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Methodology for measuring fAPAR in crops using a combination of active optical and linear irradiance sensors: a case study in Triticale (X *Triticosecale* Wittmack)

M. M. Rahman · J. N. Stanley · D. W. Lamb · M. G. Trotter

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Abstract The amount of photosynthetically active radiation (PAR, 0.4–0.7 μm) absorbed by plants for photosynthesis relative to incident radiation is defined as the fraction of absorbed photosynthetically active radiation (fAPAR). This is an important variable in both plant biomass production and plant growth modeling. This study investigates the application of a newly developed, linear irradiance sensor (LightScout Quantum Bar Sensor, LightScout, Spectrum Technologies, Inc. USA), to quantify fAPAR for a demonstrator crop, Triticale (X *Triticosecale* Wittmack). A protocol was devised for sensor placement to determine reflected PAR components of fAPAR and to determine the optimal time of day and sensor orientation for data collection. Coincident, top of canopy, normalized difference vegetation index (NDVI) measurements were also acquired with a CropCircle™ ACS-210 sensor and measurements correlated with derived fAPAR values. The optimum height of the linear irradiance sensor above soil or plant canopy was found to be 0.4 m while measuring reflected PAR. Measurement of fAPAR was found to be stable when conducted within 1 h of local solar noon in order to avoid significant bidirectional effects resulting from diurnal changes of leaf orientation relative to the vertically-placed sensor. In the row crop studied, averaging fAPAR readings derived from the linear irradiance sensor orientated across and along the plant row provided an $R^2 = 0.81$ correlation with above-canopy NDVI. Across row sensor orientation also gave a similar correlation of $R^2 = 0.76$ allowing the user to reduce sampling time.

Keywords Photosynthetically active radiation (PAR) · Triticale · Active optical sensor (AOS) · Linear irradiance sensor

M. M. Rahman (✉) · J. N. Stanley · D. W. Lamb · M. G. Trotter
Precision Agriculture Research Group, University of New England, Armidale, NSW 2351, Australia
e-mail: moshiursau@yahoo.com

J. N. Stanley · D. W. Lamb · M. G. Trotter
Cooperative Research Centre for Spatial Information, University of New England, Armidale, NSW 2351, Australia

Introduction

Incident solar radiation within the wavelength range 0.4–0.7 μm excites chlorophyll molecules and is a vital energy source for plant photosynthesis (McCree 1972). Irrespective of whether the radiation originates from direct or diffuse components of incoming solar radiation, the photosynthetically active radiation (PAR) (Gallo and Daughtry 1986) absorbed by a plant depends on the ability of the individual plant or the canopy to intercept the incident radiation (Hanan and Bégué 1995). This is linked to the phenological stage of development and morphology, in particular leaf angle distribution and leaf area index (LAI) of the plant canopy (Asrar et al. 1984; Daughtry et al. 1992). The amount of radiation absorbed by the plant for photosynthesis is defined as absorbed photosynthetically active radiation (APAR) (Gallo and Daughtry 1986) and the proportion of PAR absorbed by the plant i.e. when expressed as a fraction is fAPAR.

The fAPAR is an important biophysical characteristic in models assessing the primary productivity of vegetation and, more generally, in carbon cycle models between the terrestrial boundary layer and the atmosphere (Pitman 2003; Sellers et al. 1997; Viña and Gitelson 2005). To measure canopy APAR or fAPAR directly, four independent PAR flux density measurements are required—two above the plant canopy and two below the canopy (Hipps et al. 1983). The above canopy components are the downward incident PAR flux density I_0 and the upward reflected PAR flux density from the canopy R_{CS} (including PAR reflected by the soil but not absorbed prior to arriving at the top of the canopy). The two below canopy components are the downward transmitted PAR flux density through canopy to the soil surface T_C and the upward reflected PAR flux density by the soil, R_S. From these measurements fAPAR can be calculated as

$$\mathrm{fAPAR} = \frac{\mathrm{APAR}}{\mathrm{PAR}} = \frac{\mathrm{I_0 - T_c - R_{cs} + R_s}}{\mathrm{I_0}} \tag{1}$$

Earlier studies of solar radiation or PAR interactions with plant canopies either neglected $\mathrm{R_{CS}}$ or $\mathrm{R_S}$, or at least assumed them to have relatively small influence on APAR (Allen et al. 1964; Arkin et al. 1978; Baker and Musgrave 1964; Williams et al. 1965). However, fAPAR invariably contains a contribution from the background soil and this component needs to be considered (Myneni and Williams 1994). Moreover, due to the advent of modern sensor technologies, it is easy to account for all the components of PAR flux density for a more precise measurement (Gallo and Daughtry 1986).

