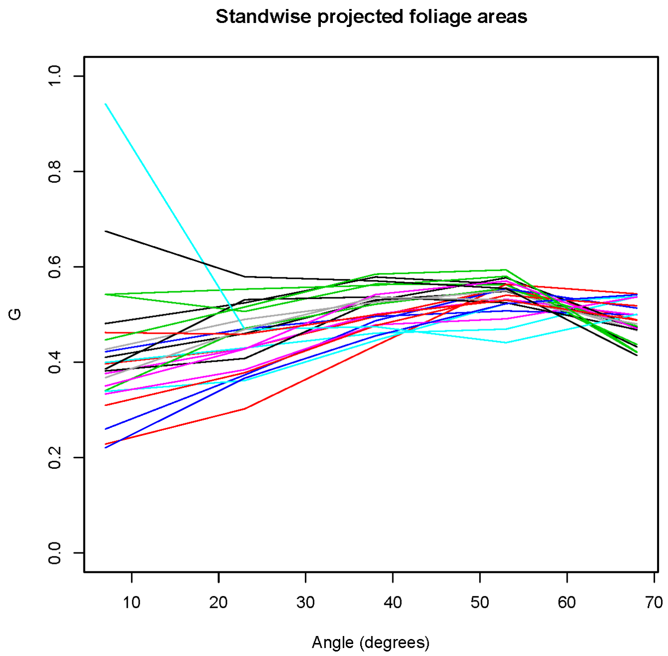
LAI estimate to differ from its true value by the observed amount. *G*-values calculated from the ground based hemispherical photos are shown in Figure 9. At the smallest zenith angle of 7 degrees (corresponding to the mean angle of the uppermost ring of the LAI-2000 instrument), the value of *G* averaged 0.4 (excluding the single outlier, a sapling stand), and was dominantly closer to 0.4 than 0.5 throughout the zenith angle range corresponding to that of the aerial photos. Subsequently, when the hemispherical photos (ground data of 2007) were analyzed using only the zenith angle range of the airborne data, the ratio of LAI derived using the full zenith angle range to LAI derived using the smaller zenith angle range was similar to the slope(s) of the regression lines in Figure 8. For all data, the ratio was on average 1.38 with a standard deviation of 0.55. The ratio for the ground based LAI values (derived using a wide angle range) to the airborne LAI values for 2008/2009 (derived using the small angle range) was on the average 1.47 with a standard deviation of 0.31. When only stands with deciduous contribution up to 15 % were analyzed the ratio was 1.41 with a standard deviation of 0.09.

Figure 9. Standwise values of the mean projection of unit foliage area (G) as a function of sun zenith angle, calculated from ground based hemispherical photos of 2008.



In addition, even if the cross sectional area of the canopy covered by the airborne and ground based photos were equal the part of the canopy detected would not be equal due to the conical viewing geometry (when fully hemispherical viewing is not applied). The airborne photos will then contain at the edges only lower parts of the trees, whereas the ground based photos will see only the top part of the same trees. Therefore the airborne LAI estimate inevitably tends to be slightly smaller than the ground based estimate, especially for Scots pine, the crown of which can be located altogether very high up.

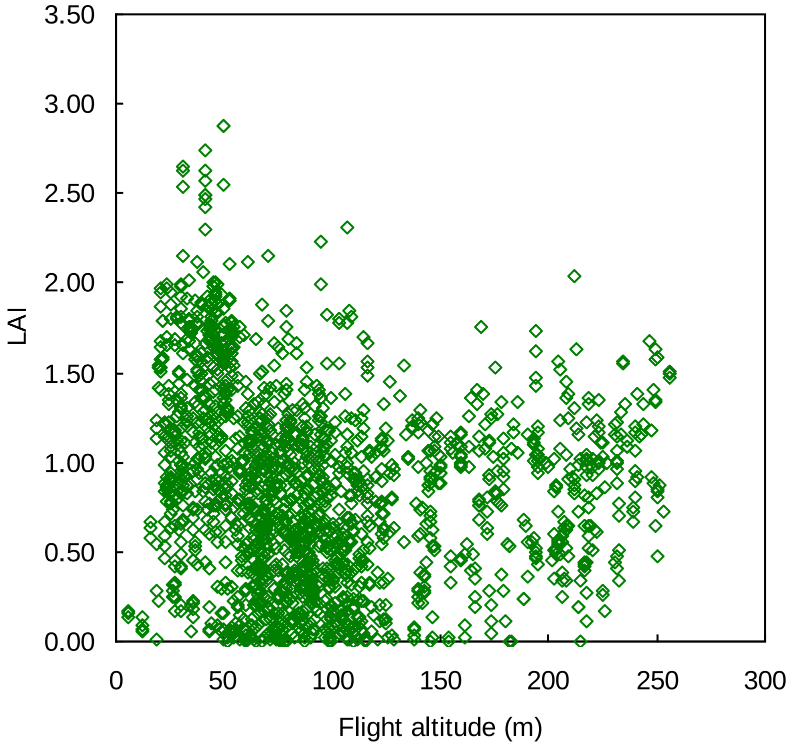
Taking into account that the LAI correlation of two different ground based methods (LAI-2000 and hemispherical photos) had a root mean square error of 0.131…0.166 (Figure 3), the difference between the airborne and ground based LAI value is of the order of the measurement method accuracy of hemispherical photos. Judging from that the coefficient of determination of the relationship between ground based and airborne LAI for purely coniferous stands is very high (Figure 9), the effect of the decreased zenith angle range is the same for all canopies in the studied area, *i.e.*, they have similar *G*-values in the zenith angle range covered by the aerial photos. If this turns out to be more generally true, the linear coefficient has to be calibrated empirically once, but then it can be used for the same kind of forests as long as the airborne camera system remains the same.

