Research Paper

Comparison of Resourcesat-1 AWiFS and SPOT-5 data over managed boreal forest stands

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In this study, the utility of AWiFS data in relation to stem volume estimation for managed boreal forest stands was investigated. Multiple linear regressions were used to predict stem volume (m^3ha^{-1}) with standwise mean spectral values as the independent variables. For comparison, two SPOT-5 images were also used, one with nearly simultaneous acquisition. The adjusted coefficient of determination (R^2_{adj}) using AWiFS data to predict stem volume was 0.573 (SE 56.9%) while SPOT had an R^2_{adj} of 0.598 (SE 55.2%). All bands were negatively correlated, with the SWIR band having the single strongest correlation with stem volume. The best two band predictor of stem volume was the NIR and red band for AWiFS, and the NIR and SWIR bands for SPOT. When stem volume was predicted based on stand size, AWiFS and SPOT produced an R^2_{adj} of 0.310 and 0.293, respectively, for stands less than 2 ha in size. A steady increase of predictive ability appeared to increase with stand size, with the highest R^2_{adj} at 20 ha (R^2_{adj} = 0.677 AWiFS, R^2_{adj} = 0.692 SPOT). For stands 20 ha and larger, the correlation between stem volume and NIR reflectance increased while decreasing for the visible bands. The explanation behind the trends observed may be due to the management practices in the area. Discriminant analysis of basic forest types showed similar results for AWiFS (65.6% correct) and SPOT (66.4% correct).

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1. Introduction

Optical satellite data have been widely used for such applications as estimation of forest parameters, post-stratification of inventory data, forest-type mapping, detection of clear-cuts, or determining insect damages (e.g. Tomppo *et al.* 2008, McRoberts and Tomppo 2007; Boyd *et al.* 2005; Cohen *et al.* 1998; Falkenström and Ekstrand 2002). In Sweden, data from the SPOT (Satellite Probatoire d'Observation de la Terre) and Landsat Thematic Mapper (TM and ETM+) satellites have commonly been used for national mapping applications (Olsson *et al.*, 2005). Examples include nationwide estimation of forest parameters with the kNN algorithm (Tomppo, 1990; Nilsson, 1997; Reese *et al.*, 2003) from Landsat and SPOT data, use of Landsat data for automated classification of forest types (Hagner and Reese, 2007), and the Swedish National Forest Agency's use of annual nationwide SPOT data for clear-cut detection. However, acquisition of Landsat TM/ETM+ data for operational activities has been impacted by sensor degradation and malfunctions (NASA, 2008). The future Landsat program sensor has a planned launch date of December 2012 (Ochs, 2009); therefore, users are searching for alternatives to fill the anticipated Landsat data gap (Wulder *et al.*, 2008). SPOT satellite data provide a medium-resolution alternative to Landsat, however, the small scene area (60 x 60 km) may pose a limit to the amount of inventory data within a single scene and, if large area coverage is needed, necessitates working with images of different dates and view angles. The large scene area coverage of the relatively new Advanced Wide Field Sensor (AWiFS) may provide one alternative data source for certain applications.

The AWiFS sensor is carried on-board the Indian Remote Sensing (IRS) satellite Resourcesat-1 (IRS-P6), launched October 2003 into a sun-synchronous orbit at an altitude of 817 km. AWiFS data are acquired in tandem with two other optical sensors on-board: LISS-IV and LISS-III. AWiFS employs a push-broom sensor having two electro-optic modules, AWiFS-A and AWiFS-B, whose 370 km swaths overlap, creating a total swath width of 740 km. The wide scene width and 11.94º sensor tilt angle results in a Ground Sample Distance (GSD) of 56m at nadir and 70m at the field edge; during system-correction, the raw data are re-sampled using cubic convolution to a standard spatial resolution of 60 m. The data have 10-bit radiometric quantization in the green, red, near-infrared, and short-wave-infrared wavelengths (NRSA, 2003). Due to the large swath width and the large overlap between adjacent paths, the revisit cycle for a given area is effectively every five days.

The use of AWiFS data is not yet widespread, however there are recent studies in the literature regarding AWiFS' radiometric properties, as well as use for agricultural crop mapping (Johnson, 2008), land cover mapping (Calle *et al.*, 2008), fire monitoring (Kirin-Chand *et al.* 2006), and snow mapping (Kulkarni *et al.*, 2006). Johnson (2008) compared same-date AWiFS and Landsat-5 TM data for crop type classification over three agricultural study sites. He found that Landsat resulted in slightly higher overall classification accuracies for two of the three study areas. In one study site, AWiFS had higher overall classification accuracy than Landsat, and it was hypothesized that the bidirectional reflectance distribution function (BRDF) effects of AWiFS may have been an advantage. Johnson concluded that AWiFS could be a viable alternative to Landsat data for the U.S. Department of Agriculture's operational classification of agricultural crops in cases where field sizes were reasonably large. Costa *et al.* (2008) investigated multi-seasonal AWiFS images for land cover classification in Portugal, and deemed the accuracies as unsatisfactory for mapping the Portuguese landscape (maximum overall accuracy was 63% for 15 classes) when considering replacement of other medium-resolution sensors. Chander *et al.* (2007) investigated the radiometric properties of the three Resourcesat-1 sensors by cross-calibration with same-date Landsat-5 and -7 images. Bandwise comparison of AWiFS and Landsat-5 TM data produced the highest coefficients of determination (R^2). The correlation was somewhat lower when compared to Landsat-7, in particular for the green band (R^2 = 0.9771). In this study, Chander *et al.* also classified land cover and canopy density with all sensors, and found that Landsat-5 gave approximately 2% higher overall classification accuracy than AWiFS, perhaps due to AWiFS' lack of blue and a longer mid-infrared spectral band (2.08-2.35 µm). Teillet *et al.* (2007) compared cross-calibration of twenty different sensors to Landsat, including AWiFS, SPOT, and MODIS. No significant anomalies were found to be inherent to the AWiFS sensor, however bandwise agreement between SPOT-5 HRG and AWiFS showed a small spectral difference detected in the green band (-1.4%). Manjunath and Muralikrishnan (2008) report that AWiFS data have shown 3% degradation in calibration between 2003-2006.

Studies regarding the utility of AWiFS for boreal forest have not yet been introduced in the literature. To date, Landsat and SPOT have been the dominant source of optical satellite data for forestry related applications, such as stem volume estimation or forest type mapping. AWiFS has important differences and similarities to these sensors that make comparison of these data of interest. For example, SPOT and AWiFS record data in four bands with similar spectral ranges, although AWiFS has higher radiometric quantization (10-bit). SPOT-4 and -5 has a smaller GSD than AWiFS, and this is also an influencing factor. The effect of AWiFS' coarser resolution data, with regard to the range of stand sizes in the managed boreal forest landscape, is an issue that should be investigated. The spatial and radiometric properties of the remotely sensed data, the landscape and the reference data have an influence on the strength of the relationship between forest parameters and spectral data (Teillet *et al.*, 1997; Hyyppä and Hyyppä 2001; Aplin 2006).

Estimation of boreal forest stem volume using remote sensing data have often employed either plot-based inventory or polygon-based stand inventory data as reference data (see Lutz *et al*., 2008). This paper concentrates on the use of polygon-based reference data. In previous work on estimation of boreal forest stem volume and biomass also using polygon-based reference data, Hyyppä *et al.* (2000) compared nine diverse remote sensing data sources for estimation of forest parameters using stand data in a managed boreal forest in Finland (mean stem volume 156 m^3ha^{-1}). SPOT XS (20m) data predicted stem volume with an R^2 of 0.44 (SE% = 50%) and Landsat-5 with an R^2 of 0.31 (SE% = 56%). The low R^2 results were attributed to the quite small mean stand size (1.06 ha) in their study area. In a follow-on study, Hyyppä and Hyyppä (2001) further examined the effect of stand size with the same sensors, and concluded that stand size had a strong influence on the results for all sensors. Muukkonen and Heiskanen (2005) used ASTER data and polygon-based stand data (1,331 stands) in managed boreal forests in Finland, and derived a total RMSE of 44.7% (multiple linear regression) and 41.0% (neural networks) for biomass estimations. The mean stand size was quite small (1.8 ha) and the mean stem volume was 165 m^3ha^{-1}.

The objectives of this study are to investigate AWiFS data both in general, and specifically in relation to boreal forest stand characteristics such as stem volume and tree species; to determine whether AWiFS' 60 m spatial resolution is suitable for standwise prediction of stem volume in a managed boreal forest landscape; to compare AWiFS' spectral properties using bandwise correlations and stem volume prediction results with those obtained from the spectrally similar, higher spatial resolution SPOT-5 data; to investigate the effect of stand size on the prediction of stem volume for both AWiFS and SPOT; and to test AWiFS ability to separate between the different forest types (coniferous, deciduous and mixed forest).The comparison of AWiFS and SPOT-5 simulates an application in which use of multiple SPOT scenes of different dates is required to cover a larger area. One of the two SPOT images used in the study was acquired with only twelve minutes difference from the AWiFS acquisition, and bandwise correlations of different spatial aggregations of SPOT and AWiFS are compared. The study is intended to give insight into the potential use of AWiFS data for estimation of standwise forest characteristics in a managed boreal forest landscape.

2. Study Area and Data

The study area in this paper is defined by the common area between one AWiFS image, two SPOT images and a forest stand database. The study area is in the province of Västerbotten in northern Sweden, and is located from 64º 35' N to 63º 35' N and 16º 50' E to 19º 30' E (figure 1). The forests are intensively managed for timber production and dominated by Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*), and contains other tree species such as Birch (*Betula sp.*). Wetlands, rivers and small lakes are also abundant within the study area, and elevations range from 40 to 580 m above sea level. Map data which have been used in this study include a 50 m resolution digital elevation model (DEM) and a 1:100 000 scale land cover map.