A basic protocol for sampling the components of fAPAR in crop canopies using a 1 m length linear radiance sensor (Li-Cor 191SB, Lincoln, NE) was reported by Gallo and Daughtry (1986). Researchers have documented measuring reflected soil and canopy PAR (R_S, R_{CS}) from different heights above plant and soil targets. Viña and Gitelson (2005) positioned their sensor (LI-191SB) 12 cm above the ground while measuring R_S reflected by the soil. To measure R_S and R_{CS}, Wiegand et al. (1991) placed their sensor at 30 cm height above both the targets, Hipps et al. (1983) used 2 and 50 cm respectively, Daughtry et al. (1992) used 80 cm above both targets while Pinter (1993) used 75 cm above the canopy for R_{CS}. It is apparent from the literature that no consistent methodology has been used insofar as the height of sensors above the plant canopy or soil. Should the height above the target actually matter? Gallo et al. (1985) reported that the measurement of PAR reflected from the soil under the canopy at a height of 2 cm above the soil surface cast a shadow on the soil surface and recommended placing the sensor 35 cm above the soil surface or above the mean height of the canopy while measuring R_S and $R_{CS.}$ Moreover, previous measurements of PAR have been made near solar noon on cloudless days;

ostensibly conditions of maximum incoming PAR. The field of view (FOV) of the radiance sensors, coupled with varying sensor-target distances and solar illumination angles will influence the readings when the bidirectional reflectance distribution function (BRDF) of canopy targets is taken into account (Suits 1972; Rao et al. 1979; Walthall et al. 1985; Ross and Marshak 1989) as well as the changing composition of direct and diffuse radiation (relative to the plant surface) during the day (Bégué et al. 1994).

There is growing experimental evidence (e.g., Asrar et al. 1992; Baret and Guyot 1991; Daughtry et al. 1983; Gallo et al. 1985; Myneni and Williams 1994 among others) to suggest that fAPAR can be estimated from above the plant canopy by using top-of-canopy reflectance measurements. A common approach is to use the Normalized Difference Vegetation Index ($NDVI = (NIR - R)/(NIR + R)$; where, NIR and R are reflectances in the near-infrared and red wavelength bands respectively) (Rouse et al. 1973). Several recent plant growth and yield models have been developed that use NDVI to infer fAPAR and ultimately the net plant primary production (e.g. Running et al. 2004; Wiegand et al. 1991). Owing to the inter-relationship between fAPAR and NDVI and the BRDF, neither is expected to be constant for a crop or pasture throughout the growing seasons when significant morphological changes occur (Daughtry et al. 1992). The relationships are often observed to be 'stable' during the vegetative stages of plant growth (Viña and Gitelson 2005). In crop and pasture research, a convenient method of measuring both NDVI and fAPAR insitu would allow an investigation of the relationship between NDVI and fAPAR under actual growth conditions.

Recently, a new class of plant canopy reflectance sensor; a portable, active optical sensor (AOS) has emerged that offers opportunities to collect spectral reflectance measurements under any ambient light conditions (including at night). When used to derive ratio-based vegetation indices such as the NDVI, the derived values are also insensitive to changes in sensor-target distances; a primary source of error in determining the reflectance characteristics of non-Lambertian targets such as plants (Holland et al. 2012). Detailed discussions on this class of sensor, performance and the underlying physical and radiometric principles guiding their applications can be found elsewhere (Holland et al. 2004; Lamb et al. 2009; Holland et al. 2012).

It is the objective of the current study to capitalize on these new sensor technologies; via the linear quantum sensor and the AOS, to develop a protocol for measuring fAPAR and for deriving an NDVI–fAPAR relationship in the context of row crops. To this end, we use a commercially available, and relatively low-cost linear radiance sensor and an example of an AOS.

