Lin, T., P.M. Rich. D.A. Heisler, and F.J. Barnes. 1992. Influences of canopy geometry on near-ground solar radiation and water balances of pinyon-juniper and ponderosa pine woodlands. American Society for Photogrammetry and Remote Sensing 1992 Annual Meeting. Albuquerque, NM. pp. 285-294.

INFLUENCES OF CANOPY GEOMETRY ON NEAR-GROUND SOLAR RADIATION AND WATER BALANCES OF PINYON-JUNIPER AND PONDEROSA PINE WOODLANDS

by

Teng-Chiu Lin, Paul M. Rich, Diana A. Heisler
Biological Sciences
University of Kansas
Lawrence, KS 66045

Fairley J. Barnes
Environmental Science Group
Mailstop J495, EES-15
Los Alamos National Laboratory
Los Alamos, NM 87545

ABSTRACT

Influences of canopy geometry n near-ground solar radiation and water balances were studied in pinyon-juniper and ponderosa pine woodlands. Canopy geometry was characterized using overstory mapping techniques; daily and seasonal near-ground solar radiation regimes were calculated using hemispherical photography and Sunfleck Ceptometer techniques; and soil moisture was assessed using time-domain reflectometry and neutron scattering techniques. Canopy geometry directly influenced near-ground solar radiation penetration, which in turn correlated negatively with soil moisture, particularly during the summer. The distribution of canopy openings as a function of zenith angle gave a unique geometric signature for each of the canopies studied, a result that may be generalizable to other canopies.

INTRODUCTION

Plant canopy geometry plays a central role in determining ecosystem processes because of its effects on microenvironment, as well as on local and regional environments. In this study we examine relations between canopy geometry, near- ground solar radiation regimes, and water balance within ponderosa pine and pinyon-juniper woodlands of New Mexico. The spatial distribution of near-ground solar radiation in such forests is of interest because it provides the opportunity to examine fundamental geometric relations in which solar angle interacts with the distribution of canopy elements. The understory solar radiation regime has importance in determining microclimate heterogeneity, which directly affects water balance. By examining a series of forest canopies with different geometries, it is possible to assess the importance of different solar radiation regimes on components of water balance such as evaporation and transpiration.

METHODS

Study Site

A series of three transects were established for study of native canopy geometry and soil moisture at the Los Alamos National Laboratory (LANL) National Environmental Research Park (NERP), New Mexico: 1) a 100 m transect in pinyon-juniper (PJ) woodland, 2) a 50 m transect in open-canopy ponderosa pine (PP) woodland, and 3) a 50 m transect in closed-canopy PP woodland.

The PJ woodland was sampled along a linear transect located at LANL Technical Area 51 at approximately 2000 m (6500 ft) elevation. The transect was 100 m long, with a compass bearing of approximately 33° and a slope of approximately 2%. The dominant overstory species were *Pinus edulis* (pinyon pine) and *Juniperus monosperma* (one-seeded juniper). *Cercocarpus breviflorus* (mountain mahogany) and *Quercus gambelii* (Gambel oak) occurred as occasional subcanopy shrubs. The location receives approximately 35 cm of precipitation per year, with about 55% as snowfall. Most rain occurs as afternoon thundershowers during the summer monsoon season, mid-July through late August. The primary snowfall months are November through February.

The PP woodland was sampled along two 50 m linear transects located at LANL Technical Area 6 at approximately 2310 m (7580 ft) elevation. The transects were situated at the center of sites for future runoff collection stations. One transect, approximate bearing 1330, was in a dense second-growth stand that was harvested approximately forty years ago. The other transect, approximate bearing 970, was located in a more open stand with much older trees. Both transects had a slope of about 6%. *Pinus ponderosa* (ponderosa pine) was the dominant overstory species. The area receives about 50 cm of precipitation annually, with about 50% as snowfall.

