

# Spectral Estimates of Absorbed Radiation and Phytomass Production in Corn and Soybean Canopies

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Numerous studies have reported a linear relation between phytomass production and absorbed photosynthetically active radiation (APAR) for a wide range of plant species. Related work has shown that APAR may be estimated from multispectral (visible and near infrared) remotely sensed observations. The combination of these two concepts may provide the basis for development of physically-based agronomic monitoring systems. These concepts are subjected to examination for two primary, mid-latitude crops; corn (*Zea mays* L.) and soybeans (*Glycine max* Merr.). Phytomass, green leaf area index (LAI), absorbed PAR, and multispectral reflectance factors of corn and soybean were measured periodically from planting to mid-grain fill in two growing seasons. As green LAI increased,

the fractional APAR asymptotically approached a maximum value between 0.95 and 0.97. Fractional APAR displayed a linear relation to the normalized difference vegetation index (NDVI), which is relatively independent of species, throughout the growing seasons. However, deviations in the relation were observed between pre- and post-onset of senescence. For both corn and soybean, a linear relation between cumulative APAR and cumulative above-ground phytomass production was found. However, the rate of accumulation per unit APAR was more than twice as great for corn as for soybean. This agrees with previous reports comparing C<sub>4</sub> grasses and C<sub>3</sub> legumes. These results indicate that remotely sensed measurements contribute valuable information concerning energy/mass accumulation in plant canopies. However, implementation of this approach in crop monitoring will clearly require a capability to discriminate between, at least, corn and soybean. The influence of stress events,

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such as drought, nutrient limitations, and disease, will also require further consideration.

## INTRODUCTION

Numerous studies have reported a linear relation between phytomass and absorbed PAR (APAR) for a wide range of plant species (Gallagher and Biscoe, 1978; Gallo et al., 1985; Green, 1987; Prince, 1991; Wiegand and Richardson, 1990). In a healthy plant, adequately supplied with water and nutrients, net photosynthesis and phytomass production are observed to be proportional to the quantity of photosynthetically active radiation (PAR) absorbed by the canopy (Monteith, 1977; Steven et al., 1983). Thus a simple model of phytomass production ( $M$ ) as a function of absorbed PAR may be given as

$$M = \int_{t_1}^{t_2} \epsilon f I_0 dt, \quad (1)$$

where  $\epsilon$  is the dry matter: radiation quotient (or radiation use efficiency) in terms of dry matter per unit of absorbed PAR (g/MJ),  $f$  is the fraction of incident PAR absorbed, and  $I_0$  is incident PAR energy (MJ/day).

Physiological development and some management practices may influence  $\epsilon$ , the conversion of absorbed PAR into dry matter (Asrar et al. 1984; Gallagher and Biscoe, 1978; Green, 1987). Prince (1991) compiled tables of  $\epsilon$  for various species and speculated that the considerable differences in the reported values of  $\epsilon$  may be due to inconsistencies among investigators in methods of measuring phytomass and radiation. Related work has shown that APAR may be estimated from multispectral (visible and near infrared) remotely sensed observations (Asrar et al., 1984; Daughtry et al., 1983; Wiegand et al., 1990). The combination of these two concepts may provide the basis for development of physically based agronomic monitoring systems, which use remotely sensed observations.

The synoptic, multirate views of agricultural land by multispectral satellite sensors acquire the data necessary to implement photosynthesis, evapotranspiration, and yield models over large geographic areas (Wiegand et al., 1979; Wiegand and Richardson, 1990). Several scenarios have been proposed, which incorporate multispectral,

meteorological, and ancillary data in physiologically based models of crop production (e.g., Daughtry et al., 1983; Maas, 1987; Steven et al., 1983; Wiegand et al., 1979).

Our objectives in this study are to 1) investigate the relationship between the fraction of photosynthetically active radiation absorbed by corn (*Zea mays* L.) and soybean (*Glycine max* Merr.) canopies and the multispectral reflectance of the canopies and 2) evaluate the relationship between above ground phytomass and cumulated absorbed PAR for these major mid-latitude crops.

## Definitions

Solar radiation is the source of energy for photosynthesis. However, this energy is available for plant growth only when it is absorbed in the canopy. Further, only radiation in the 400–700 nm wavelength interval supports photosynthesis in green plants. This region of the spectrum is referred to as photosynthetically active radiation (PAR).

Vegetation responds differently to radiation in the visible and infrared portions of the solar spectrum. Visible radiation or PAR (400–700 nm) is strongly absorbed by plant pigments while the near infrared (700–1300 nm) is strongly scattered (i.e., reflected and transmitted) by vegetation. Middle infrared radiation (1300–3000 nm) is dominated by water absorption. Because of this selective absorption by plants, the fraction of absorbed PAR is not simply twice the fraction of absorbed solar radiation (Russell et al., 1989). Thus direct comparisons of absorbed solar radiation and absorbed PAR are not possible without extensive knowledge of the optical and biological properties of the canopies (Prince, 1991). In an attempt to avoid previous confusion, the following definitions are given as a guide to the phenomena observed in this study.

