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Solar Angle Independence in the Relationship between Absorbed PAR and Remotely Sensed Data for Alfalfa

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Multispectral vegetation indices are often used to estimate the proportion of incident photosynthetically active radiation (PAR, 0.4–0.7 μm) that is absorbed by plants for potential use in photosynthesis. Field experiments were conducted near Phoenix, Arizona to establish such predictive capabilities for alfalfa and also to determine the effect of varying solar zenith angles (θ_s) on the relationships. The fraction of absorbed PAR (fA_{PAR}) was measured using a 1-m long line quantum sensor. Canopy reflectance measurements (red, 0.61–0.68 μm; near-infrared, 0.79–0.89 μm) were obtained with a hand-held radiometer. Data were collected for θ_s from 27° to 72°. Statistically significant relationships were observed between fA_{PAR} and red reflectance factors ($r^2 = 0.97$) and several commonly used vegetation indices (ratio, $r^2 = 0.96$; normalized difference, $r^2 = 0.96$; and soil adjusted, $r^2 = 0.93$). Actual values of these parameters varied with time of day, but the relationships between fA_{PAR} and various indices derived from reflectance observations were independent of θ_s, extending the potential usefulness of remote sensing approaches for inferring changes in fA_{PAR} at various times of the day and different seasons and latitudes.

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INTRODUCTION

A growing number of reports have established that the fraction of photosynthetically active radiation absorbed by a plant canopy (fA_{PAR}) can be reliably estimated from multispectral reflectance measurements (Kumar and Monteith, 1981; Daughtry et al., 1983; 1992; Asrar et al., 1984a; Gallo et al., 1985; Wanjura and Hatfield, 1986; Wiegand et al., 1991). These direct predictive approaches are cost-effective and amenable to remote sensing at all levels. Quantitative estimates of fA_{PAR} are useful for driving or validating models of plant growth and development (Norman and Arkebauer, 1991), evaluating the effect of growing conditions on canopy light use efficiency (Asrar et al., 1984b; Russell et al., 1989; Major et al., 1991) and inferring photosynthetic capacity at global scales (Tucker et al., 1986; Tucker and Sellers, 1986). Theoretical analyses exploring the functional interrelations between plant productivity, leaf area index, fA_{PAR}, and canopy reflectance properties have been addressed from various perspectives by Sellers (1985; 1987), Choudhury (1987), and Baret and Guyot (1991).

Single waveband reflectance factors, multispectral vegetation indices (VIs) and fA_{PAR} derive their usefulness because they change as a function of plant growth and development (i.e., percentage cover, leaf area index, phenology, etc.). Since each

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also varies with the direction of incident solar energy (Pinter et al., 1983; 1985; Richardson and Wiegand, 1988; Fuchs et al., 1984), it is important to know whether their interrelations (especially those between fA_{PAR} and VIs) are affected by solar zenith angle (θ_s). Modeling efforts have indicated that the relationship between intercepted or absorbed PAR and remotely sensed data should be relatively insensitive to changes in θ_s (e.g., Asrar et al., 1984a; Shultis, 1991; Goward and Huemmrich, 1992). Empirical evidence supporting a tentative hypothesis of independence for marsh cordgrass (*Spartina alterniflora* Loiseleur) communities was reported by Bartlett et al. (1991, their Fig. 3). Verification of θ_s independence in other plant canopies over a wide range of biomass levels would extend the usefulness of remote sensing techniques for monitoring diurnal, seasonal, and latitudinal trends in fA_{PAR}.

MATERIALS AND METHODS

Experiments were conducted at the University of Arizona's Maricopa Agricultural Center near Phoenix, Arizona during the MAC-VI investigations of bidirectional reflectance from agricultural targets. For measurements described here, 12 m long transects were established in three unreplicated alfalfa (*Medicago sativa* L.) plots having canopies of varying age and biomass (Table 1). A small (1 m × 1.5 m), bare soil target area with a moderate amount of decaying alfalfa litter was located at the edge of the alfalfa plots. The soils were classified as a reclaimed, Casa Grande (fine-loamy, mixed, hyperthermic Typic Natrargids). Observations were conducted at approximately hourly intervals on two successive mornings (7–8 September 1991). Skies were clear with light to moderate haze levels on both days. During these experiments θ_s varied from 27° to 72°. Solar azimuth was not considered as a separate variable because the alfalfa had no discernable row structure.

