ESTIMATION OF LEAF AREA INDEX USING OPTICAL FIELD INTRUMENTS AND IMAGING SPECTROSCOPY

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ABSTRACT

The main objective of this study was to evaluate and compare performances of LAI estimation using three selected optical field instruments namely: LAI-2000 plant canopy analyzer (PCA), TRAC and hemispherical photography. These results shall subsequently be used to calibrate and validate the estimation of LAI based on imaging spectrometer data. The study involves diverse plant functional types, namely grass, shrub and forest canopies, of a river floodplain along the river Rhine in the Netherlands. Ground-based LAI measurements were acquired from June 19 to 30, 2005 after acquiring the Airborne Hyperspectral System (AHS) image on June 19, 2005 of the study area. Ground measurements were collected following the VALERI sampling scheme. The Reduced Simple Ratio (RSR) was used to derive LAI from the AHS imaging spectrometer data and was calibrated based on the ground measurements. The potential advantages and disadvantages of each method are discussed in relation to its use in different plant functional types and to field data collection supporting remote sensing data calibration and validation. The comparison of LAI from optical field instruments indicates that TRAC and LAI-2000 PCA underestimate the LAI for grass plots when compared to hemispherical photography. This demonstrates that the LAI from TRAC and LAI-2000 PCA does not encompass the contribution of the vegetation below the sensor height for short canopies. The comparison of LAI from hemispherical photography alone and the combined method of hemispherical photography and TRAC demonstrates a good agreement (R^2 = 0.74), which indicates their comparable performance. Hemispherical photography proves to be the most appropriate method to estimate LAI of short canopy vegetation, and improved classification techniques in applied software (CAN_EYE) give a good discrimination possibility for the classification of foliage elements and gaps. A key benefit, however, of all of these estimation methods is that observations can be collected in a short period of time. A poor correlation of RSR and the LAI from all three methods of ground measurements were obtained in this study for all plant functional types. A possible reason for this can be found in the low dynamics of the reflectance in the wavelength bands which are used to compute the RSR.

Keywords: Leaf Area Index, LAI-2000, TRAC, Hemispherical Photography, Reduced Simple Ratio, Imaging Spectroscopy.

INTRODUCTION

Leaf area index (LAI), defined most recently (I,II) as half the total leaf area per unit ground surface area is one of the important vegetation parameters in climate, weather, and ecological studies, and has been routinely estimated from remote sensing measurements (III,IV,V,VI,VII). Extensive research has been done on the estimation of forest LAI from remote sensing data within the last one and half decades (VIII,IV,IX,X,VII,XI). Most of the studies on forest are based on the relation of LAI with vegetation indices (VIs), such as the simple ratio (SR) or the normalized difference vegetation index (NDVI) computed from broadband remote sensing data (XII). However, the application of such relationships to large areas or at different seasons is limited by being site and sensor specific.

Apart from this, the sensitivity of VIs to changes in LAI is often not dynamic enough to allow accurate estimation of LAI. This problem has been encountered for example in boreal coniferous forests, where NDVI typically has a very narrow range due to the presence of a green understory (XI).

Remote sensing of vegetation biophysical variables such as LAI is further complicated by the contribution of understory vegetation, litter, soil, bark as well as plant and relief shadow, all of which influence the radiometric signal (XIII,XII). Besides, the broadband indices, usually constructed with near-infrared (NIR) and red (R) bands, use average spectral information over broad bandwidths, resulting in loss of critical information available in specific narrow bands. Also, VI-based relations are known to be heavily affected by soil background at low vegetation cover (XIV). Now a days, the advent of airborne imaging spectrometers has made it possible to construct more refined VIs through the use of distinct narrow bands. Recent studies on LAI estimation (VIII,IV); suggest that inclusion of shortwave infrared (SWIR) reflectance in VIs may be useful to suppress the background influence. Results from previous studies (e.g. VIII,IV,X) comprising data from the major boreal tree species in Canada and Finnish pine and spruce stands, showed that for both coniferous and deciduous stands reduced simple ratio (RSR) correlated better with LAI than did NDVI and SR.

Despite the fact that several methods have been developed to quantify LAI, both directly and indirectly (XV,XVI,XVII,), leaf area index remains difficult to quantify accurately, owing to large spatial–temporal foliage dynamics and vegetation architectural heterogeneity. Besides, most of the previous studies solely focus on estimation of forest and agricultural crop's LAI and only minor work has been done for other plant-functional types such as shrub and grass canopies. Therefore, more studies are needed for comparison and integration of different methods and techniques to estimate LAI of varying plant-functional types. Furthermore, sampling strategy has to be developed for short canopy vegetation such as grass-lands in order to minimize the error of LAI value which results from the footprint of the instruments being used. This study focuses on evaluating and quantifying the suitability of the Reduced Simple Ratio (RSR) to estimate LAI of forest, shrub and grass from Airborne Hyperspectral System (AHS) data. In this paper, we also tried to assess the feasibility of the selected three optical field instruments for LAI determination per plant functional type and evaluate the potential of combination of these methods to enhance the accuracy of LAI estimation.