Materials and methods

Experimental site

A field experiment was conducted in 2012 at the University of New England's 'SMART farm' (30°28′51″S, 151°38′46″E), located 5 km north-west of Armidale, NSW Australia, at an altitude of 1 051 m above mean sea level. The soil in the study area is predominantly a heavy clay (vertosol). The experiment was conducted in a 1 ha, flat field of Triticale (X *Triticosecale* Wittmack), planted in north–south oriented rows with a 25 cm spacing between the rows. The crop was at tillering stage (Zadoks scale 21–25) (Zadoks et al. 1974), where the growth rate is linear and the canopy morphology has primarily an erectophile leaf orientation in regions of lower biomass (1 200–3 000 kg/ha) and a mix of erectophile and planophile at higher biomass (3 000–4 200 kg/ha) according to the definitions of Sellers (1985).

Sensors

Within the study area, twenty three quadrat (0.25 m^2) placements were used to provide biomass levels ranging from 1 200 to 4 200 kg/ha. Each quadrat was aligned ‘square’ to the row direction and covered two rows symmetrically. Each quadrat placement was checked visually to ensure the rows were similar in height and plant density within the bounds of the quadrat. Photosynthetic photon flux densities (PPFD) entering and exiting the canopies were measured with a LightScout, six sensor quantum bar (LightScout, Spectrum Technologies, Inc. USA) under clear sky conditions (cloud cover <10 %; no clouds within 10° of sun) according to Gallo et al. (1985). The LightScout six sensor quantum bar (Fig. 1) is designed to measure the PAR under non-uniform irradiance conditions such as encountered beneath plant canopies. This is facilitated by averaging the readings of six irradiance sensors located at 5 cm intervals along a length of 30 cm. Each sensor is covered with a cosine diffuser, effectively rendering transmission of the ‘fore-optics’ insensitive to incident angle. The nominal FOV is therefore 180°. The PPFD was acquired for PAR measurements with units of (μmol/m^2 s) where 1 mol/m^2 s = 6.02×10^{17} photons/m^2 s. The six sensor quantum bar included a 3-D leveling bubble to ensure consistency in physical alignment relative to the solar incident angle. The orientation of the quadrats and the sensor quantum bar (in across-row configuration) is depicted in Fig. 2.

When collecting incident PAR readings (I_0) the operator crouched at full arms-length from the probe. For these measurements, the user was estimated to occupy ~12 % of the ‘sky view’ of a sensor.

An active, LED-based CropCircle™ ACS-210 (Holland Scientific Inc., Lincoln, NE, USA) sensor (Holland et al. 2004) was used to collect the surface NDVI data from the same quadrat immediately after taking PAR readings. The CropCircle™ ACS-210 has its own light source, with an array of 15 modulated polychromatic light emitting diodes that simultaneously emit Red (650 nm) and NIR radiation (880 nm) (Holland et al. 2004). The CropCircle™ ACS-210 was positioned at a height of 90 cm above the quadrat, where it produces an illumination (and hence measurement) footprint of ~50 cm (wide) × 13 cm (long); thereby measuring NDVI over approximately the same area over which the PAR values were extracted. A bubble level was also fitted to the CropCircle™ sensor to improve the consistency when orienting the sensor. Both the PAR and NDVI data were recorded by a GeoSCOUT GLS 400 data logger (Holland Scientific Inc., Lincoln, NE, USA) along with the measurement time necessary to compute solar elevation angles.

Sensor orientation and time of day

To confirm the appropriate placement height of the sensor above a target to avoid shadow effects while measuring upward-directed R_{CS} and R_S, the height of the downward-facing LightScout sensor was varied from zero to 1 m in 5 cm increments over a bare soil target. The measurements were also repeated over the same target over a 2.5 h period centered around solar noon at 15 min intervals (11 sets of measurement corresponding to solar elevation angles ranging from 58.6° to 64°).

In order to ascertain the NDVI-fAPAR relationship for the demonstrator crop, T_C and R_{CS} were measured at ten positions within each quadrat; five locations oriented

Fig. 1 LightScout six sensor quantum bar (LightScout, Spectrum Technologies Inc.)

