A comparative analysis of image processing softwares to indirect estimation of leaf area index in forest ecosystems

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Abstract

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The leaf area of vegetation can be expressed in terms of leaf area index (LAI). This index depends on species composition, developmental stage, prevailing site conditions, seasonality and management practices. LAI is an important ecological parameter because vegetation-atmosphere processes of the canopy are controlled by the foliage. It can be estimated with hemispherical photographs using some commercial and free softwares. The choice of the software and the settings of parameters are two fundamental aspects to obtain suitable data. The paper focuses on the comparative analysis of the LAI data obtained with three image processing softwares (Spot Light Intercept Model, Gap Light Analyzer and WinScanopy) in a case study in Italy. The data were analyzed in a qualitative and quantitative way. The Wilcoxon signed rank test showed statistically significant differences among the three softwares. WinScanopy provides lower LAI values than the other two softwares. The same non-parametric test distinguishing per forest type and forest age showed statistically significant differences among softwares in three forest types (silver fir, Norway spruce and beech forests) and in the young stands. Instead, no statistically significant differences were found in the mature stands.

Keywords

forest canopy, hemispherical photographs, indirect optical methods, leaf area index (LAI)

Introduction

Canopy foliage amount controls many biological, physical and biogeochemical processes in the water, nutrient and carbon cycle (Fassnacht et al., 1994; Heiskanen, 2006). The amount of leaf area in the plant canopies influences primary production (or photosynthesis), transpiration, precipitation's interception, microclimate, and energy, water and carbon exchanges between vegetation and atmosphere (Leuschner et al., 2006). A common measure of canopy foliage used in the ecological studies is the leaf area index (LAI) which can be defined as the amount of foliage one-sided area in a canopy per unit of ground surface area (m^2/m^2) (Watson, 1947; Chen and Black, 1992). LAI is a dynamic parameter that depends on several variables such as species composition, developmental stage, prevailing site conditions, seasonality, management practices and it expresses the photosynthetic and transpiration surface of trees canopies (Jonckheere et al., 2005a).

In literature, there are several methods for ground-based estimation of LAI (Asner et al., 2003), such as: direct methods (destructive harvesting and direct determination of one-sided leaf area, collection and weighing of total leaf litterfall), indirect contact methods (allometry, plumb lines, point quadrats methods) and indirect optical methods (ceptometer, LAI-2000 and hemispherical photographs) (Liang et al., 2012). Both direct and indirect methods are complementary but the calibration is still necessary for indirect methods. The cross-validations between direct and indirect methods have pointed to a significant underestimation of LAI with the indirect methods. The selection of the most appropriate method, taking into account the physiological process, and the application of new technical solutions are useful strategies to reduce bias or discrepancies in LAI estimation (Bréda, 2003).

The hemispherical photographs were introduced for the first time by Anderson (1964) in order to compute the light penetration through the forest canopy. After this first application, this indirect optical method for LAI estimation spreads especially since the development of high resolution digital cameras, which allow images to be rapidly processed after acquisition (Thimonier et al., 2010).

The hemispherical photographs analysis is applied in many fields in order to evidence the relationship between LAI and both forest site and stand characteristics such as: light and radiation regime (Kucharik et al., 1999; Machado and Reich, 1999; Godoy et al., 2010), forest water balance (Van der Zande et al., 2009), seedling survival and growth (Puerta-Piñero et al., 2007; Marchi and Paletto, 2010), and stand response to thinning (Davi et al., 2008; Man et al., 2008). Moreover, the LAI is used as an indicator of site quality in closed canopy (Coker, 2006), as a part of data when running ecological models (Pietsch, 2002), and for improving the accuracy of remote sensing techniques (Sprintsin et al., 2007).

From the technical point of view, in order to obtain LAI values useful to support scientists and forest managers two aspects are fundamental: (1) the choice of the software to be used in the image processing and (2) the parameters settings.

In order to contribute to these issues, the main objective of this paper is to provide useful information to scientists and forest managers through the comparison of the LAI values obtained using different softwares (Spot Light Intercept Model, Gap Light Analyzer and WinScanopy) and parameters settings.

Material and methods

Study area

The study was conducted in the Trentino province (North-East of Italian Alps). The climate of the zone is cool, temperate and mild continental. The mean yearly temperature is 11.5 °C, while the annual rainfall averages 883 mm with two main peak periods, in spring (May rainfall averages 94 mm) and autumn (October rainfall averages 110 mm).

The data were collected in the eastern part of Trentino (Alta Valsugana and Adige valleys) in four pure forest types (silver fir, Norway spruce, beech and European larch forests). For each forest type, 8 sample points were selected considering the different stand structures (horizontal and vertical structures) and age classes. According to the data of forest management unit plans, the horizontal structure was subdivided in two qualitative classes (high and low diameter differentiation), while the vertical structure classification distinguished the one-layer stands from the multi-layer stands (Pastorella and Paletto, 2013a). The age of forest stands was classified in two classes: young forest stands and mature forest stands.

The sampling unit (plot) is represented by a circular area with a radius of 13 m (surface of 531 m^2) according to the standard of the second Italian National Forest Inventory. In each plot, the main site and stand attributes (GPS coordinates, slope, number of trees, species, diameter at breast height and tree height) were collected in order to calculate basal area, average diameter and height, stand volume and density. Besides, a set of hemispherical photographs of the canopy was taken in the plot with the purpose to estimate LAI. The hemispherical photographs were taken using a Nikon Coolpix 990 camera and a fish-eye converter Nikon FC-E8 (Nikon Corporation, Tokyo, Japan) at 1.5 m above the ground. The camera was run in the "programmed auto" mode where it automatically adjusts shutter speed and aperture obtaining the best exposure and using the parameters fixed in Fisheye1 lens mode (focus fixed at infinity, widest zoom, metering center-weighted, circular frame). Moreover, the camera LCD side was set facing north using a compass so that the top of the hemispherical picture was directed to the north.

In each sample plot a set of 5 images was acquired, the first picture was taken in the central point of the plot and the others at 7 m from the center in correspondence of the four cardinal points (North, South, East and West). Consequently, the total number of pictures collected in the field was 160 (40 images for each forest type).