STUDY SITE AND DATA

The study area for the validation of the remote sensing data (AHS imaging spectrometer) and ground measurements is located at a large flood-plain of the river Rhine, very close to the German-Dutch border called Millingerwaard. It is situated at 51.5^o N and 5^{o}E and covers approximately an area of 16 km^2. The mean altitude of this site is 12 m.a.s.l.. The Millingerwaard is a managed natural ecosystem which covers a wide range of species and softwood forests comprised of *Salix fragilis* L. (crack willow), *Salix alba* L. (white willow), *Populus nigra* L. (Lombardy poplar) with dense undergrowth of *Urtica dioica* L. (common nettle), *Calamagrostis epigejos* L. (wood small-reed), *Rubus caesius* L. (European dewberry). It consists also scrub and woodland species namely *Calamagrostis epigejos, Sambucus nigra, Rubus caesius* L. (European dewberry); and grass lands with dominating species of *Medicagini- Avenetun puescentis*, *Bromo inermis-eryngientum campestris* and mosaic of low and tall grasses (*Ranunculo alopecuretum*).

Table 1 shows the plot codes, geographic location, ground measurements and summary of vegetation structural information of each elementary sample unit (ESU). The geographic Northing and Easting coordinates refer to the center of each ESU. Stand height information was acquired for all grass plots. The grass/herbs height information of shrub and forest plots stands for the height of understory vegetation. From height information which is presented in Table 1, one can see high variation of vertical structure of each ESU. Generally, Millingerwaard vegetation is characterized by considerably heterogeneous managed ecosystem.

Table 1: Plot code, location, ground data and summary of stand structural information at each ESU. (GH = Grass/herbs, SH = Shrub and FR = Forest, HP = Hemispherical Photography. Projection system: UTM, Zone 31 North).

Plot Code	Northing	Easting	PFT	Ground Data			Height (m)					
				TRAC	LAI-2000	HP	Grass/herbs		Shrub		Tree	
							Min	Max	Min	Max	Min	Max
GH 1	5750334.330	706101.733	GH	√	√	√	1.6	2				
GH 2	5750262.254	705770.418	GH	√	√	√	0.05	1.5				
GH 3	5750294.722	705786.352	GH	√	√	√	0.05	1.5				
GH 4	5750370.623	705965.634	GH	√	√	√	0.01	1.5				
GH 5	5750428.011	705930.346	GH	√		√	1.5(mean)					
GH 6	5750444.447	705864.750	GH	√	√	√	0.2	1				
SH 7	5750532.409	705968.869	SH		√	√	0.5	1.5	2.5	3		
SH 8	5750547.835	706180.251	SH	√	√	√	0.1	1.5	2	3		
SH 9	5750535.831	706152.001	SH		√	√	1	1.5	2	2.5		
SH 10	5750558.173	706193.240	SH			√						
SH 11	5750801.567	706034.443	SH	√	√	√						
GH 12	5750733.425	705947.289	GH		√	√	0	1				
SH 13	5751022.338	706072.596	SH	√	√	√	1	2	5(mean)			
GH 14	5751428.314	706388.907	GH		√	√	0.05	1.2				
FR 15	5750921.008	706695.433	FR	√		√						
FR 17	5750405.864	706717.824	FR			√	0.2	2			20	29
FR 18	5750342.296	706579.805	FR			√	1.5	2			19	20
FR 19	5750219.780	706597.331	FR	√		√	0.5	2			15(mean)	
FR 20	5750231.410	706356.774	FR	√		√	1.5	2			10(mean)	

A total of 19 ground plots data acquisitions were made using hemispherical photography, 12 plots acquisitions were made using LAI-2000 and 12 plots acquisition were made using TRAC (Table 1). The Airborne hyperspectarl System (AHS) images were acquired on June 19, 2005. The data are delivered in surface reflectance after radiometric, atmospheric and geometric corrections (XVIII). The AHS imaging spectrometer has 80 bands in visible, near infrared, shortwave infrared, mid infrared and long wave infrared regions. The spatial resolution of the AHS image is 5.38 meter by 6 meter. The data is clipped spectrally from visible to shortwave infrared and spatially to study area for further processing.

METHODS

LAI Ground Measurement Protocols

A total of 19 VALERI (http://www.avignon.inra.fr/valeri/) plots were located within the study area covering the full range of plant functional types present namely grass, shrub and softwood forest. The ground plots were selected based on a random sampling scheme to cover the representative soft wood forest, shrub and grass canopy densities. The location of each ESU was determined using global positioning systems (GPSs), which has an accuracy of about ±5 m. Five ESUs in the softwood forest were selected for ground measurements with hemispherical photography and TRAC instruments. In grass and shrub plots, eight and six ESUs, respectively, selected for ground measurement with hemispherical photography, LAI- 2000 and TRAC (Table 1).

LAI Estimation from Optical Field Instruments

1. LAI-2000 Plant Canopy Analyser

LAI-2000 measurements were taken in uniform overcast cloud condition to reduce the effect of scattered blue light in the canopy and to have diffuse radiation from all directions in the hemisphere. An azimuth mask of 180° view caps were used on LAI-2000 sensor of both instruments all the time to block the bright sky near the sun's direction and to eliminate the shadowing effect of instrument operators. Two instruments were used to measure shrub plots. The first one underneath the shrub canopy and the second mounted in a nearby open cleared area with no obstruction to provide an open-sky reference of radiation conditions (XIX). For grass plots, only one instrument is used to measure reference irradiance above the canopy and under canopy measurement, since all grass plots have short canopy. Ground measurements using LAI-2000 plant canopy analyzer were made only for grass and shrub plots. Finally, measurements were averaged per ESU to get plot level LAI. In addition to full range of view zenith angle, LAIe, is also computed from the first two rings; 0.0°-12.3° and 16.7°-28.6° which are centered at 7° and 23° zenith angle, respectively. Consequently, comparative computation of LAIe is done from hemispherical photography for the same range of view zenith angle. Generally, a total of 12 ESUs data was obtained using LAI-2000 instrument.