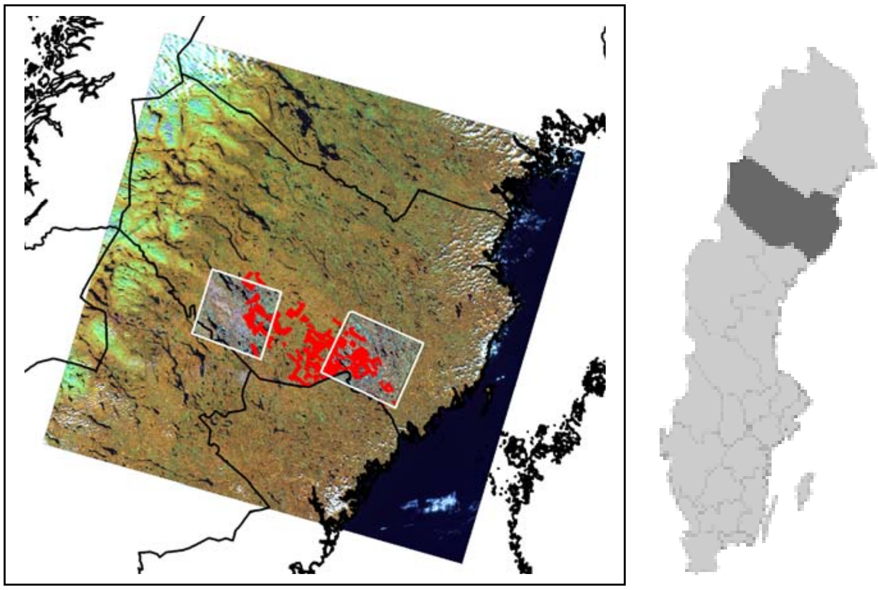

Figure 1. Study area (Västerbotten province is darkened in map of Sweden inset) with AWIFS quarter scene and two SPOT-5 images (outline in white). The forest stand database is shown in red. (AWiFS image includes material ©Antrix, distributed by Euromap.)

The stand-based inventory was provided by the forestry company Sveaskog. The inventory database covers a total area of 153,000 hectares and contains a total of approximately 9,000 stands. Just under half of these stands are covered by the two SPOT scenes in this study (4,195 stands). The database is current for the year 2005, and the forest variables were measured both *in situ* and by aerial photo interpretation. Variables such as stem volume, stems per hectare, height, age, biomass, and forest type, among others, were recorded. The mean stem volume for this area was 78.5 m^3ha^{-1}, a mean age of 57 years, and a mean stand size of 18 ha. Statistics about the forest data used in this study are provided in table 1. In figure 2, stand size and stem volume for all stands used in this study are plotted.

Table 1. Forest stand database characteristics by stand size groups and in total.

Stand size group	Samples (n)	Range Stand size (ha)	Mean Stand size (ha)	Range of Volume (m^3 ha^{-1})	Mean Volume (m^3 ha^{-1})	Std. Dev. Volume (m^3 ha^{-1})	Mean Age (years)
0.1 - 2 ha	76	0.2-2.0	1.4	0-293.1	84.6	71.9	82.1
2.1-5 ha	462	2.1-5.0	3.8	0-310.4	89.0	66.5	74.5
5.1-10 ha	913	5.1-10.0	7.7	0-325.3	89.0	69.0	62.8
10.1-20 ha	1184	10.1-20.0	14.8	0-277.0	80.2	69.3	54.2
20.1-30 ha	648	20.1-30.0	24.8	0-264.1	71.0	67.9	50.9
30.1-40 ha	345	30.1-40.0	34.5	0-287.1	63.9	66.3	44.6
40.1-50 ha	183	40.1-50.0	45.4	0-222.7	59.0	59.1	40.6
50.1 + ha	139	50.1-90.2	60.1	0-295.9	52.4	56.2	42.0
Total sample	3950	0.2-90.2	18.0	0-325.3	78.5	68.3	56.6

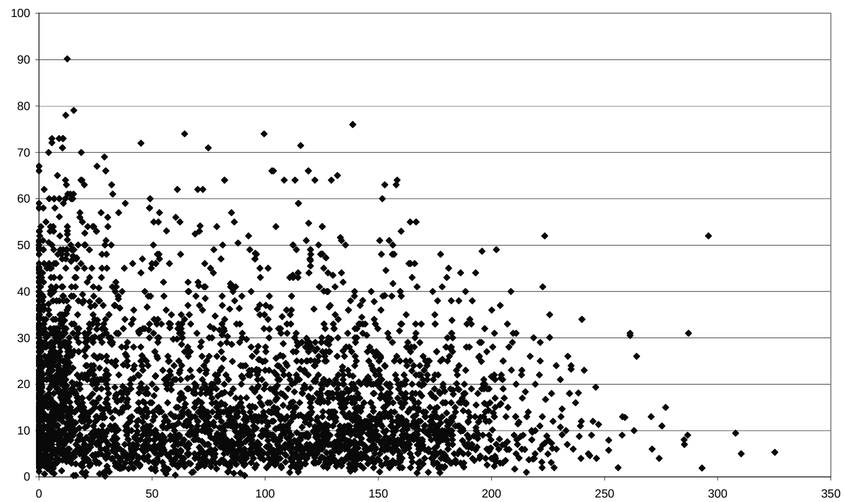

Figure 2. Scatter plot of stem volume in m^3 ha^{-1}(y-axis) and stand size in ha (x-axis). N = 3950.

The quarter AWiFS scene, acquired July 31, 2005, is the north-western quarter of the full 740 x 740 km image, and was imaged with the AWiFS-A camera (NRSA, 2003). The AWiFS data were orthorectified by Euromap (www.euromap.de) using 100 tie points. Along the eastern edge of the image there is a band of clouds, and in the western and middle areas of the scene there are some bands of haze and jet contrails. For the study area subset, the AWiFS data are cloud-free. Characteristics of all images used in this study are given in table 2.

Table 2. Satellite data used in this study

Satellite Scene ID	Sensor	Swath (km)	Spatial Resol. (m)	Radiom Resol.	Acquis. Date	Acquis. Time	Solar Azim.°	Solar Elev.°	Look Angle°
AWiFS 22/28	AWiFS-A	370	60	10-bit	2005-07-31	10:15	167.30	43.15	11.94
MODIS Mcd43a420 05209	Terra /Aqua	1200	500	16-bit	2005-07-28 to 2005-08-12	16-day composite	Pixel based	Pixel based	Nadir
SPOT-5 049/217	HRG-1	60	10	8-bit	2005-07-31	10:27	169.12	43.89	-7.04
SPOT-5 054/217	HRG-1	60	10	8-bit	2005-07-04	10:47	179.55	48.96	15.85

The two SPOT-5 images were orthorectified to an RMSE of less than 5 m. A small number of clouds and cloud shadows were present in the SPOT image acquired on July 4, 2005. The other SPOT-5 image was acquired on July 31, 2005 at 10:27 A.M., just twelve minutes after the AWiFS image was taken.

The Terra/Aqua MODIS nadir BRDF-adjusted reflectance data (16-day composites at 500m resolution - V005; Schaaf *et al.* 2002) were used in this study as the source for the relative radiometric normalization of the SPOT and AWiFS data. The 16-day composite is taken from July 28 to August 12, 2005, which corresponds with the dates of one of the SPOT images and the AWiFS image. Terra/Aqua's MODIS sensor records information in 15 wavelength bands at a 500m resolution, and for the red and NIR bands at a 250m resolution. In this paper, the MODIS bands most closely corresponding to the AWiFS and SPOT wavelengths were used. Characteristics for these wavelengths, and the nominal designations used in this paper, are given in table 3.

Table 3. The corresponding spectral band widths for the different sensors.

Sensor	Green band	Red band	NIR band	SWIR band
SPOT-5	500-590 nm (XS1)	610-680 nm (XS2)	780-890 nm (XS3)	1580-1750 nm (XS4)
AWiFS	520-590 nm (B2)	620-680 nm (B3)	770-860 nm (B4)	1550-1700 nm (B5)
MODIS	545-565 nm (B4)	620-670 nm (B1)	841-876 nm (B2)	1628-1652 nm (B6)

3. Methods

In order to investigate the relationship of the AWiFS data with forest parameters, the AWiFS data were compared to information from a forest stand database. To compare the results acquired with AWiFS to a higher spatial resolution data source, SPOT-5 data were similarly analyzed. Basic properties of the AWiFS data were first investigated, such as the collocation of the AWiFS data with other data sources. Then, AWiFS and SPOT-5 data were normalized to reflectance values and for illumination differences. Mean spectral values for all stands were calculated bandwise for both AWiFS and SPOT data. Multiple linear regression using least-squares was applied to determine predictive relationships between the spectral bands and stem volume. Bandwise correlations with stem volume were calculated, both for the entire reference data set and for subsets of the data based on stand size. Using the same date acquisition only, the AWiFS 60 m pixel data were compared band-for-band to 60 m aggregations of SPOT data. Finally, discriminant analysis was applied to determine the ability to separate volume groups and forest types using AWiFS.

3.1 AWiFS image properties

Precise geometric registration of the satellite data is important, especially in relation to collocation with forest inventory data and data from other sensors, and to applications using change detection. The image data were projected to the Swedish RT90 reference grid using cubic convolution and the tie points provided with the image data. Visual assessment was made of the geographic collocation between the AWiFS data and roads, the forest stand data, and other satellite data images with known geometric properties. The basic spectral properties of the AWiFS image were of interest, especially over forested areas. Before calculation, clouds and cloud shadows were masked out of the AWiFS data using band thresholding. Descriptive statistics and band correlations were calculated on the entire scene, as well as for the area corresponding only to the forest stand data.

