers refer to the location of the PSUs within the seven geographic zones presented in Table 1.

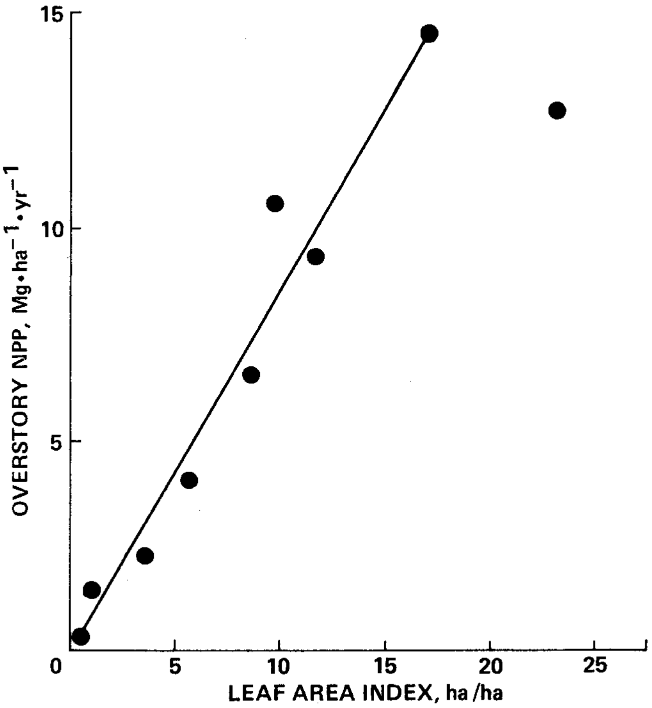
broad range of leaf area indices, and the availability of appropriate allometric equations for the estimation of leaf area index. The coniferous forests of western Oregon offer an extreme variation of forest environments in a relatively confined geographic area. Leaf area and biomass accumulations of coniferous forests along the Oregon coast and in the western Cascade range are among the highest reported in the world, with values upwards of 23 m^2/m^2 (Waring and Franklin, 1979). A number of studies have been conducted in western Oregon investigating the ecological significance of leaf area index, largely through the Coniferous Forest Biome Project of the U.S. International Biome Program (Gholz et al., 1976; Grier and Running, 1977; Waring et al., 1978; Gholz, 1982).

Two studies in particular examined regional trends in coniferous forest LAI in relation to climatic parameters by selecting study area transects within a narrow range of latitude from the Oregon coast to the interior desert. Grier and Running (1977) concluded that maximum community leaf area was primarily a function of site water balance rather than species composition. Gholz (1982) examined the relationship of aboveground net primary production, leaf area, and biomass with climatic variables along a transect crossing eight major vegetation zones. He found that a strong relationship existed between structure (leaf area and biomass) and function (net primary production) over a broad range of natural and mature ecosystems in the Pacific Northwest (Figure 2).

As a byproduct of these studies, a relatively complete set of allometric equations for estimating leaf area and foliage biomass have been developed for tree species in the Pacific Northwest (Gholz et al., 1979; OSU, 1983). Hence, the criteria for selection of a study area for the remote sensing of coniferous forest LAI was met with this Oregon transect. Study areas were identified within seven vegetation zones across west-central Oregon (Figure 1). A ground sampling scheme was developed which closely followed, and in some cases overlapped with, the study sites used by Gholz (1982).

B. Remote Sensing of Biomass

The fundamental radiometric features of remote sensing in the visible and near infrared regions of the electromagnetic spectrum for LAI and green biomass determinations are high absorption in the red region (Thematic Mapper channel 3 .63-.69 um), and strong reflectance in the near infrared (Thematic Mapper channel 4 .76-.90 um) (Woolley, 1971). The low reflectivity in the .63-.69 um region is



SOURCE: GHOLZ, H. L. 1982. ECOLOGY, 63 (2): 469-481.