Overstory Mapping

We constructed overstory maps for each of the transects, extending 10 m on both sides of the transect. Species, height, Stem diameter, crown dimensions, and location were recorded for all trees and shrubs that were at least one meter tall. Because pinyons and junipers commonly branch below breast height (1.3 m), stem diameter was measured at 0.15 m height in PJ site, and at both 0.15 and 1.3 m for the PP sites. For junipers, which have multiple stems, number of stems and stem diameters were recorded for all stems greater than 0.01 m diameter. Crown shape and size for each tree was estimated and recorded on the maps. We used the video image program IMAGE (Rich *et al.* 1989) to calculate canopy cover for each site from the overstory maps.

Hemispherical Photography

We took hemispherical photographs at sample stations located at one-meter intervals along each of the three transects at levels of 1.0 m and 1.75 m above the ground. Photographs were taken with using a Nikkor 8 mm fisheye lens fitted on a Nikon FM2 body and suspended pointing directly upward in a self-leveling mount (Rich 1988) using Kodak TMAX 400 ASA film. A Nikon MF16 databack was used to imprint unique numbers on each photograph. Most photographs were taken just before sunrise and some were taken just after sunset, times that provided even skylight conditions. Film was developed using Kodak TMAX developer with push processing to 800 ASA, and negatives were archived.

Photographs were analyzed using the video image analysis system CANOPY (Rich 1988, 1989, 1990) to calculate various indices of indirect and direct solar radiation penetration as a function of sky direction, time of day, and time of year. Each photograph was analyzed twice to assess consistency and values from the two analyses were averaged. For each photograph, we calculated indirect site factor (ISF), expressed as a proportion of indirect radiation beneath the canopy relative indirect radiation above the canopy, and direct site factor (DSF), expressed as a proportion direct radiation beneath the canopy relative direct radiation above the canopy. ISF was tabulated as a function of 20 ranges of zenith angle and 8 ranges of azimuth angle, and summarized both without cosine correction (ISFU) and with cosine correction relative to a horizontal plane (ISFC). DSF was tabulated as a function of time of day (at half-hour intervals) and time of year (at monthly intervals), and also summarized both without cosine correction (OSFU) and with cosine correction relative to a horizontal plane (DSFC). For ISF calculations, we assumed a uniform distribution of incoming indirect solar radiation, which makes ISF equivalent to angular area. For DSF calculations, we assumed clear sky conditions and corrected for effects of atmospheric attenuation as a function of zenith angle.

Decagon Sunfleck Ceptometer

We measured photosynthetically active radiation (PAR) using a Decagon Sunfleck Ceptometer (Decagon Devices, Inc.) at the one-meter sample stations along each transect. For each transect, all readings were taken under clear sky conditions and within less than half an hour of each other to control for solar angle. All readings were taken on 13 August 1991, between 9:04-9:18 am solar time for the PP Sites and between 9:42-9:59 for the PJ site. For each sample station, average values were calculated from a series of 10 readings taken at a level of 1.0 m above the ground. The 10 readings were spaced symmetrically about the center of the sample station at 0.1 m intervals. Because the sensors are spaced on a 80 cm linear array, the resulting area sampled was approximately 100 m by 0.8 m for the PJ site and approximately 50 m by 0.8 m for each PP site.

Time-Domain Reflectometry

We used TDR (Topp *et al.* 1980, Topp and Davis 1985) to measure soil moisture at the one-meter sample stations along each transect. PB30 30cm soil probes were implanted at each sample station, with the two rods attached to a twin lead 50 ohm coaxial cable. A PS1502B Power Control Module was used for signal generation, read with a Tektronix 1502B TDR Cable Tester, and digitized with a Campbell Scientific SDMI502 Communications interface attached to an IBM AT laptop computer. One data set was collected on 8 August 1991 for the PJ site and 9 August for the PP site, after a series of storms that left soils near saturation. Another data set was collected on 5 November for the PJ site and 12 November 1991 for the PP site during a period when the soil was dry.

Neutron Scattering Technique

Soil moisture was also measured using neutron scattering techniques (van Bavel 1961, Reginato and Nakayma 1987). Eleven neutron access tubes, spaced approximately 10 m apart, were placed along the PJ site transect in 1988 and soil moisture data are available from 1988 through the present (F. Barnes, unpublished data). Three neutron-access-tube data sets -- from 6 Mar, 21 June, and 8 August 1991 -- were examined. Although moisture data to the depth of 300 cm were available from the neutron access tubes, to make the results comparable to those derived by TDR, only the data for the top 20 cm were used.