Software compared and parameters settings

LAI was estimated for each plot using a canopy analysis system developed by Régent Instruments Inc. The canopy analysis system analyzed the circular hemispherical pictures taken by fisheye lens converter with a 183° field of view (FOV). Recently, several commercial software packages as well as freeware programme were developed and used in a broad range of applications (Jonckheere et al., 2005b; Jarčuška, 2008). Considering the usability (user-friendly software) and the extent of use in the forestry sector, two free softwares – Gap Light Analyzer (GLA) 2.0 (Frazer et al., 1999) and Spot Light Intercept Model (SLIM) 3.02a (Comeau and MacDonald, 2012) – and one commercial software – WinScanopy Pro 2003d – were chosen for this comparative analysis. The last available versions for the free software and the licensed version for WinScanopy (3.02) are used in the study.

WinScanopy is a widely used software designed for canopy hemispherical or rectangular image analysis. WinScanopy's standard system includes a Nikon Coolpix 990 camera, a fish-eye converter Nikon FC-E8 and a self-leveling system (Bréda, 2003). Camera and lens were calibrated together by Régent Instruments Inc., which provides also the calibration file for setting the program. Subsequently, to avoid softwares comparison, the parameters (lens manufacturer and properties) were set – whenever possible – in the other softwares on the basis of these calibrations.

GLA computes canopy and site openness, effective leaf area index, sunfleck-frequency distribution and daily duration, and the amount of above- and below-canopy (transmitted) direct, diffuse, and total solar radiation incident on a horizontal or arbitrarily inclined receiving surface (Frazer et al., 1999).

SLIM is a program designed to estimate LAI, gap fraction, and fractional transmittance from hemispherical photographs or Licor LAI-2000 Plant Canopy Analyzer data. It is part of a set of programs that model light distribution beneath a forest canopy designed by Comeau and MacDonald (2012).

For both free softwares, individual configuration settings can be created and saved to disk for later use such as camera lenses and orientations, topographic settings, regional climatic patterns and growing seasons.

The analysis of hemispherical photographs is composed of six steps (Walter, 2009): 1) acquisition; 2) input, image editing and registration; 3) classification; 4) data extraction; 5) calculation; 6) output. For the purpose of this comparative analysis we investigated how the type of software and their parameters influence LAI estimation. In each software some parameters are set by default, while others can be set by an operator. In particular, the parameters that can be set manually are the following: image editing, image registration, image classification (thresholding), lens and camera setting, azimuth and zenith per sky region, and model of sky brightness.

The main characteristics of the software and camera in LAI estimation are resumed in Table 1. Software characteristics and specifications are usually comparable but the lens calibration, the equation degree and the elaboration method seem to be specific for each software.

Table 1. Software parameters settings

Parameters	SLIM	GLA	WinScanopy
Version	3.02a	2.0	Pro2003 d
Pixel classification	Automatic (Rider clustering method)	Manual	Manual
Threshold value	–	128	128
Default settings of the camera	No	No	No
Lens calibration	Polar projection	Polar projection	FC-E8
Equation degree	6	–	9
Elaboration method	–	–	LAI-2000 original
Sky Brightness model	SOC model	SOC model	SOC model
Number of sky regions (default)	480[1]	324	144
Azimuth per region	24	36	18
Zenith per region	20	9	8
Focal length [mm]	8	8	8
View angle [°]	180	183	180

[1]Standard BCR (Below Canopy Reading Resolution).

The images – taken in color and saved in the JPG format – were converted to grey scale at the blue channel by the software GNU Image Manipulation Program (GIMP) 2.6. The blue-filtered grey scale is widely considered the best to obtain maximum contrast between trees' crowns and background compared with red- and green-filtered grayscale images (Frazer et al., 2001). The image registration was set manually, sampling photographs on the basis of its characteristics (image quality, sunflacks, etc.).

The image classification (thresholding) converts greyscale values for each pixel to black (representing foliage and also other non-sky elements) and white (representing sky) for later analysis. The goal of thresholding is to obtain a reasonably accurate discrimination between the background sky and the foliage. In the analyzed softwares, images may be processed setting the threshold manually; two of them can also make an automatic calculation. In particular, SLIM can apply two different models for the automatic thresholding (*Nobis and Hunziker* or *Ridler clustering method*), WinScanopy allows to calculate the color threshold by an automatic method or by a manual method, while GLA needs to set the threshold manually. For the purposes of this comparative analysis the threshold value was set manually at the default value (128) for GLA and WinScanopy, while for SLIM it was set automatically. As suggested by the software manuals, thresholding was evaluated and carefully monitored to obtain the best image (contrast, color, light environment).

The lens characteristics were set to "FC-E8" in WinScanopy (that has been designed to produce this type of projection, Frazer et al., 2001) and to "polar projection" in the free softwares. In fact the fish-eye converter FC-E8 was designed to produce a simple polar (equiangular, equidistant) projection (Herbert, 1987; Walter, 2009) that is characterized by a linear relationship between the radial distance from a projected point to the image centre and the zenith angle between the lens' optical axis and the same point's location in the hemispherical region (Hu et al., 2009). However, it did not conform exactly to this design specification (Englund et al., 2000; Frazer et al., 2001; Inoue et al., 2004) presenting spectral aberration. SLIM has been developed for use only with true fisheye lenses that utilize equiangular projection but require a sixth-order polynomial for lens calibration so the default calibration was used (Nikkor 8 mm lens). GLA supports four standard projections (polar, orthographic, stereographic, Lambert's Equal Area) and any number of user-defined custom lens distortion (Frazer et al., 1999). As in SLIM a polar projection and a default calibration were used.

Sky-Region Brightness describes the light intensity of a diffuse sky and it is usually analyzed using a Standard Overcast Sky model (SOC) or a Uniform Overcast Sky model (UOC). The UOC represents conditions avoiding reflections on the lens and blooming effect that are presented by a uniform cloudiness or in the hours before sunrise or after sunset, when no direct solar radiation is present. For the purpose of this comparative analysis a SOC model, that assumes sky brightness at zenith three times as at the horizon (Frazer et al., 1999), is used because it is considered more efficient under varying sky conditions (Steven and Unsworth, 1979).