Figure 2. This plot shows the relationship between overstory net primary productivity and leaf area index for the Oregon transect.

due to strong spectral absorption of incident radiation by chlorophyll pigments. Reflectance in this region is inversely related to the quantity of chlorophyll present in the plant canopy. In the near infrared region, increased reflectance is due to low absorption and the high degree of inter and intra-leaf scattering in the plant canopy. The intra-leaf scattering is a function of the cellular structure of the leaves. Reflectance in the near infrared region is directly related to green biomass. In the near infrared region, a substantial amount of the incident energy is transmitted through the leaves, allowing the lower leaf layers within the canopy to contribute to the spectral reflectance. As many as eight layers of leaves contribute to the total reflectance of a plant canopy in the near infrared (Meyers, 1975). An asymptotic relationship between biomass and near infrared relectance is reached at a level approximately two to three times greater than the level that it occurs between biomass and red reflectance (Tucker, 1977).

The atmospheric absorption/transmittance properties of the near infrared region and the red region are very similar (Tucker et al., 1981). Ratios can be used to compensate for first order variation in solar spectral irradiance. These atmospheric absorption/transmission similarities, coupled with the different response to green plant canopies, make ratios of the red and near infrared useful for monitoring vegetation biomass and leaf area index.

A large body of literature exists relating linear combinations of remote sensing variables to biomass and leaf area index. Kanemasu (1974), using a hand-held radiometer, developed regression relationships between LAI and the IR/red ratio for sorghum and soybean crops with good to excellent correlation coefficients (0.75 to 0.98). Tucker (1979) examined the correlations between leaf biomass, leaf area, water content, chlorophyll content of Blue Grama grass and a number of linear combinations of red and green bands, and red and near infrared bands. He concluded that the IR/red ratio, the square root of the IR/red ratio, the normalized difference (IR-red/IR+red) and other IR-red linear combinations were sensitive to the amount of photosynthetically active vegetation present in the plant canopy. Holben et al., (1980) investigating many plant canopy variables including green LAI, green leaf biomass, total LAI, wet-stem biomass and total wet biomass found that the most significant correlations for soybeans were between the IR/red ratio and green leaf area index and/or green leaf biomass.

The aforementioned studies attempted to determine the predictive capability of remote sensing instruments to measure biomass or LAI of grasses and agricultural crops. The estimation of biomass and LAI of forest canopies directly through linear combinations of remote sensing data is only recently under investigation. Logan (1983) found a non-linear relationship between the near infrared/red ratio and total aboveground biomass using Landsat MSS and AVHRR data. Research is in progress, (Botkin and Estes, 1984), to estimate the leaf area indices of boreal forests in northern Minnesota using multi-platform remote sensors.

III. DATA COLLLECTION

A. Field Data Collection

The ground sampling scheme employed was designed to provide a substantial range in LAI values, to characterize the variation in LAI within geographic zones and within the basic sampling units, and to provide adequate ground sample data to allow for meaningful correlations with the

TMS image data. The gross variation in LAI across the Oregon transect has been well documented (Grier and Running, 1977; Gholz, 1982). The characterization of local variation in LAI was accomplished by selecting primary sampling units (PSUs), within each geographic zone for measurement. PSUs represent closed-canopy or fully-stocked coniferous forest stands, lacking significant disturbance or natural mortality, and were located on relatively shallow planar slopes. PSUs were established at sites with homogeneous overstory and topographic conditions of at least five hectares, to provide a useful sample size of digital image data. Eighteen PSUs were identified in the field and on aerial photos.

Within each PSU, four secondary sampling units (SSUs), each 0.1 ha in size, were established. These were planimetrically square, slope-corrected fixed plots diagonally opposed at random distances from a central point of the PSU. Species, stem diameter at breast height (DBH), and crown-stem ratio were recorded for all overstory trees greater than five cm DBH for each SSU. In addition, a subsample of trees distributed by species and size range, were measured for height, sapwood area, age and radial growth. This sampling strategy provided adequate characterization of the PSUs and their inherent variability, while allowing for sampling a reasonable number of sites in a limited time. At each geographic zone (excluding the east-slope Cascades zone) one PSU overlapped with a Gholz study plot. Other PSUs were located within a few kilometers of each Gholz site to avoid problems of extrapolating leaf area/foliage biomass conversion factors to untested areas.