RESULTS

Stand Characteristics

A total of 162 trees or tall shrubs in 2 species (*Pinus edulis*, *Juniperus monosperma*) were recorded in the 20 x 100 meter pinyon-juniper transect. In addition, *Cercocarpus breviflorus* and *Quercus gambelii* were present as small shrubs. A total of 25 *Pinus ponderosa* and one *Juniperus monosperma* were recorded in the 20 x 50 meter open-canopy ponderosa transect, and 271 *Pinus ponderosa* were recorded in the 10 x 50 meter closed-canopy PP transect. Mean tree heights (with standard deviations) were 3.4 m (+/- 2.6 m), 12.7 m (+/- 6.3 m), and 9.8 m (+/- 3.8 m) for the PJ, open-canopy PP, closed-canopy PP sites, respectively. The stem basal area was 0.33%, 0.32%, and 0.72% in the PJ, open-canopy PP, and closed-canopy PP sites respectively; the canopy cover was 32.4%, 28.2% and 39.0 % in the PJ, open-canopy PP, and closed-canopy PP site respectively.

For the closed-canopy PP site, the stand density was high (2710 ind/ha); the canopy was relatively unbroken; and tree distribution was relatively homogeneous. For the open-canopy PP site, the stand density was the lowest (250 ind/ha); the spacing between tree crowns was intermediate relative to the closed-canopy PP and the PJ sites; and there was clumping of trees toward the west side of the transect. For the PJ site, the tree density was intermediate

(810 ind/ha); the trees were clumped in groups, commonly ranging from 1-6 and there were large openings between clumps.

Light Penetration

The PJ site had broad fluctuations in all site factors (ISFU, ISFC, DSFU, and DSFC) with relative regularity in amplitude and with frequency commonly between 10-20 m at both the 1.75 and 1.0 meter levels (Table 1, Figure 1). Both mean ISF and DSF differed significantly among the three sites ($p<0.05$), such that the closed-canopy PP site always had the lowest values (Table 1, Table 2). The range and the variation were always largest for the PJ site, intermediate for the open-canopy PP site, and lowest for the closed-canopy PP Site (Figure 1 and Table 1).

In the PJ site, both ISF and DSF were significantly higher at the 1.75 m level than at the 1.0 m level ($p<0.05$, Table 1). However, in both of the PP sites, ISFU and ISFC were significantly lower at 1.75 m height than at 1 m level (Table 1). DSFU and DSFC were significantly higher at the 1.75 m than at the 1.0 m level for the open- canopy PP site, but no significant difference was found between the levels for the closed-canopy PP site (Table 1). DSFU and DSFC significantly correlated with ISFU and ISFC for all sites but the correlation coefficients were highest for the PJ site and lowest for the closed-canopy PP site.

For all three sites, canopy openness (ISFU) decreased as zenith angle increased. Although canopy openness was always lower in the closed-canopy PP site, the two PP sites shared a similar pattern which differed from the Pi site as evident by the slope of the curve (Figure 2). The ISF attenuation with increasing zenith angle occurred much earlier in the PP sites than the PJ site. In the PJ site, ISF attenuation occurred earlier in the 1.0 m level than the 1.75 m level (Figure 2).

Mean PAR measured by the Ceptometer differed significantly among the three transects ($p<0.05$), with the highest values for the PJ site and the lowest for the closed- canopy PP site (Table 1). For July, when data were taken with the Ceptometer, Direct radiation penetration estimated from hemispherical photography showed great variation throughout the day as a function of time (Figure 3).

