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Estimation of Forest Canopy Cover: a Comparison of Field Measurement Techniques

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Estimation of forest canopy cover has recently been included in many forest inventory programmes. In this study, after discussing how canopy cover is defined, different ground-based canopy cover estimation techniques are compared to determine which would be the most feasible for a large scale forest inventory. Canopy cover was estimated in 19 Scots pine or Norway spruce dominated plots using the Cajanus tube, line intersect sampling, modified spherical densiometer, digital photographs, and ocular estimation. The comparisons were based on the differences in values acquired with selected techniques and control values acquired with the Cajanus tube. The statistical significance of the differences between the techniques was tested with the nonparametric Kruskall-Wallis analysis of variance and multiple comparisons. The results indicate that different techniques yield considerably different canopy cover estimates. In general, labour intensive techniques (the Cajanus tube, line intersect sampling) provide unbiased and more precise estimates, whereas the estimates provided by fast techniques (digital photographs, ocular estimation) have larger variances and may also be seriously biased.

Keywords forest canopy, canopy cover, canopy closure, Cajanus tube, line intersect sampling, spherical densiometer, digital photographs
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1 Introduction

Forest canopy cover, also known as canopy coverage or crown cover, is defined as the proportion of the forest floor covered by the vertical projection of the tree crowns (Jennings et al. 1999). Estimation of forest canopy cover has recently become an important part of forest inventories. First, canopy cover has been shown to be a multipurpose ecological indicator, which is useful for distinguishing different plant and animal habitats, assessing forest floor microclimate and light conditions, and

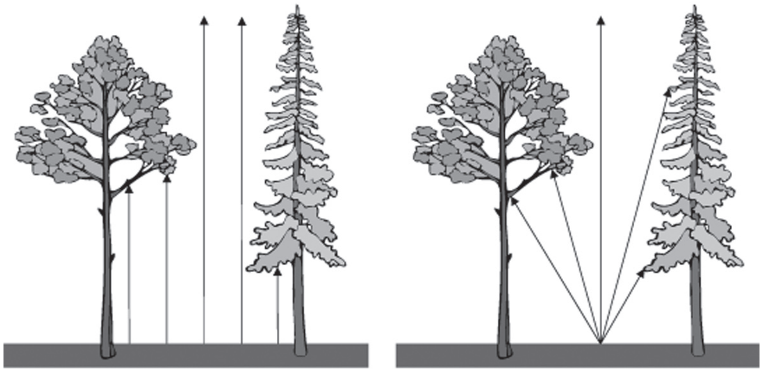

Fig. 1. Canopy cover (left) is always measured in vertical direction, whereas canopy closure (right) involves an angle of view.

estimating functional variables like the leaf area index (LAI) that quantifies the photosynthesizing leaf area per unit ground area (Jennings et al. 1999, Lowman and Rinker 2004). Secondly, many remote sensing applications involve estimation of either canopy cover (Gemmell 1999) or individual tree canopy area (Kalliovirta and Tokola 2005) as an intermediate stage in distinguishing the signals reflected from forest canopy and forest floor, after which, for instance, estimation of timber volume becomes possible (Bolduc et al. 1999, Maltamo et al. 2004). Canopy cover is also an important ancillary variable in the estimation of LAI using empirical or physically based vegetation reflectance models (Jasinski 1990, Spanner et al. 1990, Nilson and Peterson 1991, Knyazikhin et al. 1998, Kuusk and Nilson 2000). The validation of canopy cover estimates obtained from remotely sensed data and development of new remote sensing techniques require field-based canopy cover measurements. Finally, the international definition of a forest is based on canopy cover: the United Nations Food and Agricultural Organization (FAO) has defined forest as land of at least 0.5 ha with potential canopy cover over 10% and potential tree height of at least five meters (FAO 2000). To ensure compatibility of international forestry statistics, forest canopy cover needs to be included in national forest inventories.

