Performance of the SunScan canopy analysis system in estimating leaf area index of maize

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Abstract: Rapid and reliable estimates of leaf area index (LAI) are important for studies of exchanges of energy and gases in the biosphere-atmosphere continuum. This paper evaluates the field performance of SunScan canopy analysis system for rapid estimation of LAI. Direct and indirect measurements of LAI were made in a maize (*Zea mays* L.) field at four phenological stages (emergence, vegetative, flowering and physiological maturity) at a tropical site in Ghana during the Glowa Vota Project field campaign (www.glowa-volta.de). Similar measurements were repeated in early and late planting seasons with similar crop management practices. The result showed a generally good performance of this sensor at all the phenological stages. Average LAI from the sensor (LAI^S), ranged from 0.40–4.45, and was consistently higher than the actual LAI, which varied from 0.31–4.22, respectively for both seasons. Regression between LAI and LAI^S showed a range of significant correlations with $R^2 > 0.74$ for all the stages and seasons. With combined datasets for all stages and the two plantings, a simple regression model was fitted to estimate LAI from LAI^S with $R^2 = 0.97$ and standard error of 0.23 ($P < 0.0001$). The evaluated sensor yielded a good and reliable LAI estimates under maize canopy.

Keywords: SunScan probe, field evaluation, leaf area index, maize, Ghana

Citation: Oguntunde, P. G., O.J. Olukunle, J. T. Fasinmirin, and A. O. Abiolu. 2012. Performance of the SunScan canopy analysis system in estimating leaf area index of maize. Agric Eng Int: CIGR Journal, 14(3): 1−7.

1 Introduction

Rapid and reliable estimates of leaf area index (LAI) are important for studies of exchanges of energy and gases in the biosphere-atmosphere interactions. Measurement of LAI is critical to understanding many aspects of crop development, growth, and management. Availability of instruments to estimate LAI non-destructively has greatly increased our ability to determine this parameter during the growing season.

Indirect estimates of leaf area index using such portable meters as LAI-2000 plant canopy analyzer (Li-Cor Inc., Lincoln, NE); DEMON (CSIRO, Canberra, Australia); Sunfleck Ceptometer (Decagon Devices inc., Pullman, WA, US); TRAC instrument (3rd Wave Engineering, Ontario, Canada); and the SunScan canopy analysis system (Delta-T Devices, Cambridge, UK), rely on the strong dependency between canopy structure and gap fraction or size distribution of the canopy (Welles, 1990; Stenberg et al., 1994; Potter et al., 1996; Jonckheere et al., 2004). Canopy structure is usually quantified in terms of leaf area and the spatial geometric organization of individual elements within a defined canopy envelope (Broadhead et al., 2003).

Direct methods of estimating LAI are often reliable but are usually destructive and laborious. However, the closeness of coupling between radiation exchange and canopy structure often enables canopy characteristics to be inferred from radiation measurements using theory based on Beer's law as applied to leaf canopies (Potter et al., 1996; Broadhead et al., 2003), with the assumption that leaves are randomly distributed. Beer's law of

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Received date: 2010-12-27 **Accepted date:** 2012-08-23

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canopy absorption states that the penetration of direct light is described by a negative-exponential function of leaf area density integrated along that part of the solar beam within the canopy.

Several investigations used the LAI-2000 plant canopy analyzer to measure leaf area index (Stenberg et al., 1994; Broadhead et al., 2003; Deblonde et al., 1994), with results yielding either overestimation or underestimation (Smolander and Stenberg, 1996; Stenberg, 1996) depending on the degree of violation of the basic assumptions, whereas little is reported on the field performance evaluation of the SunScan sensor, which seems to be relatively new as compared to LAI-2000. The major aim of this study was to evaluate the performance of the SunScan canopy analysis system in maize (*Zea mays*) field, an important staple food crop in West African, during the growing season of year 2002.

2 Materials and methods

2.1 Theoretical analysis

The SunScan canopy analysis system (Delta-T Devices, Cambridge, UK) was designed to measure the light levels of photosynthetically active radiation (PAR), the interception of solar radiation and make estimates of LAI in plant canopies. SunScan probe estimates LAI indirectly from measurements of radiation above and below the canopy, based on a theoretical relationship between leaf area and canopy transmittance. Its optical sensor is the light sensitive "wand" of one meter long, containing 64 photodiodes equally spaced along its length (Potter et al., 1996).