Absorbed PAR is the algebraic sum of the incoming and outgoing flux densities measured above and below a plant canopy (Asrar et al., 1989). Four independent PAR flux density measurements—two above the plant canopy and two below the canopy—are required to assess canopy APAR (Hipps et al., 1983). The measurements required above the canopy are i) incident PAR flux density  $I_0$  and ii) exitant PAR flux density  $R_c$  from the canopy (including PAR reflected by the

soil but not absorbed prior to arriving at the top of the canopy). The measurements required below the canopy are i) PAR flux density transmitted,  $T_c$ , through the canopy to the soil surface and ii) PAR flux density reflected by the soil,  $R_s$ . From these measurements, absorbed PAR (APAR) of the canopy may be computed as

$$\text{APAR} = (I_0 + R_s) - (T_c + R_c). \quad (2)$$

This instantaneous APAR measurement is typically reported in either photon units ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) or energy units ( $\text{W m}^{-2}$ ).

It is often useful to consider separately the influence of canopy optics and structure on APAR without recourse to flux density considerations. This canopy structural or "state" attribute is the capacity of the plant canopy, at a given time, to absorb some fraction ( $f_A$ ) of the incident PAR flux, defined as

$$f_A = \text{APAR} / I_0. \quad (3)$$

One rather interesting question is the temporal stability of  $f_A$ . This has particular relevance to remotely sensed observations, which typically provide only limited temporal samples of plant canopy conditions.

Instantaneous APAR is not typically the measurement sought in vegetation production models, since it does not include a rate of PAR accumulation. Temporal integration of APAR measurements accomplishes this step:

$$\text{APAR}_{(t)} = \int_{t=0}^n f_{A(t)} I_0(t) dt. \quad (4)$$

This variable is typically reported in units of either  $\text{MJ m}^{-2} \text{time}^{-1}$  or  $\text{mol m}^{-2} \text{time}^{-1}$ . Time steps from seconds to years encompass the process rates generally considered in plant growth models.

The terms intercepted radiation and absorbed radiation are often used interchangeably in the literature; however, Asrar et al. (1989) and Russell et al. (1989) point out a subtle, but important, distinction between the two terms. Intercepted radiation does not explicitly consider radiation absorption. Although photons must be intercepted before they can be absorbed, not all intercepted photons are absorbed; some are scattered (i.e., reflected or transmitted). In the PAR portion of the spectrum scattering by green leaves is low (ca. 15%) and intercepted PAR (IPAR) is the difference in the PAR flux density above and

below the plant canopy. The two measurements required are the incoming PAR flux density ( $I_0$ ) and the PAR flux density transmitted ( $T_c$ ) through the canopy to the soil surface:

$$\text{IPAR} = I_0 - T_c. \quad (5)$$

The capacity of the plant canopy to intercept some fraction ( $f_I$ ) of the incident PAR flux is

$$f_I = \text{IPAR} / I_0. \quad (6)$$

Because  $T_c$  dominates Eq. (2) the fractions of absorbed PAR and intercepted PAR are very similar (Asrar et al., 1989; Russell et al. 1989). The difference between APAR and IPAR is  $R_s - R_c$ , which for incomplete canopies or canopies which include senesced plant material may be large. However, Gallo and Daughtry (1986) observed that the differences between IPAR and APAR were less than 3.5% from planting until just before physiological maturity of corn. Thus IPAR is a reasonable approximation of APAR as long as full green canopies are present.

Although the instantaneous differences between APAR and IPAR are usually small, temporal integration of these values may lead to considerable differences in estimates of PAR available to the plants over the growing season. Therefore, one must use caution in comparing values of cumulative absorbed or intercepted PAR from different investigators. In this study, APAR is the metric of interest.

## MATERIALS AND METHODS

### Experiment Design

Two experiments were conducted at Purdue University's Agronomy Farm (40°28'N, 87°00'W) near West Lafayette, Indiana in 1987. Two randomized complete blocks of adapted corn ("Beck 65X") and soybean ("Century") cultivars were planted in two row directions (N-S and E-W) at two row spacings (0.38 m and 0.76 m) on 5 May 1987. The plant density was 9.3 plants  $\text{m}^{-2}$  for both row spacings of corn and 35.8 plants  $\text{m}^{-2}$  and 31.5 plants  $\text{m}^{-2}$  for soybeans in 0.38 m and 0.76 m row spacings, respectively. Plot size was 16 m  $\times$  20 m. The soil was a Chalmers silty clay loam with 0-1% slope. Soil analyses were conducted and P and K were applied to maintain a high level of soil fertility. The recommended rate

(200 kg/ha) of N fertilizer as anhydrous  $\text{NH}_3$  was applied for high corn yields. Preemergence herbicides were applied for weed control.

A third experiment was conducted at the Beltsville Agricultural Research Center (39°02'N, 76°55'W) near Beltsville, Maryland in 1989. Two randomized complete blocks of an adapted soybean (*Glycine max* Merr. "Williams 82") cultivar were planted in two row spacings (0.18 m and 0.76 m) on two planting dates (31 May and 13 June 1989). Row direction was north-south. The plant density was 50.1 plants  $\text{m}^{-2}$  and 26.2 plants  $\text{m}^{-2}$  for the 0.18 m and 0.76 m row spacings, respectively. Plot size was 16 m  $\times$  24 m. The soil was a Codorus silt loam with a 1-2% slope. Soil analyses were conducted and P and K were applied prior to planting to maintain a high level of fertility. Preemergence herbicides were applied for weed control. All plots were irrigated with 75 mm of water on 1 September 1989.

