ESTIMATION OF LEAF AREA INDEX USING GROUND SPECTRAL MEASUREMENTS OVER AGRICULTURE CROPS: PREDICTION CAPABILITY ASSESSMENT OF OPTICAL INDICES

D. Haboudane [a], *, J. R. Miller [b], N. Tremblay [c], E. Pattey [d], P. Vigneault [c]

[a] Laboratoire d'expertise et de recherche en télédétection et géomatique, UQAC, 555, Boul. Université, Chicoutimi, Quebec, G7H 2B1, Canada - Driss_Haboudane@uqac.ca
[b] Department of Physics and Astronomy, York University, Toronto, Ontario, M3J 1P3, Canada - jrmiller@yorku.ca
[c] Horticultural Research and Development Centre, Agriculture and Agri-Food Canada, 430, Boul. Gouin, St-Jean-sur-Richelieu, Quebec, J3B 3E6, Canada - tremblayna@agr.gc.ca
[d] Agriculture and Agri-Food Canada, K. W. Neatby, 960, Carling Ave., Ottawa, Ontario, K1A 0C6, Canada - patteye@agr.gc.ca

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ABSTRACT:

Leaf area index (LAI) is a key canopy descriptor that is used to determine foliage cover, and predict photosynthesis and evapotranspiration in order to assess crop yield. Its estimation from remote sensing data has been the focus of many investigations in recent years. In this context, we have used ground measured reflectances to study the potential of spectral indices for LAI prediction using remotely sensed data. LAI measurements and corresponding ground spectra were collected over four years (2000, 2001, 2002 and 2003) for three crop types (corn, beans, and peas) in a study area at Saint-Jean-sur-Richelieu, near Montreal (Quebec, Canada). Hence, a set of vegetation indices were assessed in terms of their linearity with LAI variation, as well as their prediction ability for a range of crops types. Predictive equations have been developed from ground measured data, and then applied to airborne CASI hyperspectral images acquired over agricultural fields of corn, wheat, and soybean grown during summer 2001 (former greenbelt farm of Agriculture and Agri-Food Canada, Ottawa). The results demonstrated that while indices like NDVI suffer from saturation at medium and high LAI values others like MSAVI2 and MTVI2 result in significantly improved performances. Evaluation of predictions revealed excellent agreement with field measurements: values of CASI-estimated LAI were very similar to the measured ones.

1. INTRODUCTION

Remote sensing is seen as an important tool to provide missing or inappropriate information for the achievement of sustainable and efficient agricultural practices. Assessment of crop leaf area index (LAI) and its spatial distribution in agricultural landscapes are of importance for addressing various agricultural issues such as: crop growth monitoring, vegetation stress, crop forecasting, yield predictions, and management practices. Indeed, LAI is a canopy biophysical variable that plays a major role in vegetation physiological processes, and ecosystem functioning. Its retrieval from remotely sensed data has led to the development of various approaches and methodologies for LAI determination at different scales and over diverse types of vegetation canopies (Baret and Guyot, 1991; Daughtry et al., 1992; Chen et al., 2002; Haboudane et al., 2004; etc.). While some studies have used model inversions (Jacquemoud et al., 2000), and spectral unmixing (Hu *et al*., 2002; Peddle and Johnson, 2000; Pacheco *et al*., 2001), others have expended considerable effort to improve the relationships between LAI and optical spectral indices (Spanner *et al*., 1990; Chen and Cihlar, 1996; Fassnacht *et al*., 1997; Haboudane et al., 2004). Even though some spectral indices have shown satisfactory correlation with LAI, studies have demonstrated that those indices were as well very sensitive to other vegetation variables such as canopy cover, chlorophyll content, and absorbed photosynthetically active radiation (Broge and Leblanc, 2000; Broge and Mortenson, 2002; Daughtry et al., 2000; Gitelson et al., 2001; Haboudane et al., 2002). Furthermore, farmers are concerned with controlling the spatial variability within agricultural fields, aiming to improve farm productivity and to reduce input (fertiliser) costs. To this end, various precision agriculture technologies and tools have been developed during the recent years (Moran et al., 1997). Their primary goal is to help scientists and farmers better manage agricultural fields through the use of spatially-variable application rates that are based on localised plant growth requirements and deficiencies (Cassel et al., 2000). Hence, crop LAI status at any particular stage in the growth cycle can be a consequence of several crop and soil variables, such as soil condition, nutrient imbalances, and disease. Its spatial heterogeneity can be used as an indicator of the crop condition resulting from vegetation response to soil properties and specifically nutrients availability for given weather conditions.