2. Tracing Radiation and Architecture of Canopies (TRAC)

Ground measurement using TRAC was done for all plant functional types (grass, shrub and forest). A total of 6, 3 and 3 ESU measurements from grass, shrub and forest canopies, respectively was obtained using TRAC instrument (Table 1). One transect was selected for each grass plot to take the measurement, and one transect above understory and one transect below understory were selected for shrub and forest plots. The range of mean solar zenith angle at the time of the acquisitions was between 31.81° – 59.19°. The total leaf area index of each ESU for shrub and forest plots was obtained from below understory measurements. Averaging of clumping index is made per plant-functional type and applied for correction of LAI_e from hemispherical photography and LAI-2000, since TRAC measurements were not done for all ESUs and clumping index does not show significant variation with in the same type of vegetation class and stand (XX).

Woody-to-total area ratio was determined using digital hemispherical images, where the amount of woody material was estimated by means of image classification, assuming the stems and branches seen on the photographs were simple cone shapes (XXI). This value is used for TRAC input parameter and for correction of LAI value from hemispherical photography. The value of woody area index (WAI) by considering the clumping of stems and branches ranges from 0 – 0.15 and 0.01 – 0.04 for shrub and forest plots, respectively. In addition to this, α is also calculated only for the above story of shrub and forest canopy and ranges from 0 – 0.048 and 0.003 – 0.015, respectively.

$$\alpha = WAI / (WAI + LAI) \qquad (1)$$

Mean element width (W) which is average width of the shadow of a foliage element projected on a horizontal surface is calculated from leaf scans of representative species per plot for TRAC data analysis. W is calculated using the following equation which is proposed for broadleaf (XXII):

$$W = \sqrt{G(\theta)A} \qquad (2)$$

where A is the projected (one-sided) leaf area. For crops and natural canopies, $G(\theta) = 0.5$ is valid in many cases, especially if the solar zenith angle is near 57.3°.

3. Hemispherical Photograph Acquisition and Processing

Hemispherical photographs were acquired after establishing ESUs for forest, shrub and grass canopies of the study area. The photographs were captured by the use of Nikon Coolpix 4500 hemispherical digital camera. Hemispherical photographs were taken from all of 19 ESUs sampled in the study area. For forest and shrub canopy, two series of hemispherical images were acquired: one looking downward to characterize understory, the other looking upward to estimate tree characteristics. The two kind of images (upward and downward looking) were processed as two separate series using the CAN-EYE software (http://www.avignon.inra.fr/can_eye/) and resulting characteristics were combined to represent the whole canopy of each plot.

LAI Retrieval from AHS Hyperspectral Image

A plant functional type map is produced using maximum likelihood classification algorithm from the first 21 bands (visible to shortwave infra red) of AHS image. The end members are collected from the image visually for five possible classes of the area namely; soil, water, and three vegetation classes dominated by the corresponding plant functional type grass, shrub, and forest. The classes not representing the above three plant functional types are merged together to class 'others'. The 'others' land class was masked out to calculate the 1% minimum and maximum cutoff points in the histogram of shortwave infra red (SWIR) reflectance for reduced simple ration (RSR) vegetation index. The 1% histogram cut-off points of SWIR band reflectance were computed and resulted 0.015791 and 0.341475 as a minimum and maximum, respectively and used to compute RSR. After computing RSR (Eq. (3)) per pixel, the image is aggregated to the pixel size of ground plots (20 x 20 m); consequently, RSR was extracted for each ESU after identifying the ground plots in the scene. The relationship between ground-based LAI and RSR vegetation index was evaluated for each plant functional type. To evaluate the relative influence of RED, NIR and SWIR reflectance on the LAI-RSR relationships, plots of LAI against reflectance of the aforementioned bands were also inspected.

$$RSR = \frac{\rho_{NIR}}{\rho_{RED}}\left[1 - \frac{\rho_{SWIR} - \rho_{SWIRmin}}{\rho_{SWIRmax} - \rho_{SWIRmin}}\right] \quad (3)$$

The reflectance data of AHS spectral bands 8 (659 nm), 14 (833 nm) and 21 (1622 nm) were considered for RED, NIR and SWIR bands, respectively.

RESULTS

Comparison of Ground-based LAI

Measurement of LAIe is a key step in optical measurement of leaf area index, but to obtain LAI, other parameters need to be quantified. These include the woody-to-total area ratio (α) and the element clumping index (Ω). The full detail of the methods for obtaining these parameters are given in literature (XXIII,XX). Statistics of estimated LAI for each instrument are shown in Table 2. LAI-2000 estimates only effective leaf area index (LAIe), therefore the result is not comparable with other instruments for LAI. Comparison statistics for the data acquisitions using hemispherical photography and TRAC instruments (Table 2 and Figure 1a) show that, overall, the correlation between the retrievals is low (R^2 = 0.26), but results for different plant functional types vary. On average, the hemispherical photography retrieval was 50% higher than LAI derived from the TRAC.

Table 2: Number of collections and overall means for estimated LAI for this study.

