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Comparison of four methods for estimating relative solar radiation in managed and old-growth silver fir-beech forest

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Abstract: Methods based on the principle of hemispherical canopy projection, including hemispherical photography (digital and film), sensors like LAI 2000 (zenith cutoff anle 74,1°) and stable horizontoscope, represent less accurate, yet significantly less expensive and time-consuming techniques for radiation measurements compared to long-term measurement with a network of photosynthetically active radiation (PAR) sensors. With measurements taken at a single point in time they can provide reliable estimates of relative diffuse and direct solar radiation and can also be used to estimate the light climate in different times of the year. The four above mentioned methods for solar radiation estimation were applied at the same points in gaps and under adjacent canopies in unevenaged, mixed Dinaric fir-beech and pure beech montane forests. Locations covered a range of radiation and stand structure conditions. Data analyses showed good reliability of all four methods over the whole range (2–80%) of radiation conditions. The most comparable results come from LAI 2000 and film hemispherical photography (all R > 0.90). Digital hemispherical photography is an accurate and reliable (R = 0.89) replacement for film hemispherical photography, but the higher values estimated for direct radiation should be taken into account. Compared to the other three methods, the stable horizontoscope gives less accurate results, especially under canopies with poorly defined gaps. Our study showed that all four methods tested are suitable for estimating the solar radiation climate in gaps and stands with heterogeneous vertical structures, and have potential value as a tool in decision making when practicing silviculture.

Additional key words: light conditions, small-scale forestry, hemispherical photography

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Introduction

Obtaining accurate measurements of solar radiation is an integral part of ecological research in forests. Solar radiation has an important influence on many of the factors that affect forest ecosystems, such as air and soil temperature and moisture, humus depth, and distribution of flora and fauna. Therefore, understanding spatial and temporal variation in solar radiation can provide valuable information about many ecological processes. One important process is tree regeneration in canopy gaps, which is receiving increased attention from forest managers and ecologists as there is a growing interest in close-to-nature forest management in Europe. Many of the small-scale patterns of gap regeneration can be explained by within gap spatial and temporal variability of micro-sites (Runkle 1982; Imbeck and Ott 1987; Poulson and Platt 1989; Brunner and Huss 1994; Brang 1998; Diaci and Thormann 2002; Diaci et al. 2005). An appropriate knowledge of the radiation climate is a prerequisite for this kind of research (Diaci 2002).

In the past it was time consuming and expensive to measure the radiation climate in forests (Cieslar 1904). More recently, modern equipment for radiation measurement is easily accessible. The most frequently used methods, which give precise information on forest light conditions, include photosynthetically active radiation (PAR) sensor networks (Larcher 1983; Brunner and Huss 1994) or sensors that measure photosynthetically usable radiation (PUR) (Dohrenbusch et al. 1995).

Such long-term measurements are, however, still expensive and very demanding from a logistical point of view (Easter and Spies 1994; Comeau et al. 1998; Diaci 1999; Diaci et al. 1999; Lieffers et al. 1999). Moreover, equipment is often vandalized or damaged by wildlife. For typical gap regeneration studies, several gaps with sensors positioned on different microsites within the gaps are required. Also, because regeneration responds to improved light conditions slowly, long-term, average radiation values are needed.