In this context, the objectives of the present study were (i) to use ground-measured spectra to establish relationships between ground-measured LAI and selected spectral indices, (ii) to assess the potential of these indices for LAI predictions,

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* Corresponding author.

and (iii) to validate the indices' prediction capability using CASI (Compact Airborne Spectrographic Imager) hyperspectral images and LAI measurements collected over fields different from those used to collect ground spectra.

2. MATERIAL AND METHODS

2.1 Ground Spectra and Corresponding LAI Values for Prediction Equations

The study area is located near Montreal, at the Horticultural Research and Development Centre of Agriculture and Agri-Food Canada, St-Jean-sur-Richelieu, Quebec, Canada. It is known as the L'Acadie Experimental Research Sub-station where various crops are grown on different experimental fields. Intensive field campaigns (IFCs) were organized during the growing seasons of 2000, 2001, 2002, and 2003 in order to collect ground spectra and corresponding LAI values as well as crop growth measures. Over these four years, different crops (corn, beans, and peas) were monitored on experimental and commercial fields. Acquisition dates were planned to coincide with different phenological development stages, aiming to monitor temporal changes in crop biophysical variables such as LAI, ground cover, and other growth measures. A particular emphasis was placed on acquiring ground data covering the earliest, middle and latest periods of the growth season.

Spectral reflectance data over the region 0.4 – 1.1 mm wavelength region were acquired with the ASD spectroradiometer (Analytical Spectral Device, Boulder, CO). A white Spectralon reference panel (Labsphere, North Sutton, NH) was used to calibrate the spectroradiometer spectral radiance measurements to reflectance, by measurements of the reference panel under the same illumination conditions as the ground targets. Reflectances were calculated and corrected for the non-ideal properties of the reference panel as described by Robinson and Biehl (1979). In all experiments, radiometric data were collected close to solar noon; thus, changes in illumination conditions (solar zenith angle) were minimized.

Crop LAI values corresponding to measured spectra were determined using both non-destructive and destructive methods using the Plant Canopy Analyzer (Li-Cor model LAI-2000) and an area meter (LI-3100, Li-Cor, Lincoln, NE), respectively. The latter was used to measure the LAI at the early growth stage, as well as to determine separately LAI of green and dead leaves during the senescence stage.

2.2 CASI Hyperspectral Images and LAI Values for Validation

The study area is located in Ottawa (Canada), at the former Greenbelt Farm of Agriculture and Agri-Food Canada. Over three successive years, different crops (corn, wheat, soybean) were grown on a 30-ha field with a drained clay loam soil as well as on adjacent fields owned by farmers. The experiments consisted of dividing the main field into four regions receiving various nitrogen treatments: 100% of the recommended fertilization over a flat region, 100% of recommended nitrogen over a region with a gentle topographic slope, 60% of the recommended rate, and no nitrogen application (0%). They were thus laid out to promote development of remote sensing techniques for detection of plant stresses in precision agriculture, particularly stresses due to nitrogen deficiency, water deficit, and topographic influence. Within each region, a grid of georeferenced points spaced every 25 m was established on a representative section of 150 m x 150 m. These locations were used to monitor crop biophysical parameters during the growing season, particularly during intensive field campaigns coinciding with image acquisition. Details on the experimental site and design are presented in Pattey et al. (2001).