PFT	Hemispherical Photography		TRAC		Hemispherical Photography and TRAC	
	n	Mean(range)	n	Mean(range)	n	Mean(range)
Grass	8	6.18(3.8-10)	6	2.15(0.70-4.28)	8	4.40 (2.58-9.64)
Shrub	6	5.99(3.7-8.81)	3	3.02(1.51-5.74)	6	4.13 (2.82-5.76)
Forest	5	9.15(5.75-10.58)	3	5.59(5.25-5.96)	5	6.18 (4.45-7.61)
All	19	6.90(3.7-10.58)	12	3.23(0.70-5.96)	19	4.78 (2.58-9.64)

The hemispherical photography shows the highest average value of LAI per plant functional type followed by the combined method of hemispherical photography-TRAC, whereas TRAC shows the lowest average LAI value for all plant functional types. The highest LAI values are obtained in forest plots for all three methods (Table 2). The average LAI of grass plots ranked next to forest for hemispherical photography and the combined method of hemispherical photography-TRAC. Shrub plots showed the lowest average LAI per plant functional type using these two methods. LAI values using TRAC measurements for grass plots resulted in low values ranging from 0.7-4.28, compared to the other methods. This is due to the limited canopy height of most grass plots being below the sensor head of the TRAC instrument. This experiment was not suitable to determine a canopy height threshold for TRAC and LAI-2000 measurements. Other studies (such as XXIV,XXV) also suggested that TRAC derived LAI is least accurate for grass transects. Tests for correlation of the combination of hemispherical photography and TRAC (Figure 1b and c) suggest a high correlation (R^2 = 0.74) with hemispherical photography and low correlation (R^2 = 0.17) with the TRAC instrument.

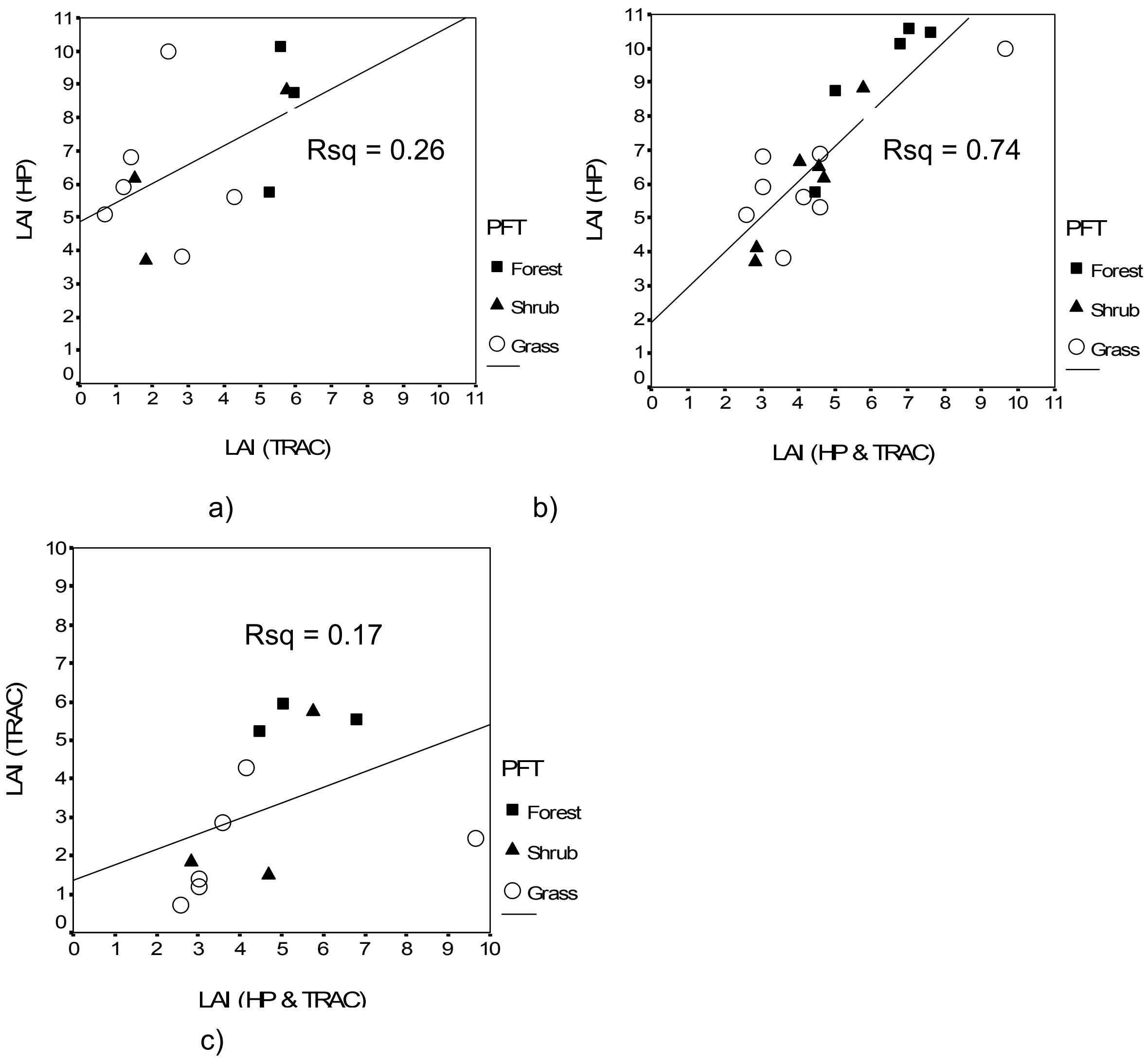

Figure 1: Relationship between LAI as estimated from (A) Hemispherical Photography and TRAC, (B), Hemispherical Photography and combination of Hemispherical Photography and TRAC, and (C) TRAC and combination of Hemispherical Photography and TRAC