Campbell (1989) analyzed the path of a beam of light from a single direction (the direct solar beam) passing through a canopy with a generalized ellipsoidal leaf angle distribution (ELADP). Wood then integrated Campbell's result over the whole sky to give a description of the transmission of diffuse light through the same canopy (Potter et al., 1996). The Wood's SunScan equations are based on the major assumptions that (i) the canopy is an infinite, uniform, horizontal slab, with leaf elements randomly distributed in proportion to the surface area of an ellipsoid, as described by Campbell (1989); (ii) the incident light consist of a component from a point source at a given zenith angle (the direct beam); and a diffuse component of equal intensity from every point in the sky (uniform overcast sky); (iii) the canopy either has a sufficiently high LAI that light reflected back from the ground below is negligible, or the reflectance of the ground is similar to that of the canopy; and (iv) of the light intercepted by the leaf element, a fraction (absorption) is totally absorbed. The remainder is re-emitted uniformly in all directions.

A brief theoretical background is as follows. It may be shown that, for the sky having uniform brightness of one per steradian over the hemisphere, the radiance (R) of a strip around the sky at angle θ is given by Potter et al. (1996) as

$$R = 2\cdot\pi\cdot\sin(\theta)\cdot d\theta \qquad (1)$$

and the irradiance on a horizontal surface due to the strip is given by

$$I_o = 2\pi\sin(\theta)\cos(\theta)d\theta \qquad (2)$$

The total irradiance due to the hemisphere is obtained by integrating over the complete sky area:

$$\int_0^{\frac{\pi}{2}} 2\pi\sin(\theta)\cos(\theta)d\theta = 1.\pi \qquad (3)$$

For each strip of the sky, the transmitted radiation (I) is given by Beer's law as:

$$I = I_o\exp(-K.L) \qquad (4)$$

where, K is the extinction coefficient, which depends on the leaf angle distribution and the direction of the beam. K is 1 for entirely horizontal leaves. L is the LAI. Campbell (1989) derives an equation for the extinction coefficient of leaves distributed in the same proportions and orientation as the surface of an ellipsoid of revolution, symmetrical about a vertical axis. The K is calculated as a function of the Ellipsoidal Leaf Angle Distribution Parameter (ELADP) and zenith angle (θ) of the direct beam:

$$K(x,\theta) = \frac{\sqrt{x^2 + \tan(\theta)^2}}{x + 1.702(x + 1.12)^{-0.708}} \qquad (5)$$

where, x is the ELADP. It should be noted that Campbell's analysis applies to only a beam of light from a specific direction, which is the direct solar beam in this case. Thus, the transmitted fraction of the direct light is given by:

$$\tau_{dir} = \exp(-K(x,\theta).L) \tag{6}$$

However, even under strong sunlight, the direct fraction rarely exceeds 80% of the total incident radiation, so penetration of the diffuse component is also important. Substituting equations (2) in (4), the total transmitted radiation is

$$I = \int_0^{\frac{\pi}{2}} 2\pi \sin(\theta)\cos(\theta)\exp(-K(x,\theta).L)d\theta \tag{7}$$

and the transmission fraction of diffuse component (τ_{diff}) is given by I/I_o

$$\tau_{diff}(x,L) = \frac{1}{\pi}.\int_0^{\frac{\pi}{2}} 2\pi \sin(\theta)\cos(\theta)\exp(-K(x,\theta).L)d\theta \tag{8}$$

These integral functions were solved numerically by Potter et al., (1996) and computable functions fitted to the results to model canopy transmission for diffuse light in cosine and hemispherical response sensors as detailed in SunScan User Manual.