Hyperspectral images were acquired by the Compact Airborne Spectrographic Imager (CASI), flown by Centre for Research in Earth and Space Technology (CRESTech). Simultaneously, a set of field and laboratory data were collected for biochemical and geochemical analysis, along with optical and biophysical measurements. Ground truth measurements included: (i) collection of leaf tissue for laboratory determination of leaf chlorophyll concentration, leaf area index (LAI) measurements using the Plant Canopy Analyzer (Li-Cor model LAI-2000), (ii) an area meter (LI-3100, Li-Cor, Lincoln, NE), and (iii) crop growth measures.

During 2000 and 2001 growing seasons, CASI hyperspectral images were collected in three different deployments, using two modes of operation: the *multispectral mode*, with 1 m spatial resolution and 7 spectral bands selected for sensing vegetation properties (489.5, 555.0, 624.6, 681.4, 706.1, 742.3, and 776.7 nm); and the *hyperspectral mode*, with 2 m spatial resolution and 72 channels covering the visible and near infrared portions of the solar spectrum from 408 to 947 nm with a bandwidth of 7.5 nm. Acquisition dates were planned to coincide with different phenological development stages, providing image data covering the earliest, middle and latest periods of the growth season.

The hyperspectral digital images collected by CASI were processed to at-sensor radiance using calibration coefficients determined in the laboratory by CRESTech (Centre for Research in Earth and Space Technology). Subsequently the CAM5S atmospheric correction model (O'Neill *et al*., 1997) was used to transform the relative at-sensor radiance to absolute ground-reflectance. To perform this operation, an estimate of aerosol optical depth at 550 nm was derived from ground sun-photometer measurements. Data regarding geographic position, illumination and viewing geometry as well as ground and sensor altitudes were derived both from aircraft navigation data records and ground GPS measurements.

Reflectance curves derived from processed CASI images showed the presence of spectral anomalies associated with atmospheric absorption features at specific wavelengths. Although we applied model-based atmospheric corrections, the calculated reflectances are still affected by spectrally-specific errors owing mostly to an under-correction of some atmospheric components effects (oxygen and water vapour absorption). The flat field calibration is a correction technique used to remove the residual atmospheric effects from hyperspectral reflectance image cubes. Its aim is to improve overall quality of spectra and provide apparent reflectance data that can be compared with laboratory spectra (Boardman and Huntington, 1996). It requires the presence, and identification, in images of spectrally-flat uniform areas where the spectral anomalies can be unambiguously attributed, in narrow spectral ranges, to atmospheric effects and the solar spectrum. In CASI images, these features were observed over asphalt and concrete areas within the same image where the reflectance spectra are assumed to be flat or nearly flat over these features. Using signatures of such scene elements, we calculated coefficients that adequately compensate effects of atmospheric water and oxygen absorption. After those coefficients were applied to the entire image, but only in the specific spectral ranges affected, we checked the signatures of different components of the image and found that observed residual features have been successfully removed.

2.3 Spectral indices

Several spectral indices have been reported in the literature and proven to be well correlated with vegetation biophysical parameters such as LAI, and biomass. Tremendous efforts have been devoted to improve vegetation indices and render them insensitive to variations in illumination conditions, observing geometry, and soil properties. A few studies have been carried out to assess and compare various vegetation indices in terms of their stability and their prediction capability for LAI (Baret and Guyot, 1991; Broge and Leblanc, 2000; Haboudane et al., 2004). Other research has dealt with modifying some vegetation indices to improve their linearity with, and increase their sensitivity to LAI (Nemani *et al*., 1993; Chen, 1996; Brown *et al*., 2000). Consequently, some indices have been identified as best estimators of LAI because they are less sensitive to the variation of external parameters affecting the spectral reflectance of the canopy namely soil optical properties, and atmospheric conditions (Broge and Leblanc, 2000), as well as to changes of leaf intrinsic properties such as chlorophyll concentration (Haboudane et al., 2004). Based on these studies we have selected three spectral indices briefly presented below.

