# HEMISPHERICAL PHOTOGRAPHS AS A TOOL TO CHARACTERIZE UNDERSTORY LIGHT ENVIRONMENTS AND REGENERATION SUCCESS UNDER VARIOUS CANOPY COVERS

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# INTRODUCTION

The purpose of this study was to examine the potential for the use of hemispherical photographs, and different software used to estimate light environments from them, to predict seedling performance under different silvicultural conditions.

Changing forest practices in British Columbia will result in the increase use of harvesting systems other than large scale clearcuts (e.g. small patch, shelterwood, and selection harvesting). It is expected that the regeneration conditions will vary greatly under these different harvesting systems and large variations in the quantity and quality of light will have a strong effect on the regeneration success of seedlings. Since light plays such a critical role in the regeneration success of trees, it is important to be able to characterize the light environment associated with different harvesting systems if we are to be able to predict the regeneration success of different tree species. Since the partial removal of a forest canopy results in patches of sky which are obscured by remaining vegetation, the measurement of light reaching the forest floor requires long term monitoring of light levels over the entire growing season. Light must also be measured at numerous locations to account for spatial variability, making the measurement of light in the forest understory a long and expensive endeavor.

As an alternative to collecting actual light data, the amount of light received at a specific point can be estimated using a hemispherical photograph. The theory and practice of this estimation has been extensively reviewed (Rich 1990, Mitchell and Whitmore 1993). Knowing the orientation of an image with a complete view angle of the sky, the amount of direct and diffuse light in the understory can be estimated. This is done by first estimating the amount and distribution of light above the canopy. The amount of diffuse and direct light in the understory is estimated by determining that amount of direct and diffuse light which passes through the canopy for the period of interest. Although this estimation can be done by hand, a number of computer programs are available which make this analysis quick and therefore a potentially useful tool for characterizing the light environment from a large number of samples. To date, no study has compared these different programs in terms of their ease of use and ability to predict plant performance under various silvicultural systems.

# RESEARCH ACTIVITIES

## Description of hemispherical image analysis programs

We examined four programs that analyze hemispherical photographs: GLI/C (Canaham 1995), Hemiphot (Steege 1994), Solarcalc version 6.03 (Chazdon and Field 1987) and Sunshine (Smith and Somers 1991). These programs are all freely distributed by their authors (see Appendix) and come with some form of documentation which give the theoretical background for the analyses. All these programs require the input of a digitized image. A number of other freely available programs were not examined. The programs SYLVA (Becker et al. 1989) and Canopy (Rich 1989) were not examined because they required a video digitized input of the images. Another program, HEMISP, which is freely available through the internet, was not examined because the program has yet to be fully implemented.

A summary of the differences between the four programs examined can be found in Tables 1 and 2, and are described in more detail below. All programs are similar in the way the image is analyzed. All programs assume the image is an equal angle projection of a hemisphere which is supposed to be produced by a 180 degree fisheye lens (Rich 1990). Since an equiangular projection does not produce regions if equal area on an image, a correction factor must be applied to different areas of the image. The amount of canopy cover is estimated by measuring the proportion of cover in the hemispherical projection, either by sampling every point (pixel) in the image, or a portion of them, after applying area correction factors to different regions of the image. All programs assume that elements in the canopy either allow the complete passage of light or prevent its passage completely. Therefore all programs require that the images be converted from shades (either grays in a black and white pictures or colours) to completely black or white pixels. This is done by the user deciding the cutoff (threshold) value on a gray or colour scale that divides pixel into black and white, creating a 1 bit/pixel image. This is the most subjective part of the image analysis procedure and the programs differ in the way they help the user decide on a correct threshold value. Once the image has been converted, each program requires that the user identifies the boundary of the hemisphere on the image and at least one cardinal coordinate so that the image can be properly oriented to the path of the sun. All programs generate a theoretical distribution of the above canopy light based on the location of the site, given by the user. Since the distribution of diffuse light is not certain and the proportion can change with geographic location, some of the programs allow the user to modify either the proportion or the distribution of diffuse light. The amount, or proportion of light below the canopy is estimated by each program by first estimating the amount of light in the unobstructed part of the sky for the time period specified by the user. This is divided into the amount of light attributed to direct and diffuse solar radiation. Although most programs give actual light levels, most users will be most interested in the proportion of direct (direct site factor) or diffuse (indirect site factor) light in the understory, relative to the direct and diffuse light above the canopy.

## Individual programs

### GLI/C

GLI/C is the only program not designed to estimate the quantity of light in the understory. Rather, the author assumes that the user is only interested in knowing the amount of light in the understory, relative to the amount of light above the canopy, and so only relative values are given. The program is easy to use and the author has given default values for input the user is unlikely to have at hand (e.g. beam fraction and clear sky transmission). This is the most sophisticated program for image manipulation and determination of threshold values. This is also the only program to use colour information and the author claims that pictures can be taken on sunny days and the colour information used to determine threshold levels. An original image and a thresholded image are displayed side by side and specific areas can be blown up and the effect of the thresholding procedure compared at a small scale. Different areas of the same picture can be given different threshold values so pictures with poor resolution or uneven sky brightness can be used. While this may allow the user to take pictures under conditions not normally allowed by other programs (i. e. uneven sky brightness) it can introduce more subjectivity in the thresholding procedure. Unlike most other programs which use north/south coordinates, hemisphere boundaries in GLI/C are set by pointing to the east and west points on the image. This can be accurately done by zooming in on the image (which must be cropped first). Unless markers are mounted on the east and west sides of the lens, the position of these coordinates is best marked on the image before using GLI/C. An active display of the coordinates of the cursor on the image would solve this problem. Data produced by GLI/C are written to a well labeled file. We found one major drawback to the current version of this program. GLI/C requires a computer video screen output of at least 1280 x 1024 resolution. Users with computers screens with lower resolution will find that menus in the program do not fit on their screens. Although GLI/C can potentially analyze an image of unlimited resolution, we found that when we tried to retrieve images of 2048 x 3072 pixels (using a computer with 32 MEG's of RAM!) that the program consistently crashed.