2.2 Study area

This study was conducted in Ejura, Ghana (latitude 07°20′ N and longitude 01°16′ W) as was shown in Figure 1. Ejura is a farming community with a population of about 200,000. Agricultural practices range from subsistence to large-scale commercial farming; maize, cowpea and rice are the main crops cultivated in this area (Oguntunde and van de Giesen, 2004). The climate is wet semi-equatorial with a long, bimodal, wet season lasting from April to October, which alternates with a relatively short dry season that lasts from November to March. The vegetation type is derived from transitional savannah. The major farming season begins in April and ends in July (early or first planting season), while the minor season lasts from August to October (late or second planting season). Mean annual rainfall and temperature, from 1973-1993, are 1264 mm and 26.6℃, respectively (Adu and Mensah-Ansah, 1995).

2.3 Measurement and analysis procedures

Measurements of LAI using direct and indirect methods were carried out between May and October. A plot measuring 12 m × 12 m in size was demarcated on maize field. The four phenological stages distinguished are (1) emergence, (2) vegetative, (3) flowering and (4) physiological maturity (Oguntunde and van de Giesen, 2004). LAI was measured directly by destructive method and indirectly with a SunScan sensor. Eight sub-plots (1 m^2) were randomly sampled in the field. Measurements were made, generally on bright days, during the early (first) and late (second) planting seasons. Crop management was similar, following the prevailing cultural practice, for both plantings. Data obtained were subjected to regression analysis. Other statistical analysis, to determine the degree of associations between LAI and LAI^S are coefficient determination (R^2), mean bias error (MBE) and root-mean-square-error ($RMSE$).

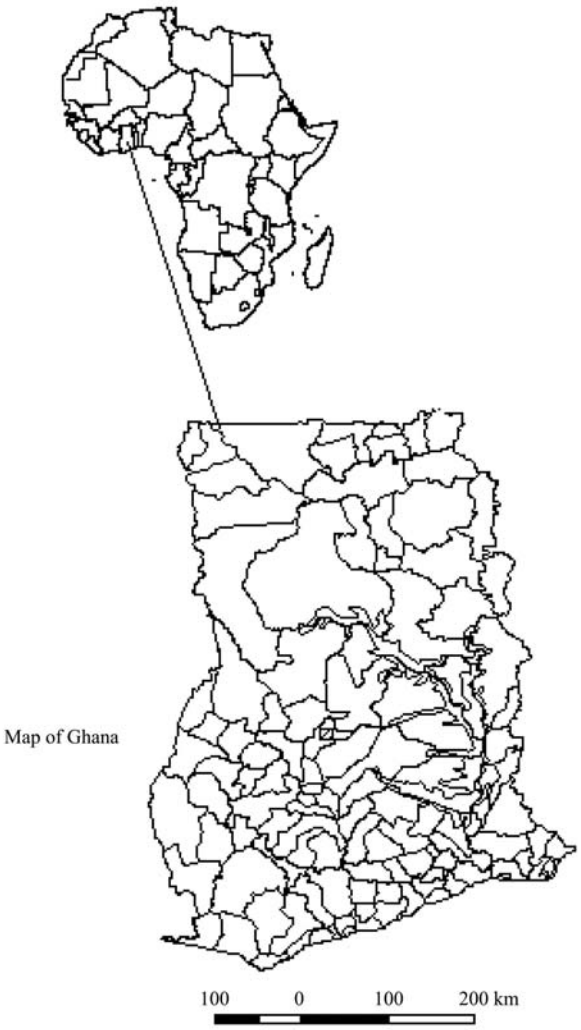


Figure 1 The study area is the shaded box within the map of Ghana (Adapted from Oguntunde and van de Giesen, 2004)

3 Results and discussion

Average values (±standard deviation) for both LAI and LAI^S, for different phenological stages of maize fields during the first and second seasons, are presented in Table 1.

Table 1 Mean (±standard deviation (SD)) of LAI and LAI^S for maize during the studied cropping seasons and different crop phenological stages

Phenological stages	#Early season		+Late season	
	LAI^S (±SD)	LAI (±SD)	LAI^S (±SD)	LAI (±SD)
Emergence	0.46 ±0.23	0.37±0.18	0.40±0.16	0.31±0.14
Vegetative	2.64±0.43	2.52±0.38	2.75±0.61	2.42±0.45
Flowering	4.01±0.41	3.68±0.41	3.86±0.78	3.33±0.65
Maturity	4.45±0.41	4.22±0.37	4.35±0.60	3.69±0.62