Table 1. Mean annual solar radiation penetration calculated from hemispherical photographs, PAR measured with a Ceptometer and percent soil moisture measured with TDR. Values are given as the mean ± standard error for the site (n=100 for PJ, n=50 for both open- and closed- canopy PP sites). PJ = pinyon-juniper and PP = ponderosa pine. ISF = indirect site factor, DSF = direct site factor, and U and C = without and with cosine correction respectively.

hemispherical photography, 1.75 m level

	ISFU	ISFC	DSFU	DSFC
PJ	0.449 ± 0.012	0.581 ± 0.018	0.561 ± 0.020	0.583 ± 0.022
Open-Canopy PP	0.405 ± 0.006	0.537 ± 0.009	0.562 ± 0.012	0.583 ± 0.015
Closed-Canopy PP	0.263 ± 0.004	0.365 ± 0.006	0.348 ± 0.006	0.379 ± 0.007

hemispherical photography and Ceptometer, 1.0 m level

	ISFU	ISFC	DSFU	DSFC	PAR
PJ	0.383 ± 0.012	0.510 ± 0.017	0.482 ± 0.019	0.511 ± 0.021	541.6 ± 37.66
Open-Canopy PP	0.417 ± 0.004	0.547 ± 0.006	0.547 ± 0.010	0.568 ± 0.012	346.3 ± 34.19
Closed-Canopy PP	0.281 ± 0.003	0.388 ± 0.004	0.355 ± 0.004	0.388 ± 0.005	136.0 ± 10.61

TDR, 1.0 m level

% Soil Moisture	Aug	Nov
PJ	32.54 ± 0.46	12.45 ± 0.27
Open-Canopy PP	42.49 ± 0.51	12.69 ± 0.61
Closed-Canopy PP	31.10 ± 0.52	13.20 ± 0.61

Figure 1. Canopy openness (indirect site factor, ISFU) as a function of spatial position.