The leaf area index value obtained using hemispherical photography from plot GH 1 was reasonably higher than TRAC and LAI-2000 plant canopy analyzer measurement for the same plot. It is the densest plot of grass plots with an average height of nearly 1.85 m and found to be difficult to be measured accurately with optical instruments. Further, the classification of downward looking hemispherical photographs into gaps and foliage elements proved to be difficult, as the distinction of real gaps (soil) and shadows cast by foliage elements was almost impossible for dense plots. The LAI result obtained using hemispherical photography from this plot has significantly affected the comparison of ground-based LAI measurements. For example removal of this plot from comparison of LAI between hemispherical photography and TRAC improves R^2 from 0.26 to 0.42. Figure 1a, 1b and 1c show the outlier effect of this plot.

Relationships between Vegetation Indices and Ground-based LAI

The relationships between RSR and ground-based LAI measurement of each instrument are assessed for both, all plant functional types together and separately. The ground based LAI data were separated into three major plant functional types: forest, shrub and grass. The relationships between RSR versus LAI effective and LAI of these three plant functional types are shown in Figure 2 and 3. The correlation between RSR versus LAI effective was made only from LAI-2000 and hemispherical photography ground measurements, since TRAC measurements were done only for one solar zenith angle. RSR with LAIe from ring one and two, and all five rings of LAI-2000 plant canopy analyzer of two pant functional types show negative slope and doesn't have real relations. Shrub ESUs show strong negative slope specially LAIe from five rings of LAI-2000. Contrary, the relationships between RSR and LAIe from hemispherical photography show positive slope with very low correlation for all plant functional types.

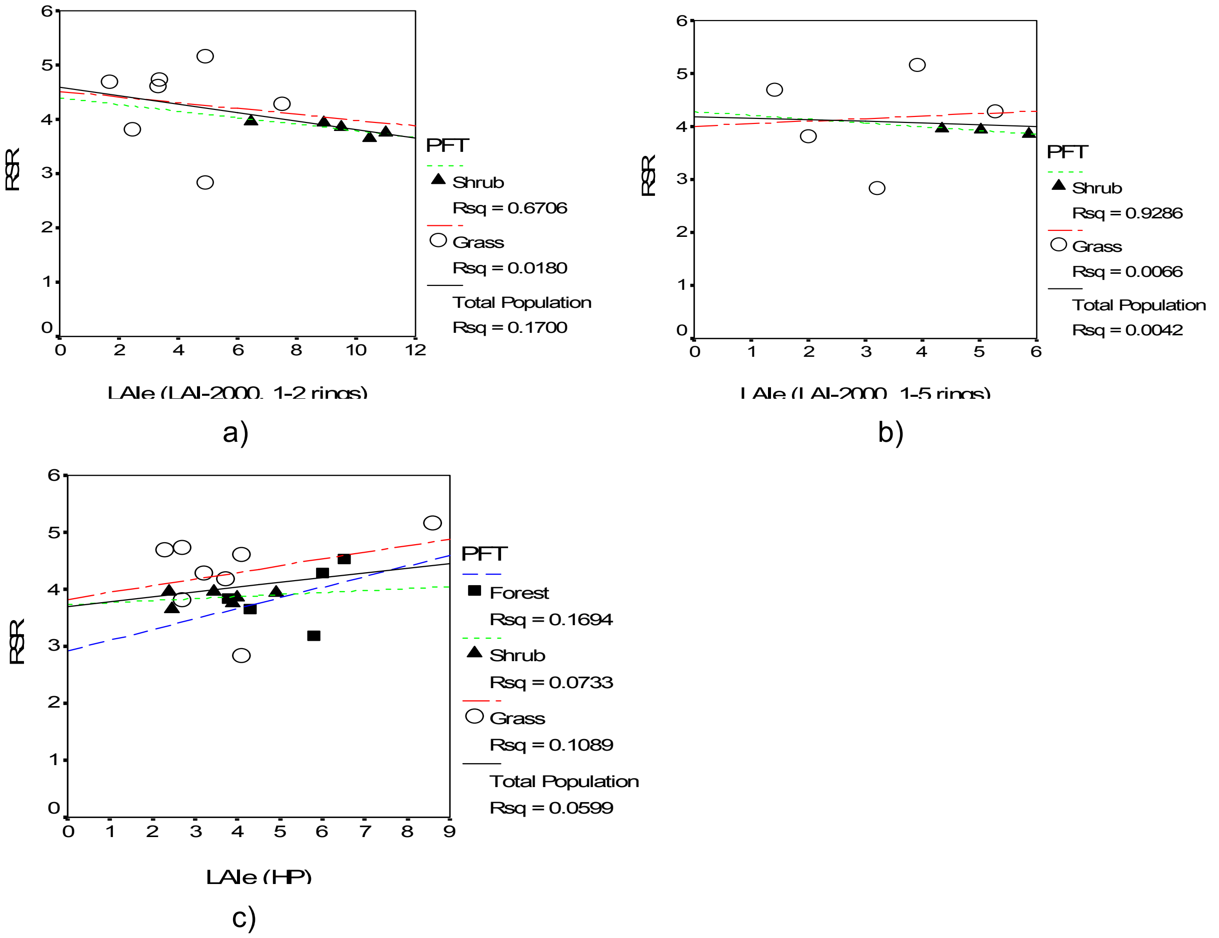

Figure 2: Correlation of RSR vegetation index derived from AHS with ground measurements of LAI effective for three plant functional types. (A) LAIe (LAI-2000, 1-2 rings)–RSR, (B) LAIe (LAI-2000, 1-5 rings)–RSR, and (C) LAIe (Hemispherical photography)–RSR.