### Agronomic Measurements

Green leaf area index, stage of development, fresh and dry phytomass, plant height, and percent soil cover were measured approximately weekly at both locations. Five corn plants per plot were harvested on each date, separated into green leaves (lamina only), brown leaves, stems (including leaf sheaths), and ears, dried at 70°C to constant weight and weighed. The area of fresh green leaves for each plant was measured with an area meter (Model LI-3100<sup>1</sup>, LI-COR, Inc., Lincoln, Nebraska). Leaf area index (LAI) was computed as the ratio of green leaf area per unit soil area occupied by each plant. The mean green LAI for each plot is the mean of the five individual measurements of LAI on each date.

In both of the soybean experiments, all plants in five 0.5 m lengths of row per plot were harvested on each date, separated into green leaves (lamina only), brown leaves, stems (including petioles), and pods, dried at 70°C to constant weight, and weighed. Green leaf area, measured with a LI-3100 area meter, and leaf dry mass were measured for a subsample of green leaves; total

dry mass was measured for the remainder of leaves in each sample. The relationship between leaf area and leaf mass of the subsample was used to convert the mass of the large leaf sample into leaf area (Daughtry, 1990). Leaf area index was computed as the ratio of green leaf area divided by the area sampled (i.e., 0.5 m times row spacing). The green leaf area of each plot is the mean of the five individual measurements of LAI on each date.

Percent soil cover was estimated by projecting 35-mm photographic slides, taken concurrently with the multispectral data from an altitude of 7.6 m above the soil, onto a dot grid and determining the proportion of the dots covered by vegetation for two locations in each plot.

### PAR Measurements

For the experiments at Purdue, photosynthetic photon flux density was measured under clear skies with a portable line quantum sensor (LI-COR, Model LI-191). Incoming, transmitted, and reflected PAR were measured under clear skies within 1 h of solar noon using the procedures described by Gallo and Daughtry (1986). The fraction of absorbed PAR,  $f_A$ , was calculated using Eq. (3). Daily APAR was calculated using  $f_A$  values measured within 0.5 h of solar noon and the daily total incoming PAR. Incoming PAR was estimated as 0.5 of solar radiation (McCree, 1972), measured with an Eppley Precision Spectral Pyranometer (Eppley Laboratory, Newport, Rhode Island). The measurement approach, outlined above, requires an assumption that  $f_A$ , measured at solar noon, is indicative of the mean  $f_A$  for the day. We examine this issue in the subsequent experiment at Beltsville.

For the experiment at Beltsville, the four PAR flux densities in Eq. (2) were measured diurnally with stationary sensors. PAR reflected from the canopy ( $R_c$ ) was measured diurnally with quantum sensors (LI-COR, Model LI-190) positioned 0.8 m above the canopy in each plot. Sensors were repositioned biweekly to maintain the height above the canopy. Transmitted PAR ( $T_c$ ) was measured diurnally with line quantum sensors (LI-COR, Model LI-191) positioned at the soil surface. The reflectance of the soil ( $\rho_s$ ) in the PAR waveband was measured with a quantum sensor inverted 0.8 m above a plot of bare soil adjacent

<sup>1</sup>Company and trade names are given for the benefit of the reader and do not imply any endorsement of the product or company by the U. S. Department of Agriculture, U. S. Department of Commerce, or the University of Maryland.

to the soybean plots. PAR reflected from the soil under the canopy ( $R_s$ ) in Eq. (2) was calculated as  $T_s \rho_s$  (Gallo and Daughtry, 1986; Russell et al., 1989). Incoming PAR ( $I_0$ ) was measured with quantum sensors facing upward. Additional meteorological data monitored within the field included air temperature, humidity, wind speed and direction, precipitation, and incoming solar radiation. The signal from each sensor was recorded at 10-s intervals and stored as 15-min means with a data logger (Campbell Scientific Inc., Logan, Utah, Model 21X Micrologger). Daily APAR was computed through summation of the 15-min means of APAR from sunrise to sunset expressed as  $\text{MJ m}^{-2}$ .

### Multispectral Measurements

Spectral radiance measurements, used to determine reflectance factors (RF), were acquired at approximately weekly intervals with a Barnes Modular Multiband radiometer (Model 12-1000, Barnes Engineering, Stamford, Connecticut). The radiometer has a  $15^\circ$  field of view and acquires data in the following seven wavebands: 450–520 nm, 520–600 nm, 630–690 nm, 760–900 nm, 1150–1350 nm, 1550–1750 nm, and 2080–2350 nm. The radiometer and a 35-mm camera were attached to a boom mounted on a pickup truck, elevated 7.6 m above the soil surface, and leveled for a nadir view. A pair of measurements, one centered over a row and one centered between the rows, was taken at two locations in each plot. Data were taken only when no clouds were near the sun and overall cloud cover was less than 25%. Only data acquired within 2 h of solar noon were used in these analyses.