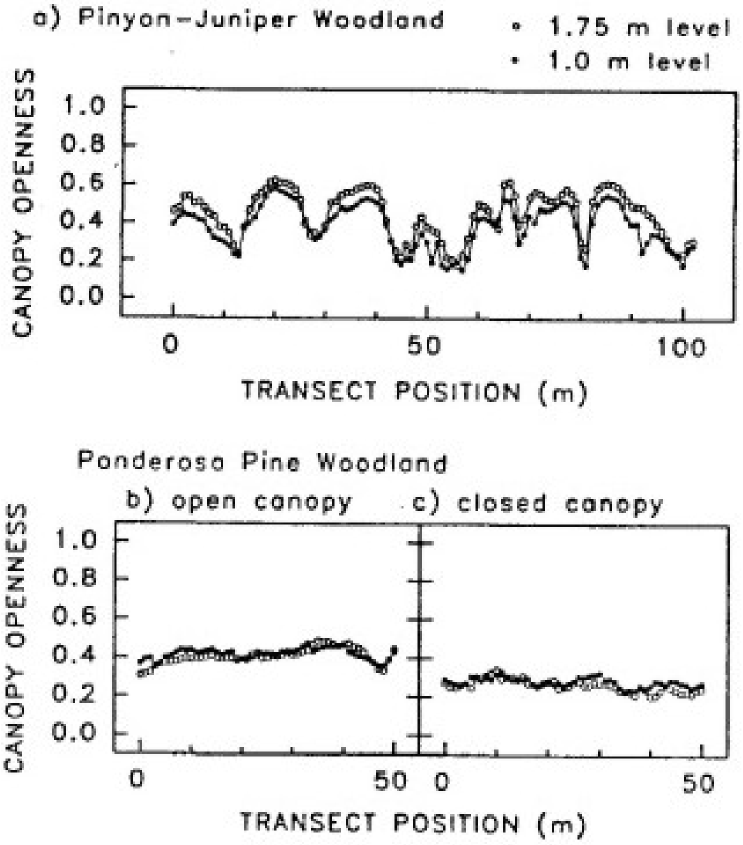


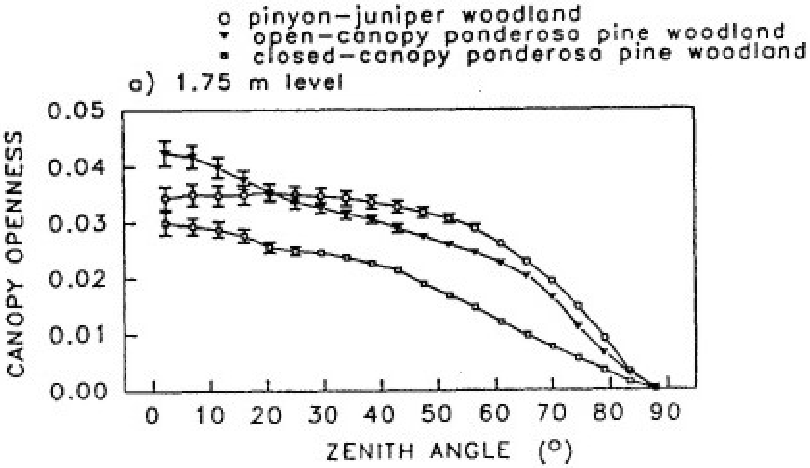
Table 2. Comparisons of means (from table 1) with a one-way ANOVA. Cells with different letters differ at α = 0.05 and the sequence of letters A-C represents the rank of the means in ascending order.

A) among transects

1.75m level	ISFU	ISFC	DSFU	DSFC	
PJ	A	A	A	A	
Open-Canopy PP	B	A	A	A	
Closed-Canopy PP	C	B	B	B	
1.0 m level	**ISFU**	**ISFC**	**DSFU**	**DSFC**	**PAR**
PJ	B	A	B	B	A
Open-Canopy PP	A	A	A	A	B
Closed-Canopy PP	C	B	C	C	A
% Soil Moisture	**Aug**	**Nov**			
PJ	A	A			
Open-Canopy PP	A	A			
Closed-Canopy PP	C	A			

B) within transect	PJ		Open PP		Closed PP	
Level (m)	1.75	1.0	1.75	1.0	1.75	1.0
ISFU	A	B	B	B	B	B
ISFC	A	B	B	B	B	B
DSFU	A	B	B	B	B	B
DSFC	A	B	B	B	B	B

Figure 2. Canopy openness (indirect site factor, ISFU) as a function of zenith angle. Values plotted represent means and standard error.



b) 1.0 m level

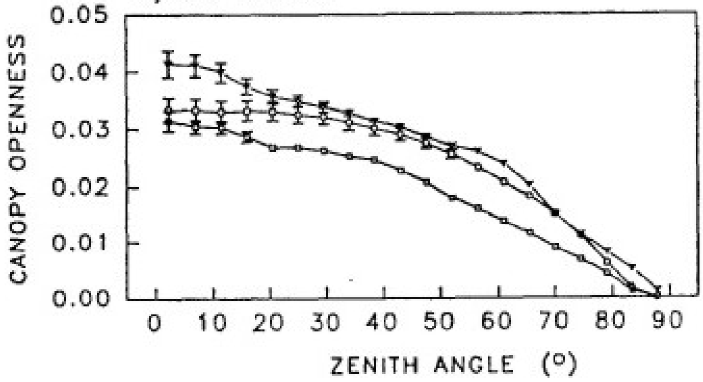
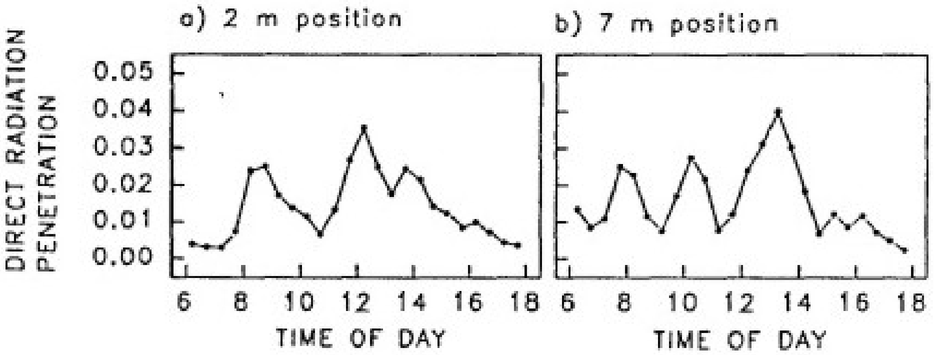


Figure 3. Expected direct radiation penetration (direct site factor, DSFU) as a function of time of day during the month of July for two transect positions in open-canopy ponderosa pine woodland.



a) 2 m position

b) 7 m position

All annual total site factors estimated from hemispherical photographs correlated positively with PAR in the PJ site ($p<0.05$, Table 3). In the two PP sites, the correlation coefficients were much smaller and mostly insignificant (Table 3b and c). PAR was highly positively correlated in the PJ site, less so in the open-canopy PP site and weakly, although negatively, correlated in the closed-canopy PP site (Table 3c). However, direct radiation penetration for the time when Ceptometer data were taken, were highly correlated with PAR measured by Ceptometer for the open-canopy PP site ($r = 0.75$, $p<0.05$).