The number of sky regions, resulting from the intersection of zenith and azimuth regular division in the sky hemisphere, was set in each software as default (see Table 1). From the theoretical point of view, if the number of sky regions increases, the quality of the gap light transmission results should be improved (Frazer et al., 1999).

Data analysis

The 160 photographs collected in the field were recorded with a resolution of 2,048 × 1,536 pixels and a compression of ¼ (Frazer et al., 2001). The images processed by the three softwares are compared using the descriptive statistics – mean, min, max and standard deviation (SD) – and the non-parametric test of Wilcoxon signed rank test. The Wilcoxon signed rank test was applied because the data does not have normal distribution (Test Shapiro-Wilk: SLIM and GLA W = 0.969, $P = 0.001$; WinScanopy W = 0.920, $P < 0.0001$) and we have paired samples (two values for the same observation obtained with different software image processing). Paired samples imply that each individual observation of one sample has a unique corresponding member in the other sample. The descriptive statistics and the Wilcoxon signed rank test were performed by XLStat 2007.

Finally, the method of bivariate line-fitting called standardized major axis (SMA) was used to summarize the relationship between the basal density (x-axis) and the differences between LAI values estimated with couple of softwares (y-axis). SMA has the advantage to use a single dimension (line) in order to describe two-dimensional data (Warton et al., 2006). The intercepts and slops of regression lines of relationship between couple of softwares were compared considering the forest type and the forest age. The graphical representation of the SMA and the estimation of slope, intercept and R^2 were performed using the "sma" function from "smatr" package in R software.

Results and discussion

The site and stand characteristics measured in the 32 sample plots subdivided in the four forest types (silver fir, Norway spruce, European larch and beech forests) are synthesized in Table 2. The slopes of the plots are in a range of 0° and 23°, while the altitude is between around 550 m and 1,600 m. In order to consider all possible structural situations, the samples included both young stands with high number of stems (more than 900 stems/ha) and low average diameter (25.8 cm) and mature stands with few stems per hectares and high average diameter (41.5 cm). The average volume for all

Table 2. Forest site and stand characteristics of 32 sample plots

Plot	Coordinates (WGS84)		Altitude [m]	Forest type	Density [stems ha^{-1}]	Basal area [m^2 ha^{-1}]	Average diameter [cm]	Average height [m]	Volume [m^3 ha^{-1}]	Age
	East	North								
1	677607	5089786	1,290	Silver fir	714	43.86	21.60	20.9	426	Young stand
2	677472	5089809	1,307	Silver fir	959	31.48	15.30	11.9	338	Young stand

Table 2. Forest site and stand characteristics of 32 sample plots – continued

Plot	Coordinates (WGS84) East	Coordinates (WGS84) North	Altitude [m]	Forest type	Density [stems ha^{-1}]	Basal area [m^2 ha^{-1}]	Average diameter [cm]	Average height [m]	Volume [m^3 ha^{-1}]	Age
3	678344	5091521	1,191	Silver fir	714	55.96	26.90	30.0	531	Young stand
4	691132	5110523	1,336	Silver fir	150	46.77	56.70	38.2	428	Mature stand
5	690180	5110897	1,432	Silver fir	338	33.03	46.90	29.1	665	Mature stand
6	691182	5110886	1,240	Silver fir	714	48.32	27.80	20.0	595	Young stand
7	681665	5088305	1,590	Silver fir	752	42.62	29.50	23.1	473	Young stand
8	681665	5088305	1,596	Silver fir	921	52.92	24.90	22.9	461	Young stand
9	672881	5090442	1,109	Norway spruce	1,015	40.45	18.40	8.8	296	Young stand
10	681094	5093158	1,509	Norway spruce	414	19.32	30.20	22.7	262	Young stand
11	681367	5087689	1,450	Norway spruce	620	26.59	25.60	24.8	350	Young stand
12	683752	5097134	984	Norway spruce	395	17.50	33.40	33.3	351	Young stand
13	675247	5112688	1,018	Norway spruce	884	28.24	24.80	14.4	379	Young stand
14	693632	5112669	1,320	Norway spruce	338	48.44	40.10	30.9	472	Mature stand
15	693634	5112672	1,320	Norway spruce	508	35.20	33.10	27.3	452	Young stand
16	694648	5113605	1,400	Norway spruce	282	26.91	43.90	31.0	440	Mature stand
17	673006	5090454	1,123	Beech	959	41.83	20.50	16.3	172	Young stand
18	681367	5087689	1,448	Beech	432	32.73	21.20	22.4	127	Young stand
19	684996	5097349	969	Beech	489	35.12	24.20	19.1	187	Young stand
20	684998	5097352	969	Beech	320	30.71	22.90	23.5	121	Young stand
21	668526	5101564	1,039	Beech	301	18.40	23.30	16.6	162	Young stand
22	669978	5094424	1,230	Beech	395	44.84	28.60	22.6	180	Young stand
23	668972	5095335	1,006	Beech	377	66.73	22.20	15.7	92	Young stand
24	682231	5086941	1,512	Beech	1,450	62.44	14.30	13.2	357	Young stand
25	678659	5105722	1,390	European larch	188	57.03	37.30	24.9	165	Mature stand
26	678976	5106214	1,418	European larch	451	54.82	32.10	27.8	466	Young stand

Table 2. Forest site and stand characteristics of 32 sample plots – continued

Plot	Coordinates (WGS84)		Altitude [m]	Forest type	Density [stems ha^{-1}]	Basal area [m^2 ha^{-1}]	Average diameter [cm]	Average height [m]	Volume [m^3 ha^{-1}]	Age
	East	North								
27	678976	5106214	1,418	European larch	395	56.02	25.80	31.2	209	Young stand
28	678973	5105587	1,549	European larch	301	54.22	22.50	13.5	108	Young stand
29	679003	5105956	1,502	European larch	339	50.20	36.10	28.4	251	Young stand
30	679082	5105837	1,518	European larch	264	25.83	34.40	23.5	178	Young stand
31	679224	5116193	1,102	European larch	188	11.73	45.80	33.1	215	Mature stand
32	666766	5100859	564	European larch	226	41.69	39.60	24.5	189	Mature stand

sample plots is 316 m^3 ha^{-1}, while the average volume per forest type ranged from 175 m^3 ha^{-1} in the beech forests to 490 m^3 ha^{-1} in the silver fir forests. Referring to the forest age, the mature stands have an average volume of 366 m^3 ha^{-1} (average basal area: 37.9 m^2 ha^{-1}), while the young stands have an average volume of 301 m^3 ha^{-1} (average basal area: 40.7 m^2 ha^{-1}).

