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Photographic measurement of leaf angles in field crops

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ABSTRACT

Leaf angle distribution (LAD) is one of the most important parameters used to describe the structure of horizontally homogeneous vegetation canopies such as field crops. LAD affects how incident photosynthetically active radiation is distributed on plant leaves, thus directly affecting plant productivity. Knowledge of LAD is also required for retrieval of other important biophysical variables from measurements of canopy radiation transmittance or spectral reflectance. Unfortunately, its determination is laborious and measured data is rarely available. In this study, we applied a recently developed method for determination of the inclination angles using leveled digital photography to the leaves of six cool-temperate crops: faba bean, narrow-leafed lupin, turnip rape, wheat, barley, and oat. The method, previously applied only to small and flat leaves of broadleaved trees and bushes, was extended to be applicable to the narrow and curved leaves of cereals. A reasonable match was found between the leaf angles determined by photographic measurements and the mean leaf tilt angles (MTA) measured using a LAI-2000 plant canopy analyzer for five out of the six species ($R^2 = 0.92$). The error caused by assuming a spherical LAD, when calculating LAI from canopy transmittance measurements, varied between 0 and 1.5 LAI units, depending on species. Finally, we analyzed the correlation between photographically determined species-specific LADs and airborne imaging spectroscopy data acquired for the same species in a similar growth stage. The highest correlation between spectral reflectance factor and leaf mean tilt angle was found at a wavelength of 748 nm ($R = 0.80$). The high correlation between MTA and this red edge waveband can be useful for MTA determination from imaging spectroscopy.

1. Introduction

In field crops grown under favorable conditions, leaves of neighboring plants form a (quasi-)continuous layer, called the vegetation canopy, that captures incident photosynthetically active radiation. The radiation fluxes reflected, transmitted and absorbed by plants determine canopy albedo, the light conditions below the canopy, and the amount of energy available for photosynthesis. The mean values of canopy radiation fluxes and the irradiance distribution on leaf surfaces, determined by the spatial distribution of leaves (in other words, canopy structure) have significant effects on the photosynthetic capacity of plants (Gutschick, 1991). At the same time, canopy structure also largely determines what the canopy looks like when observed from above, for example, by a remote sensing instrument (Knyazikhin et al., 2012). This creates a problem for retrieving canopy biophysical variables (e.g., chlorophyll content, leaf area index) using common remote sensing algorithms (Houborg et al., 2007; Viña et al., 2011).

The amount of leaf cover in a vegetation canopy is commonly quantified using the Leaf Area Index (LAI), defined as hemisurface leaf area per unit horizontal ground area (Watson, 1947). The second most commonly used structural characteristic of a vegetation canopy is the Leaf Angle Distribution (LAD) function, which is defined as the probability of a leaf element of unit size to have its normal within a specified unit solid angle. Assuming uniform distribution of leaf azimuth angles, LAD becomes the probability density function of the zenith angle θ_L of leaf normal. For simple and horizontally relatively homogeneous canopies, the two quantities, LAD and LAI, are the only two structure parameters required for accurate prediction of reflected, transmitted and absorbed radiation fluxes (Ross, 1981; Lang et al., 1985).

A set of mathematical LAD functions is commonly used to classify the measured leaf angle distributions (de Wit, 1965; Weiss et al., 2004). Here, we use the planophile, spherical, and erectophile distributions in the formulation given by Weiss et al. (2004), the abstract case of a canopy of exclusively horizontal leaves (horizontal LAD), as well as a canopy with the same proportion of leaf area

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Table 1
Description of the test plots used in the study. Soil type is given according to World Reference Base for Soil Resources (WRB, 2007): (1) fertile luvic stagnosol, sandy clay loam; (2) haplic gleysols, silty clay loam; (3) sulfic cryaquepts; and (4) fertile luvic stagnosol, sandy medium clay loam.

	Faba bean		Narrow-leafed lupin	Turnip rape	Wheat		Barley		Oat
Plot size (m × m)	25 × 8	10 × 2	25 × 8	25 × 8	25 × 8	10 × 2	50 × 12	25 × 8	25 × 8
Number of plots	4	36	4	4	4	96	6	4	4
Fertilizer application (kg N ha^{-1})	21	12–40	21	109	119	0–150	89–100	99	99
Seeding density (m^{-2})	55	60	125	300	700	650	450–550	600	500
Soil type	3	1	3	3	3	1, 2	4	3	3

at any angle (uniform LAD). Of these distributions, the erectophile canopy has the largest mean zenith angle of leaf normal (or, equivalently, the largest Mean leaf Tilt Angle, MTA) followed in order of decreasing MTA by canopies with spherical, uniform, planophile and horizontal LADs.

Traditionally, LAD has been measured with mechanical inclinometers that have been put in a contact with leaf surfaces. This direct method is laborious and requires access to and careful measurement of a large number of leaf surfaces (Lang et al., 1985). Modern alternatives to traditional inclinometer measurements include 3D digitizing of individual plant elements using specialized instrumentation (Sinoquet et al., 1998) and laser scanning (Hosoi et al., 2009), but these approaches are resource-demanding, resulting in a lack of data on the LADs of many crops. A common approach is then to use the spherical LAD, that is, to assume that leaves have no preferred orientation (Goudriaan, 1988; Campbell and Norman, 1998; Weiss et al., 2004).

