The monitoring of tree and stand characteristics using digital photogrammetry and image analysis techniques

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Abstract

Ground based forest inventory surveys can provide highly accurate measurements of tree and stand characteristics, but these are expensive to carry out. Aerial photography has been used for several decades as a tool in forest management and inventory. However, conventional methods of interpretation are both time-consuming and costly, with results varying between interpreters. With continuing development of personal computer technology, aerial photographs have become more accessible for digital analysis. This paper presents the potential operational use of digitised aerial photographs, for the estimation of tree and stand characteristics in a forest plantation of Sitka spruce (*Picea sitchensis* (Bong) Carr), in north-east Scotland, for which softcopy photogrammetry and image analysis techniques were used for individual tree crown delineation. The results suggest that the methods used can provide information for the forest manager, to a level of accuracy which is 'fit for purpose'. The estimations of stand top height, basal area, stand volume, stand biomass and stand density (-23.7%) were similar with the ground measured stand characteristics (±10%).

***Keywords and phrases*:** Aerial photographs, softcopy photogrammetry, tree crown, tree height, forest management, forest inventories**.**

1. Introduction

Field surveys are currently the principal means of acquiring data for forest inventories, but with increasing demands on forest resources, the types of information required to improve the understanding and management of forests have increased in quantity, frequency and diversity. The acquisition of forest characteristics are often based upon field observations at sample locations throughout a forest, but for modelling diversity or landscape change the representation of forest characteristics as continuous surfaces may be more appropriate. These surfaces may then be used directly within Geographic Information Systems (GIS), which have an increasing role in forest management and planning. The use of remotely sensed data has been suggested as a possible alternative means of acquiring information about forest resources.

The goal of applying remote sensing to forest inventories and to forestry generally is to add value in the planning process (Holmgren and Thuresson 1998), and aerial photographs have been used for several decades as a tool for forest management and inventory (Howard 1991). High spatial resolution remote sensing imagery can be used, together with automated approaches to analysis, to distinguish between individual trees, and several techniques been developed in this respect in an attempt to streamline the process of photo-interpretation (Nakashizuka *et al*., 1995; Wulder, 1998).

The automation of the extraction of objects from aerial and satellite images is one of the main research tasks in digital photogrammetry and computer vision (Straub *et al*., 2001). Although Digital Elevation Models (DEMs) and ortho-images have been successfully used to estimate tree height (*e.g*. Gagnon *et al.* 1993; Miller *et al.*, 2000), their use to determine a range stand parameters, in particular standing volume, has not been adequately assessed.

This paper reports upon an application of digital photogrammetry and image analysis techniques for deriving tree and stand parameters from digitised aerial photographs and to compare these methods with conventional ground-based surveys.

2.Methodology

2.1 Study area

The digital photogrammetric procedures were developed on a stand of Sitka spruce located in Rosarie Forest (57º 31´ N, 03º 05´ W), north-east Scotland (Figure 1). The stand is 6.2 hectare in size, planted in 1948 and located on an almost level site.

2.2 Ground-based surveys

Three types of ground-based survey were used in this study; random plots, abbreviated tariff and individual tree estimation. Random plots are the most common method for estimating standing volume in commercial forests in Britain (Philip 1994). The survey involved randomly setting out 8 circular 0.01 ha plots, the number and size of plots following established guidelines (Philip 1994). In each plot all live trees with a diameter at 1.3 m height greater than 10 cm were measured, along with the height of the tree with the greatest diameter. These data were used to provide information on stand parameters such as top height (estimated height of the 100 trees with the largest DBH per hectare in metres), DBH (diameter at 1.3 m in centimetres), basal area (*i.e.* total cross-sectional area of the trees in a stand, expressed in m^2, estimated at 1.3 m), mean tree volume (m^3), mean volume per hectare (m^3 ha^{-1}). Individual tree volumes were determined using the single tree tariff chart and the tariff tables for Sitka spruce (Hamilton 1975).

Abbreviated tariffs provide the most accurate estimation of the volume of saleable timber within a stand without felling any trees (Edwards 1983). The abbreviated tariff was used as the control measure at Rosarie for making comparisons in stand height and volume between the random plots survey and the digital photogrammetry approach. The Forestry Commission Single Tariff Chart for Sitka spruce (Hamilton 1975) was used to produce a tariff number for each of the trees measured for height. The mean of these tariff values, along with the DBH, was used to calculate individual tree volumes from which a mean tree volume was derived. Volume per hectare was calculated from this value and stocking density (trees per hectare). Mean tree spacing, basal area per hectare, average DBH, average basal area, and net volume per hectare (based on net fully-stocked area), were also determined. Tree and stand biomass calculations were based on the equations for Sitka spruce developed by Bormann (1990) and the charts developed by Matthews *et al*. (1991).