The data obtained with WinScanopy show the lowest LAI mean value (1.91) ($SD_{WinScanopy}$ = 0.38), while GLA and SLIM show similar LAI mean values (2.6 and 2.4 respectively) but different standard deviation (SD_{GLA} = 0.38, SD_{SLIM} = 0.45). Wilcoxon signed rank test shows that there are statistically significant differences in LAI (P < 0.0001) among WinScanopy and the other two softwares, while the differences between GLA and SLIM are non-significant. It was hypothesized that these differences are linked to the forest stand density and in order to test this hypothesis the standardized major axis (SMA) was used. The results show that the basal area is not the key variable to explain these differences (Table 3 and Fig. 1). Besides it seems that the three softwares, even starting from the same set of images and applying the same elaboration, calculate different values of LAI that in some cases are also relevant from the statistical point of view. Another study confirms that the outputs obtained by using GLA and WinScanopy for the hemispherical image analysis are not equal in the case of canopy characteristics and below-canopy light conditions (Jarčuška et al., 2010). However, these authors asserted that the outputs are mainly influenced by the threshold values set for pixel classification.

Table 3. Coefficients of standardized major axis (SMA) obtained by comparing the results of the softwares

	SLIM_GLA	SLIM_ WinScanopy	GLA_ WinScanopy
Intercept	–0.843	–0.511	–0.440
Slope	0.022	0.025	0.022
R^2	0.001	0.032	0.029
P	0.864	0.322	0.351

Moreover, LAI values estimated by each software were compared to the LAI value calculated as average of three softwares. In 18 cases (56.2%) the single LAI value closest to the mean LAI value is that obtained by GLA, in 12 cases (37.5%) is the value obtained by SLIM and only in 2 cases (6.3%) is the value obtained by WinScanopy. Considering the differences, it is assumed that values of SD < 0.30 are negligible, while the critical threshold is considered a SD ≥ 0.5. The plots in the latter situation are 12.5% of the total (plot 3, 9, 11 and 12). In these plots characterized by high differences among LAI values, the choice of one software or another should influence the relationship between estimated LAI and the other forest features (i.e. regeneration, evapotranspiration, canopy water interception). It is interesting to highlight that the four plots are young stands and three of them are Norway spruce forests. Instead, the above mentioned plots differ for the other stand characteristics: the basal area ranges between 18 m^2 ha^{-1} to 56 m^2 ha^{-1} and the stand density is between 395 stems ha^{-1} to 1,015 stems ha^{-1}.

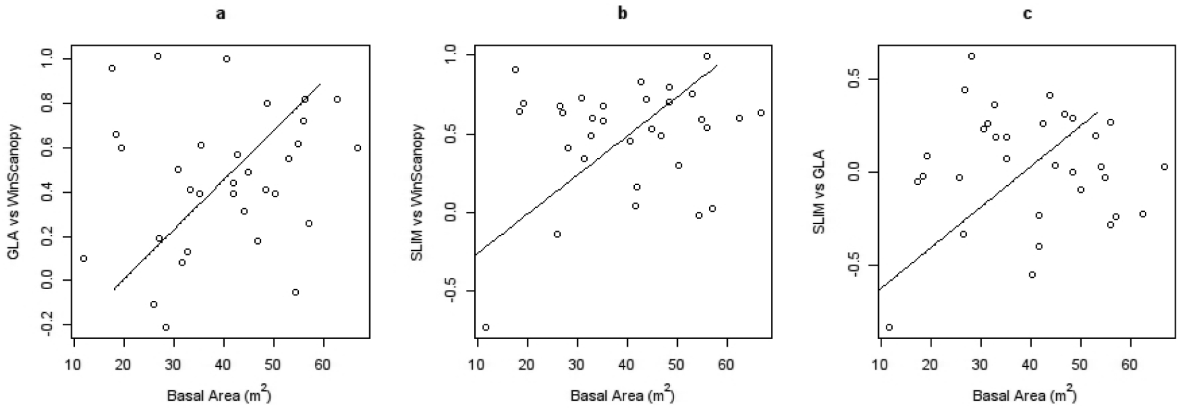


Fig 1. Scatter plots of the basal area (m^2) versus the LAI values differences obtained by comparing the results of the softwares.

The descriptive statistics of LAI values per forest type obtained using the three softwares are reported in Table 4. The data obtained by SLIM and GLA show comparable LAI mean values for two forest types (Norway spruce and beech forests), while there are high differences for European larch and silver fir forests. The LAI mean values obtained by SLIM are highest for three forest types, while the highest LAI mean value for the European larch forests are estimated by GLA. WinScanopy estimates LAI mean values lowest for all forest types when compared to the others two softwares. The maximum LAI value is in beech forests for SLIM and WinScanopy, while it is in Norway spruce forests for GLA. Otherwise the minimum LAI value is in European larch forests for SLIM and GLA, while it is in Norway spruce forests for WinScanopy. These data of LAI per forest type are slightly lower if compared with the average LAI values calculated using the data of the two databases of Scurlock et al. (2001) and Morisette et al. (2006). Considering only the indirect optical methods (hemispherical photographs and LAI-2000) the average LAI values per forest type are the following (Pastorella and Paletto, 2013b): $LAI_{beech\ forests} = 3.33$, $LAI_{European\ larch\ forests} = 2.98$, $LAI_{Norway\ spruce} = 3.49$.

Wilcoxon signed rank test per forest type shows that there are statistically significant differences ($P = 0.008$) in the following cases: in the silver fir forests between SLIM and GLA, and between SLIM and WinScanopy; in the Norway spruce forests between SLIM and WinScanopy; in the beech forests between SLIM and WinScanopy, and between GLA and WinScanopy. Instead, in the European larch forests statistically significant differences were not found.

The graphical representation of the standardized major axis (SMA) and the regression coefficients per forest type highlight a positive relationship between the basal area and the LAI values differences obtained by GLA versus WinScanopy in the silver fir and European larch forests (Table 5 and Fig. 2). Similar results in the same forest types are obtained by SLIM versus WinScanopy but with a lower R^2 values.