Measuring canopy cover accurately involves practical and theoretical difficulties. For interpreting the measurements the difference between the concepts of canopy cover and canopy closure must be recognized. *Canopy cover*, defined here as the *proportion of the forest floor covered by the vertical projection of the tree crowns*, should be distinguished from *canopy closure*, which is defined as the *proportion of sky hemisphere obscured by vegetation when viewed from a single point* (Fig. 1) (Jennings et al. 1999). The difference between these concepts is clear: if canopy is measured with instruments that have an angle of view (i.e. measure a larger area than just a vertical point), like cameras (Kuusipalo 1985) or spherical densiometers (Cook et al. 1995), the results are estimates of canopy closure. In other words, canopy closure or "site factor" (Anderson 1964) is just a percentage figure describing the fraction of non-visible sky within a certain angle, whereas canopy cover describes the fraction of ground area covered by crowns.

According to the definition by Jennings et al. (1999), if canopy cover is to be measured correctly, the measurements should be made in exact vertical direction. If instruments with an angle of view are used, canopy cover is usually overestimated, because the trees seem to "fall" towards the centre of the observed area (Bunnell and Vales 1990, Cook et al. 1995, Jennings et al. 1999). As the size of the area sampled increases, the bias also increases. Another issue worth noting is that tree height and length of the live crown do not affect the estimates of canopy cover, whereas canopy closure increases as the trees become taller, and as the height to the live base of the crown decreases (Jennings et al. 1999).

In publications concerning canopy cover and canopy closure, it has often been unclear which term to use when describing the results (Sarvas 1954, Kuusipalo 1985, Bunnell and Vales 1990, Ganey and Block 1994, Cook et al. 1995, Nuttle 1997). The definitions used here are similar to those published by Jennings et al. (1999). These definitions are not yet commonly established, but in the future it would be preferable if authors consistently use different terms when referring to different measurements.

Another difficulty in defining canopy cover has been deciding whether the gaps inside tree crowns should be counted as canopy. The traditional definition of canopy cover includes an "outer edge" or "envelope" of a crown, inside of which the cover is thought to be continuous. In practice the "outer edge" is sometimes very difficult to observe. Another approach is not to consider the gaps inside the crowns as part of the canopy so that each crown comprises only the leaves, branches and stem and not the empty spaces between them. Rautiainen et al. (2005) introduced the concept of "*effective canopy cover*" to distinguish the measurements that do not include gaps in the cover from measurements made according to the traditional definition. This study mainly concerns the measurement of traditional canopy cover, and when effective canopy cover is discussed it is always mentioned separately.

In addition to an accurate definition of canopy cover, the technique used to acquire the canopy cover information is crucial. There are three alternative approaches for obtaining this information: (1) field measurements at the place of interest, (2) statistical models, if stand parameters such as basal area, number of stems, and diameter at breast height are known from the area, or (3) remotely sensed information such as aerial photographs (Pitkänen 2001, Culvenor 2003), satellite images (Iverson et al. 1989, Gemmell 1999) or laser scanner data (Næsset et al. 2004). Preliminary results indicate that predictions of canopy cover obtained with regression models based on stand parameters, such as basal area and breast height diameter, could be used if direct measurements are not possible (Korhonen 2006). However, more data are needed to confirm these results. Remote sensing of canopy cover may also become a frequently used method along with the improved availability and reduced cost of accurate high resolution remote sensing materials and the fast development of physically based forest reflectance models to extract the information embedded in this data. Nevertheless, field measurements are needed for testing and validating all remote sensing methods.

In most cases, field measurements are the only way to define the true vertical projection of a canopy. In structurally complex forests, indirect estimates achieved with regression models or remote sensing always include at least some random variation. On the other hand, obtaining accurate (i.e. unbiased and precise) field measurements of canopy cover is very time consuming, and attempts to save time usually lead to inaccurate results. In Finland, the best-known field-based method is the Cajanus tube (Sarvas 1953, Rautiainen et al. 2005), which can be used to measure both the traditional and the effective canopy cover. The Cajanus tube is a simple sighting tube equipped with an internal mirror that allows the observer to look upwards through the tube, and then estimate if the crosshair at the top of the tube points directly at part of the canopy. The tube is placed on a holder, which allows the tube to hang freely so that the measurement is made in direct vertical direction. A supportive stick is used to keep the holder steady. Instruments similar to the Cajanus tube have been described by various authors (Walters and Soos 1962, Bonnor 1967, Jackson and Petty 1973, Johansson 1984, Stumpf 1993), but they are all used in the same way. Canopy cover is estimated by measuring a grid of points on the survey plot with the tube. The result of each individual measurement is recorded as 1 if the view is obstructed and 0 otherwise. Canopy cover is then estimated as the mean of these binomial (Bernoulli) variables. The variance of this unbiased estimate of canopy cover (cc) is given by $cc(1 - cc)/n$, where n is the number of measurements. The variance estimator assumes that measurements are not correlated. Thus, the estimator is biased for systematic grid designs. The number of measurements needed to obtain a specified accuracy thus depends on the canopy cover itself, but is independent of the area of the plot. In practice it has been observed that at least 200–250 points should be measured to arrive at stable estimates (Johansson 1984, Jennings et al.