Sixty individual trees were also measured at Rosarie. These trees were randomly located in a traverse survey of the stand. The traverse survey was carried out using a portable Criterion 400 survey laser (Laser Technology 1992). The x, y coordinates of these trees were determined along with tree height (obtained from the ground using a laser hypsometer) and DBH. The 60 trees derived from the traverse survey were located within the ortho-image using their co-ordinates and those derived from the tree crown delineation process. The tree heights derived from the ortho-image were compared with the tree heights obtained from the ground. A linear regression model was then generated to estimate ground-based tree heights from the estimated tree heights.

2.3 Source of aerial photographs

Aerial photographs were taken using a Zeiss LMK15 camera, lens type Lamegon PI, focal length 152.25 mm, photo base at approximately 914 m, and with film type Agfa Aviphot N200, at a scale of 1: 10000, on 19/09/1998 at 11:50 am. Weather conditions were clear and sunny, and a high level of detail was visible from the photographs. The azimuth of sunlight (east of north) and solar elevation were 173.8^{o} and 37.6^{o}.

2.4 Derivation of Digital Elevation Models and digital orthophotographs

Three aerial photographs were selected for coverage of the study site, which were scanned using a flatbed DTP scanner (Epson GT-12000) using commercial scanning software at a resolution of 800 dpi, with 24-bit colour depth. Taking account of the scale of the aerial photographs and the scanning resolution, the ground resolution for both sets of aerial photographs was 0.32 m.

The ERDAS IMAGINE 8.3 OrthoMAX software (ERDAS Inc. 1995) was used to create DEMs and ortho-photographs for each stereo pair. A horizontal resolution of 1 m (Figure 3) was output for the DEM as this is sufficiently small to enable identification and measurement of tree canopies (Aplin *et al*., 1999). The overall accuracy, mean and the root mean square error (RMSE) of the DEMs for the two sites, derived using additional check points, are shown in Table 1.

The ground (grid) resolution of the derived digital orthophotographs was selected to be 0.25 m, with colour balancing of the ortho-images to reduce the potential for artefacts in the derived data.

2.5 Derivation of Digital Terrain Models (DTMs) from contour lines

Digital elevation data in the form of 1:10 000 digital contour lines, purchased as Land-Form Profile tiles (Ordnance Survey, 2002), were selected for each site, the quoted accuracy of which for 5 m contour intervals is ± 1.0 m, and for 10 m contour intervals is ± 1.8 m. Gridded DTMs were generated in a two–step procedure: a) the generation of a TIN from the contour lines data sets (Flynn and Pitts, 2000); and, b) the generation of the final gridded DTMs from the TIN data sets. The final DTMs had a horizontal grid resolution of 1 m, the same as that of the DEMs.

2.6 Delineation of tree crowns using digital orthophotographs

The process of delineating tree crowns and locating individual trees employed the digital elevation data and the orthophotographs, in a four step process, as described below.

2.6.1 Removal of non-forested areas. A process of removing, or masking, non-forested areas and large shaded areas (Gougeon, 1995) used a colour transformation (Lillesand and Kiefer, 2000; Koutsias *et al*., 2000) provided in Image Pro-plus 4.1 (Media Cybernetics, 1998), followed by an unsupervised classification, using the YIQ transformation model (Y – luminance, I – inphase, Q – quadrature).

2.6.2 Enhancement of tree crowns within the imagery. The ortho-images were processed to enhance the appearance of the tree crowns when compared to the background using the logarithmic option within the 'local equalisation' enhancement functions offered by Image Pro-Plus. A window size of 15 x 15 pixels was selected after experimenting with several contrast enhancement filters. Taking account of the resolution of the digital ortho-image of 0.25 m, the selected window had an effective size of 3.75 m × 3.75 m. The selection of the size of this window was informed by estimates of the crown width of stand grown Sitka spruce trees, as derived from the abbreviated tariff ground-survey, from which a mean width at breast height was identified as being approximately 23 cm.

2.6.3 Smoothing of imagery prior to crown identification. A rectangular low-frequency kernel filter, with a size of 7 × 7 was used which comprised a constant value for each cell, with the intention of averaging the values of the cells, smooth the contour of each individual tree crown, and merge it with segments in close proximity which might otherwise be treated as separate trees (*e.g.* due to fragmentation of the representation of the crown in the imagery) (Brandtberg and Walter, 1998). With a cell size of 0.25 m, the coverage of the low frequency filter is approximately 1.75 m x 1.75 m which was chosen to be less than the estimated crown diameter of a tree within the stand and thus not have the effect of averaging the edges of several crowns.