Methods based on the principle of hemispherical canopy projection, such as hemispherical photography (Evans and Coombe 1959), sensors like LAI-2000 (Welles and Norman 1991), and horizontoscopes (Tonne 1954; Schütz and Brang 1995; Diaci and Thormann 2002), represent less expensive and time-consuming techniques that indirectly estimate long-term light levels. Although these methods have less accuracy compared to long-term measurement with PAR sensors, many studies have demonstrated a close correlation between percent PAR values from long-term measurements and relative diffuse radiation estimated from the above mentioned methods (e.g. Rich et al. 1993; Easter and Spies 1994; Comeau et al. 1998; Gedron et al. 1998; Machado and Reich 1999; Heyr and Goetz 2004). With hemispherical photography, it is also possible to improve and transform the radiation estimates to PAR values with the help of additional point selected PAR sensor data (Rich et al. 1993; Wagner 1996). In last few years, digital hemispherical photography is being widely used as a substitute for film hemispherical photography. The equipment is cheaper and processing the photographs is much faster compared to film photography. Several studies showed that the digital format provides reliable results (Frazer et al. 2001; Hale and Edwards 2002; Hyer and Goetz 2004; Inoue et al. 2004; Jonckheere et al. 2004), especially when using appropriate measurement protocol (Gonsamo and Pellikka 2008) and tresholding algoritms (Jonckheere et al. 2005; Cescatti 2007; Lang et al. 2010), which should make the practical implementation of radiation estimation in different silvicultural treatments much easier.

We have already tested three methods (excluding digital hemispherical photography) in gaps (0.08 ha) of mature subalpine spruce forest in Switzerland (Diaci and Kolar 2000; Diaci 2002) and under the canopy and small gaps (0.03–0.06 ha) in old-growth beech forest in Slovenia (Diaci and Thormann 2002). The radiation estimations were consistent with each other, with the stable horizontoscope giving slightly less reliable results. The same light measurement methods have been used in studies of natural regeneration of mountain and subalpine Norway spruce forest in Switzerland (Frehner 1989; Brang 1998) Germany (Brunner and Huss 1994) and Slovenia (Diaci 2002; Diaci et al. 2005).

However, these methods have not been tested in mixed silver fir-beech and pure beech forests of the Dinaric region, which comprise more than 15% of Slovenian forests and represent one of the largest and earliest areas with close-to-nature forest management in Europe (Mlinšek 1972; Boncina et al. 2002). These forests are selectively managed and they are characterised by a high growing stock and a unevenaged structure. With this study we wanted to explore the relationships among the used methods and see how they perform in such environment. The overall objective of this study was to examine the performance of different light measurement methods in a wide range of light conditions. Specifically, we examined the results of measuring indirect site factor (ISF-defined as the proportion of diffuse radiation transmitted through the canopy – see Hale and Edwards 2002) with the following four methods in a diversely structured mixed silver fir-beech and pure beech stands: 1) film hemispherical canopy photographs (relative diffuse radiation – FDIF), 2) digital hemispherical canopy photographs (relative diffuse radiation– DDIF); 3) LAI 2000 plant canopy analyser (LI-COR 1992) (diffuse non-interceptance – DIFN), and 4) a stable horizontoscope (relative diffuse radiation – HDIF) (Diaci et al. 1999). According to results from our and other studies we hypothesised for all four methods to be reliable enough to serve as a potential decision tool when selecting silvicultural treatment in unevenaged and structurally diverse forest.

Methods

Study sites

Research plots were established in Dinaric silver fir-beech (*Omphalodo-Fagetum* (TREG.57) MAR. et al. 93) and montane beech (*Hedero-Fagetum* KOŠ. (62,79)

94 nom.nov.) forests in the Dinaric part of southern Slovenia on rocky limestone substrates between 490-880 m in elevation. The average annual air temperature varies between 6°C and 8°C, while average temperatures in July and January are 15°C and – 1°C, respectively. The total annual precipitation reaches around 2000 mm and is equally distributed over the year, resulting in permanent air and soil humidity.

Light measurements were made in the 52 ha virgin forest remnant Rajhenavski Rog and in neighbouring managed forests with similar site conditions. The latter were managed in a small-scale (irregular shelterwood system or femel) and partly selective (group selection, individual tree selection) way during the past 50 years and have a very diverse vertical structure. Beech (*Fagus sylvatica* L.) (70 % of standing volume) and silver fir (*Abies alba* Mill.) (30 % of standing volume) are dominant, but other species, such as lime (*Tilia platyphyllos* Scop.), maple (*Acer pseudoplatanus* L.), and elm (*Ulmus glabra* Huds.), are present.