The procedures and conditions described by Biehl and Robinson (1983) were used for obtaining the reflectance factor (RF), which is the ratio of the radiant flux actually reflected by a sample surface to that which would be reflected into the same beam geometry by an ideal perfectly diffuse (Lambertian) standard surface irradiated in exactly the same way as the sample. The field calibration procedure consisted of comparing the response of the instrument viewing the scene to the response of the instrument viewing a level reference surface. A 1.2 m square panel, painted with highly reflecting  $\text{BaSO}_4$  and calibrated as a function of illumination angle, was used as a field

reference surface. This reflectance standard provided a field calibration reference with stable, known reflectance properties (Biehl and Robinson, 1983). The reference panel was viewed in the same manner (i.e., normal to the surface) as the scene, but from a distance of 1.7 m. A dark level response of the instrument was also obtained by holding an opaque, light-tight cover against the instrument's optical ports to measure internal system noise. The response of the reference panel was measured about every 20 min during the data collection period and the dark level about every hour. Normalized difference vegetation index (NDVI) was calculated as the difference between reflectance factors of a near infrared (760–900 nm) band and a visible (630–690 nm) band divided by the sum of these two bands.

## RESULTS AND DISCUSSION

### Growth and Development

For soybeans, planted on 13 June 1989, leaf area index (LAI), percent cover, and above-ground dry phytomass accumulated more rapidly in narrow rows than in the wide rows (Fig. 1). In this example, plant density and row spacing are confounded because the density of soybeans in the narrow rows is nearly double the density of the soybeans in the wide rows (50.1 vs. 26.2 plants  $\text{m}^{-2}$ ). Row spacing (and/or plant density) had no effect on stage of development, although the plants in the narrow rows did lodge more than the soybeans in the wide rows.

The fraction of absorbed PAR increased rapidly as the plants developed (Fig. 2A). Soybeans in the narrow rows absorbed more than 90% of the incident PAR from full bloom (R2) through beginning maturity (R7), whereas soybeans in the wide rows did not reach their maxima of ca. 88–90% until beginning seed (R5). Soybeans in both row spacings maintained their maximum rate of PAR absorption until just prior to physiological maturity (ca. 100 days after planting). After physiological maturity,  $f_A$  declined sharply as leaves senesced and abscised. The final  $f_A$  values just prior to harvest represent PAR absorption by non-green stems and pods when green LAI = 0.0. The trajectory of the vegetation index, NDVI, over time followed a pattern similar to  $f_A$  (Fig. 2B). Both  $f_A$  and NDVI reached and maintained

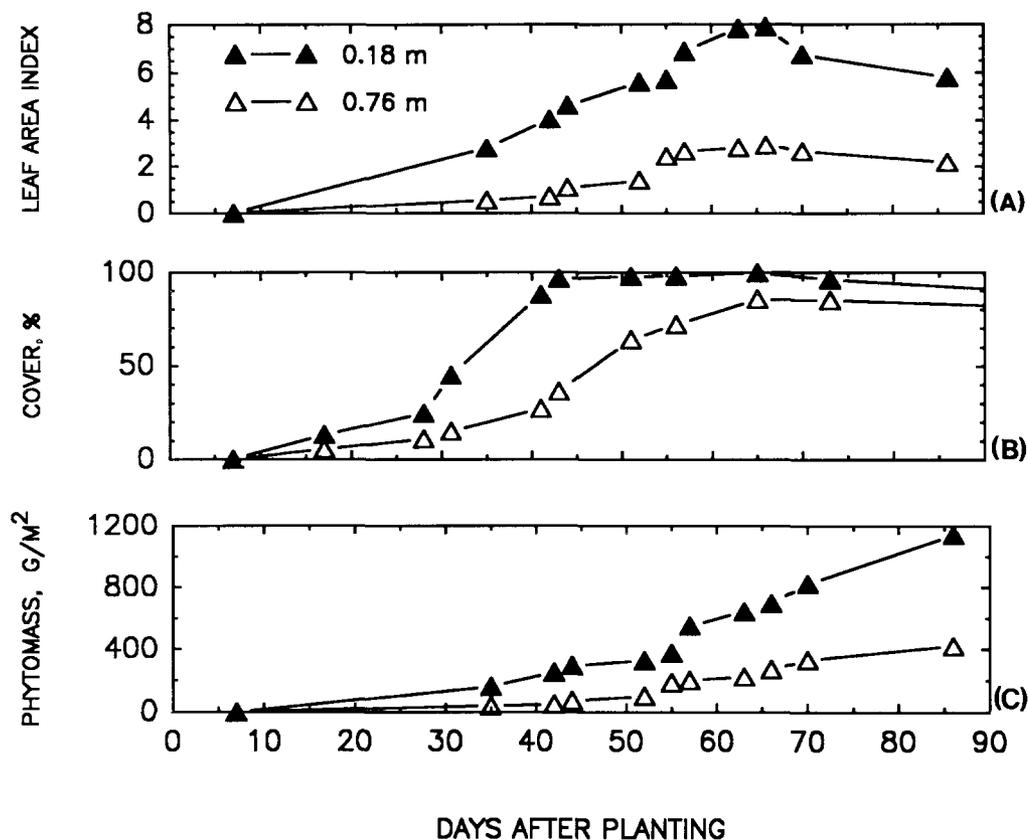


Figure 1. Agronomic characteristics of soybeans in two row spacings as a function of days after planting on 13 June 1989. Leaf area index (A), percent cover (B), and total above ground dry phytomass (C).

their maximum values at approximately the same time. Similar patterns of growth and temporal trajectories of  $f_A$  and NDVI were observed, but not shown, for the other treatments of soybeans and corn.