Normalized difference vegetation index NDVI (Rouse et al., 1974)

$$(NIR - R)/(NIR + R) \qquad (1)$$

Modified second soil-adjusted vegetation index MSAVI2 (Qi et al., 1994)

$$\frac{1}{2}\left[2 * NIR + 1 - \sqrt{(2 * NIR + 1)^2 - 8 * (NIR - R)}\right] \qquad (2)$$

Modified second triangular vegetation index MTVI2 (Haboudane et al., 2004)

$$\frac{1.5 * [1.2 * (NIR - G) - 2.5 * (R - G)]}{\sqrt{(2 * NIR + 1)^2 - (6 * NIR - 5 * \sqrt{R}) - 0.5}} \qquad (3)$$

A detailed discussion on these indices can be found in Broge and Leblanc (2000) and Haboudane et al. (2004). In the formulae G, R and NIR denote canopy reflectance in the green (550 nm), red (670 nm), and near-infrared (800 nm), respectively.

Performance evaluation of these indices was based on measured canopy spectra corresponding to a wide range of LAI (0.13 to 6.50) measured for three crop types (corn, beans, and peas), under different conditions (four different years); thus, empirical relationships between LAI and the indices were determined. Their prediction capacity for estimation of LAI was then assessed using CASI hyperspectral images and corresponding ground truth for LAI from three other crop types (wheat, soybean, and corn).

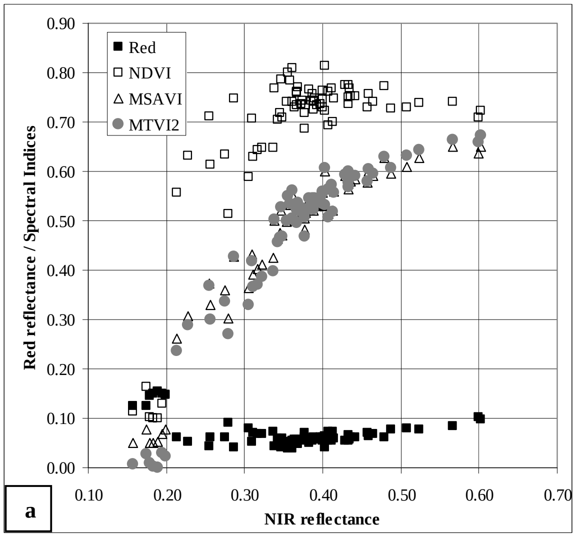
3. RESULTS AND ANALYSIS

3.1 Spectral Indices Behaviour

The main difference between these three indices resides in the saturation effect when LAI increases: NDVI reaches a saturation level asymptotically when LAI exceeds 2, while MSAVI2 and MTVI2 show a better trend without a clear saturation at high LAI levels (up to 6). This explains, in part, why MSAVI2 has proven to be a better greenness measure (Borge and Leblanc, 2000). To illustrate this effect, we plotted the indices against the near-infrared (NIR) reflectance (Figure 1) to compare each index's ability to depict LAI variations. The rationale for this analysis was that the NIR reflectance is strongly affected by changes in vegetation structural descriptors rather than by pigment variation.

Distinct behaviours are observable in Figure 1: NDVI became saturated when NIR reflectance exceeded 0.35 to 0.40 depending on the crop, while MSAVI2 and MTVI2 appear to be much more responsive to NIR reflectance increase. Indeed, MSAVI and MTVI2 showed only a slope change when NIR reflectance reached 0.40 for corn, and 0.55 for beans and peas. Moreover, NDVI seemed to be strongly affected by the red reflectance; thus, both red reflectance and NDVI approached asymptotic values, and showed virtually no further change, when NIR reflectance has exceeded 0.35 to 0.40. Conversely, NIR reflectance, which continued to increase substantially, induced virtually no change in NDVI trend. In contrast, MTVI2 and MSAVI2 appeared to be more sensitive to NIR reflectance increase, but less affected by the lack of dynamic in the red reflectance.

