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Trigonometric correction factors renders the fAPAR–NDVI relationship from active optical reflectance sensors insensitive to solar elevation angle

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ABSTRACT

The normalized difference vegetation index (NDVI), derived from ground based or satellite borne, passive sensors is often used to estimate the fraction of absorbed photosynthetically active radiation (fAPAR) of a plant canopy. It is well documented that the measured NDVI from passive sensors is affected by the sun and/or view geometry due to the non-Lambertian properties of plant canopies. Despite this the fAPAR–NDVI relationships are often found to be independent of the solar elevation angle (θ_s) because the θ_s-dependent absorption of the Red wavelengths within the canopy, which dominates the fAPAR, cancels out the θ_s-dependency of the NIR scattering which dominates the NDVI measurement. Active optical sensors (AOS), which have their own illuminating light source measure NDVI ($NDVI_{AOS}$) without any interference of solar geometry. However as fAPAR of a plant canopy does change with solar elevation angle (θ_s), the fAPAR–$NDVI_{AOS}$ relationship too changes with varying θ_s. The objective of this study was to explore a correction factor which can eliminate the θ_s-dependency in fAPAR–$NDVI_{AOS}$ relationship. Data were collected using LightScout quantum bar and CropCircle™ for Tall fescue (*Festuca arundinacea* var. Fletcher) at θ_s ranging from 40° to 80°. A θ_s-dependent vegetation index, $NDVI^*_{AOS}$ that introduces simple trigonometric correction factors to the measured Red and NIR irradiance for nadir-viewing active optical sensor provides a fAPAR–NDVI relationship that is independent of θ_s. When the solar elevation angle is introduced this way into the $NDVI_{AOS}$ the fAPAR can then be calculated from the $NDVI_{AOS}$ for any solar elevation angle within the range of 40–80°.

1. Introduction

The fraction of incident photosynthetically active radiation (0.4–0.7 μm) absorbed by plant canopies (fAPAR) is related to canopy functional processes such as photosynthesis, evaporation and transpiration rates (McCree, 1972). The fAPAR of a given plant canopy is related to the canopy structure, specifically the shape, size, density and orientation of leaves and the concentration of photosynthetically active pigments within them. The use of spectral reflectance, vegetation indices (VIs) from remote and proximal sensing devices to infer fAPAR is of considerable interest as researchers seek cost effective and convenient methods of synoptically mapping plant growth and development (Asrar et al., 1984; Tucker et al., 1986; Russell et al., 1989; Major et al., 1991; Norman and Arkebauer, 1991; Rahman et al., 2014a).

Numerous theoretical and empirical relationships between fAPAR and different VIs have been established (Choudhury, 1987; Daughtry et al., 1992; Hatfield et al., 1984; Sellers, 1987; Steinmetz et al., 1990; Wiegand et al., 1992; Rahman et al., 2014b, 2015). The most widely used VI is the normalized difference vegetation index (NDVI = (NIR − R)/ (NIR − R)) (Bégué, 1993; Goward and Huemmrich, 1992; Hanan et al., 1995; Le Roux et al., 1997). Until recently, the spectral reflectance measurements have largely been derived using passive sensors, either ground-based (e.g., Hatfield et al., 1984; Pinter, 1993; Lind and Fensholt, 1999), or air/space-borne (e.g., Prince and Goward, 1995; Ruimy et al., 1994 among others). Here the canopy reflectance is measured in response to the combined direct (sun disk) and diffuse (sky light) irradiance (Kaufman, 1989). Although previous work has shown a considerable influence of solar elevation and sensor view angle on the fAPAR and NDVI values (Ranson et al., 1985; Deering et al., 1992; Walter-Shea et al., 1992; Ishihara et al., 2015; and Cogliati et al., 2015), both the NDVI and fAPAR values respond similarly with the variation in solar elevation angle (θ_s)

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(Hatfield et al., 1984; Asrar et al., 1992; Walter-Shea et al., 1992; Pinter, 1993; Myneni and Williams, 1994; Epiphanio and Huete, 1995). In effect, by shifting along the same regression line this acts to remove any θ_s dependence (Hatfield et al., 1984; Asrar et al., 1992; Walter-Shea et al., 1992; Pinter, 1993; Myneni and Williams, 1994; Epiphanio and Huete, 1995).

Recently workers have applied active optical sensors (AOS) to the derivation of fAPAR. While these sensors are capable of measuring the same top of canopy spectral reflectance indices as passive sensors, the use of integral illumination sources and synchronous detection renders them impervious to external illumination conditions (Holland et al., 2012). While offering the obvious advantages of utility at any time of day or night, the active illumination used to derive the NDVI (hitherto referred to as $NDVI_{AOS}$) and the continued necessity of using passive sensors to measure fAPAR now means only the fAPAR component is responsive to θ_s (Rahman et al., 2014b) and this introduces a strong dependency of the $NDVI_{AOS}$–fAPAR-relationship on θ_s (Rahman et al., 2015). This poses challenges to those wishing to use AOS for field determination of fAPAR over extended periods of time (ie a range of θ_s) in a given day, such as those recently reported scenarios involving extensive on-ground field surveys (for example Trotter et al., 2010), aerial surveys (for example Lamb et al., 2009; Lamb et al., 2011), and long-term monitoring probes established at fixed locations (for example Rahman et al., 2014a).