1999, Rautiainen et al. 2005).

The standard alternative to point-based sampling is called line intersect sampling or LIS (O'Brien 1989, Jennings et al. 1999, Williams et al. 2003). Instead of a grid, transects (or 'lines') are used. The points on the lines where canopy cover begins and ends are recorded using a tape measure and the Cajanus tube, after which percent canopy cover can be calculated as a ratio of the length of the transect covered by canopy and the full length of the transect. The lines to be measured should cover the entire plot, but the placement of the lines can be either systematic or random (Jennings et al. 1999, Williams et al. 2003).

According to the definition, if unbiased canopy cover estimates are desired, instruments with an angle of view should not be used. However, if the angle of view is narrow, the bias is not significant (Garrison 1949, Bonnor 1967, Bunnell and Vales 1990). These results suggest that instruments with narrow angles of view can be successfully used in the estimation of canopy cover, and they also speed up the measurement considerably, as the number of individual measurements can be decreased when a larger area is observed at each measurement point. For methods that use an angle of view wider than 30 degrees, the bias in canopy cover becomes significant (Bunnell and Vales 1990, Ganey and Block 1994, Cook et al. 1995), and these methods should only be used for estimating canopy closure. In the estimation of canopy closure, it is best by definition to use an angle of view of 180 degrees (Jennings et al. 1999). When this is not possible, the angle of view used in the measurement should be reported.

Cameras (Kuusipalo 1985, Strandström 1999) and spherical densiometers (Lemmon 1956) have been the most popular angle-of-view instruments in forest canopy measurements. When estimating canopy closure, the canopy is photographed while the camera is kept in a vertical position. The digital or scanned camera images are first converted to binary images so that the canopy and the sky are shown in different colours, usually so that the canopy is black and the sky is white. Next, the percentage of black and white pixels in the binary image can be calculated (Teraoka 1996, Strandström 1999, Ishida 2004). Also the gaps inside the crowns are observed, which means that these gaps displayed in the image should be painted over with black for better estimates of canopy cover in its traditional sense. The spherical densiometer (Lemmon 1956) consists of a small wooden box with a convex or concave mirror, engraved with 24 squares, placed in it. The densiometer is used by holding it at breast height so that the observer's head is reflected from the edge of the mirror just outside the graticule. The curved mirror reflects the canopy above, and canopy closure can be estimated by calculating the number of squares (or quarters of squares) that the image of the canopy covers.

If no other instruments are available, ocular estimation of canopy cover (Sarvas 1953, Bunnell & Vales 1990) is an alternative. However, ocular estimates are always subjective, and the results can vary even with changing weather (Jennings et al. 1999). Objectivity can be increased in the process by dividing the plot into smaller sections and counting the average of estimates made for each section (Sarvas 1953, Bunnell & Vales 1990). This will, however, increase the needed time, and results would probably be more consistent if an instrument was available for measuring the subplots.

The impetus behind this study is to find a suitable canopy cover estimation method for the Finnish national forest inventory (NFI). Although many different methods exist, none is suitable for large-scale inventories, which require an inexpensive method that allows quick and accurate estimation of canopy cover. An ideal method should satisfy all of these conditions. In addition, a balance between costs, speed and accuracy should be possible. In this study, the objectives are to test the ground-based techniques described above, and to evaluate their performance in estimating canopy cover in Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst) stands.