#### Seasonal Changes in the Components of $f_A$

The components of  $f_A$  at approximately 10-day intervals throughout the growing season for soybeans planted on 13 June 1989 are illustrated in Table 1. The fraction of PAR transmitted ( $f_T$ ) through the canopy at solar noon decreased rapidly from a maximum of 1.0 at planting to less than 0.05 at 45 days after planting for the soybeans in the narrow rows and to ca. 0.11 at 65 days for soybeans in the wide rows. Late in the growing season  $f_T$  increased as the canopies senesced (stage R6–R7). Significantly more PAR was transmitted through canopies in wide rows than in

narrow rows on eight of the 11 dates shown in Table 1. The other treatments in the Beltsville and Purdue experiments displayed similar trends for  $f_T$ .

The reflectance of the bare soil,  $\rho_s$ , at Beltsville ranged from 0.09 when wet to 0.26 when dry. Since the fraction of PAR reflected from the soil ( $f_{RS}$ ) is the product  $f_T\rho_s$ ,  $f_{RS}$  declined as the canopy developed and was less than 0.01 for the soybeans in the narrow rows until senescence. Very little downwelling PAR reached the soil surface, to be reflected, when the canopy was fully developed.

By definition, the fraction of PAR reflected from the canopy ( $f_{RC}$ ) and the fraction reflected from the soil ( $f_{RS}$ ) are equal from planting until the plants emerge. After the canopies were fully developed  $f_{RC}$  was less than 0.06 regardless of whether the soil was wet or dry. Differences in  $f_{RC}$  for soybeans in the two row spacings were small (less than 0.01) during much of midseason.

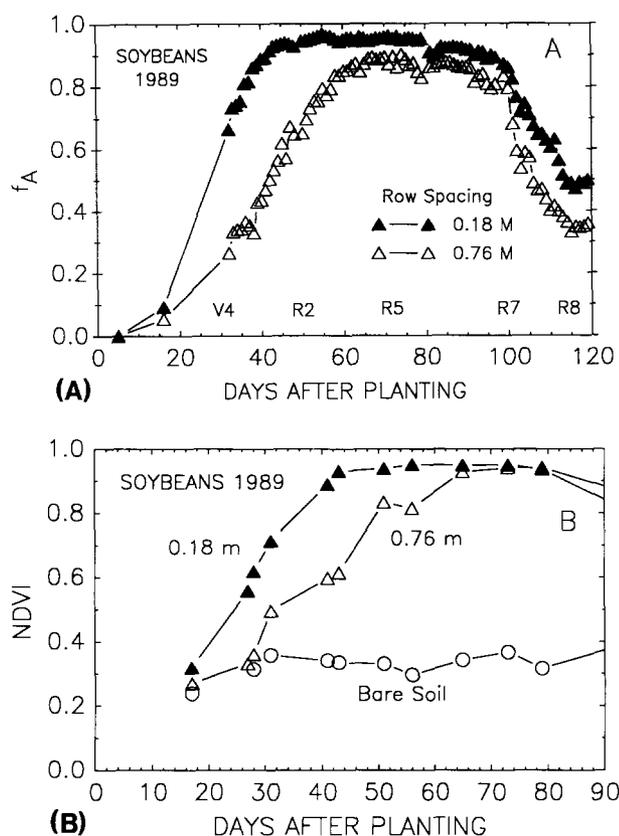


Figure 2. Fraction of absorbed PAR (A) and NDVI (B) of soybeans in two row spacings as a function of days after planting on 13 June 1989.

### PAR Absorption

Absorption of PAR by crop canopies is dependent on the stage of development, LAI, and leaf architecture of the crop. Initially as LAI increases, absorption of PAR increases rapidly (Fig. 3). The extinction coefficient ( $k$ ), which depends on leaf angle distribution and solar zenith angle (Ross, 1981), was greater for the soybeans (0.803) than for corn (0.463). The differences in Figures 3A and 3B are consistent with the differences in foliage inclination angles between corn and soybean canopies. Soybean canopies typically have a predominantly horizontal (planophile) distribution of foliage area inclination angles, while corn canopies have a more erect (erectophile) distribution of foliage area inclination angles (Ross, 1981). Planophile canopies intercept more radiation per unit leaf area and thus have larger  $k$  values than erectophile canopies.

As LAI continued to increase,  $f_A$  asymptotically approached  $1 - R_c$ , where all of the incident

PAR is either reflected by the vegetation or absorbed by the vegetation. The  $f_i$  asymptotically approaches 1.0 as LAI increases. The relationship between LAI and  $f_i$  has been described in terms of Beer's Law for numerous crops including wheat (Asrar et al., 1984; 1989) and corn (Gallo et al., 1985). The differences observed between  $f_i$  and  $f_A$  were generally less than 4% (Table 1) and were consistent with other reports (Gallo and Daughtry, 1986; Russell et al., 1989). Thus only  $f_A$  will be discussed in the remainder of this paper.