### Hemiphot

Hemiphot program provides the most diverse and user friendly output of all the programs examined. Light is calculated on daily and yearly intervals. Data is exported to a spreadsheet and can be easily manipulated. Graphs of yearly light levels and sunfleck frequency distribution are also produced. Suntracks are plotted on the image, helping the user to visualize the effect of the canopy on the amount and distribution of direct light. The hemisphere boundaries can be accurately placed on the image using the arrow keys but not with mouse. (We calculated the percent cover, 10 times each, from 13 different image, drawing new boundaries with the mouse each time. The coefficient of variation for percent cover for the images varied from 0.01 % to 1.25%. When boundaries were drawn using the keyboard arrow keys there was no variation in the percent cover, calculated repeatedly from the same image). Hemiphot allows the user to vary the distribution of diffuse light, the clear sky transmission, and the effects of the canopy on the red: far red ratio. The proportion of diffuse light, relative to the total light can't be given a value greater than 0.5 and diffuse light is likely to be greater than 0.5 in temperate regions (Mitchell and Whitmore 1993). However, in the latest version of Hemiphot (Winphot, for windows) this problem has been corrected (Steege, personal communication). Hemiphot does allow the user to adjust the brightness of different parts of an image independently. However, unlike GLI/C, Hemiphot does not present the user with a side by side presentation of an adjusted and unadjusted image. Images can be analyzed without the user setting threshold values but this means that the user has no idea of what the program considers to be either sky or foliage. We found that the program generally gave higher values of canopy openness by about 4 % when we used a gray scale image and allowed the program to set the threshold values, compared to an image in which we set the threshold value for the image before using the program. Hemiphot is limited in the size of the image that can be analyzed, to a maximum size of 400 pixels. Although Hemiphot can be run on a 80286 computer, we found that it took a 8 MHz machine approximately 15 minutes to analyze the yearly data from an image whereas a pentium 133 MHz machine completed the analysis in less than 12 seconds.

## Solarcalc

This is the oldest program of those we analyzed and is the only program operating with in the Macintosh environment. The program does not give the direct or indirect site factor but actual light levels. The site factors can be calculated by comparing light levels from an image to light levels from a completely white image. Data are written to an output file which are not easily manipulated in any spreadsheet program we had available (MS Works, SUPER ANOVA, Cricket Graph). The program does not have a feature to calculate the threshold value for images and they must be copied to the program as bitmapped black and white files from the clipboard. The advantage to this is that Solarcalc can use any image file type that can be copied to the clipboard. Hemisphere boundaries are set by entering the x and y coordinates of the image center and the radius of the image. If these values are not known beforehand, they can be guessed at by repeatedly entering values until the boundaries are properly located on the image. This iterative process can be very time consuming so it is best (and relatively simple) to determine these values using some other image software that provides cursor coordinates. Solarcalc allows the user to enter the view angle of the lens. To speed up the analysis, the proportion of pixels sampled by the program can also be adjusted, but this probably isn't wise given the low resolution of the images used.The maximum picture resolution was 300 pixels on a Mac Classic II which resulted in very coarse grained images (although a larger screen machine would allow for increased resolution). The proportion of diffuse light is set at 15% of the total incident light . Although the program does not calculate yearly data, the program will calculate daily light values for up to 12 specified days for a single run of the analysis. Since the path of the sun covers the same region of the sky twice in a year, 12 light values per year are enough to calculate the light environment for every 15 days difference in the sun's position over the course of the year. Calculating light every 15 days is sufficient for accurately measuring the yearly light levels (Mitchell and Whitmore 1993). The program comes with the source code so it is possible to modify the program. Unfortunately, the program was written in Microsoft Quick Basic for the Mac operating system, which Microsoft no longer supports. This means that only early model machines can be used to run the program (with 68030 processor or lower). Using a Macintosh Classic II, we found it took 8 minutes to calculate the light for a single image.

## Sunshine

Sunshine was designed to estimate light for a single day. Although it is possible to prompt the program to analyze light for longer period, the user is required to hit a key for each day of calculation, making the process of analyzing light for a growing season tedious. Since the amount of canopy openness and the indirect site factor do not change over the course of the year, these values can be calculated by running the analysis for any one day of the year. The package comes with two programs, one to calculate the threshold value for the image (EDIT_TIF) and the other to calculate light (SUNSHINE). The program requires a Tiff 5 file. Since most image software programs produce Tiff 6 files, the user may not be able to use this program without an older image software package (we found Correl Draw 3.0 produced Tiff 5 files). The program does not show the user an unadjusted and thresholded image side by side although it does produce a cumulative histogram of gray scale values of the unadjusted image, which is helpful in choosing a threshold value. Hemisphere boundaries can be set by an iterative process similar to Solarcalc but if the image is cropped to the boundaries before it is read by EDIT_TIF, the program will automatically set the correct boundaries (we recommend this approach). Sunshine has the most user input data of any program, partly owing to the assumptions about the above canopy light levels and environmental conditions affecting them. Default values are provided and these need not be changed if the user is only interested in the site factors and not absolute light levels. The proportion of diffuse light is fixed at 0.5. The output file is not easily manipulated by a spreadsheet program and the output is not labeled.