2 Materials and Methods

The data used for comparing ground measurement techniques were collected during summer 2005 at Suonenjoki, central Finland. There were two separate study sites located approximately 20 km apart: the Hirsikangas site (62˚38´N, 27˚01´E)

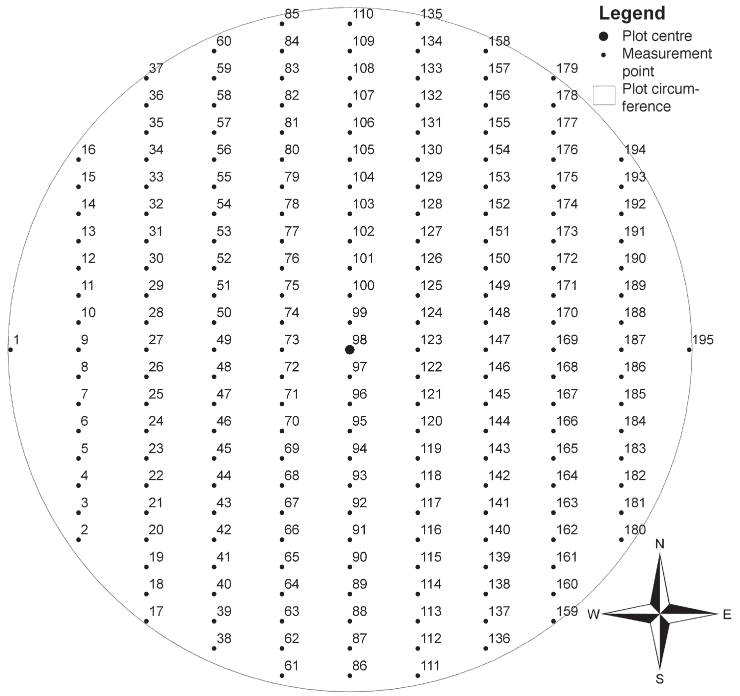

Fig. 2. Plot design with 12.52 m radius and 1 m × 2.5 m measurement point grid.

and Saarinen site (62°40´N, 27°29´E). The plots at Hirsikangas site were mostly rather poor, Scots pine dominated heaths, whereas the plots at Saarinen site were more fertile and dominated by Norway spruce. The plots were located so that the data would be as diverse as possible, with the following conditions: 1) the dominant tree species had to be either Scots pine or Norway spruce, 2) the site type had to be a heath, and 3) tree height in the stand had to be at least two meters. Altogether 19 plots were measured, of which ten were pine dominated and nine spruce dominated. In mixed stands, the species with the largest basal area was considered as the main species.

For all the plots, canopy cover was estimated with the Cajanus tube, LIS, convex spherical densiometer, and digital camera images. In addition, ocular estimates were used in the comparison. The Cajanus tube results were used as control values. For the Cajanus tube and the densiometer, different sample sizes for the number of measured points were also compared. The canopy cover estimates were gathered from circular plots with a radius of 12.52 meters, which corresponds to the maximum radius of the relascope plots used in the NFI. The circular plot included 195 measurement points in a 1 m × 2.5 m grid (Fig. 2).

In each plot, all 195 points were measured with the Cajanus tube, and the control values for comparison with other methods were calculated as an average of these points. To examine the effect of sample size on Cajanus tube results, samples of 102, 49, and 23 were also picked from the data; these sample sizes correspond to selecting every second, fourth or eighth point on each transect.

During the field campaign, several decisions concerning special situations had to be made. If a measurement point was situated on the edge of a tree crown, the decision as to whether the point was covered was made according to whether most of the tube's field of view was below a crown or below the sky. Especially in sapling stands, it happened occasionally that at the eye level (1.7 meters), where the measurement was made through the tube, only sky was visible, but the twigs of a close sapling extended to the measurement point below eye level. In such a situation, the point was considered to be covered, if the sapling was taller than 1.3 meters. Seedlings shorter than 1.3 meters were classified as undergrowth and did not influence the canopy cover estimate. All living twigs and branches of trees taller than 1.3 meters were taken into account when measuring the cover, no matter how sparse a cover they created. Dead branches were ignored in the measurements, unless they significantly hindered the light coming from the sky. For example, if the point was situated under a dead spruce whose crown still intercepted most of the light, the point was classified as covered.