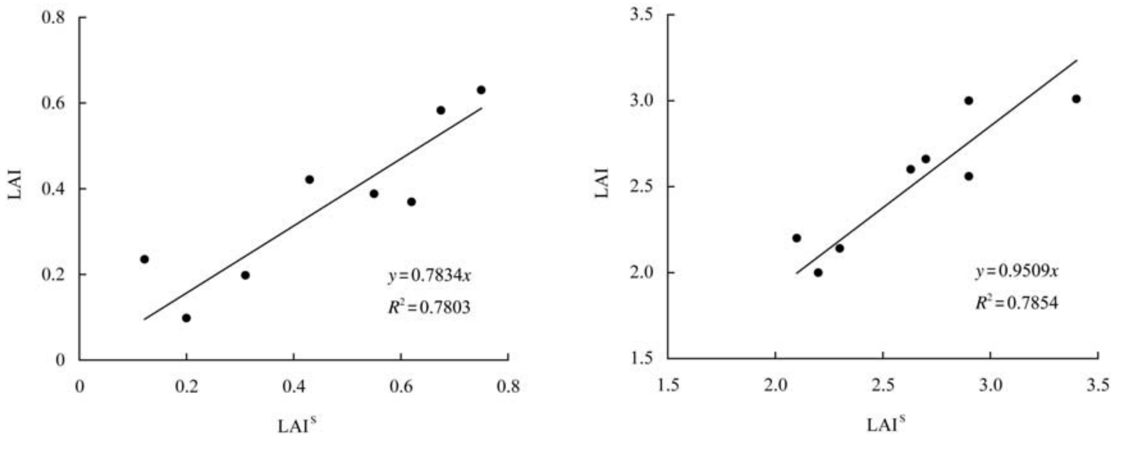
Note: # April to July; +August to October.

In accordance with growth expectations, there was an increase in leaf area index from emergence to physiological maturity. LAI^S increased from 0.46±0.23 to 4.45±0.41 for the early season and from 0.40±0.16 to 4.35±0.60 for the late season. Similarly, LAI increased from 0.37±0.18 to 4.22±0.37 for the early planting and from 0.31±0.14 to 3.69±0.62 for the late planting. Regression plots between LAI and LAI^S for the respective phenological stages are shown in Figure 2 and Figure 3, for early and late seasons respectively. In addition, Table 2 showed the summary of the evaluation statistics for the SunScan meter. A linear model (with zero intercept) was generally good enough to describe the relation between LAI^S and LAI. Coefficients of determination ranged from 0.745-0.853, MBE varied from 0.086 to 0.664 and RMSE increased from 0.040 to 0.252 for the two season's datasets (Table 2).

Table 2 Coefficients of determination (R^2), mean bias error (*MBE*) and root-mean-square-error to compare the LAI and LAI^S and different crop phenological stages

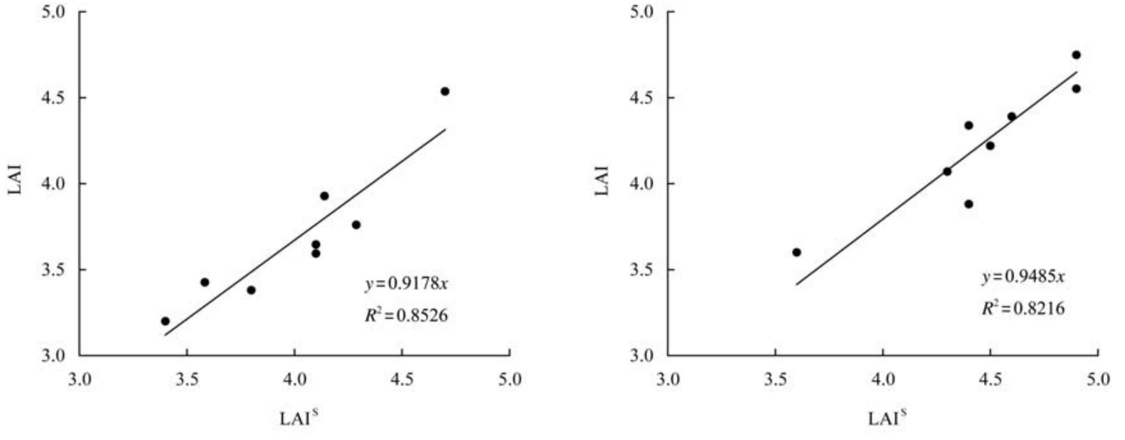
Phenological stages	#Early season			+Late season		
	R^2	*MBE*	*RMSE*	R^2	*MBE*	*RMSE*
Emergence	0.780	0.092	0.048	0.745	0.086	0.040
Vegetative	0.785	0.120	0.075	0.780	0.331	0.146
Flowering	0.853	0.330	0.128	0.821	0.523	0.214
Maturity	0.822	0.225	0.096	0.796	0.664	0.252