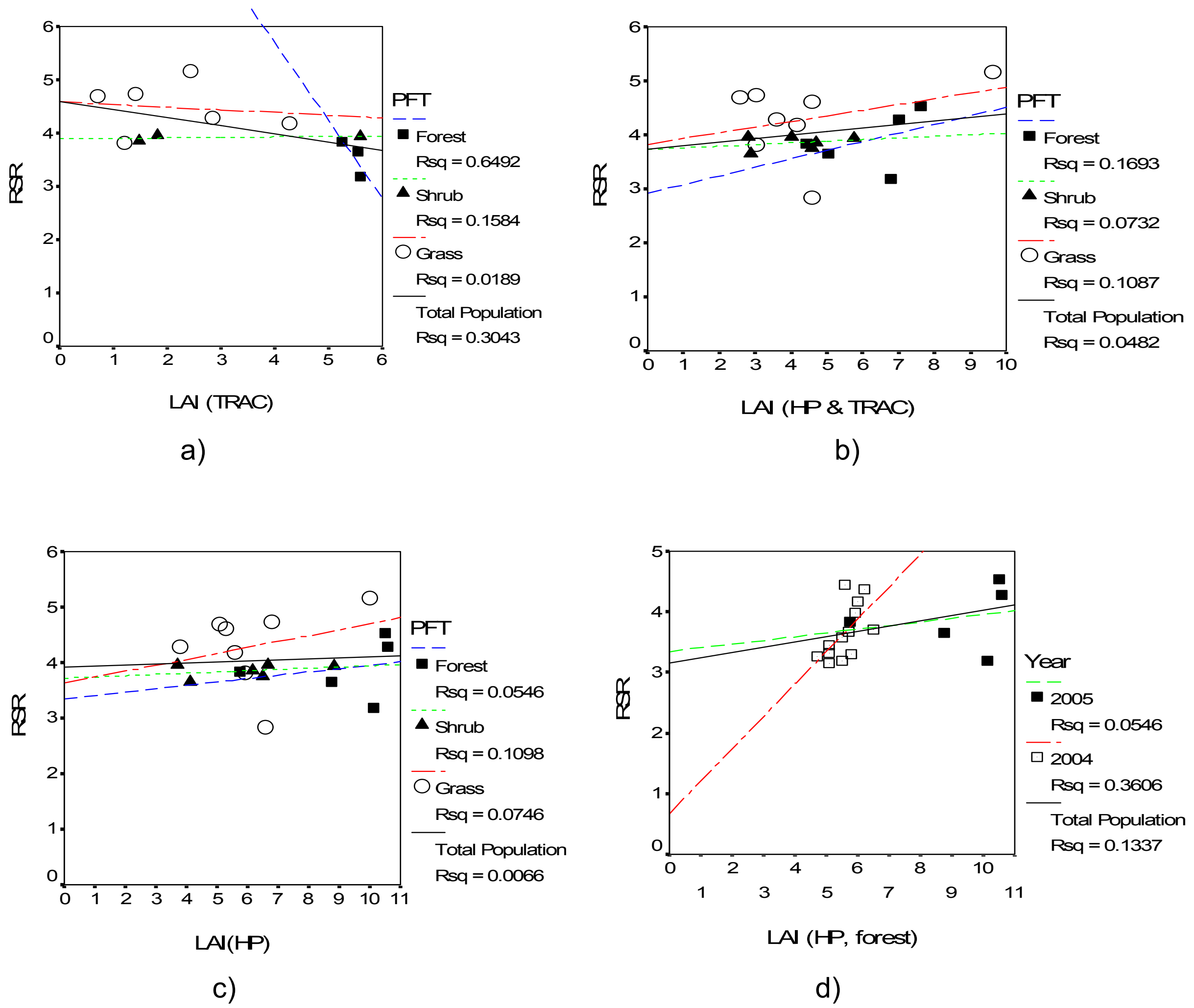

Figure 3: Correlation of RSR vegetation index derived from AHS with ground measurements of LAI for three plant functional types. (A) LAI (TRAC)–RSR, (B) LAI (Hemispherical photography and TRAC)–RSR, (C) LAI (Hemispherical photography)–RSR, and (D) LAI (HP)-RSR for forest plots from 2004 data (XXVI) and this study.

Likewise the effective LAI, the relationships between RSR and LAI from TRAC, hemispherical photography and combined method of hemispherical photography-TRAC were assessed. There appeared no real correlation of RSR with LAI of all three ground measurements (Figure 3). Even though very low R squares are obtained for all relationships of RSR and LAI, positive slops are achieved for all plant functional types but TRAC measurements. The result from previous year study (XXVI) shows also low correlation (R^2 = 0.36) between hemispherical photography LAI and RSR from HyMap2004 for softwood forest of Millingerwaard (Figure 3d).