Table 1. Characteristics of the different hemispherical image analysis programs examined.

| | GLI/C | Hemiphot | Solarcalc | Sunshine |
|---|---|---|---|---|
| Computer operating system and minimum computer requirements | Windows 3.1 or better. 1280 x 1024 resolution video output | Dos. 80286 with 640 x 480 VGA monitor | Mac (68030 or lower) Systemt 6 or 7 | Dos. 80286. EGA or VGA monitor |
| Lens area projection angle correction | no | no | no | 5-degree polynomial |
| Lens view angle | 180° | 180° | any value | based on area: angle relation |
| Cosine correction | yes | yes | yes | yes |
| Penumbral effects | no | yes | no | yes |
| Input file type | BMP | PCX | clipboard image | 4 or 8 bit gray scale uncompressed Tiff 5 file |
| Input image resolution | unlimited | 400 pixels max. | 300 pixels on small screen Mac | unlimited |
| Positioning of hemispher boundaries | E, W coordinates marked with mouse | circle. arrow keys or mouse | iterative. x, y coordinates and radius | iterative |
| Source code access | no | no | Yes. Microsoft Quick basic | no |
| Proportion of incident light which is diffuse PFD | user defined | up to 50% for yearly measurements | 15% | 50% |
| Image sampling intensity | up to 10° azimuth and 3.75° zenith angle | 1° divisions weighted for area | up to every pixel | up to every pixel |
| Sky conditions* | UOC | UOC or SOC | UOC | UOC, SOC or CS |
| Surface orientation | horizontal | adjustable azimuth and zenith angle for daily calculations only | adjustable aximuth and zenith angle | horizontal |

*Uniform overcast conditions (UOC), standard overcast conditions (SOC) and clear sky (CS) conditions.

Table 2. Available output from the hemispherical image analysis programs examined. Openness is the proportion of the hemisphere with visible sky. Direct and indirect site factors are the proportion of direct and diffuse light in the understory, relative to that above the canopy. Suntracks are plots of the sun's position over the course of a day for specified days.

| | GLI/C | Hemiphot | Solarcalc | Sunshine |
|---|---|---|---|---|
| Openness | yes | yes | yes | yes |
| Direct Site Factor | yes | yes | no* | no |
| Indirect Site Factor | yes | yes | no* | yes |
| Light quantity | no* | for daily and yearly calculation | for daily (up to 12 per year) calulations | for daily calculations |
| Gap size | no | yes | no | no |
| Sunfleck distribution | no | frequency distribution | frequency distribution | no* |
| Leaf area index | no | yes | no | no |
| Red:far red ratio | no | yes | no | no |
| Suntracks | no | yes | yes | yes |

*can be calculated from the output.

# ANALYSIS OF HEMISPHERICAL PHOTOGRAPHS TAKEN UNDER DIFFERENT SILVICULTURAL CONDITIONS

## Study sites

We estimated the light levels above planted seedlings from three sites. The coefficients of determination from linear regressions for plant size versus the canopy openness and light levels, were estimated from the different programs. These were used to determine which programs and which measures of canopy cover accounted for the most variation in plant performance. All of the sites were located in the University of British Columbia Research Forest in Maple Ridge and were within the Coastal Western Hemlock drier maritime subzone. On two of the sites, Douglas-fir and western hemlock seedlings were planted in pairs along transects which ran from small clearcuts into adjacent mature forest, in May 1993. On the first site, K, the forest was a ca. 70 year old stand of Douglas-fir, western hemlock and western red-cedar. The transect ran in an easterly direction (80° from N) from the clearcut to the forest stand. Photographs were taken at top of seedlings from a distance of 23 m from the stand edge to 24 m into the stand. At the second site, M, the forest was a ca. 120 years old and composed of Douglas-fir, western hemlock and western red-cedar. At this site seedlings were planted along two transects running in a south southeasterly direction from the clearcut to the forest stand (157° from north for transect 1 and 160° for transect 2). Photographs were taken from 38 m from the stand to 24 into the stand on transect 1 and 26 to 33 m on transect 2. The third site was in a stand that received a shelterwood cut in early 1991. This site was originally part of the stand on site M. Measurements were taken at the top of Douglas-fir seedlings planted in early 1991 as 2+0 seedlings.

## Hemispherical photographs

Photographs were taken with a 35 mm SLR camera mounted with a Minolta 7.5mm F4 MD Fisheye lens. The lens was fitted with 2 small light bulbs (Mini mag) glued to a pipe clamp which was attached to the lens. The bulbs were mounted at the top and bottom of the lens and oriented in a north/south direction when the picture were taken. Photographs were taken at seedling height halfway between pairs of planted Douglas-fir and hemlock trees on the transects and at the top of trees in the shelterwood. The pairs of seedlings along the transects were ca. 1.5 m apart. Pictures were taken on completely overcast days using Kodak Tmax 400 ASA film, using the internal red filter on the lens for maximum contrast. On the transects, pictures were taken at approximately 3 m intervals. 27 pictures were taken in the shelterwood and a total of 37 picture were taken along the three transects.