Photosynthetically Active Radiation

Incident (I_{PAR}), transmitted (T_{PAR}), and reflected (R_{PAR}) components of the photosynthetically active radiation balance (PAR, 0.4–0.7 μm; μmol m^{-2} s^{-1}) were measured using a single, hand-held, line quantum sensor (LI-191, LiCor, Inc.[1]), which was moved among all plots. Data were recorded on a Polycorder (Model 516B, Omnidata, International, Inc.[1]), which also time-stamped each acquisition for later computation of θ_s. The procedure began with six measurements of I_{PAR} having the sensor upright, above the canopy and supported horizontally on its outboard end by a monopod. Next, T_{PAR} was obtained by inserting the sensor (overall physical dimensions measured 0.025 m × 0.025 m × 1.175 m) beneath the canopy at the level of the soil surface at six different spots along each transect. Finally, R_{PAR} was determined at approximately the same six locations in each plot using an inverted sensor, supported by the monopod about 0.75 m above the canopy. Similar measurements were made in the soil plot. The sequence of measurements required 3–4 min per plot. A light balance equation (Gallo and Daughtry, 1986) was then used to compute the fraction of PAR absorbed by the canopy:

[1] Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may also be suitable.

Table 1. Agronomic Characteristics of the Alfalfa on 8 September 1991[a]

	Dry Above-Ground Biomass (g m^{-2})		*Fraction "Brown" Biomass (%)*		*Fraction Leaf Biomass (%)*	
Alfalfa Target	*Mean*	*Std Error*	*Mean*	*Std Error*	*Mean*	*Std Error*
New regrowth stubble	82	9.9	21.5	2.5	40.1	3.3
Lush growth canopy	185	11.5	16.1	2.5	48.6	2.5
Mature Alfalfa	280	31.5	4.5	0.5	36.3	1.5

[a] Data are for 5, 0.5 m^{-2} circular destructive harvest samples in each target.

$$fA_{PAR} = 1.0 - T_{PAR} / I_{PAR} - R_{PAR} / I_{PAR} + fR_{PARs}, \quad (1)$$

where the fraction of PAR reflected from the soil beneath the canopy (fR_{PARs}) was estimated as the product of fractional canopy transmittance (T_{PAR} / I_{PAR}) and the fraction of PAR reflected from bare soil (R_{PARs} / I_{PAR}).

Canopy Reflectance

An Exotech radiometer (Model 100BX, 15° field-of-view, Exotech, Inc.[1]) was used to measure red (0.61–0.68 μm) and near-infrared (NIR, 0.79–0.89 μm) reflectance factors. The radiometer was handheld so as to view each target with a nadir orientation; 24 measurements were taken along the same transect where fA_{PAR} was estimated. Radiometer voltages were recorded on a Polycorder[1]. Reflectance factors were calculated as the ratio of reflected light measured in each plot to incident energy inferred from a time-based interpolation of data collected at 6–7 min. intervals from a calibrated, painted $BaSO_4$ reference panel. Correction factors were applied to the panel data to compensate for its nonlambertian properties.