B. Remote Sensing Data Acquisition

Digital remote sensing data used in this experiment were collected by a Daedalus Airborne Thematic Mapper aboard an ER-2 high altitude aircraft on August 15, 1983. The spectral and radiometric characteristics of the TMS data are nearly identical to data available from the Thematic Mapper. The spatial resolution of the TMS data is approximately twenty meters. Scan angle dependent illumination variations of the aircraft acquired TMS data were analyzed, and were found to be negligible.

Because the Oregon transect covers 250 km, ranges from sea level to over 1600 meters in elevation, and extends from the wet Pacific coast to the dry, interior desert, variable atmospheric conditions are encountered. To account for these atmospheric variations, absolute irradiance and near surface radiometric measurements were made at each geographic zone using a Barnes radiometer mounted on a helicopter. Simultaneous irradiance measurements with the ER-2 overflight were obtained at the highest and the near lowest elevations on the transect. These data, not yet analyzed, will allow the calculation of first order atmospheric effects along the transect.

IV. DATA REDUCTION AND ANALYSIS

A. Field Data

A total of 18 PSUs were sampled during the summer of 1983. Raw field data were subsequently reduced and analyzed using algorithms derived from appropriate sources (OSU, 1983; Waring, 1983; Kaufman et al., 1982; Gholz et al., 1979; Brown, 1978; Snell and Brown, 1978; Gholz et al., 1976) These algorithms are based on allometric equations produced during the Coniferous Forest Biome studies. The species specific equations are developed by destructively sampling trees over the range of size classes. Biomass components of the tree, such as foliage biomass, are regressed against easily measured forest structural parameters, such as diameter at breast height (DBH). Actual foliage biomass of the tree is obtained by measuring the green and oven-dried weight of a sub-sample of foliage. A correction factor is calculated and applied to the total green weight of the crown. Foliage biomass is then regressed against DBH to provide a predictive equation. Most of the equations are of the form $\ln(y) = a + b*\ln(x)$, where y is foliage biomass (kg) and x is diameter at breast height (cm).

Foliage biomass is then converted to leaf area using green leaf area/dry weight ratios, determined from a subsample of foliage. Calculation of leaf area index was accomplished by summing individual tree leaf areas over an SSU, and dividing by the area of the fixed plot (0.1 ha).

Table 1 summarizes the average LAI (one-sided), stand structural variables, and species composition of the PSUs. Because the average LAI values of the PSUs are based on the four SSU LAI estimates, variances associated with the mean PSU LAI values were calculated and are listed in Table 2.

B. Image Data

A digital subset of the seven study areas was generated from the north-south flightline segments. The seven Thematic Mapper bands were extracted from the twelve channel Daedalus data sets. PSU delineation was performed using an interactive image processing display

Table 1. Summary of mean LAI, structural variables, and species composition for the 18 PSUs within the seven geographic zones.

GEOGRAPHIC ZONE	DOMINANT TREE SPECIES	PSU	AVERAGE LAI	AVERAGE DBH, cm	AVERAGE BASAL AREA, m^2/ha	AVERAGE STEM DENSITY, trees/ha
WESTERN COAST RANGE ZONE 1	TSUGA HETEROPHYLLA PICEA SITCHENSIS	9	15.4	34.7	114.6	1115
		11	11.1	58.6	99.1	283
	PICEA SITCHENSIS	10	5.7	55.6	120.5	410
INTERIOR COAST RANGE ZONE 2	PSEODOTSUGA MENZIESII ABIES GRANDIS ACER MACROPHYLLUM	8	5.0	50.5	62.5	220
		18	4.0	45.5	44.2	180
LOW-ELEV. WEST CASCADES ZONE 3	PSEUDOTSUGA MENZIESII	13	6.5	34.0	59.7	505
		17	6.7	35.2	62.1	493
MID-ELEV. WEST CASCADES ZONE 4	TSUGA HETEROPHYLLA PSEUDOTSUGA MENZIESII ABIES AMABILIS ABIES PROCERA	12	10.9	24.0	95.1	1390
HIGH CASCADES SUMMIT ZONE 5	PINUS CONTORTA ABIES LASIOCARPA	6	5.2	13.2	52.6	2620
		7	3.9	12.7	44.6	2668
	TSUGA MERTENSIANA	16	4.5	23.0	59.4	1045
EAST-SLOPE CASCADES ZONE 6	ABIES CONCOLOR	5	5.1	12.5	46.9	2370
	PSEUDOTSUGA MENZIESII ABIES CONCOLOR	4	5.4	18.7	56.5	1525
	PINUS PONDEROSA PSEUDOTSUGA MENZIESII	3	3.1	30.1	33.0	373
	PINUS PONDEROSA	14	3.1	15.4	34.9	1085
		15	2.8	11.4	35.4	1761
INTERIOR HIGH DESERT ZONE 7	JUNIPERUS OCCIDENTALIS	1	0.6	77.4*	22.4	265
		2	0.6	124.2*	26.0	154