## Lens calibration

To determine the actual view angle of the lens and any deviation from a equiangular projection, a calibration board was constructed according to the methods described in Clark and Follin (1988). The board was marked of in 15° angles in a semi circle and 5° angles from 0° to 15° and 165° to 180°. Two rows of pins were placed at each angle mark at a distance of 30 and 45 cm from the center of the semicircle. The optical center of the lens was positioned at the center of the semicircle such that the second set of pins was obscured by the first row and a photograph was taken. The relationship between the angle and the relative area on the photograph was analysed to determine the lens view angle and any deviations from an equiangular projection (as described in Herbert 1987).

## Image analysis

The photographs were digitized onto a CD-ROM by a professional photographic processing service using a Kodak Photo CD system. Although having the photographs digitized this way means that the user does not have to have access to a scanner and spend their own time digitizing the images, it does present a number of problems. First, contrary to the assurances of the staff doing the digitizing, all of the film we had processed were fed into the digitizer upside down and backwards. Secondly, the Kodak system reads the images automatically and sometimes has problems determining picture boundaries from hemispherical photographs. Thirdly, mid range gray scale values are automatically adjusted by the Kodak system. This is a proprietary procedure and so the user is never sure of how the image has been manipulated. We compared the results of the image analysis in Hemiphot from images we scanned ourselves to those that were digitized by the Kodak system. There was up to a 4.2% difference in the estimate of canopy openness, but no consistent difference between the two methods.

We compared the results of the image analysis from the four programs using standardized conditions. The threshold value for each image was determined and the image converted to a 1 bit/pixel (i. e. black or white) image before being analysed by any of the programs (Figure 1). This was done using Photoshop version 3.0 on computer with a pentium 133 MHz processor with 32 MEG's of RAM. Prior to determining the threshold values, the image of the light bulbs at the north and south end of the picture were painted black and replaced with a white marker of one pixel width. The images were sized to a height of 350 pixels for all programs except Solarcalc, where the images were sized to a height of 300 pixels. The openness, total, direct and indirect site factors were calculated for the entire year, assuming uniform overcast conditions. This was done using all programs except Sunshine, where only openness and the indirect site factor were calculated. By reducing the period over which values were calculated to half a year (from day 120 to day 330) the direct site factor (as calculated by Hemiphot) for all images increased by 6.1 %. Using a standard overcast conditions, instead of uniform overcast conditions resulted in a 5.4 % increase in the indirect site factor (as calculated by Hemiphot). Both these changes were the result of the distribution of open sky under the canopy. Patches of clear sky tended to occur close to the zenith. By eliminating winter days from the analysis, periods during which the sun is at a low angle, and therefore more likely to be obscured by the canopy, are eliminated from the analysis. This results in an increase in the proportion of direct sun passing through the canopy during the remaining (summer) days used in the calculation. Similarly, standard overcast conditions distributes more diffuse light near the zenith and therefore increases the indirect site factor when openings in the canopy are more likely to occur near the zenith. In Solarcalc, light levels were calculated every 30.42 days starting on day one of the year and rounding to the nearest day.

## Statistical analyses

Values of openness and the indirect site factor were calculated from all four programs using all the 64 images and were compared using paired t-tests. Since this involved making 6 paired test, the significance level for the test was adjusted to 0.0083 according to the Bonferonni procedure (Day and Quinn 1989). Comparisons of total and direct site factors were only made among GLI/C, Hemiphot and Solarcalc, using paired t-tests with an adjusted significance level of 0.017. Since we were interested in using these programs to predict plant performance, linear regressions were performed between openness, total, direct and indirect site factors calculated by the programs versus plant height, diameter, height x diameter$^2$ (HD$^2$ or volume) for the Douglas-fir and hemlock, as well as height increment for the Douglas-fir. In the case of the HD$^2$ measurements, values were ln transformed to achieve a linear relationship. All sites were analysed separately. A preliminary analysis using ANCOVA showed that there was no difference in the relationship between plant performance and the values estimated by the programs, for the two transects on site M. We considered programs and measurement of the light environment, with higher coefficients of determination ($r^2$ values) with plant size to be the best predictors of plant performance. Since plant performance is affected by factors other than light, it is possible that a program that gives more accurate measurement of light is a poorer predictor of plant performance.