DISCUSSION

The present study shows that in the studied floodplain vegetation of the Netherlands, a number of methods can be used to estimate LAI. However, the comparison of LAI from optical field instruments demonstrated that TRAC and LAI-2000 plant canopy analyzer underestimates the LAI for grass plots when compared to hemispherical photography. The dimension of the sensor of TRAC and LAI-2000 plant canopy analyzer may affect the estimation of LAI for short canopy vegetation such as grasses and herbs. Leaf area index which is measured using these two instruments does not encompass the LAI value which is less than the sensor height. In addition to this, the closeness of foliage element to the sensor affects the LAI result from these instruments. Downward looking hemispherical photography was found to be an appropriate optical indirect method to estimate short canopy vegetation. However, for dense and tall grass plots, it was difficult to distinguish between gaps and shadow cast by foliage elements using hemispherical photography.

Regarding the evaluation of the feasibility of optical field instruments for shrub and forest plots, some of the points which impacted the successful assessment are discussed in the following. Because of time constraints, TRAC measurements were not performed for all ESUs and measurements were made only at one sun zenith angle. The outermost three rings of LAI-2000 device were not recorded for some ESUs and LAI measurement for forest plots were not acquired because the LAI-2000 reference device was not available. Based on the aforementioned reasons and the absence or insufficient measurements using TRAC and LAI-2000 for shrub and forest plots, it is difficult to conclude the comparisons of the three field instruments used in this study for shrub and forest canopies. However, the comparison of LAI from hemispherical photography alone and the combined method of hemispherical photography-TRAC shows good agreement (R2 = 0.74), whereas the positive offset indicates that the combined method reduces the LAI values of all plant functional types compared to the LAI derived from HP observations only.

An apparent goal of using indirect techniques and approaches to estimate LAI is to be able to compare favorably with direct, destructive measurements, which are usually assumed to be more accurate and are typically the standard for comparisons. On the other hand direct methods are time consuming and can not be applied for extensive area. Currently, the combined method of TRAC and hemispherical photography/LAI-2000 is used for quick and accurate LAI assessment of a canopy. It was concluded that (XXVII) hemispherical photography is the most accurate and efficient way, as compared to LAI-2000 for long term monitoring of arid ecosystems. This was in good agreement with the recent results (XXVIII), in which hemispherical photographs in a grid offer a good potential to replace LAI-2000 and TRAC devices for canopy structure measurement. In this study, hemispherical photography is reported as the most efficient method particularly to measure LAI of grass and understory of forest plots because of downward looking capability to encompass the estimation of the whole LAI which is below the sensor height of LAI-2000 and TRAC instrument.

From Figure 2 and 3 one can see as there is no linear relationship between RSR and ground-based LAI. Several explanations can be suggested for the observed results. First, the negative relationships noted between RSR vs. LAIe and LAI from LAI-2000 and TRAC in the current study may not be only due to RSR insensitivity to explain the LAI variation, but rather to the uncertainty of the ground measurements. TRAC measurements are done using only one sun zenith angle. In addition, most of the grass plots have short canopies and forest plots have dense understory. Therfore, the leaves which are close to the instruments sensor may affect the results obtained from these instruments.

All of the LAI values obtained using hemispherical photography were higher than 3.7, suggesting that the majority of data for this category may have fallen within the region of saturation for the bands used to calculate RSR. It was reported (IV) that the vegetation indices signal saturates at a fairly low level of LAI of about 2–3. Other scientists have reported that the signal received by a sensor saturates at an LAI of 3-8 depending on the wavelength (XXIX). Plots of AHS band used to compute RSR (Figure 4) show general insensitivity with regard to in situ measured LAI. The relationships between LAI and all three bands of AHS image were virtually flat with little correlation between LAI-RED (R^2 = 0.034), LAI-NIR (R^2 = 0.176) and LAI-SWIR (R^2 = 0.194). This unusual low correlation between LAI and spectral reflectance in the near infrared bands (ETM+ 4) for mixed deciduous and coniferous forest was also reported by (XXX). The variations in the near infrared band were supposed to be the dominant factor contributing to changes of the RSR for the whole range of LAI. Contrary, higher NIR reflectance was obtained for the lower LAI values of hemispherical photography. This contradicts to the general case of other studies(XXXI,XXXII,XXXIII) of LAI-NIR reflectance relations. Scientists have noted a strong relationship between LAI and the response in the red band (XX,XXXIV,XXXV); however, this was not observed this relationship in the current study nor in LAI-SWIR relationship. The absence of trends in SWIR reflectance for various plant functional types and observed LAI ranges, contradicts the general fact of a high that large sensitivity of the SWIR to LAI obtained in other studies (e.g. VIII).