Soil Moisture

The two soil moisture data sets measured by TDR did not differ significantly among the three transects (Tables 1 and 2a). Soil moisture data collected at August negatively correlated with all of the site factors for all the three sites although only the correlations with DSF for the open-canopy PP site were significant at the 0.05 level (Table 3). Soil moisture measured during November did not relate consistently with site factors. Some of the correlations were positive, some are negative, but the negative correlations with DSF were significant only for the open-canopy PP site. The correlation between soil moisture and PAR was significantly positive for the open- canopy PP site but not for the other two sites (Table 3). When only the locations with neutron access tubes were considered, soil moisture measured with TDR was negatively correlated with DSFU ($r = -0.60$ and -0.50 for the August and November data sets, respectively) and was significant ($p<0.05$) for the August data set. Similarly, the three data sets of soil moisture measured by neutron access tubes had negative correlations with DSFU, with correlation lowest for the March data set and both highest and significant for the September data set ($r = -0.37$, -0.54, and -0.76 for March, June, and September data sets, respectively).

Table 3. Correlation among solar radiation penetration, PAR at 1.0 m level, and soil moisture; absolute coefficient coefficients greater than 0.20 for n = 100 and greater than 0.27 for n=50 are significant (α = 0.05).

A) PJ (n = 100)	ISFU	ISFC	DSFU	DSFC	PAR
ISFC	0.99				
DSFU	0.87	--			
DSFC	--	0.89	1.00		
PAR	0.45	0.45	0.37	0.37	
% Moisture, Aug	-0.002	-0.05	-0.15	-0.15	-0.15
% Moisture, Nov	0.17	0.15	0.08	0.09	0.02

B) Open-canopy PP (n = 50)	ISFU	ISFC	DSFU	DSFC	PAR
ISFC	0.96				
DSFU	0.78	--			
DSFC	--	0.73	0.96		
PAR	0.01	-0.05	-0.33	-0.44	
% Moisture, Aug	-0.04	-0.06	-0.46	-0.58	0.58
% Moisture, Nov	0.16	-0.16	-0.51	-0.55	0.60

C) Closed-canopy PP (n = 50)	ISFU	ISFC	DSFU	DSFC	PAR
ISFC	0.99				
DSFU	0.47	--			
DSFC	--	0.40	0.98		
PAR	0.08	0.07	0.21	0.21	
% Moisture, Aug	-0.03	-0.03	-0.07	-0.04	0.10
% Moisture, Nov	-0.18	-0.15	0.002	0.07	0.20

DISCUSSION

Solar Radiation Penetration as Related to Canopy Geometry

The differences in understory solar radiation among the three sites can be attributed to the differences in tree distribution and canopy geometry. Closed-canopy PP had the lowest levels of solar radiation penetration as a consequence of having the highest canopy cover. Trees of the PJ site had relatively low heights. Thus, the 1.75 m level of the PJ site was relatively closer to open sky than the same level for PP site. This accounts for part of why solar radiation penetration to the 1.75 level was higher in the PJ site than in the PP sites. Solar radiation penetration substantially decreased from the 1.75 m to 1.0 m level for the short trees of the PJ site. For the tall PP woodland, however, solar radiation penetration did not differ greatly between the 1.0 m and the 1.75 m level. This accounts for higher solar radiation penetration at 1.0 m level in the open-canopy PP site than in the PJ site.

The higher correlation between DSF and ISF for the PJ site than for the open-canopy PP site suggests that in the PJ site there was more symmetry in the distribution of openings. ISF is affected by openings in any sky direction, whereas DSF is affected only by openings along the solar track. Greater symmetry means that the openness along the solar track should be a better predictor of openness across the entire sky.