3.2 Relative reflectance normalization and topographic normalization

Normalization to a common scale of reflectance values was necessary for comparison of the spectral response of AWiFS and SPOT data, as well as to make the two different acquisition dates of SPOT data comparable. Radiance values were therefore converted to reflectance by means of relative reflectance normalization (Yang and Lo 2000; Olthof *et. al.*, 2005) in which AWiFS and SPOT data were reflectance normalized using MODIS as reference data for surface reflectance. This first required the resampling of AWiFS and SPOT data to 500 m pixels. A total of six-thousand randomly chosen plots located on forest in the study area were used in a robust regression for each band using MODIS reflectance data as the dependent variable and the re-sampled AWiFS or SPOT band as the independent variable. This provided bandwise gain and bias coefficients which were applied to each band, resulting in a reflectance normalized image. Topographic normalization was applied to the reflectance normalized images using the C-correction algorithm (Teillet *et al.* 1986; Meyer *et al.* 1993; Ekstrand, 1994). The 50 m DEM used in the topographic correction was interpolated to 10 m resolution using a natural neighbour algorithm (Sibson, 1981; Bater and Coops, 2009) in order to achieve a suitable correction of the 10 m SPOT data, and 60 m for the AWiFS data correction.

3.3 Relationship between satellite spectral data and forest stand parameters

The forest stand database required pre-processing before use. Clearly erroneous volume assignments were identified by plotting volume and bandwise spectral values, checking outliers, and excluding clearly wrong stands from the analysis (e.g. stands labeled as having volume = 0, while the image showed the stand was covered by closed forest, or vice-versa). The land cover map (1:100 000 scale) was used to identify forest stands whose area consisted primarily of wetlands or water bodies (due to occasionally poor registration of stand boundaries), and these stands were also excluded from the analysis. Additional water bodies not in the map data were identified using an ISODATA classification of the AWiFS data, and pixels clearly identified as water were masked from the AWiFS data; however, water-influenced mixed pixels may still be present. Some stands in the database were comprised of several non-contiguous polygons, and these were excluded from the analysis. This resulted in 3 950 total polygons remaining for the analysis.

Bandwise mean spectral values from the AWiFS and SPOT data were determined for the 3 950 forest stand polygons by averaging of all pixels whose majority (area) was within the stand boundaries. In order to compare the results obtainable using SPOT and AWiFS, pixels along stand boundaries were therefore included in the calculation of the mean, and not masked as done in some studies (e.g. Muukkonen and Heiskanen 2005; Johnson 2008). Bandwise values for the mean and standard deviation within each stand were sampled together with selected parameters from the forest stand database (stem volume in $m^3 ha^{-1}$, stand size, stand age, stem volume per ha of pine, spruce, birch, and other species). Data from the two SPOT-scenes were placed together into a single data file. Multiple linear regression using least squares was used to investigate relationships between stem volume (dependent variable) and the mean spectral value for each stand (independent variables). In addition, a texture variable (standard deviation) for each band was tested as additional independent variables in the model, together with the mean spectral value. Model assumptions were checked and met, such as normal probability distribution of the residuals. The coefficient of determination, R^2, reported in this paper is an adjusted R^2 value, denoted R^2_{adj}. Standard errors (SE) are reported in percent and have been calculated using the standard error of regression divided by the mean value for the target attribute (i.e. stem volume). Tests to see if the results were robust were carried out by making eight random subsets of the full dataset and calculating multiple linear regressions with each of these separate datasets.

Model predictions of volume for different stand sizes were also considered by sub-dividing the dataset into discrete groups according to stand size. Regressions using all spectral bands were run and bandwise correlations with stem volume were calculated for each of the stand size groups.

Discriminant analysis was used to determine the capability of AWiFS to separate volume classes and forest types compared to SPOT data, when using the forest stand database as reference data. The forest types were coniferous, deciduous, which were defined by 70% or greater of the stand's stem volume represented by species of the respective type, and mixed forest which was < 70% of the total stem volume for either coniferous or deciduous.

3.4 Comparison of same date SPOT image and AWiFS image

One of the two SPOT images used in this study was taken on July 31, 2005, only 12 minutes after the AWiFS image was acquired, and it is useful to compare these two images. In order to understand the comparison between the SPOT and AWiFS spectral response, the SPOT data were aggregated to three coarser spatial resolutions: 30 m, 60 m and 120 m. The aggregations were calculated by using the stand's center pixel as the midpoint of a 3 x 3, 6 x 6 and 12 x 12 window within which the 10 m SPOT spectral values were averaged for each band. To derive an AWiFS 120 m pixel, a 2 x 2 window was used similarly. These data were co-registered, and bandwise spectral values for over 1,000 identical points within the forest stands were sampled. Descriptive statistics and correlation between the spectral bands were determined. The coefficient of variation (CV) was also calculated for each spatially aggregated block, as it is useful as a normalized measure of the standard deviation based on the mean (Walsh *et al*., 1997)

4. Results and Discussion

4.1 AWiFS image properties

The majority of the AWiFS scene appears to have satisfactory geo-location, as judged by checking against other data sources (e.g. other Landsat data, SPOT data, the forest stand database, and 1:100 000 map data). Figure 3 shows an example of the co-registration between the forest stand database and the AWiFS data. A slight mis-registration of nearly one pixel (60 m) was observed between the AWiFS data in some areas of the western part of the scene and the 31 July SPOT image, although not within the forest stand database. This was most likely due to the increased topographic relief in this area and indicates the need for better orthorectification of the data than that achieved with the supplied 100 tie points. The need for a higher level orthorectification of AWiFS products in areas with topographic variation has also been noted by Garg *et al.* 2008.

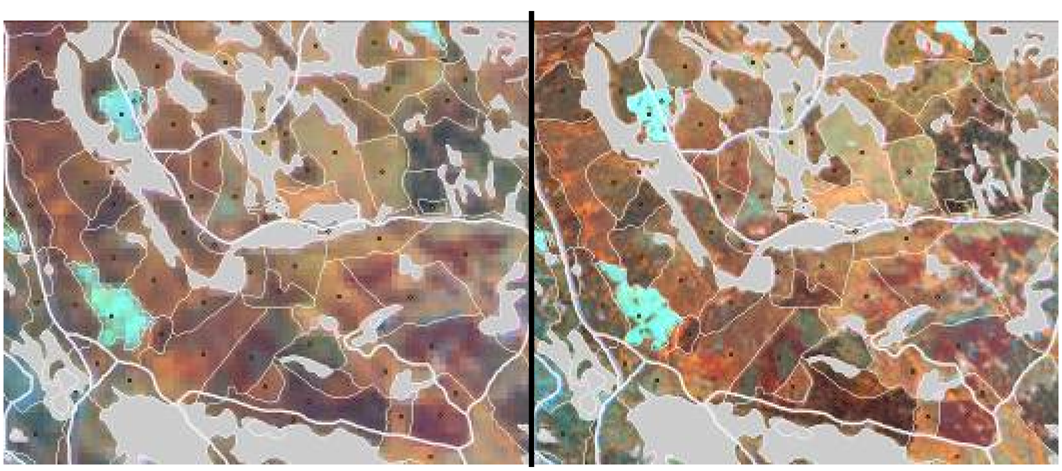

Figure 3. An example of the geometric collocation with the stand data (AWIFS on left, SPOT-5 on right) Stand boundaries in white, non-forest in gray. Center point of stand also shown. NIR, SWIR, and Red displayed as RGB. The spectral variation within the stands can also be observed here. The area shown is 17 km^2. (AWiFS image includes material ©Antrix, distributed by Euromap; SPOT image ©SPOT Image corporation.)

The dynamic range in the AWiFS image as a whole and the area covered by the forest stand database are presented table 4 and for the two SPOT images in table 5. The AWiFS data show no saturation and a wide dynamic range is seen particularly in the NIR and SWIR bands. Table 6 shows that AWiFS' visible bands are rather correlated (r = 0.92) while the red and near-infrared bands are the least correlated (r = 0.52).

Table 4. AWiFS' band statistics (in DN) for the area covered by the forest database and the full image.

	Forest database area				Full image area			
	Green	Red	NIR	SWIR	Green	Red	NIR	SWIR
Min	40	14	9	28	34	5	1	11
Max	270	263	357	393	361	371	474	501
Mean	61	33	180	139	60	33	171	138
Std.Dev	5.9	8.2	31.8	30.4	8.3	9.7	55.3	42.9

Table 5. SPOT's band statistics (in DN) for the area covered by the forest database.

	SPOT 049/217				SPOT 054/217			
	Green	Red	NIR	SWIR	Green	Red	NIR	SWIR
Min	58	33	18	15	63	36	15	22
Max	162	142	224	209	210	229	196	240
Mean	85	56	122	87	91	63	86	93
Std.Dev	8.7	11.8	24.1	22.3	10.3	14.8	16.5	23.9

Table 6. Pearson correlation coefficient (*r*) for AWiFS bands over the quarter scene

Spectral band	Green	Red	NIR	SWIR
Green	1.00	0.92	0.73	0.84
Red		1.00	0.52	0.80
NIR			1.00	0.78
SWIR				1.00

4.2 Reflectance and topographic normalization

Relative reflectance normalization was applied to both the AWiFS data and the SPOT data. Since the data were normalized to 16-bit MODIS reflectance data, the resulting AWiFS and SPOT reflectance values are also given in 16-bits. The corrections were assessed visually and by plotting bandwise spectral values from pre- and post-normalization, with linear relationships maintained and no anomalies observed.

4.3 Relationship between satellite spectral data and forest stand parameters

Table 7 shows the adjusted coefficient of determination (R^2_{adj}) and standard error (SE%) from the multiple linear regression models, and bandwise correlations with stem volume (r). Using all bands of SPOT-5 data, stem volume was predicted with an R^2_{adj} of 0.598 and a SE of 55.2%, while the result from using all AWiFS bands was not much lower with an R^2_{adj} of 0.573 and a SE% of 56.9%. The correlation of all spectral bands to stem volume were significant (p<0.001) and negative in all cases for both AWiFS and SPOT, similar to results shown by Trotter *et al.*, 1997. The SWIR band had the highest single band correlation with stem volume (r = -0.651 and -0.680 respectively). Scatterplots of volume versus the standwise mean spectral values for each band and sensor are shown in figures 4 and 5.