These distinctive behaviours are illustrated by indices values scattering in response to red reflectance variability. While MSAVI2 is the less sensitive to this effect, NDVI showed the highest level of scattering particularly in the case of corn and peas canopies (Figure 1 a & c). As for the dynamic range, MTVI2 exhibited more sensitivity to NIR reflectance than the other indices.



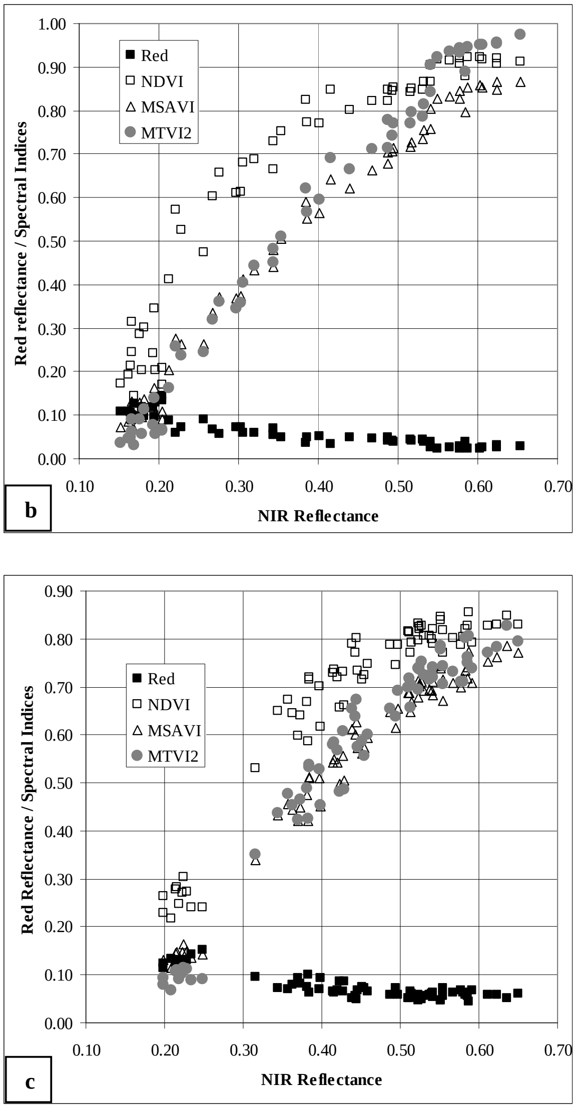


Figure 1. Sensitivity of red reflectance, NDVI, MSAVI2 and MTVI2 to changes in the NIR reflectance of crop canopies (Corn (a), Beans (b), and Peas (c)). Data are from the campaign of 2003.

3.2 Relationships Indices - LAI

The relationships between vegetation indices and LAI are not unique; they exhibit a considerable scatter caused by chlorophyll content variation and/or the influence of other canopy characteristics. In fact, the indices are designed to measure vegetation greenness in which chlorophyll content plays a major role as well as the amount of green leaves.

Our result for the four years of measurements revealed that equations relating indices to crop canopy reflectance is crop type-dependent. This is due to the range of LAI values, which was found to be wide for soybean, beans and peas, intermediate for corn, but intermediate to low for wheat. In this section, we present the relationships between NDVI, MSAVI, and MTVI2 and measured LAI for the only case of pea canopies (Figure 2).