The same transects located inside the circular plot (Fig. 2) were also used in LIS and spherical densiometer measurements. In LIS, the beginnings and ends of connected crowns were recorded with an accuracy of 0.1 meter. The spherical densiometer, on the other hand, was used at the same 49 and 23 points grids as the Cajanus tube. For this study, a new modification of the densiometer was designed to decrease the instruments angle of view from the original 60 degrees. In the modification only the four squares out of 24 that were located closest to the observer were used. These four were selected so that the light coming from the zenith would reflect in the direction of the observer's eyes; at the centre of the convex mirror, the light coming from above reflects back to the zenith. With this modification, the angle of view could be reduced to a third of the original (i.e. to about 20 degrees). Along with the systematic densiometer measurements, a subjective sample of ten points was tested as a faster alternative. In this measurement scheme ten representative points were selected by the measurer.

Digital photographs were taken with a standard digital camera, with an angle of view of about 55 degrees. Five photographs were taken at each plot – one at the centre and the other four in cardinal points at an 8.5 meters distance from the centre. The original images were converted to binary images with a standard image analysis software. Because the camera method actually measures canopy closure, which correlates better with effective canopy cover, the crowns in binary images were painted black so that the result would be closer to the traditional canopy cover estimate. However, the results achieved with both painted and unpainted images were used in the comparison.

The ocular estimation of canopy cover was carried out by three observers. Observer A estimated the percent canopy cover by eyesight before measuring the control value with the Cajanus tube, and was thus able to learn from previously measured plots. Observers B and C were experienced forestry professionals, who had been making similar estimates throughout the previous summer. They visited the plots after the field campaign had ended and were not given feedback until estimates were obtained for all plots.

In addition to the canopy cover measurements, routine stand inventory parameters were also measured at each plot to characterize the structure of the stands (Table 1.). The parameters included plot coordinates, soil type and site class classification, stand age, basal area, stand density by size class, diameter at breast height (DBH), tree height and crown length. The data included four sapling stands and also some mixed forests (species: spruce, pine, birch and other deciduous species).

The comparison of measurement techniques and sample sizes was based on the arithmetic differences between the results acquired with a given method and the control values (i.e. Cajanus tube measurements from 195 points). Because the comparison was made using the differences obtained from different plots, the results from different measurements could be handled as independent samples. The mean difference indicates whether the method is biased: a positive mean difference indicates that the method produces overestimates, and respectively, a negative mean difference indicates an underestimate. The standard deviation of the differences describes the precision of the method, i.e. how much the results typically differ from the mean. An ideal method would thus be unbiased and precise (i.e. accurate), and, simultaneously, quick and inexpensive. The problem with using arithmetic means and standard deviations was that for most methods, the distributions of the differences were not normal; instead, they were usually skewed and included some outliers. Therefore medians and quartiles were also used as supplemental measures. The box-and-whiskers plot (Moore and McCabe 1993) is one useful median-based method for illustrating the distributions.

The statistical significance of the observed

Table 1. Key information of the data.

Plot	Dominant species	Canopy cover	Basal area (m^2/ha)	Stand density (stems/ha)	Height (m)	Diameter (cm)
1	Pine	0.42	19.2	690	26.4	34.6
5	Pine	0.48	14.0	390	16.1	20.5
7	Pine	0.32	13.6	260	18.7	25.7
8	Pine	0.83	29.2	2500	15.0	13.3
9	Pine	0.68	27.2	480	21.0	25.2
10	Pine	0.72	18.4	3200	13.4	13.4
11	Pine	0.66	11.4	1600	10.3	11.0
13	Spruce	0.59	25.6	580	24.2	26.1
14	Pine	0.47	18.8	490	17.7	22.1
18	Spruce	0.63	26.8	610	25.6	27.3
22	Pine	0.51	9.6	2700	5.8	6.3
24	Pine	0.71	16.4	4700	6.1	6.6
39	Spruce	0.74	24.8	1800	14.9	17.5
40	Spruce	0.77	9.0	16000	6.2	6.5
44	Spruce	0.56	19.6	1100	19.8	21.9
45	Spruce	0.89	26.0	1700	12.9	15.2
47	Spruce	0.81	23.4	2300	12.9	13.3
54	Spruce	0.51	21.2	1200	21.0	23.7
56	Spruce	0.34	1.0	5100	3.4	3.3