During grain fill, as green LAI decreases,  $f_A$  decreases slowly. Even at harvest maturity (R8), when no green leaves are present, 35–50% of incident PAR was absorbed by nongreen stems and pods of soybeans (Fig. 2A). Thus the relationships of  $f_A$  to LAI and spectral vegetation indices typically are biphasic (Asrar et al., 1984; Gallo et al., 1985; Steven et al., 1983; Wiegand et al., 1990). One equation is required to describe  $f_A$  as a function of LAI for increasing LAI and another equation for decreasing LAI. The hysteresis is due to PAR absorption by senescent vegetation. Thus, direct measurements of  $f_A$  during senescence overestimated PAR absorption by green, photosynthetically active vegetation.

Ideally, one would like to know the quantity of PAR absorbed by green vegetation only. Absorption of PAR by senescent vegetation and nongreen plant parts is of little benefit for dry matter production. Spectral vegetation indices (e.g., NDVI) appear to respond primarily to green vegetation (Baret and Guyot, 1991; Wiegand and Richardson, 1990), and strong relationships between these vegetation indices and  $f_A$  have been reported for various crops when LAI is increasing (Asrar et al., 1989; Gallo et al., 1985; Wiegand et al., 1990). Other research has suggested that the  $f_A = f(\text{VI})$  relationship, developed for increasing LAI, may be employed to estimate the proportion of PAR absorbed by green vegetation even during senescence when LAI is decreasing (Gallo et al., 1985; Wiegand and Richardson, 1990). Thus,  $f_A$  derived from spectral vegetation indices may more accurately represent PAR absorption by green, photosynthetically active vegetation than direct measurements of  $f_A$ .

The relationship between  $f_A$  and NDVI from planting to mid-grain fill (prior to rapid leaf senescence) of corn and soybeans is shown in Figure 4. The linear regression lines for corn and soy-

Table 1. Components<sup>a</sup> of the Fraction of Absorbed PAR and Green Leaf Area Index (LAI) as a Function of Days after Planting (DAP) for Two Row Spacings of Soybeans Planted on 13 June 1989

DAP	$f_T$	$f_{RC}$	$f_{RS}$	$f_I$	$f_A$	$f_I - f_A$	LAI
<i>0.18 m</i>							
0	1.000	0.251	0.251	0.000	0.000	0.000	0.0
16	0.955	0.193	0.240	0.045	0.092	-0.047	-
35	0.234	0.050	0.040	0.766	0.755	0.010	2.8
45	0.033	0.037	0.006	0.967	0.936	0.031	4.6
56	0.013	0.031	0.003	0.987	0.959	0.028	5.8
65	0.012	0.036	0.002	0.988	0.954	0.033	7.9
75	0.018	0.034	0.005	0.982	0.952	0.029	6.5
85	0.057	0.033	0.014	0.943	0.923	0.020	5.9
96	0.065	0.043	0.008	0.935	0.900	0.035	4.7
105	0.246	0.071	0.029	0.754	0.712	0.042	-
116	0.506	0.079	0.057	0.494	0.472	0.022	0.0
<i>0.76 m</i>							
0	1.000	0.251	0.251	0.000	0.000	0.000	0.0
16	0.989	0.205	0.248	0.011	0.054	-0.043	-
35	0.688	0.088	0.117	0.312	0.342	-0.029	0.6
45	0.390	0.061	0.071	0.610	0.620	-0.010	1.1
56	0.248	0.042	0.065	0.752	0.775	-0.023	2.4
65	0.114	0.034	0.021	0.886	0.873	0.013	2.9
75	0.107	0.032	0.027	0.893	0.888	0.005	2.5
85	0.111	0.037	0.027	0.889	0.879	0.010	2.2
96	0.185	0.042	0.022	0.815	0.795	0.020	1.8
105	0.405	0.068	0.048	0.595	0.575	0.020	-
116	0.639	0.084	0.073	0.361	0.349	0.011	0.0

<sup>a</sup> $f_T$  = PAR fraction transmitted through the canopy to the soil surface,  $f_{RC}$  = exitant PAR fraction reflected from canopy,  $f_{RS}$  = PAR fraction reflected by the soil,  $f_I$  = PAR fraction intercepted by the crop [Eq. (5)], and  $f_A$  = PAR fraction absorbed by the crop [Eq. (3)].

beans are not significantly different at the 0.01 level. It appears that a single, species-independent, linear relationship could be used to estimate  $f_A$  in these two crops with very different growth habits. The maximum values of NDVI and  $f_A$  for corn and soybean were similar for both the Beltsville and Purdue experiments.

The variance in the observed relationship appears to originate in the NDVI of bare soil. Soil background differences are particularly important when canopy cover is sparse (Baret and Guyot, 1991; Hall et al., 1990). Thus the slope and intercept of the relationship between  $f_A$  and NDVI may change unless a vegetation index adjusted for soil moisture and soil color is used. Several soil-adjusted spectral vegetation indices have been proposed and are being investigated (Baret and Guyot, 1991; Huete, 1989; Major et al., 1990).