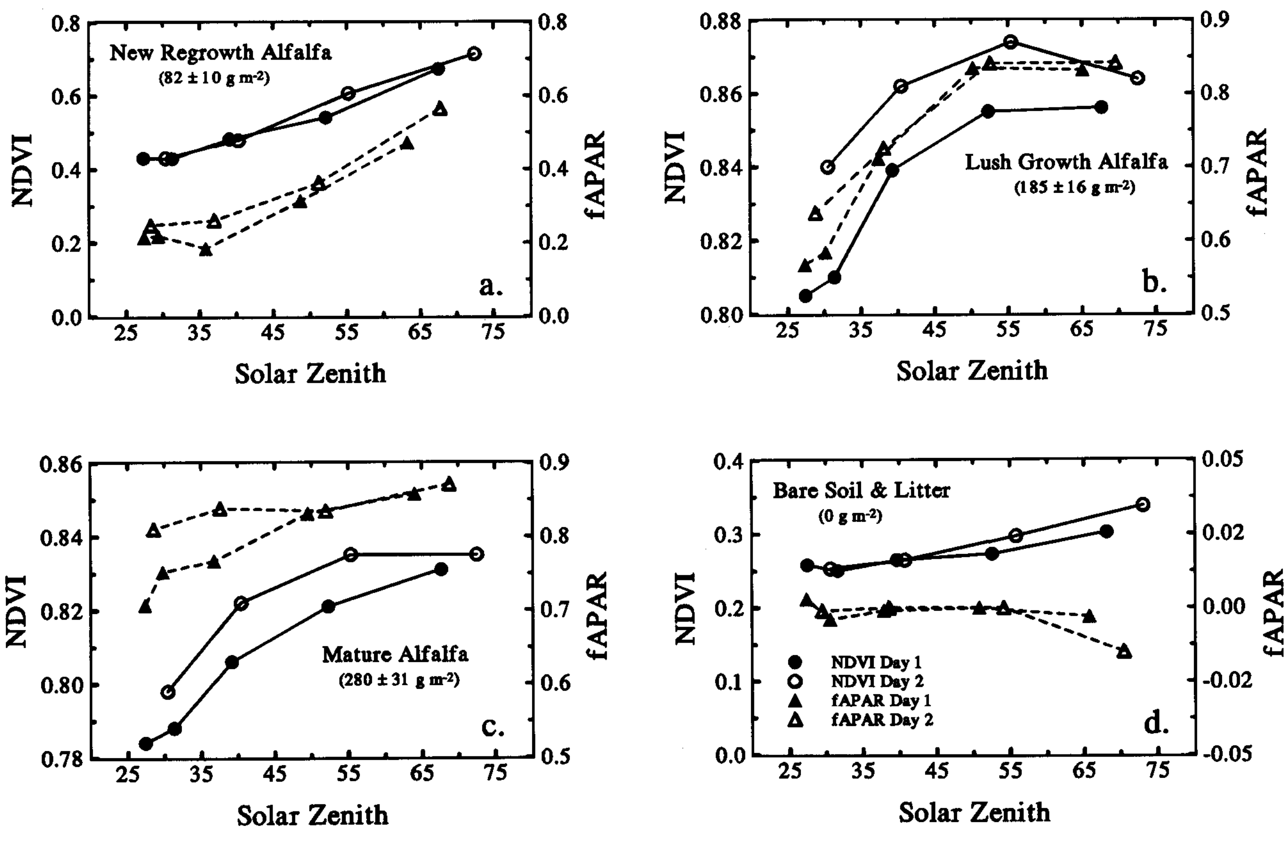
Agronomic Data

At the conclusion of the experiment, above-ground biomass was determined from five circular (0.5 m^2) samples taken at random from the measured transect in each alfalfa plot. These were separated into brown and green components, and dried to a constant weight in a 55°C oven.

RESULTS AND DISCUSSION

Alfalfa canopy reflectance factors, vegetation indices, and fA_{PAR} varied considerably with θ_s during each morning. This is illustrated with a commonly used vegetation index, the normalized difference [NDVI = (NIR − Red) / (NIR + Red)], and fA_{PAR} from all targets on both days (Fig. 1). Maxima for both parameters occurred at large solar zeniths

Figure 1. Normalized difference vegetation index (NDVI) (—) and fraction of absorbed photosynthetically active radiation (fA_{PAR}) (- - -) versus solar zenith angle on 7–8 September 1991. Data are shown for three alfalfa canopies at different stages of regrowth following harvest and a bare soil plot. The vertical scale in each figure is different. The legend for all figures appears in Figure 1d.



when direct beam sunlight entered the canopy obliquely and had the highest probability of interacting with foliage elements. Minima were attained near solar noon when light had the shortest path length through the canopy to the soil.