Measurements were performed in 16 canopy gaps, and extended approximately 20 m into the closed canopy areas surrounding the gaps. Six gaps were selected in the virgin forest and ten were located in the managed forests. Gap size ranged between 200-2300 m^2 in area. We established a 5 × 5 m grid in and around the gaps, and measurements were made at grid intersections in a N-S oriented direction. All measurements were preformed at breast height. For hemispherical photographs and diffuse non-interceptance, all measurements were done in completely overcast sky conditions close to dawn or dusk to avoid direct radiation.

Measurements of diffuse non-interceptance (DIFN) were made with LAI 2000 instrument. The instrument proved to be a reliable tool for leaf area index estimation of different canopies including forest (Gower and Norman 1991; Welles and Norman 1991; Gatch et al. 2002). The measurements are performed with fisheye lens and silicon detector. The detector is filtered and responds only to radiation below 490 nm, due to minimal leaf reflectance and transmittance below that value (LI-COR 1992). Above canopy radiation was estimated with measurements in open areas close to the study sites. All measurements were performed without view caps with a technique that excluded the measurer out of the sensor view. Both the above and below canopy sensors were oriented facing N. For the DIFN calculations, only data up to a 58° zenith angle were used because measurements above this angle contributed little to the total estimates.

Film hemispherical photographs were taken with a Nikon F50 camera body and a Sigma 8 mm, f/4 Fisheye Circular Image (FC-E8) lens. In order to correctly interpret the hemispherical photographs, the fisheye lens was calibrated to establish the lens distortion (Diaci and Kolar 2000). The camera was mounted to a tripod at 1.30 m and horizontally levelled by a spirit level device. Four wire rods with light-emitting diodes (LED) were fixed to the outer ring of the lens to mark cardinal points. Photographs were taken with the top of the camera oriented north. Ilford PAN 400 black & white film (ISO 400) was used, and light conditions were measured at each data assessment point with a digital exposure meter. Three photographs were taken at each point with a different exposure, including one with settings defined by the exposure meter, one underexposed one aperture stop, and one overexposed one aperture stop. This assured at least one appropriate photo for further analysis, especially since underexposed photos are appropriate for small gaps, and overexposed for large gaps. The exposed film was processed by a commercial lab following standard film specifications, and then scanned by a Nikon Coolscan III LS-30 35 mm Film Scanner at 1350 pixels/inch resolution. Scanned images were processed on a computer with Corel PHOTO-PAINT 9 software to acquire quadratic binary images in GIF format, and finally analysed by hemIMAGE software (Brunner 2002).

Digital hemispherical photographs on all plots were taken with a Nikon Coolpix 995 digital camera and calibrated fish-eye (FC E8, magnification ×0,21, 35 mm equivalent, f/2,4) lens from Regent WinScanopy accessories. Light intensity parameters were processed with WinScanopy 2003 pro-b (WinSCANOPY 2003b for hemispherical image analysis 2003) software (Regent 2003). We set the following parameters within the software: 1) the vegetation period was defined from May 5th to September 25th; 2) the Standard overcast sky (SOC) model was used for the diffuse light distribution in the hemisphere as defined by Anderson (1971); 3) the sun position was calculated every 3 minutes; 4) A value of 1370 Wm^{-2} was used for the solar constant; 5) a value of 0.6 was used for the atmospheric transmissivity; 6) a value of 0.51 was used for the Rad to PAR conversion factor; 7) a value of 0.15 was used for the diffuse radiation fraction of direct radiation; 8) the real size was used for the sun size setting; and 9) the pixel classification method was based on color.

A stable horizontoscope was used to create maps of canopy projections, which were used to establish projections of visible sky segments (Diaci and Thormann 2002). Areas of sky and canopy obstructions visible from a reference point were drawn into a diagram. The sky component was then obtained by evaluating the projection area (of a gap) within the diagram and relative diffuse radiation was estimated. The stable horizontoscope was used during the day, since more light is needed to carry out the measurement. We avoided direct light in the hemisphere of the instrument to increase the precision of the results.