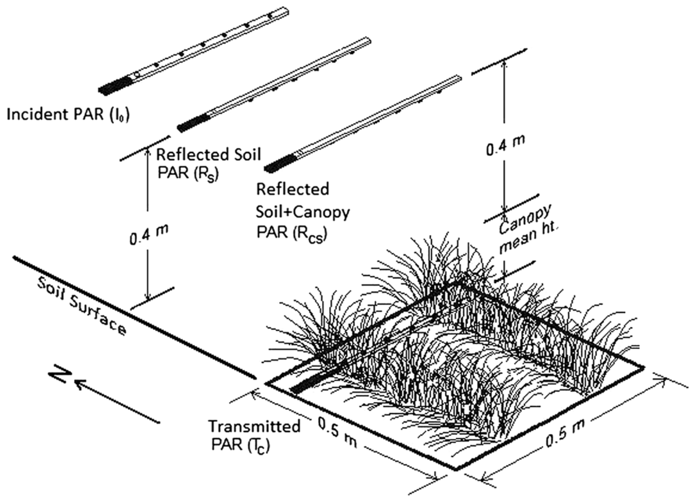

Fig. 2 Sensor configuration for across-row measurement of fAPAR in one location within a quadrat. Sensor is orientated perpendicular to the plant row direction. Sensors facing upward when measuring I_0 and T_C; and downward when measuring R_S and R_{CS}

perpendicular and five locations oriented parallel to the plant row direction. Prior to each measurement, the values of I_0 and R_S were recorded outside of the canopy as shown in Fig. 2. During the measurements, a nearby location was stripped of pasture (area $\sim$0.5 m^2) in order to preserve similar soil moisture (hence reflectance characteristics) and this was used to provide a measure of R_S. The recorded PAR values of each quadrat were averaged and fAPAR calculated using Eq. (1). The relationship between NDVI and fAPAR was determined by calculating standard linear regressions in Microsoft Excel (v. 2007).

Results and discussion

Sensor height

The average values of R_S acquired at different sensor heights are shown in Fig. 3. Here each data point is the average of the eleven individual measurements acquired during the 2.5 h period and the standard deviation of the values is depicted by the vertical error bars. The value of R_S increases from the surface up to 0.4 m height and the error bars indicate greater variances in values exist when the sensor is closer to the target. The greater variance observed at smaller sensor-target distances is thought to be the result of the varying solar angle over the 2.5 h measurement window changing the position of the sensor's shadow in its own FOV, similar to that observed by Gallo et al. (1985). We note that drying of the soil surface may also affect the size of the error bars, but careful observation indicated no discernible effect with the soil moisture levels encountered. Geometric considerations demonstrate that for a hemispheric FOV sensor, the shadow never leaves the FOV, regardless of the sensor-target distance. However the sensor-target distance dictates the relative proportion of the FOV is occupied by the shadow zone and hence the magnitude of the shadow effect. The maximum variance did not exceed ±0.007 μmol/m^2 s (i.e. at 0.05 m, corresponding to ±11.4 %). Given the solar zenith angles encountered here, the bidirectional reflectance properties of the soil surface are likely to contribute by only a few percent to the variations observed (Walthall et al. 1985).

The data of Fig. 3 indicated that with this particular sensor, sensor-soil distances exceeding 0.4 m achieve a stable result, and even with a 5° variations in solar elevation angle (either side of solar noon; corresponding to 2.5 h), yields a variance of ±0.005 μmol/m^2 s (i.e. ±0.5 %). This effect is also translatable to the measurement of R_{CS} which is why the measurement height of 0.4 m was set to be that above the canopy, rather than the soil.

The impact of solar elevation angle on fAPAR

The variation of calculated fAPAR with solar elevation angle is shown in Fig. 4. Here each data point is the average of eleven fAPAR measurements taken at 15 min intervals within the 2.5 h period. The standard deviation of the measurements values is depicted by the vertical error bars. Within the measurement variance, the fAPAR values did not significantly change with solar elevation angle. There is a suggestion in the data of a reduction in fAPAR at higher solar elevation (i.e. near solar noon), which is consistent with the observations of Hipps et al. (1983). Pinter (1993), who acquired their measurements over a range of solar zenith angles from 27° to 72° observed maximum values of fAPAR at larger solar zenith (lower solar elevation) angles. They concluded that the direct beam of solar radiation entering the canopy obliquely had the highest probability of interacting with foliage elements. In the case of the crop studied in this present work, the predominantly erectophile leaf orientation associated with the early stage of development, is consistent with the trend in fAPAR with solar elevation angles, albeit small, in the data. Gallo et al. (1985) suggests that the daily estimates of fAPAR, based on measured fAPAR at solar noon, is likely to under-estimate the energy available to a developing crop canopy especially in north–south crop row orientation. However, they suggested taking sensor measurements within 1 h of solar noon.