Table 7. R^2_{adj} results and SE% from multiple linear regression of all four spectral bands as independent variables and volume ($m^3\ ha^{-1}$) as the dependent variable. N=3950. Band-wise Pearson correlation coefficient (*r*) with volume are also presented.

Sensor	R^2_{adj}	SE(%)	Correlation (*r*) Green	Correlation (*r*) Red	Correlation (*r*) NIR	Correlation (*r*) SWIR
AWiFS	0.573	56.9%	-0.611	-0.525	-0.620	-0.651
SPOT	0.598	55.2%	-0.653	-0.553	-0.626	-0.680

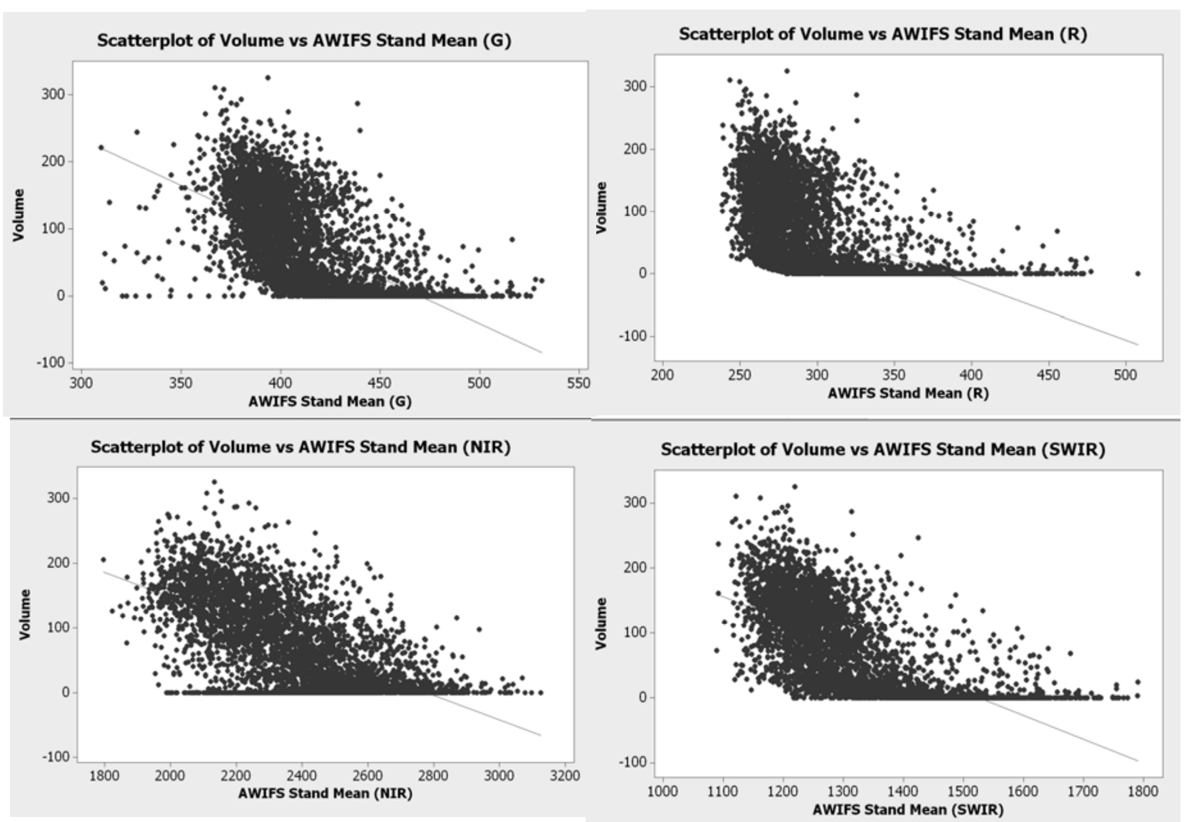

Figure 4. Scatterplots of stem volume (m^3ha^{-1}) and standwise mean spectral values for AWiFS (UL=green band, UR = red band, LL= NIR band, LR=SWIR band)

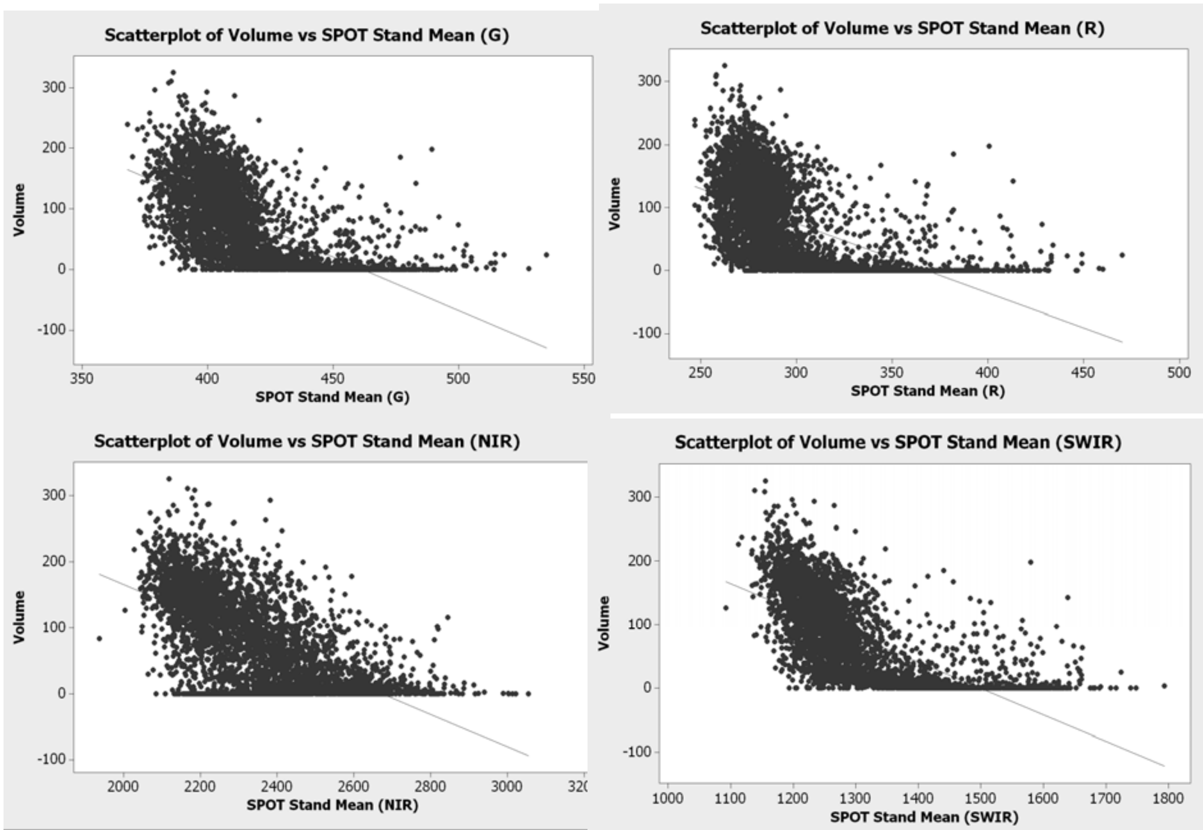

Figure 5. Scatterplots of stem volume (m3ha-1) and standwise mean spectral values for SPOT (UL=green band, UR = red band, LL= NIR band, LR=SWIR band)

The regression models presented here have used all spectral bands, however, the best two band combination using the AWiFS standwise mean spectral value was obtained using the red and NIR bands, which resulted in an R^2_{adj} of 0.573, while for SPOT the best two band combination was that using the NIR and SWIR bands, resulting in an R^2_{adj} of 0.595. This difference in the contribution of the bands in the regression model may be due to AWiFS' higher dynamic range in the infrared bands as compared to SPOT, and the lower correlation between AWiFS' NIR and red bands.

Inclusion of a texture measure, i.e. the bandwise standard deviation within the stand, slightly increased the R^2_{adj} for both AWiFS (results were R^2_{adj} 0.587 and 57.9% SE) and SPOT (R^2_{adj} 0.606 54.7% SE), but this result was not focused upon since it did not result in a large improvement for either SPOT or AWiFS. Wunderle *et al*., (2007) found texture to be helpful in determining forest structural complexity when using SPOT-5 pan-sharpened data. However, Lu (2006) states that in forest sites with relatively simple vegetation stand structure, spectral signatures play a more important role than image textures.

When the robustness of the results were tested by randomly dividing the full database into eight unique and approximately equal sized groups, and multiple linear regression was run for each separate dataset, the results were somewhat consistent (figure 6). Seven out of eight times, SPOT provided a higher R^2_{adj} and lower SE, with a difference on average of 1.8%. In one trial, AWiFS data produced a marginally higher R^2_{adj} (0.605) and lower SE than the SPOT data (R^2_{adj} = 0.604), but this was seen as an exception among the eight trials.