While LAI 2000 is sensitive only to certain radiation wavelengths, the rest of the methods are using approximately the same spectrum of radiation, generally addressed as visible radiation. The least accurate of all methods used in the study was stable horizontoscope with 1 % of relative radiation as the smallest unit that can be measured.

Statistical analysis

Three different sample sizes were used for the analysis. The 2 larger samples were used for performance analysis of the LAI 2000 and film hemispherical photography (N = 660) and comparison of the LAI 2000, film, and digital hemispherical photography (N = 86). Pearson's product-moment correlation and linear regression were calculated from the larger samples to analyze the relationship between methods. Slopes and intercepts of the regression lines were tested with standard t-tests to see if they differed significantly from unity and zero, respectively. Differences in means for the two methods used were tested with paired t-test. Nonparametric Wilcoxon Matched Pairs Tests were performed to examine the differences between the LAI 2000 and film hemispherical photography in range classes that were established according to FDIF values. We only used the stable horizontiscope in one gap, therefore we used the smaller (N = 23) sample for its comparison to other methods. The light measurement data were not normally distributed and transformation of the data was not successful, consequently we used a Friedman ANOVA and Spearman rank order correlation to examine the differences and relationships among the four methods in this case. All analyses were performed using Statistica 7.0 edition (StatSoft, Inc., Tulsa, USA).

Results

Relationship between film hemispherical photography and the LAI 2000

The response of film hemispherical photography and the LAI 2000 to a wide range of light and canopy conditions was studied on a large sample (N = 660). The mean values for film hemispherical photography and the LAI 2000 were 19.39% (range: 1.39% – 82.70%) and 19.92% (range 0.60% – 83.40%), respectively. The difference in means between the two methods was significant (paired t test, d.f. = 659, $P < 0.0001$), but minimal, and accounted for 0.53. Values of relative diffuse radiation (FDIF) acquired from film hemispherical photography and diffuse non-interceptance (DIFN) from the LAI 2000 had an overall coefficient of determination (R^2) of 0.97 ($P < 0.0001$), and showed a strong correlation when all the data were analysed together (N = 660) (Table 1, Fig. 1).

In order to examine the response of each method under certain light conditions, we calculated the regression between values from the the LAI 2000 and film hemispherical photography in 4 separate classes according to FDIF values (Table 1). In all cases, regressions were significant with the percentage of explained variation ranging from 68.5 to 77.8 %.

The comparison of relative diffuse radiation (FDIF) acquired from film hemispherical photography and diffuse non-interceptance (DIFN) from the LAI 2000 showed a positive correlation. The lowest percentage of variation explained by the correlation was found in the 20–40% FDIF class ($R^2 = 68.5$; $P < 0.0001$). Other authors found inconsistencies among different methods of estimating radiation in stands with less than 10 % canopy openness (or below 5–15 % transmission) (Machado and Reich 1999; Diaci 2002). The looser relationship between the two methods could be partly due to the non-uniform canopy present in the 20–40% FDIF class in Dinaric beech and mixed fir-beech forest, causing more variation in canopy openness estimates produced by both methods.

A more detailed analysis of the differences in relative diffuse radiation estimation between the LAI

Table 1. Results of regression analysis between values from the LAI 2000 and film hemispherical photography in 5 separate classes according to FDIF values and for all data

FDIF	n	Intercept	S.E.	Slope	S.E.	R^2
All data	660	0.00451*	0.00181	1.00400	0.007219	0.9671
<20%	420	0.00854**	0.00271	0.96382	0.025796	0.7696
20–40%	160	0.00877	0.01567	0.98602	0.053163	0.6853
40–60%	61	–0.01626	0.03709	1.03949	0.076555	0.7576
60%<	19	0.004560	0.09017	1.02454	0.132666	0.7782

All regressions were significant ($P < 0.001$). All slopes were significantly different from zero and not significantly different from one (standard t-test). Intercepts were not significantly different from zero except where marked (* $P < 0.05$, ** $P < 0.01$).