Sensor orientation

The measured fAPAR for a range of biomass levels is given in Fig. 5. Data are for sensor orientations both across and along the crop rows. Each data point is the average of the five individual measurements acquired at sensor positions displaced progressively across the quadrat in incremental steps of one fifth of the quadrat size. Again the standard deviation of the values is depicted by the error bars. The fAPAR values measured in the two sensor orientations follows similar biomass trends with the most telling difference being in the size of the standard error. fAPAR can, of course, be driven by the variation in T_C and R_{CS} components and therefore larger errors are indicative of greater spatial heterogeneity in these radiation fields within the quadrats. The variance between measurements taken with the sensor aligned along the rows is largest at lower biomass levels when the leaf orientation is predominantly erectophile. This variance is attributed to the scale of measurement (i.e. the sensor geometry) and the size of the plants and the inter-row spacing. When measured in 'along-row' orientation, sensor position is very important. Whether the sensor

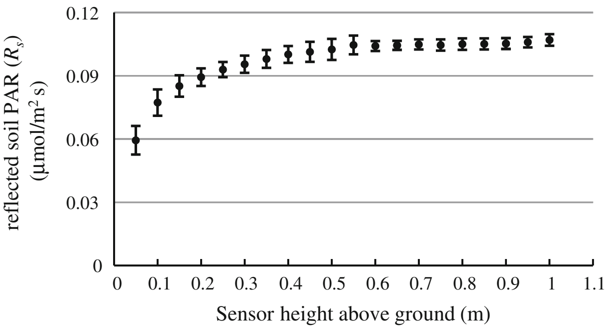

Fig. 3 Reflected soil PAR (R_S) as a function of sensor height above the target. Each data point is the average of the 11 measurements during the 2.5 h period centered on local solar noon. Sensor height = 0.4 m above soil surface; *error bars* ±1 SD

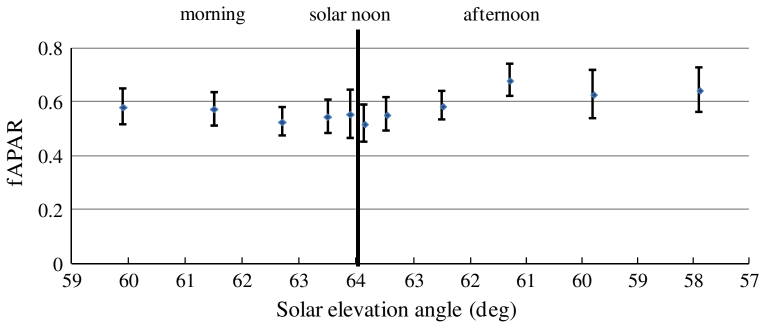

Fig. 4 fAPAR variation with solar elevation angle (degrees above horizon). *Note* elevation angles ascend towards, then descend from, solar noon. The values of T_C and R_{CS}, are averages of both across- and along-row measurements; *error bars* ±1 SD

is positioned mid-row, or close to plant stems along one row will alter the reading. This effect is not as significant when the sensor is deployed in 'across-row' orientation. Hence we see the higher variances for the 'along-row' orientation. At higher biomass levels, where the inter-row gap is closed due to plant size and a predominantly planophile leaf orientation, the size of the along-row measurement variance is now similar to that of the across-row measurements. To this end, it is recommended that across-row sensor orientation be deployed for consistency. It is clear, however, that the use of fAPAR to infer plant biomass is inherently problematic owing to the magnitude of the variance encountered when working at the scale of meters with the plant geometries encountered in this work. Caution should be exercised when taking this approach and consideration should be given to plant and row dimensions and the sensing footprint of the particular sensor used.

