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Intercomparison and sensitivity analysis of Leaf Area Index retrievals from LAI-2000, AccuPAR, and digital hemispherical photography over croplands

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ABSTRACT

Validation of Leaf Area Index (LAI) derived from moderate resolution remote sensing observations generally involves optical technique to measure ground LAI. As the current validation datasets are derived using multiple optical retrieval techniques, assessment of the consistency between these techniques is required. In this study the effective Plant Area Index (PAI_{eff}) retrievals by three major optical instruments, LAI-2000, AccuPAR, and Digital Hemispherical Photographs (DHPs), were analyzed over 10 crops (soybean, corn, alfalfa, sorghum, peanut and pasture) at Manfredi site in Cordoba province, Argentina. The focus of research was on quantifying PAI_{eff} sensitivity to the type of instrument, retrieval parameters and gap fraction inversion methods as well as environmental conditions (canopy heterogeneity, senescent vegetation, illumination conditions). Results indicate that sensitivity of DHP method to illumination conditions is low (14% compared to 28% and 86% for LAI-2000 and AccuPAR, respectively). The intercomparison of PAI_{eff} retrievals indicates large discrepancies between optical techniques for short canopy over which downward-pointing DHP technique performs better than LAI-2000 and AccuPAR. Better agreement was found for tall canopy without senescent vegetation and low spatial heterogeneity. Overall, discrepancies in PAI_{eff} between instruments are mainly explained by differences in spatial sampling of transmittance between instruments (over short and heterogeneous canopies) caused by variations in instrument footprint, azimuthal range, and zenith angle spatial resolution (coarser for LAI-2000 than DHP). Our results indicate that DHP is the most robust technique in terms of low sensitivity to illumination conditions, accurate spatial sampling of transmittance, ability to capture gap fraction over short canopy using downward-looking photographs, independence from canopy optical ancillary information, and potential to derive clumping index. It can thus be applied to a large range of canopy structures, and environmental conditions as required by validation protocols.

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1. Introduction

Leaf Area Index (LAI) is a key biophysical variable, used in most global models of climate, ecosystem productivity, biogeochemistry, hydrology, and ecology. It is defined as half the total developed area of green leaves (all sided) per unit ground horizontal surface area (Chen and Black, 1992). Global LAI products are operationally produced from remote sensing observation of major space-borne instruments (e.g. MODIS/TERRA-AQUA, VEGETATION/SPOT4-5). Assessment of the uncertainties of LAI remote sensing products, *i.e.*, validation of the LAI products with ground measurements, is critical for their proper use in land surface models (Morisette et al., 2006; Garrigues et al., 2008; Weiss et al., 2007). One major shortcoming of the current validation studies is that they poorly document uncertainties associated with LAI measurement—a key information to properly validate satellite product (Garrigues et al., 2008; Weiss et al., 2007).

LAI measurements can be subdivided into two major categories: direct and indirect techniques (Gower et al., 1999; Breda, 2003; Jonckheere et al., 2004). Direct measurements involve destructive harvest techniques and litter fall traps. While laborious, such measurements provide a reference for indirect measurements if the spatial sampling properly represents canopy heterogeneity. The most commonly used indirect techniques in validation studies are optical due to their fast and easy sampling of LAI over large spatial areas (Morisette et al., 2006). Optical techniques are based on measurement of light transmittance through the canopy (Jonckheere et al., 2004; Weiss et al., 2004). They have been implemented with multiple commercial optical instruments, including LAI-2000 Plant Canopy Analyzer (LI-COR, Lincoln, Nebraska USA), AccuPAR (Decagon Devices, Inc., Pullman, Washington, USA), Tracing Radiation and Architecture of Canopies (TRAC, 3rd Wave, Ontario Canada), Digital Hemispherical Photographs (DHPs) among others (Jonckheere et al., 2004).