Table 4. Mean, min, max and SD of LAI values per forest type obtained by three softwares

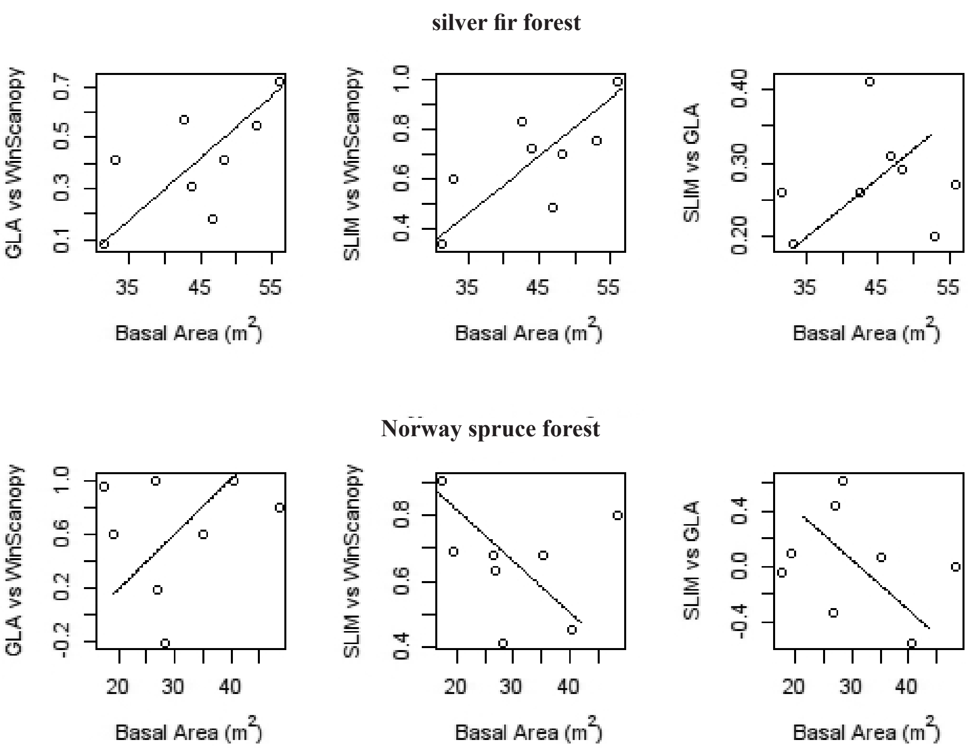
Forest type	SLIM				GLA				WinScanopy			
	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
Silver fir	2.57	2.29	2.85	0.16	2.30	2.09	2.44	0.12	1.89	1.54	2.27	0.25
Norway spruce	2.56	2.19	2.88	0.23	2.53	2.05	3.21	0.43	1.91	1.51	2.27	0.28
Beech	2.53	2.17	3.04	0.31	2.49	2.14	2.74	0.23	1.99	1.54	2.55	0.33
European larch	1.92	1.15	2.43	0.41	2.15	1.89	2.57	0.24	1.84	1.62	2.17	0.19

Table 5. Coefficients of standardized major axis (SMA) obtained by comparing the results of the softwares per forest type

	SLIM_GLA	SLIM_ WinScanopy	GLA_ WinScanopy
Silver fir forests			
Intercept	–0.077	–0.352	–0.677
Slope	0.008	0.023	0.024
R^2	0.018	0.521	0.414
P	0.752	0.043	0.085
Norway spruce forests			
Intercept	1.126	1.134	–0.635
Slope	–0.036	–0.016	0.041
R^2	0.067	0.0418	0.021
P	0.537	0.627	0.730
Beech forests			
Intercept	0.581	0.984	–0.031
Slope	–0.013	–0.011	0.013
R^2	0.185	0.002	0.160
P	0.288	0.922	0.327
European larch forests			
Intercept	–0.977	–1.032	–0.542
Slope	0.017	0.025	0.019
R^2	0.408	0.689	0.273
P	0.088	0.011	0.184

The descriptive statistics of LAI values per forest age obtained using the three softwares are reported in Table 6. These results show that in the young stands the differences among softwares are greater in comparison with the mature stands. Wilcoxon signed rank test emphasizes statistically significant differences in the young stands between GLA and WinScanopy ($P < 0.0001$) and between SLIM and WinScanopy ($P < 0.0001$), while no differences were found in the mature stands. The differences in the young stands are probably due to the fact that these stands are characterized by low density and volume stock that poorly affect LAI estimation. The graphical representation of the standardized major axis (SMA) and the regression coefficients per forest age are shown in Table 7 and Fig. 3.

Synthesizing, the main research finding is that WinScanopy shows LAI values different from the other two softwares suggesting that the choice of the software may strongly influence the estimation. In particular, the highest differences were registered in young and dense forests such as silver fir forests. Results confirm that the need for harmonization and objectivization of techniques at both image capturing and analysis is of fundamental importance as highlighted by Jarčuška (2008). Indeed to obtain comparable LAI values is very important for the optimal choice of the silvicultural practices. In particular, in young forests, basal area and LAI have an influence on the choices of the intensity of thinning in order to increase the economic outcome or the car-