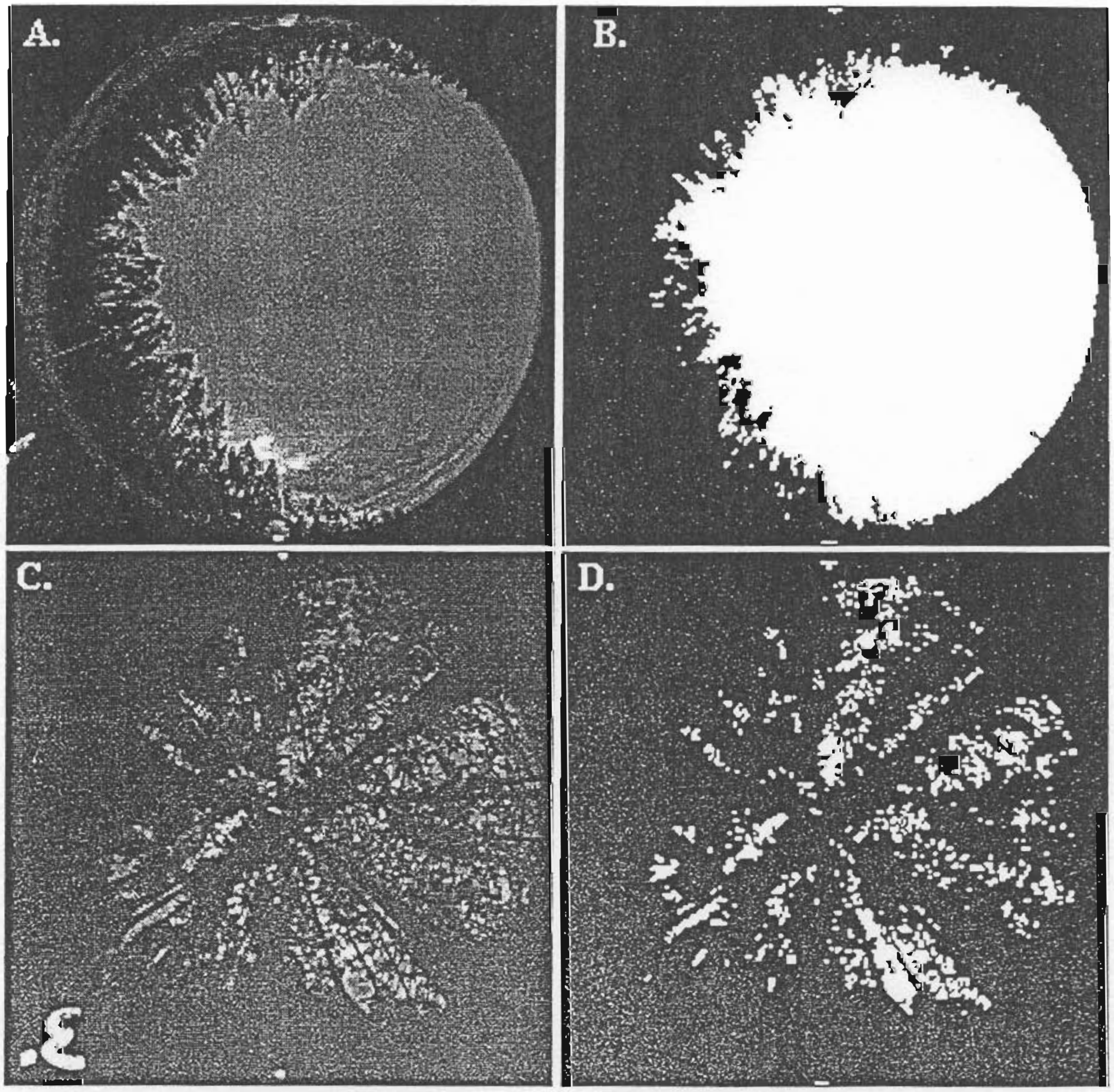


Figure 1. An example unadjusted pictures (A and C) and images converted to either black or white pixels (B and D) for image analysis. Picture A is from the clearcut and picture C from the forest understory on site M.

# RESULT OF ANALYSES

## Lens calibration

The distances between the calibration board pegs were measured from a picture, taken with the Minolta 7.5 mm fisheye lens, using a set digital calipers. A linear regression of distance to actual angle gave a linear regression with a coefficient of determination greater than 0.9999. This indicates that the polynomial correction given in the Sunshine program does not need to be applied for this lens. The lens view angle was calculated from the relationship between the peg radius to image radius ($r^2/R^2$) vs $1 - \sin\alpha$ where $\alpha$ is the elevation angle (Clark and Follin 1988). We obtained an $r^2$ value of greater than 0.9999 for this relationship using a two degree polynomial and estimated a lens view angle of 179.5 for the lens. This value was used in Solarcalc.

## Plant performance and relation with estimated light levels

There was a large variation in plant size for both Douglas-fir and western hemlock across the three transects on the two sites (Table 3, Figure 2). For all measures of plant performance there was a large increase in plant size as the distance from the forest increased. The greatest height change occurred in western hemlock and the greatest diameter and volume change occurred in Douglas-fir. Both Douglas-fir and western hemlock had smaller diameters and volume on site K, for a given distance from the forest edge. This was likely the result of lower canopy openness for a given distance on site K (Figure 3).

Plant size and canopy openness calculated by GLI/C varied much less in the shelterwood than along the transects. Mean $\pm$ one standard deviation of height, diameter, height increment and $HD^2$ was 144 $\pm$ 32.8 cm , 1.49 $\pm$ 0.40 cm, 33 $\pm$ 14 cm and 377 $\pm$ 304 $cm^3$ in the shelterwood. Mean canopy openness was 12.93 $\pm$ 4.09 % and ranged from 5.3 to 22.0 %.

All programs were similar in their ability to account for variation size of both Douglas-fir and western hemlock on the transects (Table 4) and Douglas-fir in the shelterwood (Table 5). No program consistently accounted for the most variation in plant size. The mean coefficient of determination averaged across all programs, for all measures of plant size was 0.828 for the Douglas-fir seedlings and 0.798 for the western hemlock seedlings. More variation in plant size was accounted for on site K ($r^2 = 0.851$) than on site M ($r^2 = 0.773$). The mean coefficients of determination from the programs averaged across all measures of plant size for both plant species were 0.816, 0.818, 0.799, and 0.839 for Hemiphot, GLI/C, Solarcalc and Sunshine, respectively. The higher mean for Sunshine is partly the result of measuring only openness and the indirect site factor with this program. These measures generally accounted for the most variation in plant size.

in all programs, whereas the direct site factor generally accounted for the least amount of variation.