The largest dynamic range of NDVI and fA_{PAR} was observed in the relatively short, new regrowth alfalfa (Fig. 1a), where midday values were only half those observed earlier in the morning. Values for the lush and mature growth canopies were significantly greater and also changed appreciably with solar zenith. NDVI and fA_{PAR} increased slightly on the second day in these "older" canopies (Fig. 1b and c), corroborating visual impressions of rapid leaf area expansion that had occurred during the previous 24 h.

In the vigorously growing, lush canopy (Fig. 1b), fA_{PAR} was probably underestimated at $\theta_s < 40°$ because inserting the line quantum sensor between closely spaced alfalfa stems caused the canopy to separate slightly along a plane above and parallel to the sensor. A potential solution to this measurement artifact would have been to cut the interfering stems. This was not done since the intent was to avoid destructive activities where reflectance measurements were to be taken. The problem was not encountered in the mature alfalfa (Fig. 1c) where stem density was lower, the "understory" was more open, and the tall, partially lodged plants created an interlocking canopy over the sensor. NDVI and fA_{PAR} values in the soil target (Fig. 1d) were significantly lower than those in the vegetated alfalfa targets. NDVI in the soil plot exhibited a monotonic decrease towards midday which was attributed to a gradual drying of the surface soils and to a reduction in shadows caused by microtopography. The fA_{PARc} from unvegetated targets (Fig. 1d) has no biological significance to the alfalfa plant. Nevertheless, measured values were needed to anchor the fA_{PAR} vs. VI relationship for low biomass levels. Soil fA_{PAR} deviated slightly from expected values of zero at large θ_s (Fig. 1d), because it was difficult to maintain the line quantum sensor exactly horizontal during measurements.

Although not shown in the figures, the NIR, ratio (ratio = NIR / Red), and soil adjusted vegetation index [SAVI = (NIR − Red) / (NIR + Red + 0.5)*1.5; Huete (1988)] in all plots behaved in a manner that was very similar to the NDVI. Red reflectance displayed an inverse relation with solar zenith, with maximum values occurring at smallest solar zeniths (also not shown).

Simple correlation coefficients between fA_{PAR} and the various reflectance indices were computed separately for each alfalfa canopy and also for the alfalfa targets combined with data from the soil (Table 2). All correlations except those between fA_{PAR} and NIR in the regrowth alfalfa stubble were statistically significant at $p < 0.05$. This suggests that θ_s effects on fA_{PAR} were partially compensated for by similar changes in the remotely sensed canopy reflectance parameters.

Figure 2 shows measured values of fA_{PAR} from all targets plotted against red, NIR, and each VI. Linear, quadratic, exponential, and power functions were applied to the data. The solid line represents the curve for the equation having the largest *F*-value from least squares linear regression. Good predictive capabilities were obtained with the red reflectance factor and each of the multiband ratio type VIs. In fact, an exponential

Table 2. Pearson Product-Moment Correlation Coefficients between fA_{PAR} and Canopy Reflectance Parameters Indicated in First Column[a]

Wavelength Interval or VI	*Regrowth Stubble (n = 9)*	*Lush New Growth (n = 9)*	*Mature Canopy (n = 9)*	*All Targets Combined (n = 36)*
Red (0.61–0.68 μm)	−0.960***	−0.833**	−0.887**	−0.946***
NIR (0.79–0.89 μm)	+0.658[NS]	+0.827**	+0.731*	+0.702***
Ratio VI	+0.987***	+0.905***	+0.908***	+0.931***
NDVI	+0.977***	+0.916***	+0.920**	+0.982***
SAVI	+0.979***	+0.904***	+0.835**	0.963***

[a] Significance levels: NS = $p > 0.05$; * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. The soil target is not shown separately because fA_{PAR} should always be zero. However, the soil target is included in the column titled "All targets combined."