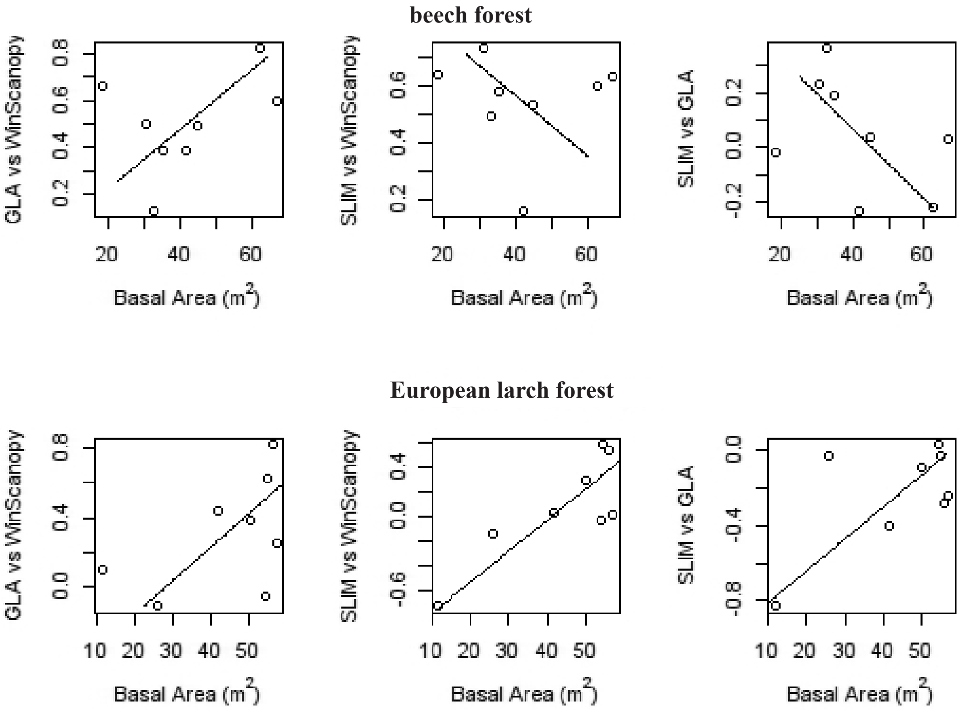


Fig 2. Scatter plots of the basal area (m^2) versus the LAI values differences obtained by comparing the results of the softwares per forest type.

Table 6. Mean, min, max and SD of LAI values per forest age obtained by three softwares

Forest age	SLIM				GLA				WinScanopy			
	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
Young stands	2.48	2.01	3.04	0.28	2.43	1.98	3.21	0.31	1.93	1.51	2.55	0.28
Mature stands	2.16	1.15	2.85	0.59	2.17	1.89	2.44	0.21	1.84	1.62	2.13	0.19

bon storage in forest standing biomass (Slodicak et al., 2005).

Table 7. Coefficients of standardized major axis (SMA) obtained by comparing the results of the softwares per forest age

	SLIM_GLA	SLIM_ WinScanopy	GLA_ WinScanopy
Young forest stands			
Intercept	–0.219	0.818	–0.470
Slope	0.019	–0.019	0.024
R^2	0.000	0.014	0.011
P	0.961	0.571	0.627
Mature forest stands			
Intercept	–1.052	–1.183	–0.250
Slope	0.035	0.029	0.016
R^2	0.215	0.096	0.205
P	0.295	0.500	0.307

Conclusions

Leaf area is a relevant information to investigate biogeochemical fluxes and productivity, consequently different results in the estimation of the LAI value may influence the predictive models. The choice of the software and the parameters settings are two important aspects in consideration of the objective of the analysis. It should take into account technical considerations (i.e. minimum number of available sky regions, possibility of selecting a specific range of colors for thresholding) and the purposes of the work (i.e. research study or management practices).

In general terms, the image analysis may be affected by errors depending from thresholding in pixel classification, Sky Brightness model and number of sky regions. It seems that using automatic processes and standardized methods may improve the quality analysis (Jarčuška et al., 2010). Sky brightness may cause an under- or over-estimation of LAI, due to a direct effect

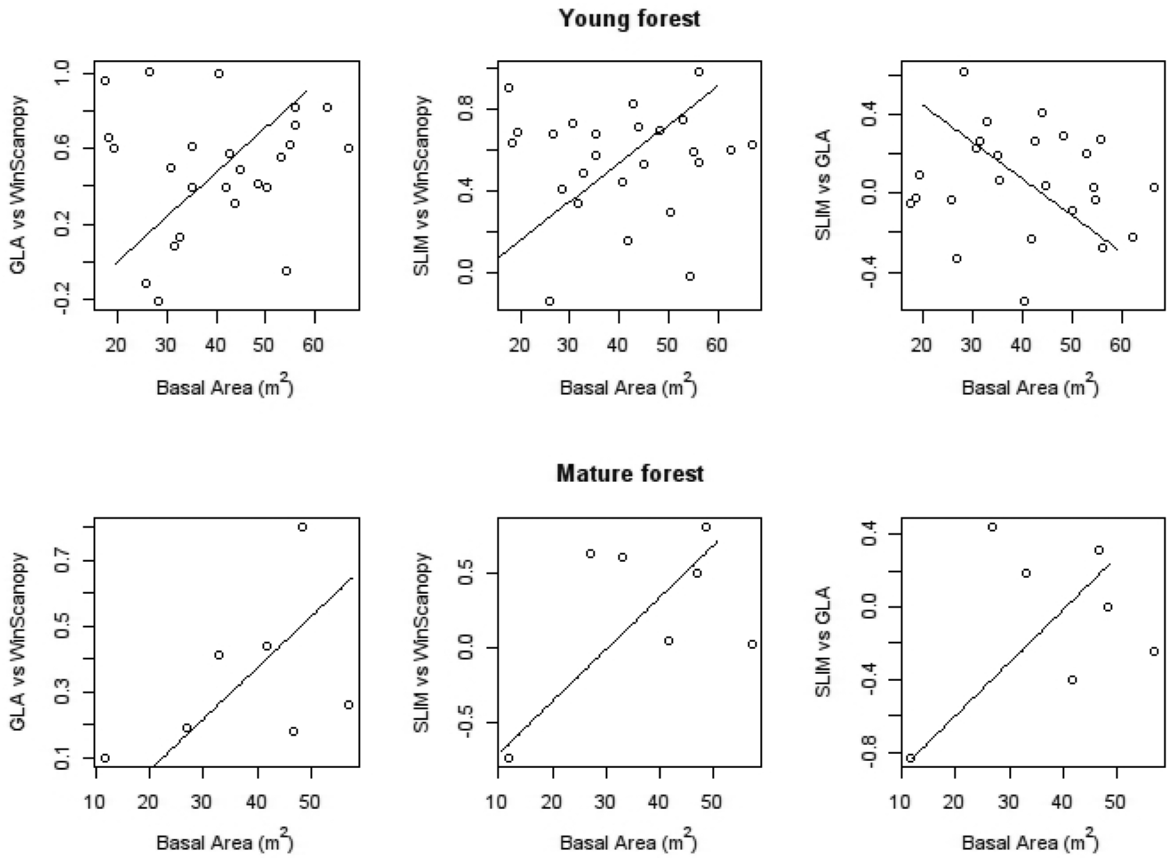


Fig 3. Scatter plots of the basal area (m^2) versus the LAI values differences obtained by comparing the results of the softwares per forest age.