Indirect methods have been developed to retrieve the information on leaf inclination angles from measurements of radiation penetration of the canopy at different view angles (Lang, 1986). Unfortunately, it is almost impossible to differentiate the effects of leaf angles on canopy transmittance from other structural influences.

A new method has been developed, based on analyzing leveled digital camera images of canopies consisting of flat leaves (Ryu et al., 2010a; Pisek et al., 2011, 2013). This method, here called the photographic method, allows for a rapid, non-contact and accurate estimation of LAD (Ryu et al., 2010a). It has shown potential to overcome many of the shortcomings of other LAD measurement techniques. The photographic method has been applied successfully to a number of broadleaf canopies (Pisek et al., 2011, 2013).

The aim of this research was to extend the photographic LAD estimation method to field crops with long non-flat leaves that do not have any unique inclination angle. We determined the LAD of six cool-temperate crops with diverse growth habits, and compared the results of the photographic method to a well-established technique based on the angular dependence of canopy transmittance and to literature values. Finally, we tested the potential for using crop LAD and transmittance measurements to calculate LAI and the influence of LAD on the spectral reflectance in visible and near-infrared wavebands.

2. Materials and methods

2.1. Study site

The study site was part of the Viikki Experimental Farm in Helsinki, University of Helsinki, Finland (60.224°N, 25.021°E, altitude 10 m above sea level). Six crop species, narrow-leafed lupin (*Lupinus angustifolius* L. 'Haags Blaue'), faba bean (*Vicia faba* L. 'Kontu'), turnip rape (*Brassica rapa* L. ssp. *oleifera* (DC.) Metzg. 'Apollo'), wheat (*Triticum aestivum* L. emend Thell. 'Amaretto'), barley (*Hordeum vulgare* L. 'Streif', 'Chill' and 'Fairytale') and oat (*Avena sativa* L. 'Ivory' and 'Mirella') were included in this study, representing three plant families and different growth habits, and widely grown throughout cool-temperate regions of the world (Table 1). They were grown in four different field experiments and a single plot of each species was used for photographic determination of leaf angles in 2012. The values were considered to be typical to each species, i.e., we assumed crop LAD to be a species-specific parameter (Ross, 1981; Campbell, 1990; Campbell and Norman, 1998; Weiss et al., 2004). Spectroscopic information on a set of 162 plots of these species had been obtained one year before photographic measurements, in 2011 in the same crop development stage. The number of plots of each species as well as the sizes of the plots for which spectral data was available varied between treatments, soil type and species (Table 1). The row spacing for all crops was 12.5 cm and the canopy height was less than 1 m. Although three barley and two oat cultivars were used in 2011, variation between cultivars was small in comparison to that between species, and cultivar datasets were pooled.

2.2. Airborne imaging spectroscopy data

Imaging spectroscopy data was acquired on July 25, 2011, with the AISA Eagle II airborne imaging spectrometer (Specim Ltd., Oulu, Finland) onboard a twin-engine Piper PA-23 aircraft at a flying height of approximately 600 m. Measurements were carried out between 09:36 and 10:00 local time, when solar zenith angle varied between 50.4° and 48.1°. For each pixel, the measurement zenith angle was between zero and half of the sensor field of view (i.e., 0–18.9°) and the sensor azimuth angle measured relative to the solar direction was approximately 90°.

Reflected radiation was measured in 64 channels spanning the visible and near-infrared parts of the solar spectrum (400–1000 nm) with a spectral resolution of 9–10 nm, and a spatial resolution of 0.4 m. The spectroscopic image was radiometrically calibrated using the CaliGeo software package (Specim Ltd., Oulu, Finland). Next, the data were georectifed using Parge (ReSe Applications Schläpfer, Wil, Switzerland) with the help of ground control points and the inertial navigation data recorded during the flight. Finally, the data were calculated to below-atmosphere hemispherical-directional reflectance factors using ATCOR-4 (ReSe Applications Schläpfer, Wil, Switzerland).

We extracted the spectral data corresponding to the 162 test plots and calculated the average reflectance spectrum for each plot. Finally, to cope with the large imbalance in the data set dominated by wheat and faba bean, we grouped the measurements by LAI values and calculated the averaged spectrum for each species and unit LAI interval (Table 2). The grouped dataset consisted of 18 averaged spectra. However, for some analyses, the distribution of plots between species was non-significant and we treated the average spectrum of each of the 162 plots as a separate measurement.

2.3. Leaf area index measurement

The SunScan SS1 ceptometer bar (Delta-T Devices, Cambridge, UK) canopy analysis system was used to measure the LAI of the 162 test plots weekly in July 2011. By choosing the data with the date closest to the airborne campaign, the LAI data used in our analyses was collected within five days of the airborne data acquisition. SunScan was entered from one edge of the plot at about 45° to the