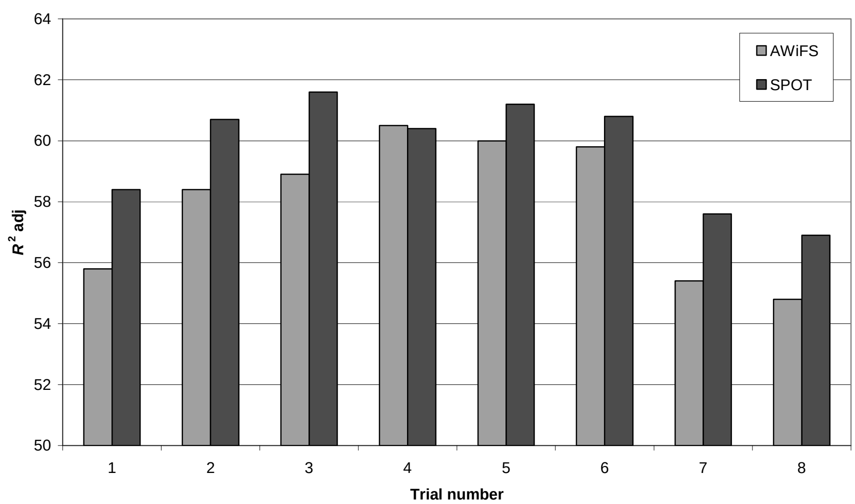

Figure 6. Results from multiple linear regression of eight unique subsets of the full database. R^2_{adj} in %.

To compare whether the use of AWiFS and SPOT data performed differently for the prediction of stem volume at different stand sizes, the data were partitioned according to stand size and regressions were calculated for each subset. The R^2_{adj} results are plotted for each stand size subset in figure 7. For the smallest stands (0.1 to 2 ha), both AWiFS and SPOT standwise means produce weak results (R^2_{adj} = 0.310 and 0.293, respectively). On examining this group, collocation of the stand boundaries with the satellite data did not appear to be the obvious cause of the low R^2_{adj} result. That AWiFS and SPOT give a similar result at this stand size is surprising, and may be a result of a combination of factors affecting the result both negatively and positively. The negative influence may include the effect of mixed border pixels, the low number of samples in this group (n = 76), and the wide range and relatively higher mean volume in this group (86.3 m3 ha-1). It is noted that the relationship is weaker between spectral data and higher stem volumes (Franklin, 1986; Spanner *et al.* 1990; Danson *et al.*, 1993; Ekstrand 1994). A reason why the result may be similar for AWiFS and SPOT is that the mean size of the stands at this level is not so small (1.4 ha). Also, due to the management practices here, smaller stands may tend to share boundaries with other small stands having similar characteristics, resulting in fewer mixed pixels.

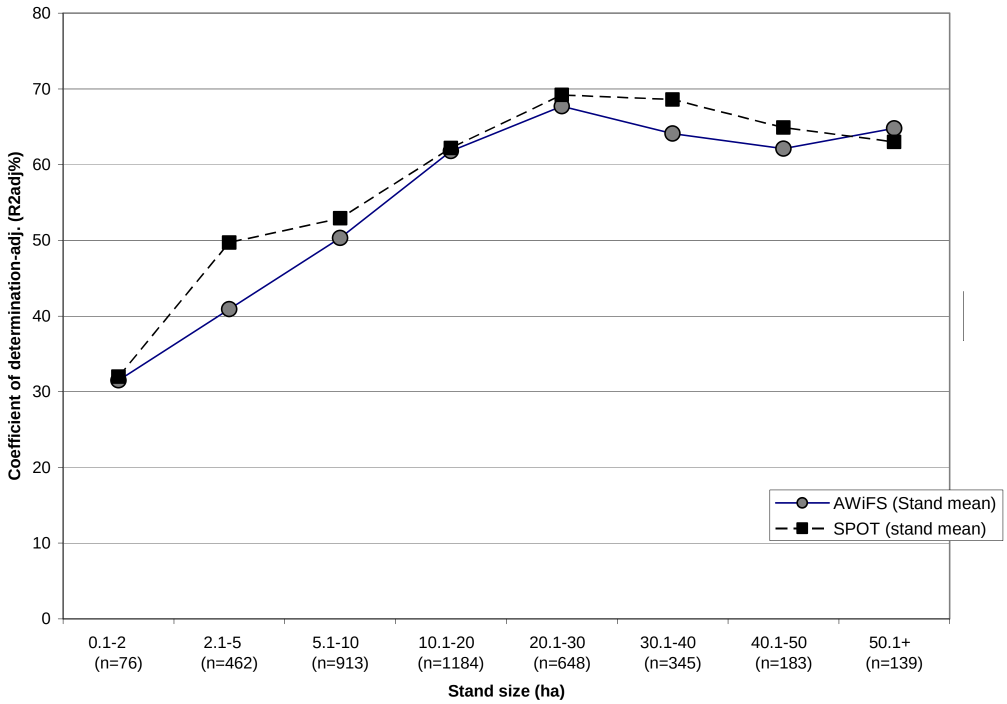

Figure 7. R^2_{adj} results of multiple linear regression for data subsets based on stand size.

For the other stand size groups, as the stand size increases, the R^2_{adj} also generally increases, with the highest R^2_{adj} achieved at the 20.1 to 30 ha area (mean volume 71.0 m^3ha^{-1}) for both SPOT (R^2_{adj} = 0.692) and AWiFS (R^2_{adj} = 0.677). For stand sizes greater than 20 ha, the R^2_{adj} remains rather constant. In the present study, the standwise spectral mean value from SPOT provides a higher R^2_{adj} at all except the largest stand size level, and this may be due primarily to the higher spatial resolution of SPOT. It was also noted that when AWiFS' and SPOT's spectral values were extracted from the stand's center pixel only (i.e. not the standwise spectral mean), the regression produced a similar trend of increasing R^2_{adj} up to the 20.1-30 ha stand size, although with lower R^2_{adj}. This indicates that the results are not due simply to the averaging of an increased number of pixels within larger stands.

To observe the correlation of AWiFS' and SPOT's individual spectral bands in relation to volume at different stand sizes, bandwise correlations to volume were also calculated by stand size groups. This is shown in figures 8 and 9. From these figures it can be seen that there is a peak in correlation of the NIR band at the 20.1-30 ha stand size group for both AWiFS and SPOT (r = -0.703 and -0.701, respectively). The change in the NIR and visible band correlations observed in the stand size group of 20.1-30 ha, and the levelling off of R^2_{adj} at this stand size could possibly be due to the change in volume distribution at this stand size. It appears that many of the stands in the 20.1-30 ha group are of a young age and are in fact regenerating forest. A change in the stem volume distribution can also been seen in stem volume histograms for this stand size group (figures 10a-c). It is possible that the forestry company often performs fellings at this scale. It can also be observed that the correlation of the visible bands decreases more markedly for AWiFS than for SPOT, most notably in the green band, especially for stands of 30.1-40 ha in size. The causes of this are not yet fully determined, but after checking a subset of stands which had higher internal standard deviation of the AWiFS green band, these stands tended to be bordered by contrasting cover types and therefore may have been influenced by mixed pixels.

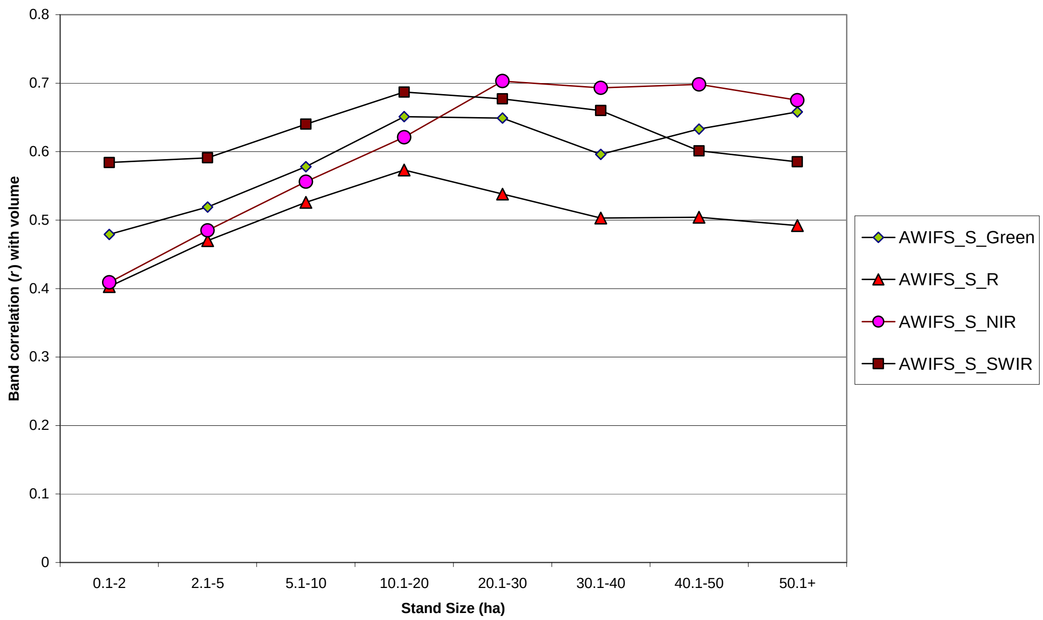

Figure 8. Band correlations (*r*) with stem volume for AWiFS standwise spectral mean, by stand size groups. The correlations are negative, but shown as absolute values here.