*BASAL CIRCUMFERENCE FOR JUNIPERUS OCCIDENTALIS

system on a super minicomputer. The eighteen PSUs were delineated using the digital data displayed on a color monitor. PSU sites previously located in the field on color infrared aerial photography were referenced during boundary delineation. The means and variances of each channel were calculated for all PSUs.

The mean spectral response for each PSU, each channel, was converted to radiance (milliwatts per square centimeter per steradian) based on the gain settings published in the flight summary report. The ratio of TMS channels 4 and 3 were regressed against the leaf area index for each PSU. In addition, nonlinear relationships between the near IR/red ratio and LAI were investigated using a power transform of these data.

V. RESULTS AND DISCUSSION

The summary of field measurements for the eighteen PSUs is provided in Table 1. The measured leaf area index is well distributed and varies from 0.6 to 15.4 m^2/m^2. These values account for most of the LAI range that can be expected worldwide for conifers.

Table 2. Variances associated with the mean PSU leaf area index values.

ZONE	PSU	MEAN LAI	VARIANCE
1	9	15.4	1.281
1	10	5.7	0.685
1	11	11.1	10.718
2	8	5.0	7.221
2	18	4.0	1.481
3	13	6.5	0.877
3	17	6.7	0.088
4	12	10.9	1.741
5	6	5.2	0.000*
5	7	3.9	5.498
5	16	4.5	0.260
6	3	3.1	0.943
6	15	2.8	0.910
6	14	3.1	1.444
6	4	5.4	1.138
6	5	5.1	1.025
7	1	0.6	0.007
7	2	0.6	0.053

*ONLY ONE SSU WAS SAMPLED AT PSU 6

A good relationship is evident between one-sided LAI and the near IR/red ratio (Figure 3), with an R^2 of .71, significant at the .01 level. As expected from review of the canopy modeling literature, LAI and the 4/3 ratio are nearly linearly related up to an LAI of approximately 7-8. Above this level, the relationship approaches an asymptotic state. The near IR/red ratio increases above an LAI of eight, but much more slowly. Canopy development affects reflectance weakly beyond this point. The fact that the canopy affects reflectance at all beyond an LAI of eight may be due to openings between branches, allowing radiation to penetrate within the crown.

A nonlinear relationship between LAI and near IR/red reflectance was explored using the power function $Y = aX^b$, where Y is the near IR/red ratio, X is the LAI and a and b are the coefficients. Estimates of a and b were obtained by fitting the power function directly by least squares using arithmetic units. This fit provided an R^2 of .87, and described the asymptotic relationship between LAI and reflectance quite well. The critical assumption in using this model is that the variance of Y is constant for each X, when expressed in arithmetic units.

Figure 3 indicates that the reflectance/LAI relationships were species independent for conifers, even though the morphological/physiological characteristics of the species gradient is large. The full range of LAI for these conifer stands align along the power function line fairly well. Interestingly, the worst outlier of this data set, PSU 18, consists of approximately twenty percent of a deciduous tree species, Big-Leaf Maple (<u>Acer macrophyllum</u>). The near IR/red reflectance of PSU 18 was substantially higher than the regression prediction of LAI. Different spectral and physical properties between conifer needles and broad leaves account for these differences.