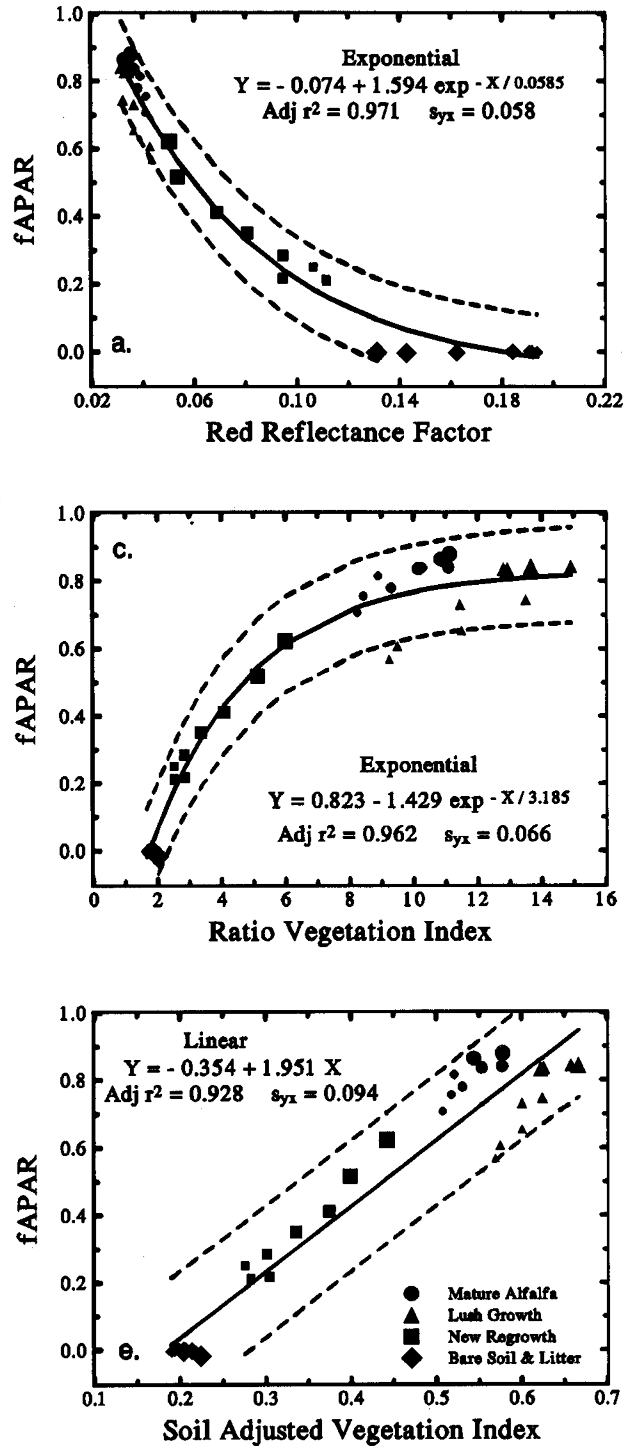


Figure 2. The relation between fA_{PAR} measured with the line quantum sensor and reflectance parameters obtained using the hand-held radiometer. The legend for Figure 2e refers to all figures. Symbol size is proportional to the solar zenith angle at the time of measurement (largest is 72°, smallest is 27°). (—) Best fit least squares regression through all data points; (- - -) 95% confidence limits.

fit of single waveband red reflectance factors (Fig. 2a) predicts fA_{PAR} of all the targets better than VIs which combine both the NIR and visible light (Figs. 2c–e). NIR reflectance factors by themselves (Fig. 2b) performed poorly when regressed against fA_{PAR}. These results, which appear to contradict theoretical predictions of Sellers (1987), are likely a result of the relatively bright, background soil of this study. Because the contrast between soil and dense vegetation was much greater in the visible than in the NIR, the latter was less sensitive to the amount of vegetation that was present (viz., the overlap of NIR reflectances between the soil and regrowth alfalfa, Fig. 2b). Had the soils been darker, the NIR might have been a better predictor.