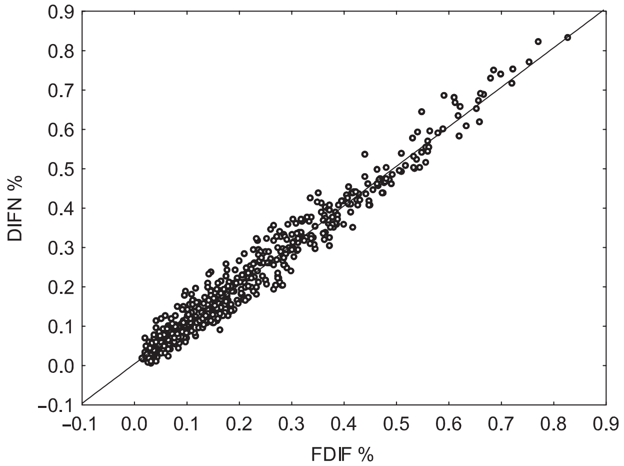

Fig. 1. Scatterplot and linear best fit (line) comparing DIFN (LAI 2000) and FDIF (film hemispherical photography) values in proportion (DIFN = 0.00451 + 1.0040 * FDIF; R^2 = 0.9671; N = 660)

2000 and film hemispherical photography was performed on the whole range of measured FDIF values. We performed a series of nonparametric Wilcoxon Matched Pairs Tests separately for each 10% FDIF class (Fig. 2, Table 2).

Significant differences between relative diffuse radiation (FDIF) and diffuse non-interceptance (DIFN) were only found in the 0–10% and > 60% FDIF class, with differences in the median of 0.42 and 2.12, respectively. In both cases, the LAI 2000 estimated higher values (Table 2). Some authors have reported that both methods are appropriate in the whole range of diffuse radiation measurements (Gendron 1998; Comeau et al. 1998), but their range was smaller compared to one in our study. In other cases, under poor light conditions, film hemispherical photography systematically overestimated the value of relative diffuse radiation (Machado and Reich 1999; Diaci and Thormann 2002), while the LAI 2000 gave results that strongly correlated to long term PAR measurements. This was not the case in our study, where the DIFN (LAI 2000) values were significantly higher compared to values produced by film hemispherical photography (FDIF) in both ends of the range. The exact reason for that difference was not clear.

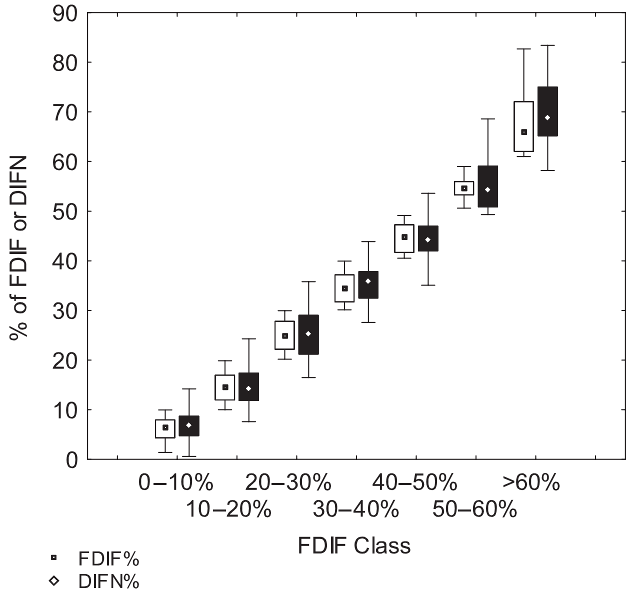

Fig. 2. Range (whisker), quartiles (box) and median (marker) values (%) according to 10 % FDIF classes measured with the LAI 2000 (DIFN, black box) and film hemispherical photography (FDIF, white box)