The topographic orientation of selected PSUs affected the spectral response. In the low elevation Cascades site, PSUs 13 and 17 (Table 1) have LAIs of 6.5 and 6.7, respectively. However, the south facing PSU has an IR/red ratio higher than the corresponding ratio of the north facing slope. In addition to the topographic effect, it has been reported that additive path radiance and skylight irradiance cause an increase in ratios (with the longer wavelength in the numerator) when proceeding from poorly to well illuminated sites (Kowalik, 1983). Atmospheric and topographic effects require further investigation to determine their impact on the estimation of the leaf area index of coniferous forests.

The spatial variability of the PSUs as expressed by the four SSUs is shown in Table 2. Some PSUs, such as PSUs 9 and 10 in the western coast range, and PSUs 13 and 17 in the low elevation Cascades, vary

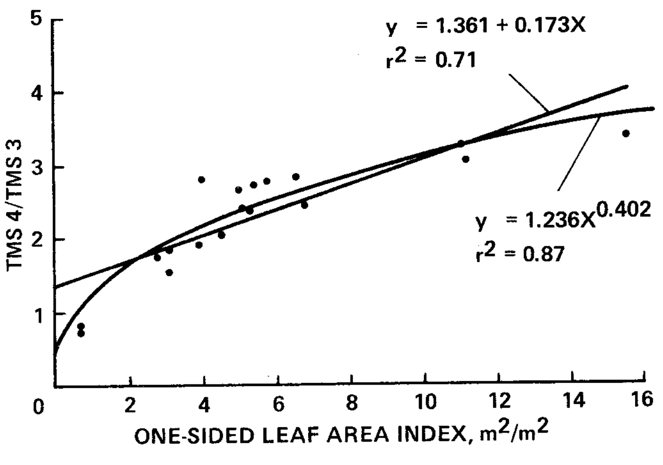


Figure 3. Relationship between TMS 4/TMS 3 and one-sided leaf area index for the Oregon transect. The residual standard deviation of Y for the linear regression function is .419. The residual standard deviation of Y for the non-linear regression function is .286.

only slightly. These are relatively young (approximately 100 years old), even aged stands. Other PSUs, such as PSU 8 in the interior coast range have significant variability. The Douglas fir (Pseudotsuga menziesii) stand is relatively old (upwards of 450 years), with many large irregularly spaced trees, affecting the variance of the four SSUs within the PSU. This variation is significant when correlative relationships are investigated at the PSU level.

Another highly variable site is PSU 11 from the western coast range. As indicated in Table 2, the variance of this PSU is 10.3. In addition, the leaf area index of this PSU is somewhat lower than what the near IR/red ratio suggests. This underestimation is due to the averaging of four SSUs in a variable PSU. This PSU has three SSUs with approximately average LAI values, given it's reflectance, and one SSU signifcantly below average. A solution to the problem of heterogeneity within a PSU is under investigation through examination of the relationship between reflectance and LAI at the SSU level.

VI. CONCLUSIONS AND FUTURE WORK

A good predictive relationship exists between leaf area index and the IR/red ratio for coniferous forest stands. A conifer species independent asymptotic relationship was observed between LAI and near IR/red reflectance, with near radiometric saturation occurring at an LAI of approximately 7-8. However, this relationship does not hold up when applied to other vegetation types. For example, grassland and Alder (vegetation types not selected as PSUs), in addition to PSU 18 (Big-Leaf Maple) had higher IR/red ratios than many of the coniferous forest sites, although their leaf area indices were lower. This may be attributable to increased backgound reflectance and/or to the different spectral reflectance characteristics of their respective canopies. Extrapolation of equations estimating the LAI of temperate coniferous forests can be applied regionally only after stratification of an area into broad vegetation types. Each major vegetation type would require independent equations for the estimation of leaf area index or biomass.

Leaf area index was well estimated using the near IR/red reflectance ratio for closed canopy temperate coniferous forest stands. We intend to investigate the effect of variable canopy closure on reflectance in future work. Because the effect of topographic orientation was evident, techniques to reduce the effect of topography will be explored. The helicopter-mounted radiometer data will be analyzed to determine if atmospheric effects impact the estimation of LAI from remotely sensed data. Finally, we will investigate the relationship between LAI and reflectance at the SSU level, as well as determine the relationship between other spectral ratios and transforms of TMS data for the estimation of leaf area index of temperate coniferous forests.

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