Note: # April to July; +August to October.



a. Emergence

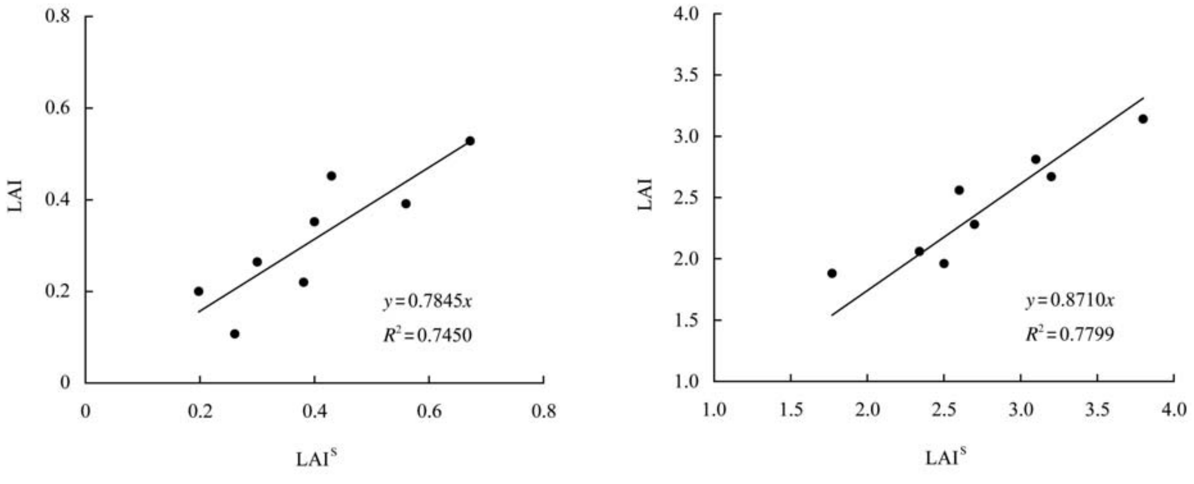
b. Vegetative



c. Flowering

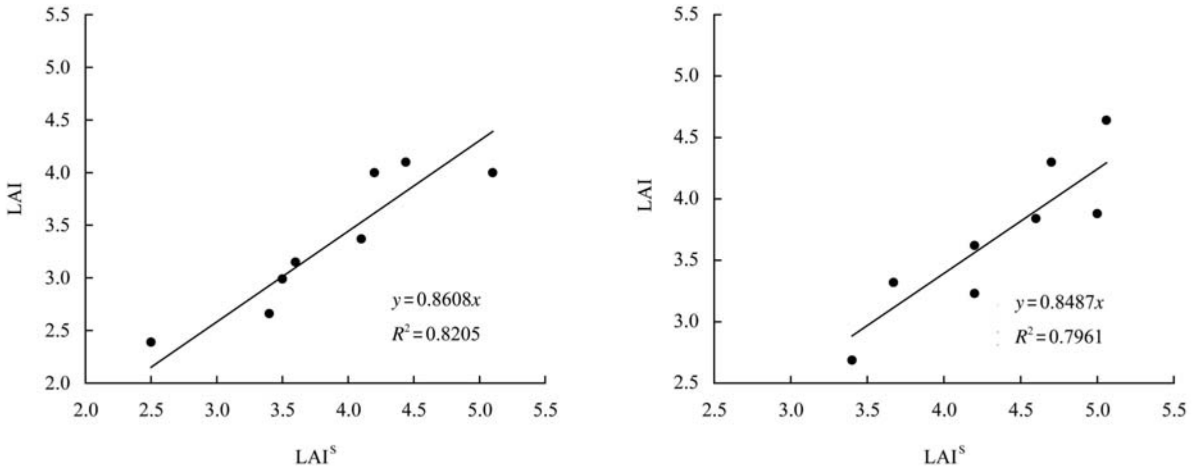
d. Maturity

Figure 2 Regression plot of LAI against LAI^S for emergence, vegetative, flowering and physiological maturity during the early season cropping