When the regression line of Figure 8 comprising all data points was applied to the airborne data (to scale them to the level of the ground data), the average difference between the LAI values of the two data sets was 0.14 for the whole data and 0.06 for stands with up to 15% deciduous trees. The three obvious airborne LAI underestimates seen in Figure 8 were obtained in stands with a larger fraction of deciduous trees among the coniferous species, which naturally decreases the LAI value in winter (airborne) from that obtained in the autumn (ground based) (Figure 10). The results of 2008/2007 are deteriorated due to the mismatch of the location of the airborne and ground based measurements, which was obvious also from the images.

Figure 10. LAI is underestimated in forests with large percentage of deciduous trees.

The measured LAI values depend on the flight altitude. The lower the altitude is the smaller is the area seen by the camera and the larger is the variation of diverse scenes, whereas high altitude flights produce more averaged LAI values. The range of variation in LAI with varying flight altitude is shown in Figure 11 for all points acquired March 13, 2009. The data contains the vertical profiles and the horizontal flights between the successive profile locations. Obviously the maximum LAI value decreases markedly when the flight altitude increases from the tree tops to about 100 m. There is no single optimal flight altitude to derive LAI estimates. If one is interested in characterizing small forest stands, the flight altitude should be chosen so that the image area matches about that of typical ground measurements. On the other hand, if one is interested in comparing the values with satellite based LAI estimates it might be more useful to cover the area of a satellite pixel, so that both instruments would directly measure the same target area. However, one has to take into account that the resolution decreases with increasing flight altitude, so that the detection of gaps inside crowns may not be possible after some critical altitude. Further studies and comparison with satellite based LAI estimates are needed to find the optimal flight altitude range.

Figure 11. The observed LAI value versus the flight altitude above ground in March 13, 2009. The values are scaled using the regression line of Figure 8 for all data points of 2009.



The derived LAI retrieval method is well suited to areas with difficult accessibility at ground level. Cloudy weather is better than sunny, because then there are no obvious shadows at the forest floor. However, the shadows can be removed using the principal component analysis (Figure 2) [17]. The snow cover at the forest floor makes a good background, but no snow on the trees can be accepted.

4. Conclusions

The airborne wide optics technique presented here has been shown to be applicable for LAI estimation in the boreal zone in winter time. The achievable accuracy of the obtained LAI estimates seems to be comparable to that of the ground measurements. The derived method suits for LAI measurements in large areas and especially well in areas which are difficult to access. One alternative for reducing costs is to use UAV (unmanned aerial vehicle) platforms instead of a helicopter, as many UAVs can carry lightweight cameras well suited for obtaining this kind of simple aerial images. They can also fly safely at low altitudes. Their drawback is the need for relatively calm weather.

Clear need for further studies is in the analysis of this kind of imagery. Waiting for overcast flight conditions may not be always possible, although the boreal zone winters are dominantly cloud covered, so methods for processing images gathered in clear sky conditions must be developed. The main problem in sunny images is the effect of shadows. The shadow detection method based on principal components analysis that we tested functioned reasonably well, but other methods based on spectral and directional properties of shadows could function better. Automatic removal of other dark non-canopy objects, such as roads or open water, should also be possible based on spectral properties of green vegetation. In this study such objects were removed manually from the binary images, but if the number of images is large and frequency of such objects is high, this may become too laborious. The basis for an improved method should still be that the trees are classified correctly in all illumination conditions, as it is much easier to remove extra objects during the binary image check than add missing trees.

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