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Prediction of leaf area index in almonds by vegetation indexes

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ABSTRACT

Three levels of scale for determining leaf area index (LAI) were explored within an almond orchard of alternating rows of Nonpareil and Monterey varieties using hemispherical photography and mule lightbar (MLB) at ground level up to airborne and satellite imagery. We compared LAI estimates of 56 fisheye photos strategically placed in the orchard to validate 500,000 MLB point scans of a small portion of the aisles between tree rows to water and vegetation indexes of MASTER (MODIS/ASTER simulator) and Landsat 5 imagery. The high correlation of fisheye photo LAI to MLB LAI estimates establishes this new method against the measurement standard within the plant community while significantly increasing sample size. MLB LAI and MASTER vegetation indexes, such as NDWI (normalized difference water index), GMI (Gitelson–Merzlyak index) and NDVI (normalized difference vegetation index), were highly correlated ($r^2 = 0.90$). In addition, a high correlation ($r^2 = 0.80$) between the MLB measured LAI and selected Landsat derived vegetation indexes (VI) was found. This scaling and validation of LAI estimate expands the spatial area and frequency of determination for time series analysis of crop phenology studies.

1. Introduction

1.1. LAI and measurement methods

Leaf area index (LAI) is defined as the total, one-sided area of leaves per unit ground surface area (Watson, 1947). This parameter is essential to modeling the processes occurring in the soil–plant–atmosphere continuum, such as evapotranspiration, CO_2 assimilation, earth surface light extinction, and for estimating primary productivity of natural and managed ecosystems (Baret and Guyot, 1991; Turner et al., 2004). Bréda (2003) and Jonckheere et al. (2004) provide a comprehensive review of the methods available for LAI determination. Direct methods for LAI determination are time consuming and destructive, and alternatively, indirect methods such as point quadrant, allometric and non-contact methods, have been developed. In the last two decades these non-contact, optical methods, have gained popularity through their reliability and ease of operation, although they were conceptualized early in the 1950s (Martens et al., 1993; Bréda, 2003).

Optical methods measure transmitted and non-intercepted light through the canopy within part or all the photosynthetically active radiation (PAR) spectral region between 400 and 700 nm due to photosynthetic absorption, while reflecting the majority of longer near infrared wavelengths for heat control (Jensen, 2007). These techniques are based on the analysis of either the sky gap fraction or the gap size distribution of light transmitted through the canopy. The AccuPAR LP-80 (Decagon Devices, Inc., Pullman, WA, USA), LAI-2000 plant canopy analyzer (Li-COR Bioscience, Lincoln, NE, USA) and hemispherical (fisheye lens) canopy photography are examples of optical methods based on gap fraction analysis. The Tracing and Architecture of Canopies (TRAC, Third-Wave Engineering, Ottawa, Canada) and Multiband Vegetation Imager (MVI, Spectrasource Instruments, Westlake Village, Canada) are based on the analysis of gap size distribution below the canopy.

The AccuPAR LP-80 ceptometer measures sky gap fraction by comparing the intensity of PAR above to that below the canopy to assess canopy light interception and leaf distribution. LAI is determined instantaneously by the instrument when sun zenith angle, sunbeam fraction and leaf angle distribution are specified. The two main disadvantages of this instrument, as compared with other devices based on gap fraction analysis, are the poor

Abbreviations: EVI, enhanced vegetation index; fPAR, fractional PAR (photosynthetically active radiation) intercepted by the canopy; GMI, Gitelson–Merzlyak index; LADP, leaf angle distribution parameter; LAI, leaf area index; MASTER, MODIS/ASTER simulator; MCARI, modified chlorophyll absorption reflectance index; MLB, mule lightbar; NDVI, normalized difference vegetation index; NDWI, normalized difference water index; RMSE, root mean squared error; SR, simple ratio; VI, vegetation index(es).

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estimation of LAI in coniferous forests (Jonckheere et al., 2004; Weiss et al., 2004; Garrigues et al., 2008) and the need of taking multiple observations to obtain a reliable result (Bréda, 2003). This latter can be easily overcome with highly intensive ceptometer measurements using a mule lightbar (Lampinen et al., 2012).

In the LAI-2000, the sensor measures diffuse blue light (320–490 nm) at five different zenith angles (7°, 23°, 38°, 53° and 68°) to determine the gap fraction for each of the zenith angles and calculates LAI instantaneously by analyzing the remaining portion of this highly absorbed light region that is transmitted through the canopy compared to that measured above canopy.

Hemispherical photography is based on the estimation of position, size, density and distribution of canopy gaps. High resolution digital cameras with 180° fisheye lenses acquire photos quickly from beneath the canopy, and are rapidly analyzed with computer software based on algorithms of zenith angle, light attenuation and contrast between sky and canopy elements. In addition to LAI values, fisheye photography provides a record for characterizing canopy structure, below-canopy radiation microclimate and solar radiation indices (Bréda, 2003).