a. Emergence

b. Vegetative



c. Flowering

d. Maturity

Figure 3 Regression plot of LAI against LAI^S for emergence, vegetative, flowering and physiological maturity during the late season cropping

This result showed that the performance of SunScan canopy analysis system under maize (*Zea mays*) canopy was satisfactory. LAI estimates from the sensor showed a consistent slight over-estimation of the actual LAI. This is reflected from slopes of the "best fit" lines, which ranged from 0.783-0.951 during the early season and 0.785 - 0.871 during the late season (Figure 2). A perfect estimate would have resulted to 1.0 value of slopes. Lower slope values also indicated more over-estimation during the emergence stage compared to other phenological stages, possibly due to low LAI values at this growth stage.

This result is easy to reconcile because this meter, similar to other LAI instruments, uses light interception in computing LAI (Levy and Jarvis, 1999; Broadhead et al., 2003; Jonckheere et al., 2004). Meters do not discriminate between leaf, stem, and ear tissue; all plant parts are counted as leaf area in proportion to the amount of light they intercept. In contrast, destructive sampling measured only the leaf areas. The differences in definition of leaf area between the methods suggest that meters would over-estimate LAI. The data presented here support this theory. Combining all the datasets (N = 64), a general regression model was fitted between LAI and LAIS. The equation is of the form:

$$LAI = 0.8971{*}LAI \qquad (9)$$

With $R^2 = 0.976$, $SE = 0.23$ and $P < 0.0001$.

Several studies have used indirect methods to estimate LAI in field crops and forests with reasonable successes (Levy and Jarvis, 1999). However, these results yielded either overestimation or underestimation (Smolander and Stenberg, 1996; Stenberg, 1996) depending on the degree of violation of the basic assumptions. The degree of accuracy in this study seems reasonable and comparable with other results. For example, Wilhelm et al. (2000) compared the LAI estimates by three meters (AccuPAR, LAI-2000, and SunScan) to LAI measured by destructive sampling in two corn (*Zea mays* L.) hybrids, grown on a Pachic Haplustoll. All the three meters underestimated LAI compared with destructive sampling. However, when all data from all rings of the LAI-2000 meter were included in the calculations, LAI-2000 estimates of LAI differed significantly from those of the other two meters. Similarly, Antunes et al. (2001) used LAI 2000 to measure leaf area index of maize leaves and found an RMSE of 0.8 (greater than RMSE values in this study), when compared with observed LAI values. The results seem logical since the LAI-2000 uses a different mechanism for determining LAI than the SunScan meter. The main difference is that the SunScan uses a remote beam fraction sensor to determine the fractions of incoming light which are direct and diffuse, whereas the LI-COR LAI-2000 meter requires uniform sky brightness, i.e. uniform overcast or early/late in the day when the sun is at a very low angle, to give reliable estimates of LAI (Malone et al., 2002). The good performance SunScan sensor lends a support to the manufacturer's claim that SunScan system gives a good estimate of LAI especially in cereal crops (Potter et al., 1996).

4 Conclusion

The evaluation carried out revealed that SunScan canopy analysis system is reasonable in its estimate of LAI, a parameter useful to model many processes, such as photosynthesis and evapotranspiration. The meter can provide reliable estimates of LAI if proper procedures, designed to ensure basic assumptions in the calculation of LAI from gap fraction, are properly followed.

Acknowledgements

The first author thanks the German Academic Exchange Service (DAAD) and GLOWA Volta Project for financial support while at Center for Development Research, Bonn, German. Helpful comments from anonymous referees and the editor are greatly appreciated.

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