### Phytomass Production

Plants grow in response to the quantity of PAR absorbed (APAR), not the fraction of PAR ab-

sorbed ( $f_A$ ), by their leaves. Diurnal measurements of the four component flux densities of APAR [Eq. (2)], to determine the daily integral of APAR, may be suitable for small scale research projects with a limited number of treatments, but are impractical for large scale studies involving many fields. An alternative approach, using one-time-of-day measurements, is more suitable to areal extensions of these field studies and is critically important to the use of remotely sensed observations for assessing crop conditions. To evaluate this possibility, estimated daily APAR was calculated as the product of  $f_A$ , derived from solar noon measurements, times daily total incident PAR. The relationship between measured daily APAR and estimated daily APAR is shown in Figure 5 for soybeans in 1989. The data include both clear and cloudy days throughout the growing season. From these data it appears that daily APAR may be reliably computed for crops from a measurement of  $f_A$  near solar noon and daily incident PAR. This indeed suggests that  $f_A$  is a reasonably stable description of the plant canopy's

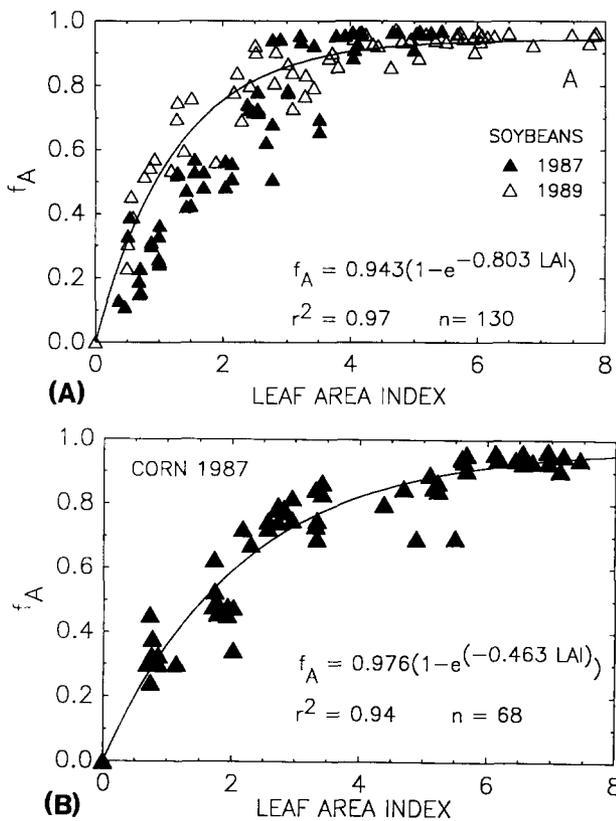


Figure 3. Fraction of absorbed PAR ( $f_A$ ) as a function of leaf area index for soybeans (A) and corn (B). Data from experiments at Purdue and Beltsville are included.

capacity to absorb radiation throughout most of the day and under variable irradiance conditions. This result is particularly relevant to remotely sensed observations which can provide excellent spatial resolution of plant conditions but only a limited temporal view of plant conditions. Thus daily APAR for many individual fields can be estimated from measurements of  $f_A$ , perhaps using remotely sensed multispectral data from a satellite, and daily incoming PAR, which can be measured at a ground station or by a geostationary meteorological satellite, for example, GOES (Yates et al., 1986).

Direct estimates of standing phytomass from spectral vegetation indices are generally site specific and have limited applicability (Daughtry et al., 1983). An alternative perspective, using remotely sensed measurements to estimate LAI and/or  $f_A$  as a component in a plant process model, may be more successful in estimating phytomass production. In this approach, spectral indices are used as estimators of LAI and/or absorbed

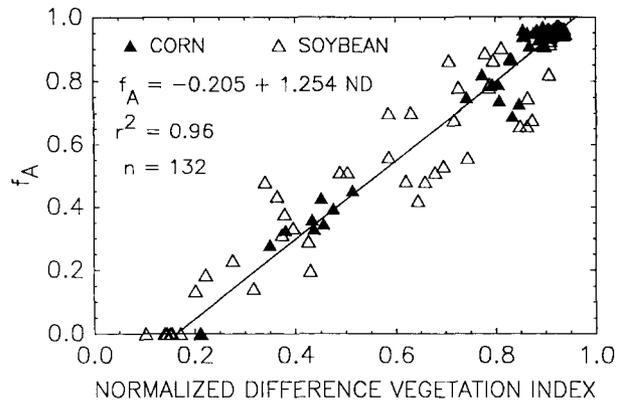
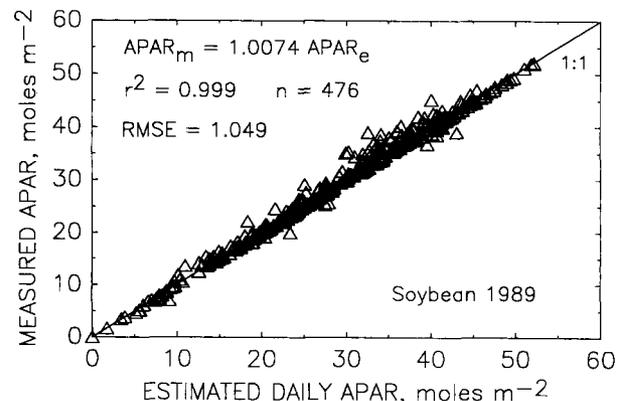


Figure 4. Fraction of absorbed PAR ( $f_A$ ) as a function of normalized difference vegetation index (NDVI) for corn and soybeans. Data from experiments at Purdue and Beltsville are included.

PAR in a plant process-based model and the performance of a plant canopy in terms of its phytomass production and grain yield is evaluated. Evidence suggests that remotely sensed data can be used to verify and/or update such plant process models (Asrar et al., 1989; Maas, 1987).