on color classification, while the number of sky region may influence direct openness and LAI estimation. Sky Brightness was set as a SOC model in the three softwares so this aspect does not influence our research. The number of sky regions was used as a default parameter but, as showed by Van Gardingen et al. (1999), it seems that a number of segments higher than 100 does not influence LAI estimation. Moreover, during the image analysis it is recommended to choose the software that makes the best thresholding in terms of image quality. In addition, our results show limited differences between softwares using manually (GLA, WinScanopy) and automatically (SLIM) thresholding. In our opinion, the key aspect linked to the thresholding is to monitor step by step the image quality in order to obtain the most precisely estimated LAI. Moreover, findings from this research suggest that threshold setting is not always adequate to explain differences in LAI estimation.

Our results suggest that probably the differences in LAI estimation using different softwares may be due to differences in software approaches (i.e. knowledge, image processing techniques, threshold choice methods). These findings are confirmed by España et al. (2008) and Jarčuška et al. (2010). These authors indicated that the estimation of LAI might be very dependent on the gap fraction model used and associated inversion techniques. The current international literature concerning indirect LAI estimation from hemispherical digital photography focuses primarily on the determination of an optimal threshold value (i.e. GLA, WinScanopy) (Chianucci and Cutini, 2012). In this research framework we investigated the performances of a new software named SLIM.

Our findings indicate that the differences in LAI estimation are not explained by the main forest stand characteristics (e.g. forest type and age). Differences in LAI estimation are related to forest structure (in terms of basal area) only in silver fir and European larch forests. Further researches should deeply analyze these relationships.

Differences in LAI estimation using different softwares are not a relevant problem when the LAI is not the target of the investigation and the data collected are used as support data. Vice versa, if LAI is the target of the analysis and the data are compared to the outcomes of other studies these differences are crucial. Recently, more complex algorithms and softwares (i.e. CAN_EYE software) were developed by adjusting a clumping index in order to provide not only the effective LAI, but also several estimates of the true LAI (Demarez et al., 2008). Consequently, the future steps of the analysis could be the comparison of the outcomes with the true LAI and the LAI obtained by destructive measurements.

We recommend to implement this kind of studies with up-to-date results about LAI estimation using different softwares. From these further studies it would be possible to foster international sharing of experiences that represents a key to reach higher successfulness in using and developing softwares which concretely support LAI estimation in forest research.

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References

Anderson, M.C. 1964. Studies of the woodland climate. I. The photographic computation of light conditions. *J. Ecol.,* 52: 27–41.

Asner, G.P., Scurlock, J.O., Hicke, J.A. 2003. Global synthesis of leaf area index observations: implications for ecological and remote sensing studies. *Glob. Ecol. Biogeogr.*, 12: 191–205.

Bréda, N.J.J. 2003. Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. *J. exp. Bot.*, 54: 2403–2417.

Chen, J.M., Black, T.A. 1992. Foliage area and architecture of clumped plant canopies from sunfleck size distributions. *Agric. Forest Meteorol.*, 60: 249–266.

Chianucci, F., Cutini, A. 2012. Digital hemispherical photography for estimating forest canopy properties: current controversies and opportunities. *iForest*, 5: 290–295.

Coker, G.W.R. 2006. *Leaf area index in closed canopies: an indicator of site quality*. Master of Science thesis. Canterbury: University of Canterbury, School of Forestry. 114 p.

Comeau, P., MacDonald, R. 2012. *Modeling light using SLIM & LITE.* 25 p. [cit. 2013-01-04]. http://www.ualberta.ca/~pcomeau/Light_Modeling/lightusingSLIM_and_LITE.htm

Davi, H., Baret, F., Huc, R., Dufrêne, E. 2008. Effect of thinning on LAI variance in heterogeneous forests. *Forest Ecol. Mgmt*, 256: 890–899.

Demarez, V., Duthoit, S., Baret, M., Weiss M., Dedieu, G. 2008. Estimation of leaf area and clumping indexes of crops with hemispherical photographs. *Agric. Forest Meteorol.*, 148: 644–655.

Englund, S.R., O'Brien, J.J., Clark, D.B. 2000. Evaluation of digital and film hemispherical photography and spherical densitometry for measuring forest light environments. *Can. J. Forest Res.*, 30: 1999–2005.

España, M. L., Baret, F., Weiss, M. 2008. Slope correction for LAI estimation form gap fraction measurements. *Agric. Forest Meteorol.,* 148: 1553–1562.

Fassnacht, K.S., Gower, S.T., Norman, J.M., McMurtric, E.R. 1994. A comparison of optical and direct methods for estimating foliage surface area index in forests. *Agric. Forest Meteorol.*, 71: 183–207.

Frazer, G.W., Canham, C.D., Lertzman, K.P. 1999. *Gap Light Analyzer (GLA): imaging software to extract canopy structure and gap light transmission indices from true color fisheye photographs. User manual and program documentation.* 40 p. [cit. 2013-01-14]. http://www.rem.sfu.ca/forestry/

Frazer, G.W., Fournier, R.A., Trofymow, J.A., Hall, R.J. 2001. A comparison of digital and film fisheye photography for analysis of forest canopy structure and gap light transmission. *Agric. Forest Meteorol.,* 109: 249–263.

Godoy, O., Saldaña, A., Fuentes, N., Valladares, F., Gianoli, E. 2010. Forests are not immune to plant invasions: phenotypic plasticity and local adaptation allow Prunella vulgaris to colonize a temperate evergreen rainforest. *Biol. Invasions*, 13: 1615–1625.

Heiskanen, J. 2006. Estimating aboveground tree biomass and leaf area index in a mountain birch forest using ASTER satellite data. *Int. J. Remote Sens.*, 27: 1135–1158.

Herbert, T. J. 1987. Area projection of fish-eye photographic lenses. *Agric. Forest Meteorol.*, 39: 215–223.