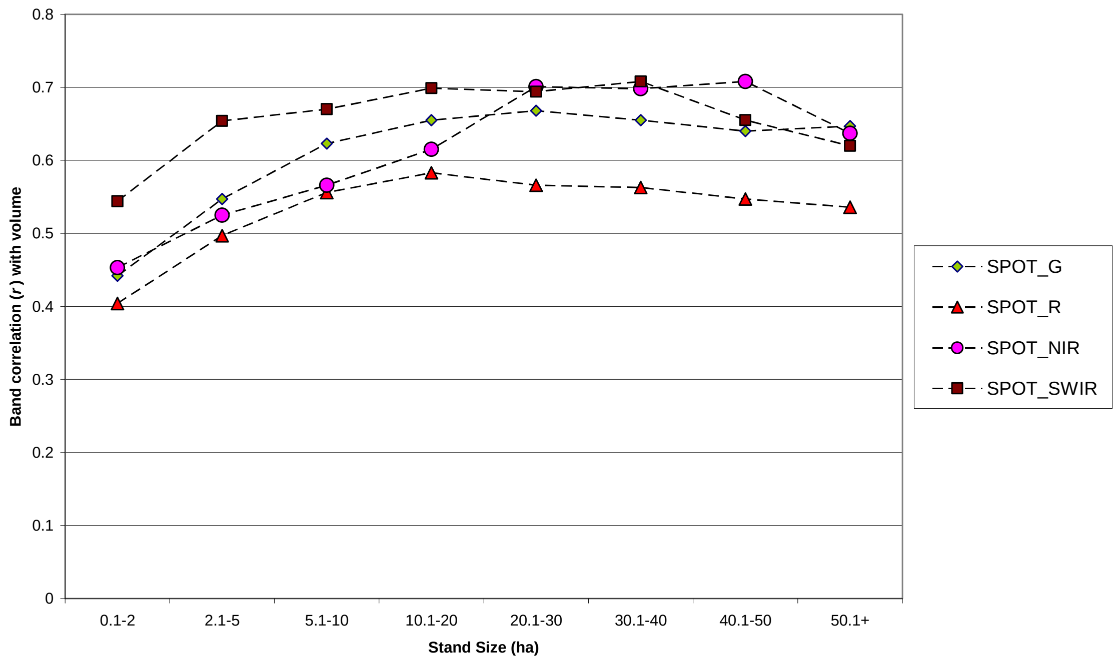

Figure 9. Bandwise correlations (*r*) with stem volume for SPOT standwise spectral mean, by stand size groups. The correlations are negative, but shown as absolute values here.

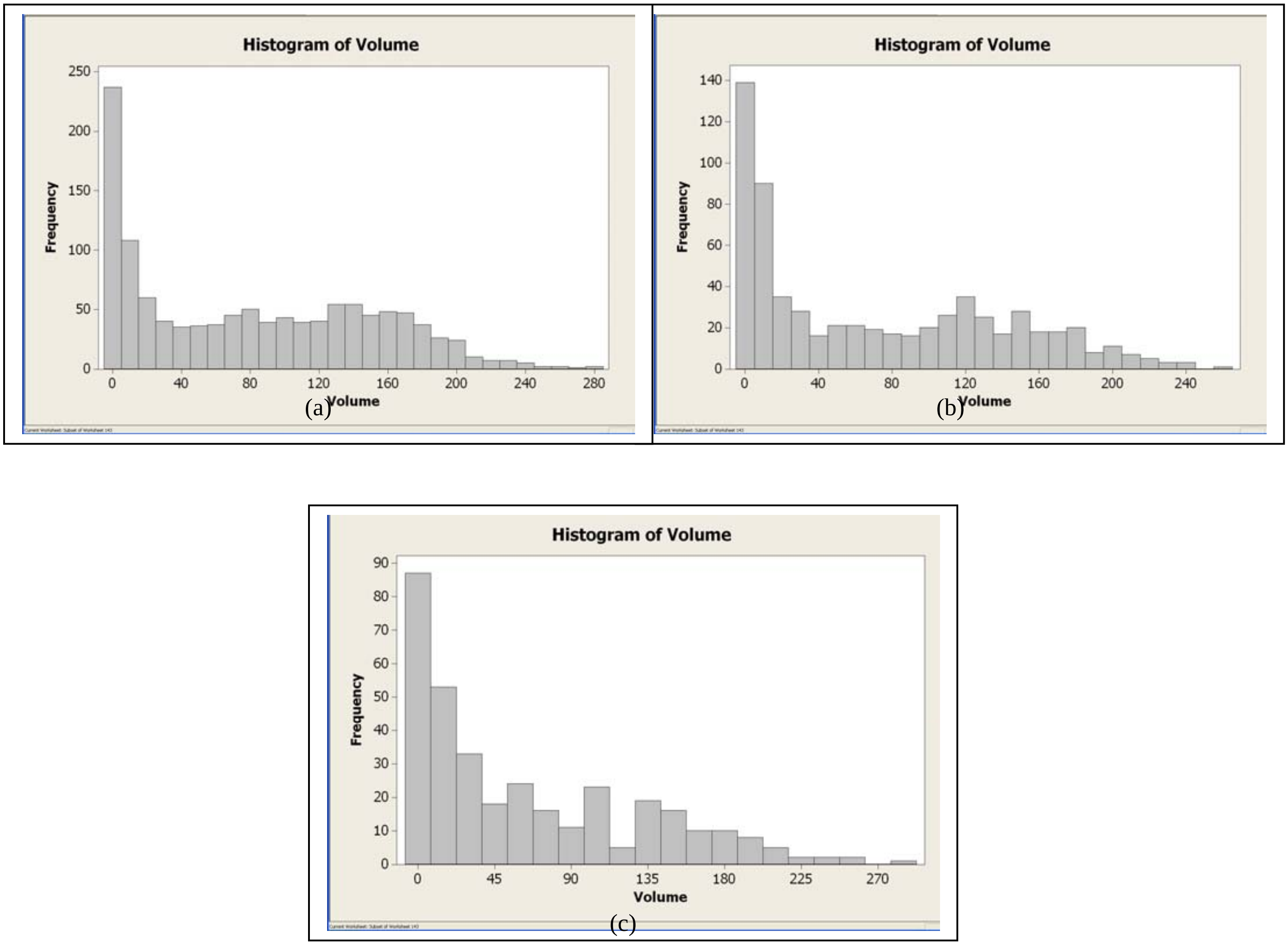

Figure 10a-c. Histogram of stem volume (m^3 ha^{-1}) for 10.1-20 ha stand size group (a), 20.1-30 ha stand size (b), and 30.1-40 ha stand size (c).

Hyyppä and Hyyppä (2001) show similar trends in R^2_{adj} for different stand sizes when predicting standwise stem volume for managed boreal forest in Finland. They demonstrated a peak R^2_{adj} at approximately 10 ha stand size when comparing results from several different sensors with different spectral and spatial resolutions. They state that "no individual reason can be reported to be responsible for the observed phenomenon," but say that it may be a result of the number of samples used, (with a higher number of samples resulting in a higher R^2_{adj}), and additionally that larger stands tend in general to be more homogenous. However, in our case, the 20.1-30 ha stand size had a higher R^2_{adj} but a lower sample size (n = 648) while the 10.1-20 ha stand size had a larger sample size (n = 1184) but a lower R^2_{adj}. In addition, because many large stands are regenerating forest in this area, they do not necessarily appear to be more spectrally homogenous than smaller stands (refer to figure 3). It's possible that in this study, since the relationship between younger stands and stem volume is stronger than with higher volume stands, that the R^2_{adj} for this stand size group is higher because of the presence of large, regenerating stands. In this case, it is the distribution of volumes and the management regime which, at least in part, are affecting the estimation of volume for the different stand size groups. As Hyyppä and Hyyppä (2001) state, "the test site characteristics typically dominate in the results."

Discriminant analysis of stem volume groups and forest types was carried out using the stand mean spectral value. The results in tables 8 and 9 show that SPOT performed slightly better (63.8% correct) than AWiFS (61.9% correct) in discriminating four different stem volume groups (0, 1-25, 25-100, >100 m^3ha^{-1}). The highest volume group (100 m^3ha^{-1} and greater) was initially divided in two groups of 100-200 m^3ha^{-1} and 200 m^3ha^{-1} and greater, but results were poor (34.8% correct with n=1336, and 68.9% correct with n=156, respectively). Tables 10 and 11 show the discriminant analysis results for the forest classes of coniferous, deciduous, and mixed forest. Overall, the standwise mean value from SPOT provides a slightly better discrimination (66.4%) than AWiFS (65.6%). This accuracy for both cases is rather low for the discrimination of basic forest types, and may be due in part to the use of a stand mean value and also to defining the forest classes based on stem volume. These results are preliminary and further work on discrimination of forest types would be expected to produce better forest class separation and subsequent classification accuracy.

Table 8. Discriminant analysis of volume groups, using AWiFS stand-wise mean spectral value.

Volume groups	0 m^3ha^{-1}	1-25 m^3ha^{-1}	25-100 m^3ha^{-1}	>100 m^3ha^{-1}	Total N	Correct %
0 m^3ha^{-1}	316	173	84	37	610	51.8
1-25 m^3ha^{-1}	137	550	211	45	943	58.3
25-100 m^3ha^{-1}	23	119	440	272	854	51.5
> 100 m^3ha^{-1}	66	38	301	1138	1543	73.8
Total N	542	880	1036	1492	3950	
% Correct	58.2	62.5	42.5	76.2		61.9%

Table 9. Discriminant analysis of volume groups, using SPOT stand-wise mean spectral value

Volume groups	0 m^3ha^{-1}	1-25 m^3ha^{-1}	25-100 m^3ha^{-1}	>100 m^3ha^{-1}	Total N	Correct %
0 m^3ha^{-1}	329	170	74	27	600	54.8
1-25 m^3ha^{-1}	127	554	180	32	893	62.0
25-100 m^3ha^{-1}	18	114	457	252	841	54.3
> 100 m^3ha^{-1}	68	42	325	1181	1616	73.1
Total N	542	880	1036	1492	3950	
% Correct	60.7	63.0	44.1	79.2		63.8%

Table 10. Discriminant analysis of forest type groups, using AWiFS stand-wise mean spectral value.

Forest type groups	Coniferous	Deciduous	Mixed Forest	Total N	Correct %
Coniferous	2240	4	121	2365	94.7
Deciduous	394	34	158	586	5.8
Mixed Forest	597	12	177	786	22.5
Total N	3231	50	456	3737	
% Correct	69.3	68.0	38.8		65.6%

Table 11. Discriminant analysis of forest type groups, using SPOT stand-wise mean spectral value.