The relation between above ground dry matter accumulation and absorbed PAR is linear from planting to mid-grain fill for both corn and soybeans (Fig. 6). The rate of above ground dry matter accumulation of corn, a C4 grass, is greater than for soybeans, a C3 legume. This agrees with previous reports that the seasonal efficiency of C4 grasses is greater than C3 legumes (Prince, 1991). Because corn and soybeans convert absorbed PAR to phytomass at different rates, a capability to discriminate these crops is essential for estimating

Figure 5. Relationship between measured daily APAR ( $\text{APAR}_m$ ) and estimated daily APAR ( $\text{APAR}_e$ ) for soybeans. Estimated daily APAR is the product of  $f_A$ , measured at solar noon, and daily incident PAR.



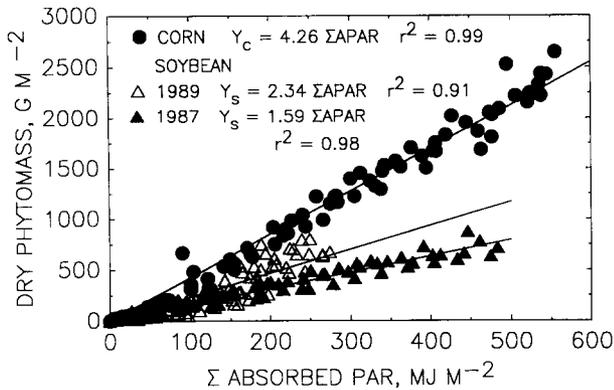


Figure 6. Above ground dry phytomass production as a function of cumulated APAR for corn and soybeans. Data are from planting to mid-grain fill.

phytomass production from APAR. Much of the early remote sensing research focused on crop identification and area estimation. For example, the results of the Large Area Crop Inventory Experiment (LACIE) clearly indicated that multi-temporal, multispectral remotely sensed data from satellites could be used to identify various crops (MacDonald and Hall, 1980). Subsequent research demonstrated that corn and soybeans could be readily discriminated using transformations of multirate Landsat data and parameters derived from a model of each crop's spectral response over time (Hall and Badhwar, 1987). Thus not only can daily APAR be estimated for many fields from multispectral data, but phytomass production can be estimated also.

## CONCLUSIONS

The development of functional relations between plant characteristics and remotely sensed observations has been paramount in many agricultural studies. In this study, we demonstrated that the fraction of absorbed PAR ( $f_A$ ) can be estimated with remotely sensed multispectral data and that phytomass production can be estimated as a function of cumulated absorbed PAR for two agronomically important mid-latitude crops, that is, corn and soybean. Furthermore, we provide evidence that  $f_A$ , measured at solar noon and combined with daily total incoming PAR, is a reliable estimate of daily APAR for these crops. This result is particularly important to remote sensing systems which can typically acquire only one view per day of a

region of interest. Thus, it appears possible to combine these fundamental concepts and provide the basis for developing physically based agromonitoring systems.

From an economic point of view, the production of grain is more important than total dry phytomass. Because grain yield of corn crops is closely linked to the accumulation of dry phytomass under a wide range of conditions (Sinclair et al., 1990), it may be possible to estimate grain yields from total dry phytomass. However, harvest index (i.e., ratio of grain mass to total phytomass) may not be constant for all crops (Green, 1987). Nevertheless, canopies with the lowest seasonal values of LAI generally absorb the least PAR and produce the least phytomass and the lowest grain yields (Daughtry, et al., 1983; Wiegand et al., 1990).

Plant response to PAR typically is confounded with the effects of temperature and moisture on plant growth and yields. Thus, the applicability of models based solely on spectral data are limited. Several approaches have been proposed to use multispectral data in conjunction with meteorological, soils, and ancillary data in models to predict crop yields.

For example, spectral estimates of intercepted radiation may be incorporated into the Energy-Crop Growth (ECG) model (Coelho and Dale, 1980). This model combines the concept of intercepted solar radiation with a moisture stress term and a temperature function to predict growth and development of corn. Models using the sum of the daily values of ECG were associated with more of the variation in corn yields than models which used only spectral or only meteorological data (Daughtry et al., 1983). A portion of the unexplained variation in grain yields is due to the effects of meteorological variables not included in the ECG model on plant growth and development. Other more physically based models should better represent the impact of environmental conditions on crop yield than the rather simple ECG model.

When moisture and/or temperature limit crop production, approaches, like the ECG model, should be superior to approaches using only spectral or only meteorological data for predicting crop yields (Daughtry et al., 1983). Maas (1987) described a strategy for making large area yield estimates using a simplified crop growth model

with weather and remotely sensed data as inputs. The remotely sensed data were used to update the state variables of the model based on multispectral vegetation indices and to compute crop stress based on canopy temperature measurements. Periodic updating of the state variables in the model with remotely sensed data improved the model's estimates of LAI, phytomass and grain yields and allowed predicted crop growth to approximate observed crop growth.

Implementation of this remote sensing approach for crop monitoring will clearly require a capability to discriminate between corn and soybeans. Other research has successfully demonstrated this capability. Furthermore, we speculate that both multispectral and meteorological data may be required to depict the additional limitations imposed on phytomass production by the environment. Additional work is underway to address this issue using multispectral data from satellites and meteorological data from ground stations and/or satellites.

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