1.2. Imagery spectral indexes and LAI

Airborne and satellite spectral estimates of LAI have used the principle of incoming radiation (I) is either absorbed (A), transmitted (T) or reflected (R) by the canopy.

$$I = A + T + R \quad (1)$$

The amount of visible light in the PAR region absorbed by plant pigments is directly related to LAI. This relationship was initially demonstrated in cereals and other crops and natural vegetation with sensors mounted on terrestrial platforms (Asrar et al., 1984; Sellers, 1985; Tucker and Sellers, 1986; Christensen and Goudriaan, 1993), and then scaled up to airborne and satellite imagery in many reports (e.g. Prince and Astle, 1986; Kerr and Ostrovsky, 2003; Petorelli et al., 2005; Glenn et al., 2008). The association of specific wavelengths absorption or reflectance to specific pigments and plant constituents, such as water, lignin, cellulose, starch and protein, and with water and soil, has led to the creation of a large number of vegetation indexes (VI) calibrated to specific biophysical conditions. These include many VI developed to overcome limitations due to soil background, leaf inclination angle, leaf optical properties and atmospheric conditions. While some authors consider VI are poor estimators of LAI because of only moderate, non-linear correlation with canopy attributes, including LAI (Baret and Guyot, 1991), and recommend using VI to predict canopy light absorption (Glenn et al., 2008), others have found a good correlation between green LAI and chlorophyll related VIs (Viña et al., 2011).

In these techniques, the difficulty of scaling a few point measurements from mixed components of plant canopy, non-photosynthetic vegetation (NPV) and soil within the pixel area may reduce the accuracy of the broad view acquired with airborne and satellite imagery. There are several sources of error contributing to low correlations between point sampled LAI and image VI, including variation in the component mixture within each image pixel, some misregistration of image to ground point measurement locations, as well as inadequate number of LAI samples and measurement errors. Aspinall et al. (2002) suggest that while increasing pixel area reduces georegistration errors, large pixels also require a substantially greater number of ground reference sites to represent the pixel mixture of reflectance. In agricultural applications, the structure and repeated regularity of alternating row canopy with soil in exposed furrows and clean orchard aisles presents a significant problem in determining the actual variability within the component mixtures with misalignment between crop rows and pixel ground spatial distance caused by constructive and destructive phase resonance that appears to enhance and reduce albedo within the pixel area (Meggio et al., 2008).

Beyond the estimation of LAI, some studies have aimed to predict crop yield with spectral measurements, in some cases with a high degree of accuracy (Asrar et al., 1984; Christensen and Goudriaan, 1993). Yield is directly related to plant cover in many crops, mainly annual crops (Ferencz et al., 2004). Zarco-Tejada et al. (2005) associated NDVI and 44 other VI to yield in cotton due to ground cover, and Maas et al. (1999) demonstrated that area covered by cotton (ground cover) was highly predictive of yield. In the perennial crops of almond, walnut and peach, Lampinen et al. (2012) demonstrated that yield potential is directly proportional to light interception by the canopy. Water consumption, nutrient status, and other precision farming-related inputs are directly linked to LAI and plant biomass (Broge and Mortensen, 2002; Thenkabail, 2003). Early determination of LAI and prediction of yield potential would provide better distribution and utilization of crop resources.

The objective of this study was to compare the effectiveness of using MLB spatially intensive sampling measurements under orchard canopy in calibrating airborne and satellite image vegetation indexes for determining LAI over entire orchards or multiple orchards. These spatially intensive MLB measurements were validated from point samples using hemispherical photography.

2. Materials and methods

2.1. Site description

This study combines canopy data collected during the mid-season of 2009 in two experiments in separate commercial almond (*Prunus dulcis* (Miller)) orchards. The orchards, of approximately 66 and 84 ha, are located near the town of Lost Hills, Kern County, in southern San Joaquin Valley of California (Belridge 35.51°, −119.67° and Spur Dynamics 35.60°, −119.67°) and are owned by the Paramount Farming Corp. (Los Angeles, CA). The location, age and general characteristics of the two sites are described in Table 1. These orchards are on soils of fine sandy loam surface, mixed mineralogy, superactive, calcareous, Thermic Typic Torriorthents (Kimberlina) and sandy loam surface, mixed mineralogy, superactive, calcareous, Thermic Typic Haplargids (Milham), well drained, formed on nearly level Quaternary alluvium. However, in portions of both orchards, zinc deficiency leaf chlorosis was diagnosed from visual appearance and leaf analysis. Nonpareil trees were planted in alternating rows running north and south with Monterey and with Monterey and Wood Colony in Belridge and Spur Dynamics sites. Before harvest, the orchards floor was mowed and the aisles were scraped smooth. In the orchard given the name of its locality Belridge, fertilizer was injected at various application rates into two irrigation system trials of small emitter types (fan jet micro-sprinkler and drip). The range of nitrogen rates was 140–392 kg ha^{-1} in two soluble forms, urea and calcium nitrate, as well as various potassium rates. This "fertigation" study also included an increased water application by 20% more than the anticipated crop evapotranspiration (ET_c) commonly used by local growers to schedule irrigations. In the second orchard named for its experiment Spur Dynamics, fertilizer with micro-sprinkler irrigation were consistent with general grower practices of the area to evaluate the dynamics of almond spur bearing as related to previous bearing as well as leaf area and sunlight exposure (Tombesi et al., 2011). These important treatment distinctions between orchards presented broad variations in canopy age and density to evaluate the robustness of LAI models. Almond trees in this