On the shelterwood site, less variation in plant size was accounted for using the estimates of openness and light levels from the programs. The overall mean coefficient of determination averaged across all programs and measures of plant size was 0.324. Again, no program consistently accounted for the most variation in plant size and the direct site factor accounted for the least amount of variation. The mean coefficients of determination from the programs averaged across all measures of plant size were 0.334, 0.295, 0.328 and 0.347 for Hemiphot, GLI/C, Solarcalc and Sunshine, respectively. The lower coefficients of variation on the shelterwood site are likely the result of more uniform light environments and less variation in growth between plant, compared to the transects.

Data from all images was pooled to determine if there were any significant differences in the estimates given by the different programs. Although differences were quite small, there were a number of significant differences in the estimates between the programs (Table 6). Solarcalc gave a significantly higher and a significantly lower estimate of canopy openness and the indirect site factor, respectively. GLI/C gave a significantly higher estimate of the total site factor, due to a significantly higher estimate of the indirect site factor, compared to Hemiphot or Solarcalc. There was no difference in the direct site factor between any of the programs.

Table 3. Range in plant size across transects running from mature forest to clearcuts. Data from the three transect has been pooled. In all cases plant size increased with increasing distance from the forest.

| | Species | |
|---|---|---|
| | Douglas-fir | western hemlock |
| height (cm) | 34 - 173 | 38 - 214 |
| diameter (cm) | 0.34 - 3.75* | 0.32 - 3.3* |
| height increment (cm) | 6 - 68 | not measured. |
| height x diameter$^2$ (cm$^3$) | 3.4 - 2400*† | 3.9 - 1600*† |

* Measurement was significantly lower on site K, relative to the two transects on site M, at a given distance from the forest edge, according to ANCOVA.

† ANCOVA analysis performed on ln transformed data.

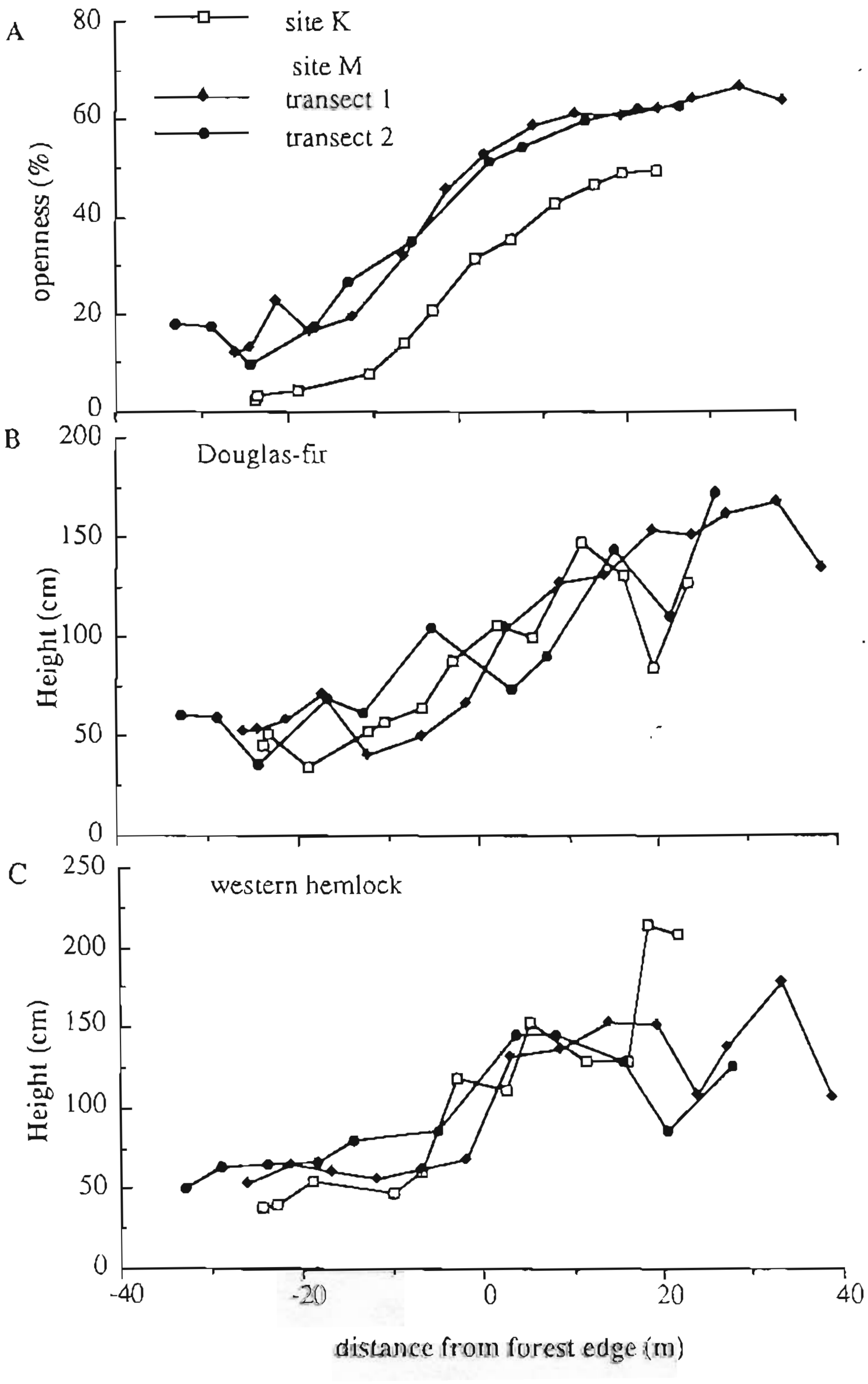


Figure 2. Percent Canopy openness calculated from GLI/C (A) and plant height of 4 year old Douglas-fir (B) and western hemlock (C) across three transects on two sites from mature forest to clearcuts. Negative distances from the forest edge indicate locations within the forest.