NDVI–fAPAR for across and along-row sensor orientation

The fAPAR values derived for each biomass quadrat as a function of average quadrat NDVI is given in Fig. 6. The $fAPAR_{comb}$ values for each quadrat are derived from all ten across- and along-row sensor placements (solid circles and solid trend-line). The $fAPAR_{across}$ and $fAPAR_{along}$ values for each quadrat are derived from either the 5 across- or 5

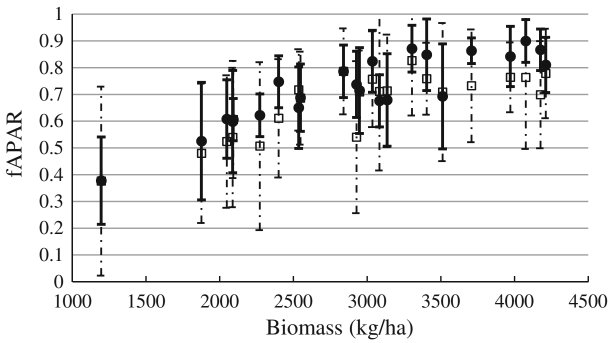

Fig. 5 Measured fAPAR variation as a function of biomass (kg/ha) with the sensor aligned across (*solid circle*) and along (*open square*) the crop rows. Each data point is the average of the five measurements at each location; *error bars* ±1 SD

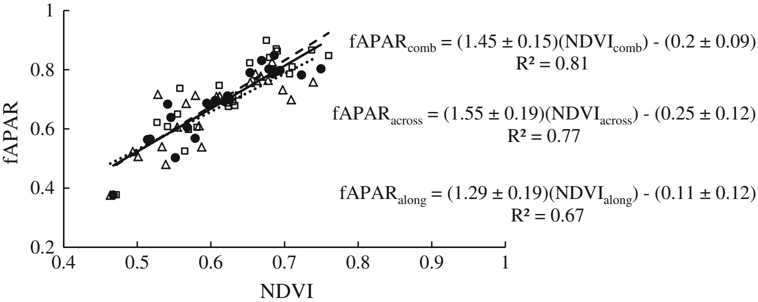

Fig. 6 Observed fAPAR–NDVI relationship using combined across and along-row sensor data (*solid circle*), across-row only (*square box*) and along-row only (*triangle box*) sensor data. The *solid trend line* is for the combined data, the *long-dash trend line* is for across-row only data and *small-dash trend line* for along-row only data

along-row orientation measurements only (square symbol and long-dash trend line, triangle symbol and short-dash tend line, respectively). Linear equations adequately describe the relationship between fAPAR and NDVI in each data set. The coefficients of determination (R^2) were found to be 0.81, 0.77 and 0.67, respectively. The observed trends are consistent with the observations of Drolet et al. (2005) and Daughtry et al. (1992), who used quantum sensors (LI-COR, model LI-190, Lincoln, NE) and NDVI data acquired from radiometers. Pinter (1993) also found a strong linear relation ($R^2 = 0.96$) between the ground measured fAPAR and NDVI measurements. According to Myneni and Williams (1994), an increase of soil reflectance at lower biomass can decrease NDVI and increase fAPAR; however, light intercepted by the canopy has higher impact on fAPAR which can eliminate the influence of soil reflectance to increase the value of fAPAR in lower biomass. Importantly, a linear regression analysis of each data set in Fig. 6 (inset) shows the slope and intercept values in each of the equations are not significantly different.

The magnitude of the variance encountered in this data highlights, again the importance of matching the sensor footprint to that of the crop or pasture in question. Inter-row, or inter-plant, variability remains the dominant cause of the uncertainty encountered when inferring one of these parameters from the other at the scale used in this work and with the sensing dimensions of the instrument used.

Conclusions

Consistent measurement of the different components of fAPAR requires consideration of sensor placement (height and orientation) and solar illumination conditions. In this work, it was demonstrated that temporally-stable of readings from a linear quantum bar sensor can be achieved within an elevation of 5° of local solar noon, and that the sensor, when collecting R_S and R_{CS} measurements while inverted over bare soil or plant canopies, respectively, should be positioned a minimum of 40 cm above the target surface. Also, sensor orientation along or across the crop rows, in conjunction with a small, handheld active reflectance sensor, can yield a fAPAR–NDVI relationship for a crop with biomass ranges that encapsulate both erectophile and planophile leaf components. Orienting the linear quantum sensor across the crop rows is recommended to reduce measurement variance across the area of interest, especially when dealing with canopies that are predominantly erectophile at the time of measurement, or where, owing to biomass variations, are a mix of both erectophile and planophile. The magnitude of the variance encountered in the data of this present work illustrates the importance of matching the sensor footprint to that of the crop or pasture in question. Inter-row, or inter-plant, variability is a significant cause of uncertainty when inferring plant parameters from insitu reflectance measurements and caution should always be exercised when undertaking such an endeavor.

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