Relationships among film hemispherical photography, digital hemispherical photography and the LAI 2000

Spearman rank order correlation analyses showed significant positive correlations for all three combinations of comparisons ($R_{DDIF\text{-}FDIF}$ = 0.91; $R_{DDIF\text{-}DIFN}$ = 0.74; $R_{FDIF\text{-}DIFN}$ = 0.90; N = 86; $p < 0.01$). According to a Friedman ANOVA there were significant differences among the methods, with the LAI 2000 giving the highest median and mean values followed by digital and film hemispherical photography (Table 3). This relationship between methods was similar through the whole range of the diffuse radiation estimation values.

Relative direct radiation values were compared between digital and film hemispherical photography. Here, the correlation was also positive and significant ($R_{DDIR\text{-}FDIR}$ = 0.89; N = 102, $p < 0.01$), but values of relative direct radiation were significantly different between the two methods (Wicoxon matched pairs

Table 2. Results of Wilcoxon Matched Pairs Test performed between the LAI 2000 and film hemispherical photography relative diffuse radiation values for 7 classes according to FDIF

FDIF Class	n	Mean DIFN	Mean FDIF	Median DIFN	Median FDIF	T	Z	p-level
<10	260	6.80	6.24	6.90	6.48	12563.5	3.6264	0.00029
10–20	160	14.96	14.51	14.35	14.59	5675.0	1.3033	0.19248
20–30	94	25.20	24.93	25.40	24.78	2107.0	0.4733	0.63603
30–40	66	35.41	34.64	35.85	34.54	861.0	1.5619	0.11832
40–50	39	44.53	44.51	44.20	44.64	371.0	0.2651	0.79090
50–60	22	55.30	54.58	54.30	54.62	120.0	0.2110	0.83287
60 <	19	69.84	67.72	68.90	66.02	36.0	2.3743	0.01758

test; T = 548; N = 102; $p < 0.0001$). The median values for digital and film hemispherical photography were 38.34 and 27.61 respectively.

In both cases, the digital method gave higher values, which was also observed by other authors (Frazer et al. 2001; Hale and Edwards 2002). This was reported to be a result of the higher sensitivity of digital cameras compared to film (Frazer et al. 2001) in a whole range of light conditions.

Relationships among film hemispherical photography, the LAI 2000 and stable horizontoscope

We analysed the differences among FDIF (film hemispherical photography), HDIF (stable horizontoscope), and DIFN (LAI 2000) values using a Friedman ANOVA. Even though the mean and median calculated for HDIF were higher compared to values calculated for FDIF and DIFN, no significant differences were found when the whole range of data was compared (Table 3, Fig. 3).

The mean value for FDIF (13.38%) was used to split the data in two classes (Low and High) according to the range of measured values. Analyses were then performed separately for each class. In lower part of the range (FDIF < 13.38%), the stable horizontoscope (HDIF) gave a lower mean and median value compared to film hemispherical photography (FDIF) and the LAI 2000 (DIFN) (Chi Sqr. = 8.22, N = 9, df = 2, $p = 0.0164$), while in the higher part of the range (FDIF > 13.38%), the values for HDIF were significantly higher (Chi Sqr. = 15.43, N = 14, df = 2, $p < 0.001$).

The performance of the LAI 2000 and film hemispherical photography was uniform, regardless of light conditions, and only minor differences in the mean and median were observed (Table 4, Fig. 3).

We tested the relationships among methods with Spearman rank order correlations. All correlations were highly significant (N = 23, $p < 0.0001$). Spearman rank correlation coefficients were 0.76 (HDIF-DIFN), 0.92 (FDIF-DIFN), and 0.87 (FDIF-HDIF), indicating that all three methods of relative diffuse radiation estimation produce similar results in the same light conditions. The highest correlation was observed between the LAI 2000 and film hemispherical photography.