The fA_{PAR} vs. ratio function (Fig. 2c) was very robust for predictions at less than full canopy cover. The data scatter for the soil target in the ratio was minimal compared with the NDVI (Fig. 2d). However, residual analysis revealed the overall predictive capabilities of the ratio and NDVI to be similar. Compared with NDVI, SAVI (Fig. 2e) tightens the scatter of data for the soil target, while retaining a good fit to the data at low biomass densities. But it does so at the expense of poorer predictions at higher biomass levels.

To test whether the predictive equations shown in Figure 2 were independent of illumination angle, θ_s was included as an additional independent variable in stepwise multiple regression analysis. Without exception, θ_s did not meet conservative criteria (probability < 0.25) for retention in the model. The principal effect of decreasing θ_s (smaller symbol sizes in Fig. 2) was to descend along the regression curves towards smaller fA_{PAR} values. This was shown most clearly by the mature canopy and also the regrowth alfalfa which had the widest range of observed fA_{PAR} conditions.

As the proportion of nonphotosynthesizing elements in a plant canopy increases, VIs decline rapidly while fA_{PAR} values remain relatively large. This causes considerable hysteresis in the fA_{PAR} vs. VI relationship after the onset of senescence (Asrar et al., 1984a; Gallo et al., 1985; Wiegand et al., 1991). At this stage fA_{PAR} begins to lose its biological significance for estimating potential productivity. In fact, in order to predict net carbon exchange of marsh cordgrass canopies, Bartlett et al. (1991) found it necessary to adjust estimates of intercepted PAR by the proportion of green foliage elements in the biomass samples. In the present data set, residual analysis revealed modest effects of phenology which were explained partially by differences plant architecture and physical problems attendant to measuring fA_{PAR} with lightbars and partially by the canopy composition (Table 1). Hysteresis could become more important in alfalfa if the canopy changed significantly. It is likely, however, that a multispectral estimate of PAR captured by the canopy will continue to retain biological relevance.

CONCLUSIONS

The capability of using multispectral vegetation indices to estimate the proportion of incident solar energy absorbed by a community of plants for potential use in photosynthesis is a promising and biologically significant technique that has emerged from agricultural remote sensing research. Although the actual reflectance, multispectral VIs, and fA_{PAR} values may vary dynamically with canopy architecture and viewing/illumination geometry, the relationship between fA_{PAR} and remotely sensed parameters appears independent of illumination angle. This observation extends the potential usefulness of remote sensing measurements for inferring fA_{PAR} to all times of the day, different seasons and latitudes.

In many vegetation types, remote fA_{PAR} estimates will prove superior to conventional, invasive techniques because they are faster and capable of sampling larger areas. Such techniques also have special application in canopies where physical dimensions of the PAR sensor precludes its use. An additional benefit is likely to accrue in senescent, dormant, or deciduous canopies that are dominated by photosynthetically inert elements. There, traditional methods for measuring fA_{PAR} with PAR sensors above and below the canopy are misleading, because absorption remains high although energy is not used in photosynthetic pathways. A remote estimate of fA_{PAR} based on multispectral vegetation indices sensitive to "green" canopy elements will convey the appropriate biological meaning.

Naturally, there are important statistical and biological caveats concerning simplistic interpretations of cumulative plant growth as a function of cumulative absorbed PAR (Russell et al., 1989; Demetriades-Shah et al., 1992). Nevertheless, in the absence of other limiting plant stresses, fA_{PAR} ultimately controls the potential productivity of plants at individual, community, and ecosystem scales. Its remote assessment from space appears well suited for monitoring the effect of climate change on potential carbon balance at large spatial scales. Equally important from a research perspective, these remote sensing approaches may spawn additional insight into interactions between incident solar energy and the dynamic light capturing apparatus of plant canopies (e.g., heliotropic leaf movements, light competition, etc.), which are difficult to assess with conventional tools.

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