differences was tested with the nonparametric Kruskall-Wallis analysis of variance (Zar 1984, p. 176). Analysis of variance allows comparison of multiple methods in a single test, which decreases the probability of finding a statistically significant difference by chance when it in fact does not exist; this would probably happen if a series of T-tests were used instead of an analysis of variance. A nonparametric test was chosen because the differences were not normally distributed. The nonparametric Kruskall-Wallis test uses ranks rather than the actual differences. This decreases the influence of skew distributions and outlier values on the results. Since the output of the test shows whether a significant difference exists, multiple comparisons were used to define which methods actually differed from the control. The multiple comparisons used nonparametric comparisons of a control to other groups (Zar 1984, p. 201). The test results for each method were then compared to a critical value obtained from Q-table (Zar 1984, p. 569), and if the test coefficient was larger than the critical value, the difference was considered statistically significant.

3 Results

The main differences between the measurement methods can be easily seen from the box-and-whiskers plot (Fig. 3). The detailed data of the means, medians, standard deviations etc. are presented in Table 2.

There are statistically significant differences between the results produced by different measurement methods (Fig. 3, Table 2). Some methods, like the Cajanus tube with a sample size of 102 and LIS, produce unbiased results, whereas some of the others, like the ocular method and unpainted digital photographs, provide very large underestimates. Also precision varies considerably: the Cajanus tube with a sample size of 102 and the LIS-method have very small standard deviations, whereas the ocular estimates and digital photographs yield significantly different results at different plots.

The analysis of variance confirms the conclusions made from looking at Fig. 3: the initial hypothesis of the equality of medians is rejected as the test p-value is remarkably small (testing: χ^2-test coefficient = 59.5, d.f. = 16, $P < 0.01$). The multiple comparisons (Table 3) reveal that the

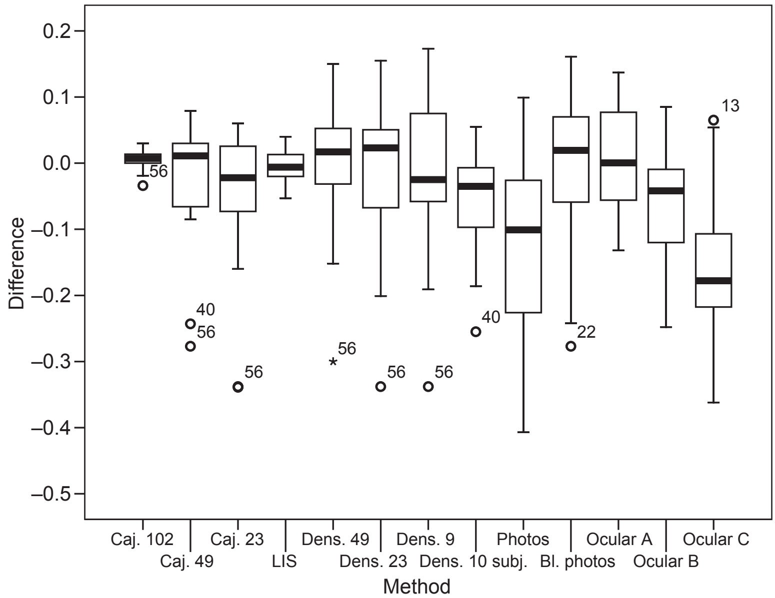

Fig. 3. A box-and-whiskers plot for comparison of the measurement methods and used sample sizes. The numbers close to outlier values refer to individual plots (Table 1).
Abbreviations: Caj. = Cajanus tube (followed by sample size), LIS = line intersect sampling, Dens. = densiometer (followed by sample size; subj. = subjective sample), Photos = unpainted digital photographs, Bl. photos = black-painted digital photographs, ocular A–C = ocular estimates by the three different observers.

Table 2. Information on the differences between the results of the control method and each evaluated measurement technique.