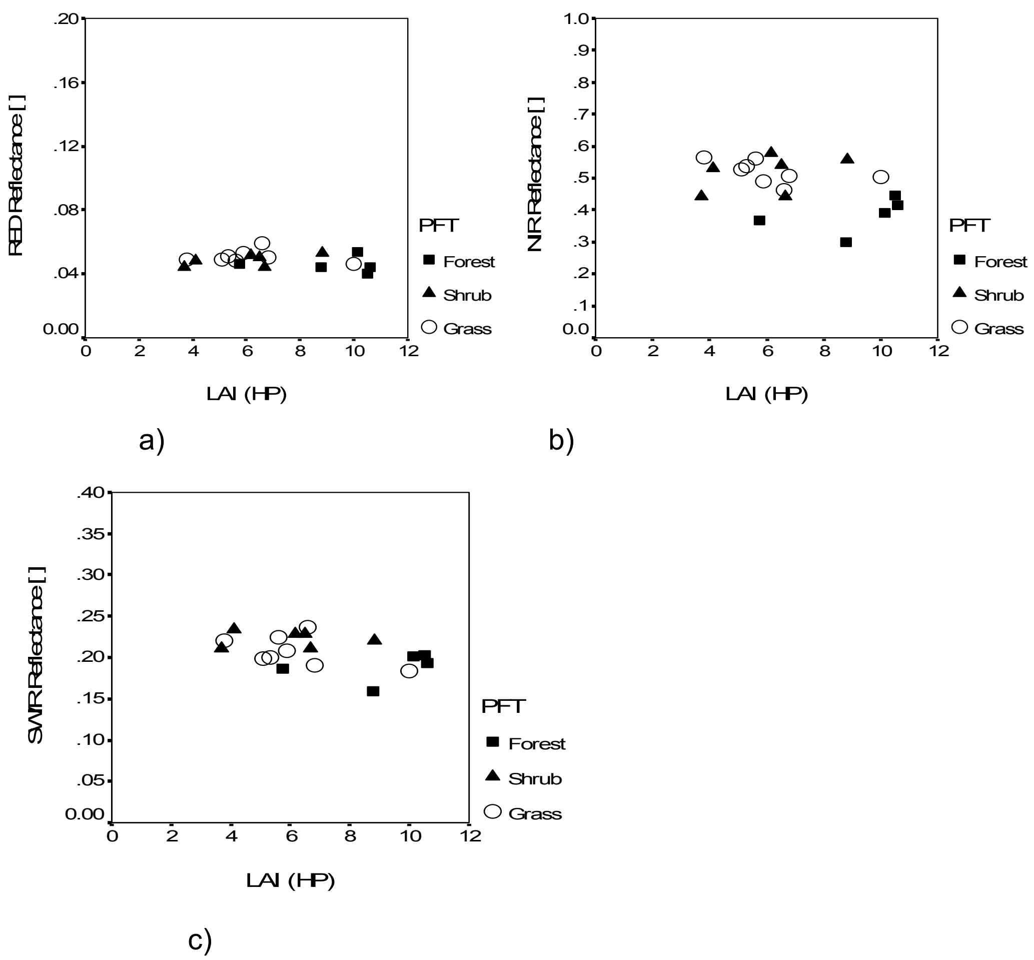

Figure 4: Relationship between Hemispherical photography LAI and Reflectance. (A) Red (AHS band 8), (B) near-infrared (AHS band 14), and (C) short wave infrared (AHS band 21)

In addition to the aforementioned factors which affect the LAI-RSR relationship, the probable dislocation of ground plots from AHS image could affect the relationships although the area represented by the field instrument readings cannot be precisely defined. Regarding the calculation of RSR from AHS image, the presence of water in some forest plots could affect the resulting index values. In this study the ground-based information was not available on canopy closure and therefore the 1% cut-off point of SWIR reflectance histogram were used to obtain SWIR minimum and maximum from the AHS image after masking out the water and bare soil. Even though it is preferable not to determine the minimum and maximum SWIR reflectance from the image as the presence of water affects the SWIR reflectance (XXXVI,VIII), the obtained values SWIR minimum and SWIR maximum may not represent the reflectance from completely closed and an open canopy of the Millingerwaard vegetation, respectively. In addition the absence of sufficient lower LAI plots from ground measurements complicated the comparison of the AHS image utility for remotely estimating the LAI of the Millingerwaard vegetation. Generally, the performance of RSR in this study was remarkably weak unlike other studies (VIII,IV,X) which obtained strong relationships of LAI-RSR in forest and mixed vegetations.

CONCLUSIONS

These estimates of LAI using the optical field instruments, however, are all indirect estimates; therefore, a possible bias in all of these measurements is not accounted for in this comparison. Additional work at the study site investigating direct methods could provide more of an unbiased estimate in the future. This study also demonstrates that each method has its strengths and can provide significant additional information that can be important for ecological modeling. Hemispherical photography has proven to be an appropriate method to measure LAI, particularly for short canopy vegetation and improved classification techniques in CAN_EYE gave a good discrimination possibility for classification of foliage elements and gaps. The TRAC is also more reliable in determining the effect of foliage clumping and proved in various studies(XXXVII,XXXVIII,XX,XV). A key advantage of all of these estimation methods is that observations can be collected in a short period of time in contrast to weeks, months or even years required for direct estimation (e.g. litterfall or harvest), which is a major benefit, particularly for remote sensing investigations, where timely ground reference data collection of adequate size and spatial distribution is often a constraint.

A poor correlation of RSR and all three methods of ground measurements was obtained in this study for all plant functional types. Besides the insufficient number of plots with a small LAI, the majority of plots covered by the ground-based measurements show high LAI values which cause saturation in the wavelength regions of the spectral bands which are required to calculate the RSR. Further, the unsuitability of TRAC and LAI-2000 instruments for LAI measurements of grass canopies could be the major factors which resulted in the poor relationship between RSR and ground-based LAI. Additionally, it is reasonable to say on the basis of these results that exploring the applicability of different vegetation indices alongside developing physical reflectance models remains an important field of research particularly in heterogeneous vegetations.

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