Examining canopy openness as a function of zenith angle can further explain the relationship between canopy geometry and solar radiation penetration among sites. Not surprisingly, the closed-canopy PP site had the lowest solar radiation penetration. The similar pattern of canopy openness attenuation with increasing zenith angle of the open- and closed-canopy PP sites might result from unique canopy geometry. However, canopy geometry for more forests are needed to confirm whether such unique “stand signatures” might exist.

The difference in the angular distribution of openings between open-canopy PP site and PJ site has important implications. At small zenith angles, lateral shading had little effect on solar radiation penetration. Higher canopy openness for open-canopy PP site resulted because of its lower coverage. As zenith angle increased to 50 degrees, canopy openness greatly decreased for PP sites but did not change for the PJ site. The effect of lateral shading as a function of zenith angle on solar radiation penetration occurred earlier in the taller ponderosa pine canopy. That is, the attenuation of canopy openness occurred earlier in places that were relatively lower in the canopy than in places close to the top of the canopy. As soon as the shading effect occurred in the PJ site, however, the rate of attenuation in canopy openness did not differ between PJ site and PP sites as indicated by the roughly equal slopes. This inference was supported by the canopy openness attenuation pattern observed at two levels for the PJ site. The canopy openness curve was relatively much lower for the 1.0 m level than for the 1.75 m level. For the relatively short PJ canopy (3-4 m). the 1.75 m level was relatively much closer to the top of canopy. Because the 1.0 m level had a relatively greater distance to the top of the canopy than the 1.75 m level, the attenuation in canopy openness as a function of zenith angle started earlier in the 1.0 in level (Figure 3 and 4). The lack of such a pattern for the open-canopy PP site may result, again, simply because that in tall canopy woodland there is not much difference in solar radiation penetration between 1.0 and 1.75 m.

Temporal Variation in Solar Radiation and Evaluation of Techniques

Mean ISF and DSF values from hemispherical photographs taken at the 1.0 m level were highest for the open-canopy PP site, but mean PAR measured by Ceptometer was highest for the PJ site. The differences between the two techniques can be largely explained because the values calculated from hemispherical photographs were integrated over the year whereas the Ceptometer readings were made at one point in time. The great fluctuation in direct sunlight penetration as a function of time of day further demonstrates that the PAR measurements taken at one point in time do not characterize the overall solar radiation availability. This weakness accounts for the low correlations between PAR and annual total site factors and for why the correlation between soil moisture and PAR was not consistent with the correlation with site factors.

By contrast, with hemispherical photographs it is possible to make calculations of solar radiation penetration for times of day and year other that the time of photograph acquisition. It is also possible to integrate the measures over time, as is done in calculating yearly ISF and DSF values. Thus, unlike the Ceptometer and most other techniques which require ongoing measurements through time, hemispherical photography can effectively predict solar radiation penetration from canopy geometry. However, to extrapolate solar radiation environment to future or past times with existing photographs, constant canopy geometry is assumed. Such an assumption should be carefully examined if the data from hemispherical photographs are to be used to predict canopy responses to changes in environmental conditions (Gholz *et al.* 1991). Another major limitation of the technique results because uneven skylight leads to uninterpretable photographs. For this reason it is advisable to take photographs under uniform overcast skies or during twilight. Other limitations have been discussed by Rich (1990).

Soil Moisture as Related to Canopy Geometry

Relations between canopy geometry and soil moisture are complex. Local variation in soil moisture is affected by factors such as interception of precipitation, evaporation, and root uptake/transpiration. The data were inconclusive, however we did observe significant negative correlations between DSF and top soil moisture, both measured by neutron access tubes and TDR. Greater canopy openness tended to be associated with lower soil moisture. It is possible that evaporation was higher under conditions of greater openness, particularly during the summer when the temperature was high. The significant negative correlations occurred in the August and September data set and smallest coefficient in the March data set. However, it should not be overlooked that the transpiration by understory vegetation, whose distribution was concentrated on areas with canopy openings, might also explain the lower soil moisture in canopy openings. In addition, tree root distribution might account for the observed results if there was more root growth, or more uptake, in openings.