Method	N	Mean	Median	Std. dev.	Quartile range	Min	Max
Cajanus tube 102 points	19	0.004	0.007	0.015	0.015	–0.034	0.030
Cajanus tube 49 points	19	–0.029	0.011	0.094	0.106	–0.277	0.079
Cajanus tube 23 points	19	–0.055	–0.022	0.117	0.099	–0.339	0.060
LIS	19	–0.003	–0.006	0.026	0.038	–0.053	0.040
Densiometer 49 points	19	–0.001	0.017	0.097	0.094	–0.300	0.150
Densiometer 23 points	19	–0.013	0.023	0.111	0.126	–0.338	0.155
Densiometer 9 points	19	–0.019	–0.025	0.119	0.146	–0.338	0.173
Densiometer 10 points subjective sample	19	–0.056	–0.035	0.081	0.113	–0.255	0.055
Digital photographs	18	–0.143	–0.101	0.140	0.212	–0.407	0.099
Black-painted digital photographs	18	–0.004	0.020	0.123	0.144	–0.277	0.161
A’s ocular estimate	14	0.008	0.001	0.080	0.136	–0.132	0.137
B’s ocular estimate	19	–0.064	–0.042	0.089	0.152	–0.248	0.085
C’s ocular estimate	19	–0.162	–0.178	0.104	0.117	–0.362	0.065

Note: negative mean and median values indicate underestimates

Table 3. Multiple comparisons.

Method	N	Mean rank	Difference from control	Standard error	Test coefficient
Cajanus 195 points (control)	19	182.0	0.0	14.82	0.00
Cajanus tube 102 points	19	193.5	11.5	14.82	0.77
Cajanus tube 49 points	19	165.9	–16.1	14.82	–1.08
Cajanus tube 23 points	19	144.3	–37.7	14.82	–2.54
LIS	19	176.7	–5.3	14.82	–0.35
Densiometer 49 points	19	196.5	14.5	14.82	0.98
Densiometer 23 points	19	188.2	6.2	14.82	0.42
Densiometer 9 points	19	167.3	–14.7	14.82	–0.99
Densiometer 10 points subjective sample	19	125.3	–56.7	14.82	–3.83*
Digital photographs	18	78.1	–103.9	15.02	–6.92*
Black-painted digital photographs	18	189.7	7.7	15.02	0.51
A's ocular estimate	14	187.3	5.3	15.91	0.34
B's ocular estimate	19	120.7	–61.3	14.82	–4.14*
C's ocular estimate	19	58.9	–123.1	14.82	–8.31*

* Statistically significant difference at α=0.05 (critical value 2.955).
Note: test coefficient with negative sign denotes an underestimate.

methods yielding significantly different results from the control values are (in decreasing order): ocular estimates by observer C, unpainted digital photographs, ocular estimates by observer B, and the densiometer measurements with ten subjectively chosen points. All the significant differences were underestimates.

The effect of sample size on the results acquired with the Cajanus tube was as expected; the limit under which the estimates become imprecise is between 102 and 49 points. This result is different from the previous results that 200–250 points should be measured (Johansson 1984, Jennings et al. 1999, Rautiainen et al. 2005), as the 102 points (i.e. every second point from the circular plot) seem to be enough for this measurement scheme. The maximum difference compared to using every point was approximately three percent, and the arithmetic mean was practically unbiased. When the sample size was decreased to 49 or 23 points, the standard deviations rose to approximately ten percent, and, in addition, some outlier values appeared. The outliers were plots 40 and 56 (Fig. 3), i.e. two spruce sapling stands with short average tree heights (Table 1). This indicates that a sparse grid could not find all the trees on these plots. It should also be noted that the difference in results for grids of 49 and 23 points was negligible.

The LIS-method proved to be another accurate method for measuring canopy cover. The average difference between LIS and the control was 2.5%, and never more than 5%. Both the Cajanus tube, with sample sizes of 195 and 102, and LIS were precise and unbiased methods for estimating canopy cover, and they also provided very similar results for each plot. The well-known disadvantage of these methods is that they are time consuming: measuring a plot with 195 points usually takes, depending heavily on the terrain, more than an hour.

The modified spherical densiometer acted as a compromise between measurement speed and accuracy. In practice, the results acquired with systematic sampling seem to be unbiased, even though in theory the results should be overestimates because the densiometer measurement involves an angle view. A closer inspection of the data revealed that at a considerable number of plots, the densiometer results were 0–10% higher than the control values, but in the whole data the differences were not statistically significant. The standard deviation was approximately ten percent and interquartile range also comparable to the other methods. Decreasing the sample size to 23 points or only nine points weakened the results, but there were no significant differences between the estimates obtained with smaller sample sizes: the results were slight overestimates with standard deviations of 11–12% and somewhat larger interquartile ranges. The most distinctive feature of the densiometer method is that it is not suitable for stands with tree heights less than five meters, because the shorter trees are more difficult to observe. Because the measurement is made at breast height, the angle of view gives only little advantage in finding the shorter trees, i.e. the sample point should be almost inside the sapling canopy to be able to create any cover. This explains the outlier values related to densiometer results in Fig. 3. If all trees need to be sighted, it is better to use the Cajanus tube and a dense grid.