The question remains as to which is the more important parameter to be able to adjust in terms of an fAPAR–AOS index response curve that includes all values of θ_s. Is it the fAPAR or the AOS index? In the context of the present work, the rationale for inferring fAPAR is to be able to quantify plant growth under real conditions during the daily growth periods. So from a purely biophysical perspective, while active optical sensors have that desirable attribute of producing reflectance measurements that are invariant to time of day (i.e. θ_s), knowing the fAPAR at any time of the day (θ_s) is essential for determining accumulated growth during the day length.

The objective of this present work is to therefore introduce simple θ_s-based trigonometric correction factors into AOS-derived indices for inferring fAPAR so that the fAPAR–AOS-derived index data all lie along a common regression line irrespective of θ_s. In this work we will focus on the NDVI. Owing both to its importance as an Australian pasture species and for its relevance to previously cited and ongoing work, this paper focusses on the pasture species, tall fescue (*Festuca arundinacea*) as an example of the process.

2. Materials and methods

2.1. Field experiment

The study was conducted at the University of New England's 'SMART Farm' (30°28′51″S, 151°38′46″E), located 5 km northwest of Armidale, NSW, Australia, at an altitude of 1051 meters above mean sea level. The predominant soil type in this area is heavy clay (vertosol) (Isbell, 2002). The experiment was conducted during summer (December, 2014) in a 0.6 ha field of tall fescue (*Festuca arundinacea* var. Fletcher) pasture at vegetative-leaf development stage (E6–E15) (Moore et al., 1991). At this growth stage the canopy morphologies were primarily erectophile leaf orientation in regions of lower biomass (1600–2800 kg/ha) and a mix of erectophile and planophile (approximate ratio 70:30) at higher biomass (2800–4000 kg/ha) according to the erectophile–planophile definitions of Sellers (1985).

Within the study area, twelve quadrat plots (0.5 m × 0.5 m) were selected with biomass levels ranging from approximately 2000 kg/ha to 4000 kg/ha. Each quadrat placement was checked visually to ensure that the height and density of the plants were similar within the bounds of the quadrat. Field measurements of fAPAR and top of canopy NIR_{AOS} and Red_{AOS} reflectances were conducted over 15 min periods at approximately 45 min intervals on two days (15 and 17 December, 2014) under clear sky conditions. The fifteen-minute field measurement windows were scheduled to achieve solar elevation angles (θ_s) within the ranges of 40–43°, 50–53°, 60–63°, 70–73° and 80–83°. Solar azimuth was not considered as the pasture plants in the study site had no discernible row structure nor azimuthal leaf orientation.

Following the protocol of Gallo et al. (1985) and Rahman et al. (2014a), a LightScout 6 sensor quantum bar (LightScout®, Spectrum Technologies, Inc. USA) was used to measure the four independent PAR (i.e. photosynthetically active radiation) flux density components that account for the PAR entering and escaping a plant canopy. The fAPAR was calculated using Eq. (1) (Hipps et al., 1983)

$$\text{fAPAR} = \frac{I_0 - T_c - R_{cs} + R_s}{I_0} \quad (1)$$

where I_0 is the incoming PAR, T_C is the transmitted PAR, R_{CS} is the upward reflected PAR from the canopy (including PAR reflected by the soil but not absorbed prior to arriving at the top of the canopy) and R_S is the upward PAR reflected from the soil surface. The sensor logs 10 consecutive readings per second, and twenty readings were recorded within a 2 s period for each component of the fAPAR; that is, the 4 PAR measurement components of the fAPAR required 8 s to complete. Six fAPAR values were generated from each field quadrat and then averaged to yield a single fAPAR value for each individual quadrat. The total time required to complete all the fAPAR measurements for each quadrat was approximately 48 s.

The top-of-canopy, nadir viewed, reflectance measurements (Red_{AOS} (650 nm) and NIR_{AOS} (880 nm)) were completed using a CropCircle™ ACS-210 (Holland Scientific Inc., Lincoln, NE, USA) sensor directed at the same 6 places within each quadrat as the fAPAR measurements. The 32° × 6° angular field of view of the CropCircle™ ACS-210 and nadir positioning of the sensor at a height of 95 cm above the top of the plant canopy resulted in an illumination (and hence measurement) footprint measuring 50 cm × 13 cm. A 'bubble level' was fitted to the CropCircle™ sensor to ensure nadir orientation. Both the individual component PAR measurements and the canopy reflectance values (Red_{AOS} and NIR_{AOS}) were recorded by a GeoSCOUT GLS 400 data logger (Holland Scientific Inc., Lincoln, NE, USA) along with the time of measurement to determine θ_s. Six measurements of $NDVI_{AOS}$ were derived from each quadrat in a 12 s window and the average calculated.

All fAPAR–reflectance index relationships were examined using Microsoft Excel (version 2010). A combination of highest coefficient of determination (R^2) and the lowest root mean square error (RMSE) (Eq. (2)) was used as the basis for identifying suitable indices:

$$\text{RMSE} = \sqrt{\sum (\text{observed fAPAR} - \text{Estimated fAPAR})^2/(n-1)} \quad (2)$$

In order to compare the slopes and intercepts of fAPAR with NIR_{AOS} and RED_{AOS} reflectances at different solar elevation angles (θ_s), an analysis of variance (ANOVA) was performed, also in Microsoft Excel (v. 2010).

3. Results and discussion

The relationships between fAPAR with the top of canopy NIR_{AOS} and Red_{AOS} reflectances at different θ_s are shown in Fig. 1 (a) and (b), respectively. The *x*-axes in Fig. 1(a) and (b) indicate increasing reflectance values. Here the AOS data have been selected, somewhat unconventionally, as the abscissa because in terms of responding to the solar elevation angle it is the