Soil moisture relations with canopy geometry are further complicated because canopies can intercept up to 40% of rainfall (Parker 1983). Thus, soil moisture may be expected to be higher in larger openings, especially after rainfall events. However, it is more likely that evaporation and transpiration had greater effects on soil moisture. After intensive precipitation, most top soils, whether in openings or under a canopy, were saturated and soil moisture was then more related to the subsequent evapotranspiration than to the precipitation interception by the canopy. The negative, but insignificant correlation between soil moisture and canopy openings in March suggests that canopy interception may be more important in cool seasons when the evapotranspiration is lower.

Further study is necessary to assess the relative importance of evaporation, transpiration by understory plants, root uptake/transpiration by trees, and interception of precipitation as they influence soil moisture heterogeneity. Precipitation interception by the canopy would be expected to be most important immediately after an isolated precipitation event when the soils in the openings were more moist than those shaded by canopy. On the other hand, solar radiation interception by the canopy should be most important during warm and dry seasons when the evaporation is high.

CONCLUSION

Because canopy interception of solar radiation and precipitation act both directly and indirectly on processes of evaporation, transpiration, and root uptake, all of which affect soil moisture, it is very difficult to evaluate the significance of any single factor. The importance of any one factor may shift seasonally or with respect to recent weather. Within PJ woodland we observed greater variability in near-ground solar radiation, which would be expected to lead to more soil moisture heterogeneity than in PP woodlands. A comprehensive approach is necessary to understand the complex relation between plant canopies and water balance. Such an approach requires detailed data about microclimate and all components of water balance, and could use a multiple regression or a multivariate analysis procedure such as principle component analysis to evaluate the significance for each of the factors.

ACKNOWLEDGMENTS

This research was supported by National Science Foundation Grants BSR89-18185 and BSR90-02326, a University of Kansas General Research Fund Grant, the Los Alamos National Laboratory Environmental Restoration Program (under Department of Energy Contract W-7405-ENG-36), the Kansas Applied Remote Sensing Program, and the Kansas Biological Survey. We would like to give special thanks to Kathy Lee and Katie Forrnan for field assistance and to Molly Jones for moral support.

REFERENCES

Gholz, H.L., S.A. Vogel, W.P. Cropper, K. McKelvey, Jr., K.C. Evel, R.O. Teskey, and P.J. Curran. 1991. Dynamics of canopy structure and light interception in *Pinus elliottii* stands, north Florida. Ecological Monographs 61: 33-51.

Parker, G.G. 1983. Throughfall and stemfall in the forest nutrient cycle. Advanced Ecological Research 13: 57-133.

Reginato. R.J. and F.S. Nakayama. 1987. Plastic standards for transferring neutron probe calibrations. International Conference of Measurement of Soil and Plant Water Status, Volume 1, July 6-10, 1987, Utah State University, Logan, Utah.

Rich, P.M. 1988. Video image analysis of hemispherical canopy photography. pp 84-95 In: P.W. Mausel (ed). First Special Workshop on Videography, Terre Haute, Indiana, May 19-20, 1988. American Society for Photogrammetry and Remote Sensing.

Rich, P.M. 1989. A manual for analysis of hemispherical canopy photography. Los Alamos National Laboratory Report LA-11733-M.

Rich, P. M. 1990. Characterizing plant canopies with hemispherical photography. In: N. S. Goel and J. M. Norman (eds). Instrumentation for studying vegetation canopies for remote sensing in optical and thermal infrared regions. Remote Sensing Reviews 5:13-29.

Rich, P.M, D.M. Ranken, and J.S. George. 1989. A manual for microcomputer image analysis. Los Alamos National Laboratory Report LA-11732-M.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content: measurement in coaxial transmission lines. Water Res. Res. 16:574-582.

Topp, G.C. and J.L. Davis. 1985. Measurement of soil water content using time- domain reflectrometry (TDR): a field evaluation. Soil Science Society of America Journal 49:19-24.

van Bavel, C. H. N. 1963. Neutron scattering measurement of soil moisture: development and current status. Soil Science Proceedings 25:329-334.