Forest type groups	Coniferous	Deciduous	Mixed Forest	Total N	Correct %
Coniferous	2295	4	134	2433	94.3
Deciduous	412	30	164	606	5.0
Mixed Forest	524	16	158	698	22.6
Total N	3231	50	456	3737	
% Correct	71.0	60.0	34.6		66.4%

4.4 Comparison of same date SPOT image and AWiFS image

When the SPOT data are aggregated from the original 10 m resolution to the coarser resolutions, the data show that the standard deviation increases for all bands at the 30m aggregation, and then decreases at the 60 m and 120 m levels (table 12). The fact that the 30 m aggregation has a higher standard deviation than the 10m, 60m and 120m data is likely a result of the more varied (and less averaged) spectral response occurring within the 30 x 30 m window. Pearson correlation coefficients are shown in table 13 for bandwise correlation between the SPOT aggregated 60 m and 120 m pixel and the AWiFS original 60 m and aggregated 120 m pixel. The results show good bandwise correlations between the SPOT aggregated 60 m pixel and the AWiFS pixel, and relationships are approximately linear. This demonstrates that the spectral response of the AWiFS 60 m pixel is a good approximation of the corresponding 60 x 60 m window as recorded by SPOT’s 10 m GSD. Although care was taken to assure geographic alignment, it should be noted that mismatches in the geographic areas between the SPOT and AWiFS pixels are possible; also, the pixels used here were not hand-selected for homogeneity, and may be heterogeneous areas. The lowest correlation was between the AWiFS and SPOT NIR band (r = 0.868). When both SPOT and AWiFS are aggregated to 120 m level, the correlations between them are higher (green band with lowest r = 0.938), as expected, and relationships are approximately linear. The high bandwise correlations at the 120 m aggregation, which is approximately the size of a 1.4 ha forest stand, may help explain why AWiFS and SPOT give similar results in the regression analysis.

Table 12. Statistics for the spectral values (in DN) for the different aggregations of SPOT and AWiFS data. N=1022.

	Green Band			Red Band			NIR Band			SWIR Band		
Sensor & pixel size	Mean	Std Dev	Coef Var	Mean	Std Dev	Coef Var	Mean	Std Dev	Coef Var	Mean	Std Dev	Coef Var
SPOT 10m	85.8	8.6	9.9	57.7	12.9	22.3	121.1	20.6	17.0	89.6	23.8	26.6
SPOT 30m	84.6	12.2	14.4	56.7	14.3	25.3	119.6	24.6	20.6	88.4	26.3	29.8
SPOT 60m	85.6	8.2	9.6	57.4	12.4	21.6	121.6	19.8	16.3	89.4	23.4	26.2
SPOT 120m	85.4	7.6	8.9	52.2	11.7	20.4	121.2	18.7	15.4	89.1	22.2	25.0
AWiFS 60m	60.1	5.3	9.0	32.0	8.3	26.1	182.2	31.1	17.1	141.1	32.7	23.2
AWiFS 120m	59.9	5.0	8.4	31.8	7.8	24.6	183.1	28.6	15.6	141.5	31.2	22.1

Table 13. Pearson correlation coefficients between SPOT and AWiFS at 60m and 120m aggregation.

Pixel size	Green Band (r)	Red Band (r)	NIR Band (r)	SWIR Band (r)
60 m	0.875	0.899	0.868	0.898
120 m	0.938	0.960	0.951	0.958

For the aggregated pixels, the mean value and dynamic range of the visible bands is generally higher for SPOT, while AWiFS has a higher mean and dynamic range in the NIR and SWIR bands. When the coefficient of variation is considered, it can bee seen that SPOT's SWIR band consistently has the highest coefficient of variation, while AWiFS' red band has the highest coefficient of variation. This may partially explain why the red band is more significant in the regression model with AWiFS data, while the SWIR band is more significant when using SPOT data.

A thorough study of the effect of spatial resolution on classification accuracy was not a focus of this study, and it will certainly be an important determining factor for some applications. AWiFS may not be appropriate in certain landscapes if finer scale data is needed. However, this study showed that AWiFS may be a reasonable alternative for large area prediction of standwise stem volume in a managed boreal forest landscape with characteristics similar to the study area presented here. The wide swath width of AWiFS may certainly be an advantage when a large amount of field data is needed (e.g. kNN or regression tree algorithms), or when projects can be simplified due to large areas being imaged on a single date (e.g. change detection). However, the wide swath width also introduces issues to consider differently than when using smaller scenes, such as BRDF effects, and the potential need to stratify images based on meaningful delineations (e.g. ecosystem boundaries). The high temporal imaging frequency of AWiFS also provides increased probability of acquiring cloud-free images, or for creating time series with short intervals. The cost involved in the acquisition of an AWiFS image, as compared to other commercially available image data, is advantageous if calculated in cost by km^2, and somewhat less if calculated in cost per pixel. However, final cost advantages will be dependent on additional aspects of individual applications, such as the amount of image pre-processing that might be needed.

Resourcesat-1 was scheduled to have a five year mission life cycle (ending October 2008), however, plans are to keep it in operation beyond this life cycle, if possible until the launch of Resourcesat-2 (Euromap, pers. comm.). The launch of Resourcesat-2 is planned for approximately 2009-2010, and specifications are similar to those of Resourcesat-1. However, the Resourcesat-3 series (estimated launch 2011-2012) plans to carry an AWiFS sensor with a 25 m spatial resolution and 600 km swath width (with two cameras), in addition to three LISS sensors and a hyperspectral sensor (Kumar, 2007)

5. Conclusions

In this study, the properties of a quarter AWiFS scene were investigated, with a focus on their utility for deriving information over managed boreal forest stands. An inventory database with 3 950 forest stands in northern Sweden, collected during the same year as the image, was used to derive forest parameter values and define stand boundaries. For comparison, two SPOT-5 images were also used, one of which had an acquisition time twelve minutes apart from the AWiFS image. Multiple linear regressions using ordinary least squares to predict stand stem volume (m^3ha^{-1}) were run using standwise mean spectral values. The adjusted coefficient of determination (R^2_{adj}) using AWiFS data to predict stem volume was 0.573 (SE 56.9%) while SPOT had an R^2_{adj} of 0.598 (SE 55.2%). Given the larger pixel size (60 m) of AWiFS as compared to SPOT-5 (10 m), the result may seem surprising. However, given the mean stand size in the database (18 ha), and also the demonstration in this paper that the AWiFS 60 m pixel may be a good approximation of the spectral values as identified by SPOT-5 over a 60 x 60 m area, the result can be understood. When volume was predicted using subsets of the data based on stand size, both AWiFS and SPOT produced a lower R^2_{adj} for stands less than 2 ha in size (0.310 and 0.293, respectively), but with a steady increase of predictive ability which increased with stand size, with the highest R^2_{adj} at 20.1-30 ha group (0.677 and 0.692, respectively). It was observed that for stands of 20 ha size and greater, the correlation between volume and the NIR band increased while it decreased for the visible bands, and it’s thought that the mechanism responsible for the trends seen in the band correlations and the regression model predictions of stem volume is the management practices in the area.

For both AWiFS and SPOT, the SWIR band had the single strongest correlation with stem volume (r = -0.651 and -0.680 respectively), however the best two band model for prediction of stem volume using AWiFS data consisted of the NIR and red bands, while SPOT’s best two band model consisted of the NIR and the SWIR bands. The difference in AWiFS radiometry (10-bit as opposed to 8-bit) may partly explain this result. Discriminant analyses to separate forest types (coniferous, deciduous and mixed forest) for both AWiFS and SPOT showed that AWiFS was slightly less accurate (65.6% correct for AWiFs and 66.4% for SPOT). The conclusion from the studies in this paper indicate that the utility of AWiFS data for estimations related to stem volume for boreal forest stands appears to be good. Despite AWiFS' lower spatial resolution, the prediction of stem volume over a managed boreal forest landscape was comparable to that achieved using SPOT-5 data. These results are also certainly dependent on the characteristics of the landscape.

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References

APLIN, P., 2006, On scales and dynamics in observing the environment. *International Journal of Remote Sensing*, **27,** pp. 2123-2140.

BATER, C.W., AND COOPS, N.C., 2009, Evaluating error associated with lidar-derived DEM interpolation. *Computers & Geosciences*, **35**, pp. 289-300.

BOYD, D.S. AND DANSON, F.M., 2005. Satellite remote sensing of forest resources: Three decades of research development. *Progress in Physical Geography*, **29**, 1-26.

CALLE, A., GONZALEZ-ALONSO, F., AND MERINO DE MIGUEL, S., 2008, Validation of active forest fires detected by MSG-SEVIRI by means of MODIS hot spots and AWiFS images. *International Journal of Remote Sensing*, **29**, pp. 3407-3415.

CHANDER, G., COAN, M.J., AND SCARAMUZZA, P.L., 2008, Evaluation and Comparison of the IRS-P6 and the Landsat Sensors. *IEEE Transactions on Geoscience and Remote Sensing*, **46**, pp. 209-221.

COHEN, W.B., FIORELLA, M., GRAY, J., HELMER, E., AND ANDERSON, K., 1998, An efficient and accurate method for mapping forest clearcuts in the Pacific Northwest using Landsat Imagery. *Photogrammetric Engineering and Remote Sensing*, **64**, pp. 293-300.

COSTA, H., CARRÃO, H., BAÇÃO, F., AND CAETANO, M., 2008, Land cover classification in Portugal with multitemporal AWiFS images: a comparative study. In *Proceedings from the 28th EARSeL Symposium*, 2-7 June 2008, Istanbul, Turkey.

DANSON, F. M. AND CURRAN, P.J,. 1993, Factors affecting the remotely sensed response of coniferous forest plantations. International Journal of Remote Sensing, **43**, pp. 55-65.

EKSTRAND, S., 1994, Assessment of forest damage with Landsat TM: Correction for varying forest stand characteristics. *Remote Sensing of Environment*, **47**, pp. 291-302.

FALKENSTRÖM, H AND EKSTRAND, S., 2002, Evaluation of IRS-1c LISS-3 satellite data for defoliation assessment on Norway spruce and Scots pine. *Remote Sensing of Environment*, **82**, pp. 208-223.