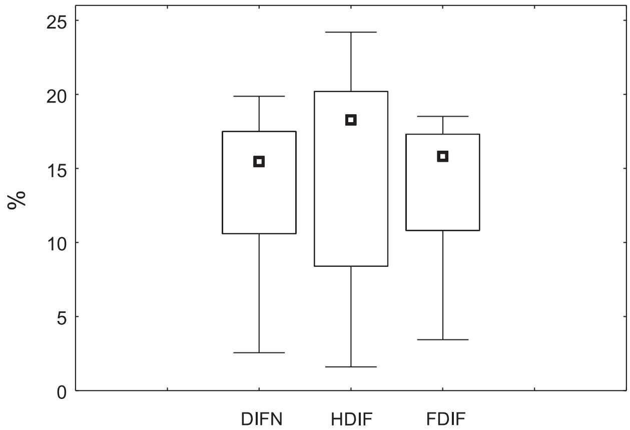

Fig. 3. Range (whisker), quartiles (box) and median (marker) values (%) for three different diffuse radiation estimation methods DIFN – the LAI 2000, HDIF – stable horizontoscope and FDIF – film hemispherical photography (N = 23)

Discussion

All the analyses show that the stable horizontoscope, the LAI 2000, and film and digital hemispherical photography give reliable and comparable results in spite of some observed operational differences (Table 4). The resemblance between the LAI 2000 and film hemispherical photography values was high over the whole range of relative diffuse radiation measurements. Both methods were reported to be the most accurate when compared to long term measurements of photosynthetic active radiation (PAR) in other studies as well (Gendron et al. 1998; Diaci 1999a; Diaci et al. 1999; Machado and Reich 1999; Diaci and Thormann 2002). The performance of the stable horizontoscope was more variable and less reliable, since it produced significantly lower values in the lower part of the range and higher values in higher

Table 3. Friedman ANOVA separately for combination of DIFN (LAI 2000), DDIF (digital hemispherical photography) and FDIF (film hemispherical photography) and combination of DIFN (LAI 2000), HDIF (stable horizontoscope) and FDIF (film hemispherical photography)

Method	Average rank	Sum of ranks	Median	Mean	SD
Silver fir-beech: Chi Sqr. (N = 86, df = 2) = 48.65116; p < 0.0000					
DIFN	2.40	206.00	30.40	30.31	13.7588
DDIF	2.21	190.00	26.90	27.72	10.6997
FDIF	1.40	120.00	23.53	24.86	12.9278
All data: Chi Sqr. (N = 23, df = 2) = 1.652174; p < 0.4378					
DIFN	1.87	43.00	15.47	13.38	5.1855
HDIF	2.22	51.00	18.30	14.68	7.3973
FDIF	1.91	44.00	15.80	13.38	5.1164

Table 4. Comparison of performance of four methods for estimating relative solar radiation: LAI 2000, digital hemispherical photography, film hemispherical photography and stable horizontoscope.

Data	LAI 2000	Film hemispherical photography	Digital hemispherical photography	Stable horizontoscope
	relative diffuse radiation	relative diffuse and direct radiation	relative diffuse and direct radiation	relative diffuse and direct radiation
Time consumption (image acquisition)	very low	medium	low	high
Time consumption (image digitisation)	no	medium	no	high
Time consumption (image analysis)	very low	high	medium	very high
Expertize		trained person nedded in all steps of data acquisition		
Sensitivity to measurement conditions	very high	high	high	low
Price	very high	medium	high	low

part of the range. Measurements with the LAI 2000 and film hemispherical photography were both performed simultaneously with completely overcast sky conditions assuring the same measurement conditions and avoiding problems with beam enrichment because of direct sun radiation (Gendron et al. 1998). Stable horizontoscope measurements demand more light and the results are much more dependent on the canopy conditions (well defined and larger gaps in the canopy are simpler to detect than smaller, scattered canopy openings) and the skill of the person performing the measurements. As a result, the results are much more variable, especially towards the end of the measurement range. The usage of a stable horizontoscope is therefore problematic in stands with many small canopy openings (e.g. selection forest) (Diaci et al. 1999).