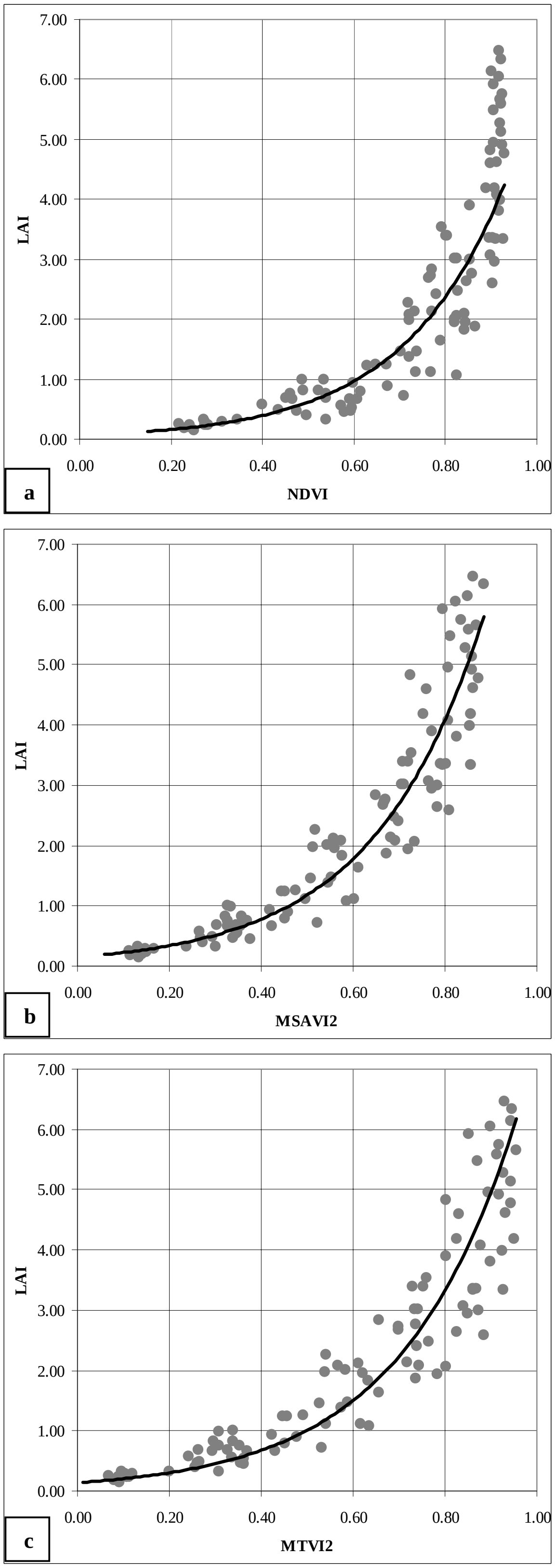


Figure 2. Relationships between spectral indices and measured LAI for pea canopies (2000-2003): NDVI (a), MSAVI2 (b), and MTVI2 (c).

3.3 Predictions and Validation

Predictive equations were determined from the relationships between the spectral indices (NDVI, MSAVI2 and MTVI2) using ground data collected over peas, beans, and corn canopies. The overall best fits were given by an exponential fit with a coefficient of determination (r^2) depending on the index of interest and the crop type. Indeed, for the three indices, we have obtained values around 0.91, 0.92, and 0.70 for beans, peas and corn, respectively. Equations obtained were applied to CASI hyperspectral images to map LAI status over agricultural fields seeded with corn, wheat, and soybean. Results were validated using ground truth measurements collected during the field campaigns of 1999, 2000, and 2001.

In this paper, we present preliminary results based on the use of predictive equations derived from the measurements over bean and pea canopies (Figure 3). The aim is to show the relative dependency of prediction algorithms on crop type. Work is in progress to evaluate overall results concerning corn canopies, as well as predictive algorithms determined from data representing all the three canopies.