Table 4. Coefficients of determination for linear regression of plant size, for plants on transects running from small clearcuts to mature forest stands, versus estimates of canopy openness, total (TSF), direct (ISF) and indirect (ISF) site factors calculated from the four hemispherical image analysis programs . Plant size was measured as total height (H), basal diameter (D), height increment (Hi) and height x diameter$^2$ ($HD^2$). Sample size on site M was 25 with data from 2 transects pooled. Sample size on site K was 12.

| | Douglas-fir | | | | | | | | western hemlock | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | site M | | | | site K | | | | site M | | | site K | | |
| | H | D | Hi | $HD^2$ | H | D | Hi | $HD^2$ | H | D | $HD^2$ | H | D | $HD^2$ |
| **Hemiphot** | | | | | | | | | | | | | | |
| Openness | 0.789 | 0.853 | 0.803 | 0.891 | 0.801 | 0.914 | 0.898 | 0.869 | 0.722 | 0.736 | 0.823 | 0.833 | 0.901 | 0.911 |
| TSF | 0.819 | 0.853 | 0.846 | 0.846 | 0.779 | 0.892 | 0.872 | 0.837 | 0.656 | 0.724 | 0.771 | 0.847 | 0.890 | 0.891 |
| DSF | 0.741 | 0.732 | 0.767 | 0.738 | 0.770 | 0.883 | 0.863 | 0.829 | 0.527 | 0.597 | 0.633 | 0.848 | 0.881 | 0.882 |
| ISF | 0.808 | 0.863 | 0.828 | 0.890 | 0.790 | 0.900 | 0.883 | 0.843 | 0.724 | 0.752 | 0.833 | 0.835 | 0.897 | 0.893 |
| **GLI/C** | | | | | | | | | | | | | | |
| Openness | 0.780 | 0.842 | 0.776 | 0.885 | 0.790 | 0.907 | 0.887 | 0.865 | 0.728 | 0.736 | 0.823 | 0.852 | 0.903 | 0.915 |
| TSF | 0.802 | 0.841 | 0.812 | 0.852 | 0.775 | 0.889 | 0.868 | 0.835 | 0.681 | 0.731 | 0.790 | 0.858 | 0.894 | 0.894 |
| DSF | 0.760 | 0.788 | 0.780 | 0.778 | 0.761 | 0.874 | 0.855 | 0.822 | 0.576 | 0.645 | 0.684 | 0.862 | 0.884 | 0.885 |
| ISF | 0.807 | 0.855 | 0.811 | 0.885 | 0.785 | 0.897 | 0.877 | 0.844 | 0.575 | 0.782 | 0.858 | 0.850 | 0.899 | 0.898 |
| **Solarcalc** | | | | | | | | | | | | | | |
| Openness | 0.812 | 0.850 | 0.803 | 0.882 | 0.661 | 0.721 | 0.740 | 0.762 | 0.707 | 0.775 | 0.831 | 0.771 | 0.780 | 0.834 |
| TSF | 0.807 | 0.821 | 0.818 | 0.820 | 0.760 | 0.869 | 0.854 | 0.836 | 0.644 | 0.731 | 0.765 | 0.869 | 0.888 | 0.904 |
| DSF | 0.791 | 0.800 | 0.812 | 0.789 | 0.758 | 0.878 | 0.852 | 0.824 | 0.613 | 0.704 | 0.732 | 0.861 | 0.881 | 0.886 |
| ISF | 0.814 | 0.851 | 0.804 | 0.882 | 0.713 | 0.772 | 0.778 | 0.760 | 0.705 | 0.776 | 0.829 | 0.868 | 0.828 | 0.840 |
| **Sunshine** | | | | | | | | | | | | | | |
| Openness | 0.796 | 0.853 | 0.798 | 0.894 | 0.789 | 0.908 | 0.887 | 0.863 | 0.729 | 0.740 | 0.829 | 0.851 | 0.900 | 0.913 |
| ISF | 0.809 | 0.855 | 0.818 | 0.888 | 0.785 | 0.898 | 0.877 | 0.844 | 0.730 | 0.756 | 0.837 | 0.850 | 0.899 | 0.898 |

Table 5. Coefficients of determination for linear regression of plant size, for Douglas-fir planted in the shelterwood versus estimates of canopy openness, total (TSF), direct (ISF) and indirect (ISF) site factors calculated from the four hemispherical image analysis programs. Plant size was measured as total height (H), basal diameter (D), height increment (Hi) and height x diameter$^2$ ($HD^2$). Sample size was 27.