FRANKLIN, J., 1986, Thematic Mapper analysis of coniferous forest structure and composition. *International Journal of Remote Sensing*, **7**, pp. 1287-1301.

GARG, R.D., AGRAWAL, S., DADHWAL, V.K., 2008, Evaluation of approaches for AWiFS multi-date registration. *International Journal of Applied Earth Observation and Geoinformation,* **10**, pp. 175-180.

JOHNSON, D.M., 2008, A comparison of coincident Landsat-5 TM and Resourcesat-1 AWiFS Imagery for classifying croplands. *Photogrammetric Engineering and Remote Sensing*, **74**, pp. 1413-1423.

HAGNER, O., AND REESE., H., 2007, A method for calibrated maximum likelihood classification of forest types. *Remote Sensing of Environment*, **110**, pp. 438-444.

HORLER, D.N.H, AND AHERN, F.J., 1986, Forestry information content of Thematic Mapper data. *International Journal of Remote Sensing*, **7**, pp. 405-428.

HYYPPÄ, J., HYYPPÄ, H., INKINEN, M., ENGDAHL, M., LINKO, S., AND ZHU, Y.-H., 2000, Accuracy comparison of various remote sensing data sources in the retrieval of forest stand attributes. *Forest Ecology and Management*, **128**, pp. 109-120.

HYYPPÄ, H, AND HYYPPÄ, J., 2001, Effects of stand size on the accuracy of remote sensing-based forest inventory. *IEEE Transactions on Geoscience and Remote Sensing*, **39**, pp. 2613-2621.

JOHNSON, D., 2008, A comparison of coincident Landsat-5 TM and Rsourcesat-1 AWiFS imagery for classifying croplands. *Photogrammetric Engineering and Remote Sensing*, 74(11):1413-1423.

KIRIN-CHAND, T.R., BADARINATH, K.V.S., PRASAD, V.K., MURTHY, M.S.R, ELVIDGE, C.D., AND TUTTLE, B.T.., 2006, Monitoring forest fires over the Indian region using Defense Meteorological Satellite Program-Operational Linescan System nighttime satellite data, *Remote Sensing of Environment*, **103**, pp. 165-178

KULKARNI, A.V., SINGH, S.K., MATHUR, P., AND MISHRA, V.D., 2006, Algorithm to monitor snow cover using AWiFS data of Resourcesat-1 for the Himalayan region, *International Journal of Remote Sensing*, **27**, pp. 2449-2457.

KUMAR, V., 2007, Indian Remote Sensing Satellites: Current and future missions. Available online at : www.pecad.fas.usda.gov/pdfs/2007/1%20Virender%20Kumar.pdf (Accessed March 1, 2009).

LU, D., 2006, The potential and challenge of remote sensing-based biomass estimation. *International Journal of Remote Sensing*, **27**, pp. 1297-1328)

LUTZ, D.A:, WASHINGTON-ALLEN, R.A., AND SHUGART, H.H., 2008, Remote sensing of boreal forest biophysical and inventory parameters: a review. *Canadian Journal of Remote Sensing,* **34,** pp. 286-313.

MANJUNATH, A.S., AND MURALIKRISHNAN, S., 2008, Geometric and radiometric evaluation of Resourcesat-1 sensors. *International Journal of Applied Earth Observation and Geoinformation,* **10**, pp. 159-164.

MCROBERTS, R.E. AND TOMPPO, E.O., 2007, Remote sensing support for national forest inventories. *Remote Sensing of Environment*, **110**, pp. 412-419.

MEYER, P., ITTEN, K.I., KELLENBERGER, T., SANDMEIER, S., SANDMEIER, R., 1993, Radiometric corrections of topographically induced effects on Landsat TM data in an alpine environment. *ISPRS Journal of Photogrammetry and Remote Sensing*, **48**, pp. 17-28

MUUKKONEN, P., AND HEISKANEN, J., 2005, Estimating biomass for boreal forests using ASTER satellite data combined with standwise forest inventory data. *Remote Sensing of Environment*, **99**, pp. 434-447.

NASA, 2008, Landsat then and now. Available online at: http://landsat.gsfc.nasa.gov/about/ (Accessed March 1, 2009).

NILSSON, M., 1997. Estimation of forest variables using satellite image data and airborne Lidar. Acta Universitatis Agriculturae Suecia. Silvestria 17. Swedish University of Agricultural Sciences. Department of forest resource management and geomatics, Umeå, Sweden.

NRSA, 2003, IRS-P6 Data User's Handbook. Technical Reference Document No: IRS-P6/NRSA/NDC/HB-10/03. Available online at: http://www.euromap.de/download/P6_data_user_handbook.pdf. (Accessed March 1, 2009)

OCHS, B., 2009, Status of the Landsat Data Continuity Mission [PowerPoint slides]. Retrieved from USGS, Landsat Science Team Meeting, January 6-8, 2009, Fort Collins, Colorado, USA. Available online at: http://landsat.usgs.gov/documents/6_NASA_LDCM_Status_Ochs.ppt (Accessed March 1, 2009)

OLSSON, H., EGBERTH, M., ENGBERG, J., FRANSSON, J., GRANQVIST PAHLÉN, T., HAGNER, O., HOLMGREN, J., JOYCE, S., MAGNUSSON, M., NILSSON, M., OLOFSSON, K., REESE, H., AND WALLERMAN, J., 2005, Current and Emerging Operational Uses of Remote Sensing in Swedish Forestry. In Proceeding of the Forest Inventory and Analysis Symposium. U.S. Forest Service, Portland, Maine, USA, October 2005.

OLTHOF, I., BUTSON, C., AND FRASER, R., 2005, Signature extension through space for northern landcover classification: A comparison of radiometric correction methods. *Remote Sensing of Environment*, **95**, pp. 290-302.

REESE, H., NILSSON, M., GRANQVIST-PAHLÉN, T., HAGNER, O., JOYCE, S., TINGELÖF, U., EGBERTH, M., AND OLSSON, H., 2003, Countrywide estimates of forest variables using satellite data and field data from the National Forest Inventory. *Ambio*, **32**, pp. 542-548.

SCHAAF, CB., GAO, F., STRAHLER, A.H., LUCHT, W., LI, X.W., TSANG, T., STRUGNELL, N.C., ZHANG, X.Y., JIN, Y.F., MULLER, J.P., LEWIS, P., BARNSLEY, M., HOBSON, P., DISNEY, M., ROBERTS, G., DUNDERDALE, M., DOLL, C., D'ENTREMONT, R.P., HU, B.., LIANG, SL., PRIVETTE, J.L., ROY, D, 2002, First operational BRDF, albedo nadir reflectance products from MODIS. *Remote Sensing of Environment*, **83**, pp. 135-148.

SIBSON, R., 1981., *A Brief Description of Natural Neighbor Interpolation*, in Interpolating multivariate data, John Wiley & Sons, New York, 1981, pp. 21-36

SPANNER, M.A., PIERCE, L.L., PETERSON, D.L., AND RUNNING, S.W., 1990, Remote sensing of temperate coniferous forest leaf area index: The influence of canopy closure, understorey vegetation and background reflectance. *International Journal of Remote Sensing,* **11**, pp. 95-111.

TEILLET, P.M., 1986, Image correction for radiometric effects in remote sensing. *International Journal of Remote Sensing,* **7**, pp. 1637-1651.

TEILLET, P.M., STAENZ, K., AND WILLIAMS, D.J., 1997, Effects of spectral, spatial, and radiometric characteristics on remote sensing vegetation indices of forested regions. *Remote Sensing of Environment,* **61**, pp. 139-149.

TEILLET, P.M., FEDOSEJEVS, G., THOME, K.J., AND BARKER, J.L., 2007, Impacts of spectral band difference effects on radiometric cross-calibration between satellite sensors in the solar-reflective spectral domain. *Remote Sensing of Environment,* **110**, pp. 393-409.

TOMPPO, E., 1990, Designing a satellite image-aided national forest survey in Finland. In: The Usability of Remote Sensing for Forest Inventory and Planning. SNS/IUFRO workshop, Department of Forest Resource Management and Geomatics, Swedish University of Agricultural Sciences, Umeå, Sweden, pp. 43-47.

TOMPPO, E, OLSSON, H., STÅHL, G., NILSSON, M., HAGNER, O, AND KATILA, M., 2008, Combining national forest inventory field plots and remote sensing data for forest databases. *Remote Sensing of Environment* **112**, pp. 1982-1999.

TROTTER, C.M., DYMOND, J.R., AND GOULDING, C.J., 1997, Estimation of timber volume in a coniferous plantation forest using Landsat TM. *International Journal of Remote Sensing*, **18**, pp. 2209-2223.

WALSH, S.J., MOODY, A., ALLEN, T.R., AND BROWN, D.G. 1997, Scale dependence of NDVI and its relationship to mountainous terrain. In *Scale in Remote Sensing and GIS,* D.A. Quattrochi and M.F. Goodchild (Ed.), pp. 27-56 (Boca Raton:CRC Press).

WULDER, M.A., WHITE, J.C., GOWARD, S.N., MASKE, J.G., IRONS, J.R., HEROLD, M., COHEN, W.B., LOVELAND, T.R., AND WOODCOCK, C.E., 2008, Landsat continuity: Issues and opportunities for land cover monitoring. *Remote Sensing of Environment,* **112**, pp. 796-809.

WUNDERLE, A.L., FRANKLIN, S.E:, AND GUO, X.G., 2007, Regenerating boreal forest structure estimation using SPOT-5 pan-sharpened imagery. *International Journal of Remote Sensing*, **28**, pp. 4351-4364.

YANG, X.J., AND LO, C.P., 2000, Relative radiometric normalization performance for change detection from multi-date satellite images. *Photogrammetric Engineering and Remote Sensing,* **66,** pp. 967-980.