Hu, L., Gong, Z., Li, J., Zhu, J. 2009. Estimation of canopy gap size and gap shape using a hemispherical photograph. *Trees*, 23: 1101–1108.

Inoue, A., Yamamoto, K., Mizoue, N., Kawahara, Y. 2004. Calibrating view angle and lens distortion of the Nikon fish-eye converter FC-E8. *J. Forest Res.*, 9: 177–181.

Jarčuška, B. 2008. Methodological overview to hemispherical photography, demonstrated on an example of the software GLA. *Folia oecol.*, 35: 66–68.

Jarčuška, B., Kucbel, S., Jaloviar, P. 2010. Comparison of output results from two programmes for hemispherical image analysis: Gap Light Analyser and WinScanopy. *J. Forest Sci.*, 56: 147–153.

Jonckheere, I., Muys, B., Coppin, P. 2005a. Allometry and evaluation of in situ optical LAI determination in Scots pine: a case study in Belgium. *Tree Physiol.*, 25: 723–732.

Jonckheere, I., Nackaerts, K., Muys, B., Coppin, P. 2005b. Assessment of automatic gap fraction estimation of forests from digital hemispherical photography. *Agric. Forest Meteorol.*, 132: 96–114.

Kucharik, C. J., Norman, J. M., Gower, S.T. 1999. Characterization of radiation regimes in nonrandom forest canopies: theory, measurements, and a simplified modeling approach. *Tree Physiol.*, 19: 695–706.

Leuschner, C., Voss, S., Foetzki, A., Clases, Y. 2006. Variation in leaf area index and stand leaf mass of European beech across gradients of soil acidity and precipitation. *Pl. Ecol.*, 182: 247–258.

Liang, S., Li, X., Wang, J. 2012. *Advanced remote sensing: terrestrial information extraction and applications.* Amsterdam: Academic Press. 799 p.

Machado, J.-L., Reich, P.B. 1999. Evaluation of several measures of canopy openness as predictors of photosynthetic photon flux density in deeply shaded conifer-dominated forest understory. *Can. J. Forest Res.*, 29: 1438–1444.

Man, R., Kayahara, G.J., Rice, J.A., Macdonald, G.B. 2008. Eleven-year responses of a boreal mixedwood stand to partial harvesting: Light, vegetation, and regeneration dynamics. *Forest Ecol. Mgmt*, 255: 697–706.

Marchi, A., Paletto, A., 2010. Relationship between forest canopy and natural regeneration in the subalpine spruce-larch forest. *Folia for. pol.*, 52: 3–12.

Morisette J., Baret F., Privette J. L., Myneni R. B., Nickeson J., Garrigues S., Shabanov N., Weiss M., Fernandes R., Leblanc S., Kalacska M., Sanchez-Azofeifa G. A., Chubey M., Rivard B., Stenberg P., Rautiainen M., Voipio P., Manninen T., Pilant D., Lewis T., Iiames J., Colombo R., Meroni M., Busetto L., Cohen W., Turner D., Warner D., Petersen G.W., Seufert G., Cook R. 2006. Validation of global moderate resolution LAI products: a framework proposed within the CEOS Land Product Validation subgroup. *IEEE Trans. on Geosci. Remote Sens.*, 44: 1804–1817.

Pastorella, F., Paletto A. 2013a. Stand structure indices as tools to support forest management: an application in Trentino forests (Italy). *J. Forest Sci.*, 59: 159–168.

Pastorella, F., Paletto A. 2013b. Analisi della copertura forestale in ambiente alpino: metodi di stima a confronto [Forest canopy analysis in the Alpine environment: comparison among assessment methods]. *Forest@*, 10: 43–54.

Pietsch, S. 2002. Using mechanistic modeling within forest ecosystem restoration. *Forest Ecol. Mgmt*, 159: 111–131.

Puerta-Piñero, C., Gómez, M., Valladares, F. 2007. Irradiance and oak seedling survival and growth in a heterogeneous environment. *For. Ecol. Mgmt*, 242: 462–469.

Scurlock, J. M. O., Asner, G.P., Gower, S.T. 2001. *Global leaf area index data from field measurements, 1932–2000*. Data set from the Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA [cit. 2013-03-04]. http://www.daac.ornl.gov

Slodicak, M., Novak, J., Skovsgaard, J.P. 2005. Wood production, litter fall and humus accumulation in a Czech thinning experiment in Norway spruce (Picea abies (L.) Karst.). *Forest Ecol. Mgmt,* 209: 157–166.

Sprintsin, M., Karnieli, A., Berliner, P., Rotenberg, E., Yakir, D., Cohen, S. 2007. The effect of spatial resolution on the accuracy of leaf area index estimation. *Remote Sens. Envir.*, 109: 416–428.

Steven, M.D., Unsworth M.H. 1979. The diffuse solar irradiance of slopes under cloudness skies. *Quart. J. Roy. Meteorol. Soc.*, 105: 593–602.

Thimonier, A., Sedivy, I., Schleppi, P. 2010. Estimating leaf area index in different types of mature forest stands in Switzerland: a comparison of methods. *Eur. J. Forest Res.*, 129: 543–562.

Van Gardingen, P.R., Jackson, G.E., Hernandez-Daumas, S., Russel, G., Sharp, L. 1999. Leaf area index estimates obtained for clumped canopies using hemispherical photography. *Agric. Forest Meteorol.*, 94: 243–257.

Van der Zande, D., Mereu, S., Nadezhdina, N., Cermak, J., Muys, B., Coppin, P., Manes, F. 2009. 3D upscaling of transpiration from leaf to tree using ground-based LiDAR: application on a Mediterranean Holm oak (Quercus ilex L.) tree. *Agric. Forest Meteorol.*, 149: 1573–1583.

Walter, J.-M. N. 2009. *Hemispherical photography of forest canopies. Practice*. Université de Strasbourg. 19 p. [cit. 2013-01-16]. http://jmnw.free.fr

Warton, D.I. 2006. Bivariate line-fitting methods for allometry. *Biol. Rev.*, 81: 259–291.

Watson, D.J. 1947. Comparative physiological studies in growth of field crops. I. Variation in net assimilation rate and leaf area between species and varieties, and within and between years. *Ann. Bot.*, 11: 41–76.

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