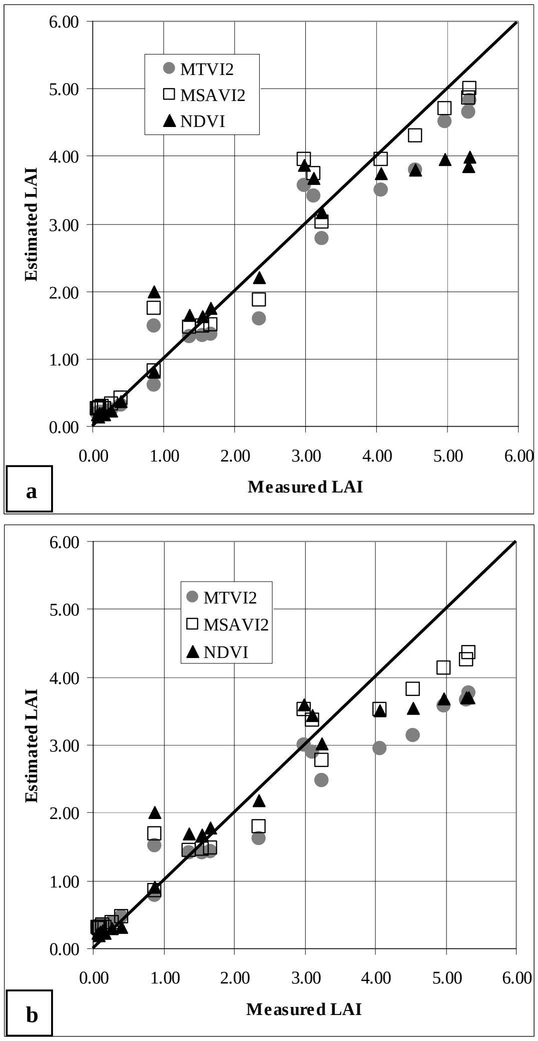


Figure 3. Comparison Measured LAI – Estimated LAI from CASI images over corn and soybean, using predictive equations determined from pea (a) and bean (b) data.

Figure 3 compares LAI estimations from CASI reflectance data and LAI measurements in the field and laboratory. In general, it reveals very good agreement between the predictions and the ground truth. It shows, however, significant differences in indices' performances, and the specific predictive equation by crop type.

First, the crop type influence on the predictions is well illustrated by the difference in LAI estimation between the equations established from pea data (a) and bean data (b). The latter tends to underestimate canopy LAI over intermediate and high density canopies (LAI > 3).

Second, these preliminary results lead to the following remarks:

- NDVI, MSAVI2, and MTVI2 have similar predictive power for LAI estimation in the case of low to intermediate canopy densities (LAI < 3);
- NDVI is not adequate for LAI predictions of intermediate to dense canopies. It exhibits a clear saturation when LAI exceeds the value of 3;
- MSAVI2 and MTVI2 have similar behaviors, following the one-to-one slope for the pea-based equation (Figure3a);
- MSAVI2 seems to have the best overall performance regarding the underestimation issue, though it has the highest level of overestimation for intermediate LAI values.

These results contrast with those based on predictive equations derived from simulated data using PROSPECT and SAILH (Habaoudane et al., 2004). Indeed, using same indices (MTVI2, MSAVI2), we noticed that algorithms based on ground measurements tend to underestimate LAI, while algorithms based on simulated data have a tendency to overestimate LAI.

4. CONCLUSIONS

This paper presents the results from a study that focused on using ground measurements of spectral and biophysical properties over crop canopies in order to develop predictive equations for LAI estimation from CASI hyperspectral images. Based on recommendations from previous studies, three indices (NDVI, MSAVI2, and MTVI2) were evaluated regarding their potential for LAI prediction from remotely sensed data. Comparison between CASI-estimated LAI and ground truth from different sites, with different crop types (soybean and corn) has led to the following conclusions:

- Relationships between measured LAI and spectral indices from measured spectra are crop type-dependent;
- Use of different predictive equations resulting from different crop types influences estimations results at medium to high LAI levels;
- In comparison with NDVI, MSAVI2 and MTVI2 showed no saturation effects even when LAI values exceed 5.

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6. ACKNOWLEDGEMENTS

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