An alternative, quicker approach in using the densiometer was subjective sampling with only ten measurement points. This implementation method resulted in statistically significant underestimates, as the mean and median results were underestimates of 5% and 3.5%, respectively. Selection of measurement points was not an easy task. In heterogeneous mature stands it was often difficult to assess how many points should be located in large gaps between trees and how many in dense spots. As the results show, the points were typically more often located in open places or gaps between the trees, which led to underestimates. However, the standard deviation and interquartile range were better than with systematic measurements, and in more homogenous pine stands the results were practically unbiased. This indicates that in some stands subjective densiometer sampling could be used as a quick alternative to the more time consuming methods: the subjective densiometer sampling typically takes about five minutes, whereas measuring a systematic grid of 49 points takes approximately 30 minutes. Because the densiometer results could still easily differ ten percent from the actual cover even with 49 points sample size, using instead the Cajanus tube or the LIS method is more advisable.

From the estimates based on digital photography a clear conclusion can be made: if canopy cover estimates are desired, the gaps inside tree crowns must be painted non-transparent to avoid underestimates. The mean and median values of canopy cover obtained from unpainted images were 15% and 10% smaller than the control values, i.e. statistically significant underestimates. As the images were painted, the differences were reduced to 0 and +2%, i.e. practically unbiased. Those values are surprisingly small, considering the fairly large angle of view (55 degrees) which theoretically should provide clear overestimates. It is probable that the painting of small gaps within the crowns did not quite correspond to the classification of crown/sky in the field measurements. Another explanation for the negative bias is that the method did not work in sapling stands where underestimation occurred. In addition, the estimated mean and median values are subject to random variation due to limited numbers of plots and fairly large standard deviations. The digital photography was tested mainly as another quick alternative for more accurate methods, similar to the subjective densiometer sampling. The conclusion was that painted photographs can be used if information for effective canopy cover or canopy closure is needed in addition to canopy cover. Even then it would be more sensible to take more photographs and use a narrower angle of view, if the main interest is in canopy cover. Otherwise, some other method would probably be a better choice.

The ocular estimates of the observers B and C were also statistically significant underestimates: C's mean and median results differed from the control values by –16% and –18%, and B's by –6% and –4%, respectively. However, the estimates made by A prior to starting the actual measurement were practically unbiased. The standard deviation and interquartile range were approximately the same for each observer. This indicates, as expected, that the ocular estimates achieved without proper training might be seriously biased in either direction, but underestimation seems to be the most common mistake. However, as A's results show, after some experience and knowledge of true canopy cover in different stands, the bias of the results should decrease considerably. However, increasing the precision of estimates is probably more difficult.

4 Discussion

The results of the comparison of measurement techniques confirm that the conventional methods cannot quickly provide accurate canopy cover estimates; the conclusion is essentially the same as Sarvas (1953) made more than fifty years ago. If accurate values are desired, unbiased methods such as the Cajanus tube or LIS should be used, and an adequate amount of time should be reserved for field measurements. If time is a limiting factor, subjective densiometer sampling could be a possible alternative in mature stands. If even five minutes per plot is regarded as too long time for the measurements, the only possibility is to rely on ocular estimates. However, ocular estimation requires training with carefully measured training sites and careful monitoring of the results. When canopy cover data are gathered for modelling purposes, using accurate but time-consuming methods is the only alternative.

In the near future, new methods of canopy cover estimation are needed to better satisfy the growing need for canopy-related information. Geographically representative regression models might be the most cost-effective and feasible solution for obtaining canopy cover estimates for large areas. However, substantial amounts of resources and research efforts are required if nation-wide models are to be developed. In the long run, remote sensing may become a more popular and appropriate means for canopy cover estimation. Nevertheless, for the development and validation of remote sensing techniques, reliable ground truth measurements and models of canopy cover need to be obtained and tested first.

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Total of 38 references