There are three basic steps involved in estimating relative diffuse radiation under forest canopies when using the projection of a hemisphere: image acquisition, digitisation, and analysis (Hale and Edwards 2002). Since all three are a possible source of significant errors, we must ensure uniform measurement conditions and usage of precise protocols when digitising and analysing hemisphere images. As a result of our research, there are several guidelines we recommend using in all three steps of radiation measurement. Image acquisition should be performed in completely overcast sky conditions with no direct sun radiation in the image of lens. Unfortunately, this condition is difficult to meet in the field. We used a method where images were taken before sunrise or after sunset. However, if pictures are taken under these conditions the rapidly changing light environment has to be considered, especially since exposure measurements are only valid for a few minutes. Moreover, these images have the clear disadvantage of an uneven sky brightness distribution, which makes analysis procedures more time consuming. Hemispherical images have to go through a process of localized thresholding in order to get proper binary information, because sky portions close to the zenith are brighter than those close to the horizon. This is due to (1) uneven sky brightness (even under perfectly overcast conditions the sky is brighter at the zenith than at the horizon), and (2) the fact that photographic lenses cause a decrease in light intensity from the zenith to the horizon. Selection of the threshold greatly affects results, and therefore setting the threshold level is an important part of the analysis procedure. Setting just one threshold level for the entire image (Nobis and Hunziker 2005) could give less reilable results, however it would lead to more automatized and thus objective analysis of hemispherical images, which is supported by recent studies (Jonckheere et al. 2005; Cescatti 2007; Lang et al. 2010). Through our experience in acquiring hemispherical images in different light conditions (i.e. in gaps of different sizes), we established that underexposed images are more appropriate for analysis of light conditions in small gaps, and overexposed images are more appropriate for large gaps. In both cases one aperture stop from the values given by the exposure meter is enough. This way the position of edge pixels, designating sky and canopy, are better defined and thus easily detected.

Conclusions

Basic forest processes and structures are strongly dependent on the radiation levels reaching certain layer of vegetation in forest ecosystems. The implementation of small-scale forest management systems normally results in diverse vertical and horizontal structure of forest stands, which strongly influences the performance of radiation measurement methods.

In our study, we tested the reliability of four methods for diffuse radiation estimation in Dinaric silver fir-beech and pure beech forest where small-scale silvicultural measures were used and high spatial and temporal variability of radiation under the canopy was present. Results from this study show that all four methods for relative diffuse radiation estimation tested (film – FDIF and digital – DDIF hemispherical photography, LAI 2000 – DIFN and stable horizontoscope – HDIF) are suitable for research in a structurally diverse Dinaric silver fir-beech and pure beech forest. They are relatively cheap and fast compared to setup of long term PAR measurements and will provide reasonable estimates of average growing season light climate in a wide range of light conditions.

Our study shows that in combination with vegetation and regeneration studies, all the tested instruments have potential value as a tool in decision making when practicing silviculture. They can be especially valuable when applying different small-scale (gap regeneration, single and group tree selection, and irregular shelterwood) management techniques, where they can play a role in defining the optimal light conditions for development of stands with a desired tree species composition and wood quality. With that said, forest managers should be aware of the limitations that these methods have when used for forest management techniques (Table 4). They should at least be tested in the field before used as an aid to forest decision making practices.

In the future, research should focus more on the performance of diffuse radiation estimation methods (LAI 2000, film and digital hemispherical photography and stable horizontoscope) at the ends of their measurement range. For example, a focus on the very low (< 5%) and high (< 60%) end of the radiation spectrum, where in this study we observed larger deviations, may provide more improved measurement and analysis techniques.

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