The reference *in situ* LAI estimate (called hereafter *actual* LAI) is achieved using destructive samplings for foliage element area estimates, and locally calibrated allometric relationships to scale these estimates over plots (Chen et al., 1997; Jonckheere et al., 2004). In contrast, optical measurements provide *effective* LAI, which is an approximation of the *actual* LAI because of two main issues. First, except when using color DHP, optical measurements do not allow distinguishing between photosynthetically active tissues ("green elements") and other plant elements such as branches, stems, trunks, and senescent leaves, leading to a positive bias in estimated LAI (Chen et al., 1997; Kucharik et al., 1998; Barclay et al., 2000; Stenberg et al., 2003). For this reason, the term Plant Area Index (PAI) will be used in this paper to represent the quantity measured by optical instruments. In addition, most optical techniques retrieve PAI assuming that the spatial distribution of vegetation elements within the canopy is random which is generally not the case in actual canopies (Nilson, 1971; Chen and Black, 1992; Weiss et al., 2004). Typically, the deviation from the random case is quantified through the clumping index, Ω (Chen and Black, 1992), in the expression $PAI_{eff} = \Omega PAI$, where PAI is the actual PAI as measured from destructive sampling and PAI_{eff} is the effective PAI derived from optical measurements assuming a random leaf distribution. Clumping index is equal to 1 for randomly distributed foliage, >1 for regularly distributed foliage, and <1 for clumped canopies (Weiss et al., 2004). It depends both on plant-scale structure, *i.e.*, the spatial distribution of foliage elements along plant stems and trunks, branches or shoots for trees, and on canopy-scale structure, *i.e.*, the spatial heterogeneity of plant arrangements within the canopy as it occurs in discontinuous canopies (e.g. row crops). When leaf clumping is not accounted for, as in the case of PAI_{eff}, the *actual* PAI values may be significantly underestimated (Begue, 1993; Chen and Cihlar, 1995; Stenberg, 1996; Cohen et al., 1997; Fernandes et al., 2003; Jonckheere et al., 2004; Leblanc et al., 2005). Other sources of errors associated with optical measurement includes illumination conditions (direct versus diffuse illumination), variations in the instrument footprint, saturation of the optical signal in dense canopies (gap fraction saturates as LAI approaches to 5–6, Gower et al. (1999)), simplification of leaf optical properties (Leblanc and Chen, 2001; Hyer and Goetz, 2004), poor performances of some instruments (e.g. AccuPAR, LAI-2000) for short canopies, and the ability of the sampling scheme to capture canopy spatial heterogeneity (Weiss et al., 2004).

Some of LAI retrieval errors described above can be corrected through appropriate techniques. Vegetation clumping can be taken into account using clumping index values taken from literature or directly derived from DHP (Van Gardingen et al., 1999; Leblanc et al., 2005) or TRAC (Chen and Cihlar, 1995), while separation of green elements from non-green elements can be achieved with DHP under specific (diffuse) illumination conditions or using near-infrared cameras (Chapman, 2007). Since these corrections are not systematically applied to LAI ground measurements used in current validation datasets (Morisette et al., 2006), evaluating the impact of these uncertainties on LAI retrieval is needed. While destructive sampling is mandatory to assess the absolute accuracy of optical measurements, intercomparison and sensitivity analysis to key retrieval parameters of optical techniques bring useful insights on the relative performances of each instrument (Hyer and Goetz, 2004; Zhang et al., 2005). Besides, since current validation datasets are derived using multiple optical retrieval techniques, assessment of the consistency between these techniques is required. Such exercise is also valuable to identify stable and repeatable measurements of PAI among existing optical retrieval techniques.

In this study, we intercompare PAI_{eff} retrievals from LAI-2000, AccuPAR, and DHP instruments which are widely used in validation studies. Overall, the literature indicates that consistency between these retrieval techniques vary with vegetation type, range of retrieved LAI, selection of retrieval parameters, and illumination conditions (Martens et al., 1993; Chen et al., 1997; Planchais and Pontailler, 1999; White et al., 2000; Wilhelm et al., 2000; Hyer and Goetz, 2004). Nevertheless, few studies have simultaneously compared these three instruments over the same site, and no consensus between past intercomparison studies has been reached. Up to now most intercomparison of optical instruments have been achieved over forests (Hyer and Goetz, 2004; Zhang et al., 2005), while croplands were underrepresented in such studies.

The objective of this research is to consolidate former experiences on optical measurements, and more specifically