| | H | D | Hi | $HD^2$ |
|---|---|---|---|---|
| Hemiphot | | | | |
| Openness | 0.213 | 0.160 | 0.351 | 0.197 |
| TSF | 0.383 | 0.390 | 0.271 | 0.446 |
| DSF | 0.319 | 0.362 | 0.187 | 0.402 |
| ISF | 0.445 | 0.335 | 0.463 | 0.419 |
| GLI/C | | | | |
| Openness | 0.349 | 0.162 | 0.367 | 0.282 |
| TSF | 0.404 | 0.234 | 0.285 | 0.368 |
| DSF | 0.340 | 0.243 | 0.177 | 0.351 |
| ISF | 0.395 | 0.173 | 0.383 | 0.306 |
| Solarcalc | | | | |
| Openness | 0.457 | 0.224 | 0.404 | 0.363 |
| TSF | 0.410 | 0.237 | 0.231 | 0.373 |
| DSF | 0.382 | 0.227 | 0.193 | 0.356 |
| ISF | 0.443 | 0.212 | 0.389 | 0.347 |
| Sunshine | | | | |
| Openness | 0.445 | 0.193 | 0.405 | 0.336 |
| ISF | 0.465 | 0.194 | 0.402 | 0.343 |

Table 6. Mean values of canopy openness, total (TSF), direct (DSF) and indirect (ISF) site factors for all images calculated from the four programs examined. Values followed by the same letter in a row are not significantly different according to a paired t - test.

| | Hemiphot | GLI/C | Solarcalc | Sunshine |
|---|---|---|---|---|
| Openness* | 0.258a | 0.267b | 0.296c | 0.262a |
| TSF** | 0.315a | 0.332b | 0.315a | not measured |
| DSF** | 0.318a | 0.323a | 0.320a | not measured |
| ISF* | 0.328b | 0.340c | 0.290a | 0.337c |

alpha value = 0.00625* or 0.0167** according to the Bonferonni procedure.

## CONCLUSIONS AND RECOMMENDATIONS

1. All programs examined give similar values of canopy openness and light levels. Although differences between programs are small, Hemiphot and Sunshine give the lowest, and Solarcalc the highest, estimates for canopy openness. GLI/C gives the highest estimates of total and indirect site factors. Solarcalc gives the lowest estimate for indirect site factors.

2. Since there is little difference in the values estimated by the different programs, the choice of program should depend on their ease of use and output (Tables 1 and 2). In this regard, all programs except Sunshine have certain advantages and disadvantages:

   **Hemiphot** is easy to use, has a wide range of output and can be used on a wide range of computer systems. However fairly low resolution images must be used and the way the program converts gray scale images to black/white images is unclear.

   **GLI/C** is easy to use and has the best design for helping the user set a threshold value to convert images to 1 bit/pixel black/white images. However, GLI/C has the most sophisticated computer system requirements.

   **Solarcalc**, while slow and does note allow for the adjustment of diffuse light conditions, has the least sophisticated computer system requirements and the actual program can be modified by the user.

3. Estimates of canopy openness and light levels from hemispherical photographs account for more variation in conifer seedling size when there is a larger variation in canopy cover and plant size. However, even with fairly low variation in canopy cover, in situations such as a shelterwood cut, a substantial amount of variation in plant size can be accounted for by using hemispherical photographs.

4. In this study, estimates of diffuse light from hemispherical photographs account for more variation in plant size than do estimates which include direct light. It may therefore be more economical to measure diffuse light using some other technique (e.g. a light sensor on a completely overcast day) if accounting for variation in plant size is the main purpose of an investigation. However, there are data showing that direct light can be an important predictor of the understory light environment, depending on site conditions (e.g. Easter and Spies 1994).

## EXTENSION ACTIVITIES

We have been contracted by Phil Commeau, at the Ministry of Forests (Research Branch in Victoria) to analyze some additional photographs and will be presenting these finding to later in the summer to his group, when the work is completed. Two of the authors of the image analysis programs are also interested the analysis presented here and will receive a copy of this report. More data on plant growth and survival will be included in Daniel Mailly's Ph.D. thesis. We are also preparing a manuscript for a peer reviewed journal which should be ready by mid summer. Andreas Brunner, a post doctoral fellow working in conjunction with the Research Branch in the Ministry of Forests has also used information in this report in the construction of his own hemispherical image analysis program. Simulations from this program are to be used in a larger scale forest yield model developed by the Research Branch in the Ministry of Forests.

# APPENDIX: SOFTWARE SOURCES

The hemispherical image analysis programs described here are distributed by their authors. They can be contacted at the addresses listed below:

GLI/C

Charles Canham
Institute of Ecosystem Studies
Box AB
Millbrook, New York
12545
email: 73611.747@compuserve.com

Hemiphot

Hans ter Steege
Tropenbos-Guyana Program
12E Garnett street
Campbellville, Georgetown
Guyana
fax: 592 2 62846

or

The Tropenbos Foundation
Lawiskse Allee II
P. O. Box 232
6700 AE Wageningen
The Netherlands
fax: 31 8370 23024

Solarcalc

Robin Chazdon
Department of Ecology and Evolutionary Biology
Box U-42
The University of Connecticut
Storrs, CT
06269-3042

fax: (203) 486-4320
e-mail: chazdon@uconnvm.uconn.edu

Sunshine

W. Rick Smith
USDA Forest Service, Southern Forest Experimental Station
701 Loyola Ave.
New Orleans, LA.
70113
email: smithr@forestry.auburn.edu

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