2.6.4 Extraction and measurement of tree crowns. The measurement tools in the Image Pro-Plus image processing software (Media Cybernetics 1998) were used to measure the dimensions of the individual tree crowns, or tree crowns clusters. This step employed the pre-processed imagery as the input, on which manual checking of appropriate thresholds for canopy extents was carried out, using the image segmentation tool, working across the area sub-compartment at a time.

For each delineated tree crown or crowns cluster the X, Y coordinates of the object centroid and the area of the canopy were extracted and exported to a text file for further processing. The measurements made were of the crown projection, plus maximum, minimum and mean crown diameter and roundness were measured for each delineated tree canopy (Figure 2). These coordinates were used to locate the individual measured tree from within the traverse survey at the Rosarie Forest, and subsequently used to locate the apexes of each delineated tree crown within the DEM and DTM.

2.7 Estimation of tree and stand parameters from digital orthophotographs

The estimation of tree height was made using three sets of data. The first dataset was the coordinates of the centroid of each delineated tree crown. These coordinates enable the location of individual trees within the photogrammetrically derived DEMs, and within the DTMs derived from the digital contour maps. Since topography does not change and that the DTMs are representative of the topography at ground level at each site, the DTMs were subtracted from the DEMs to produce a digital canopy model using the image modelling tools from ERDAS IMAGINE 8.3 (ERDAS Inc., 1994). Tree height data were then extracted for the locations of the coordinates of the individual trees.

Derived tree heights were compared with ground measurements to provide an estimate of the accuracy of the modelled representation of the tree canopy surface. Using linear regression analysis, a model was developed to represent the relationship between the ground measured tree heights and those derived from the digitised aerial photographs. A regression model for estimating DBH was derived, based upon crown area derived from the delineation process and on the estimated tree height (Hall *et al.*, 1989).

Estimations of tree volume from the derived tree height and estimated DBH were made for each delineated tree within the selected forest stand, reporting mean tree height, top height, average DBH, and average tree volume and biomass. The net area of fully stocked forest, together with the estimated tree top height and the predicted DBH for each crown cluster, were then used to calculate stand parameters using the same functions as used for the calculation of parameters from the ground surveys.

3. Results

3.1 Traverse survey

A comparison of individual heights of the 60 Sitka spruce trees located and measured in the traverse survey, and identified from the aerial ortho-photography, revealed an underestimation compared with the latter method of 0.98 m based upon the RMSE of height differences, and an intercept in the regression model of 1.11, representing approximately 4.5% of the mean tree height. The underestimation was expected due to the morphology of the top of Sitka spruce trees (*i.e.* the leader has not been resolved by the imagery and thus not derived in the DEMs), pus the possible contribution of errors in the representation of the terrain in the underlying DTM. Nevertheless, these two forms of measurement were highly correlated ($r=0.88$, $P<0.05$). The relationship between DBH (diameter at 1.3 m), measured on the ground, and crown area, measured from the ortho-image, was strongly linear with the coefficient of determination (R^2) of 0.607 ($P < 0.000$) (Table 2).

A linear regression used to predict tree DBH, using tree height and crown area estimated from the ortho-image, revealed a strong relationship ($R^2 = 0.787$, $P<0.000$) (Table 3), which is an over-estimate due to the assumption made that the tree crowns are circular in shape, thus leading to an over-estimation of the crown area, despite the removal of derived crown areas which were least circular in shape.

3.2 Tree and stand volume-biomass estimations

A linear regression, applied to ground measured tree volume (V_g) and estimated tree volume (V_{est}) (derived from tree height and DBH inferred from the ortho-image), revealed a strong relationship ($R^2=0.759$, $P<0.000$) (Table 4), the underestimation of which reflects the underestimation in tree height reported in Table 2.

The net area of the stand at Rosarie Forest, estimated from the image analysis of the ortho-image, was 3.8 ha. From this, net volume and biomass per hectare could be determined. Table 5 shows a comparison between methods of the number of trees per hectare, mean DBH, mean height, average volume per tree, basal area per hectare and net volume per ha. The tree crown delineation method tended to underestimate the number of trees per hectare in comparison with the abbreviated tariff and random plots. It also overestimated the mean tree height due to the omission of suppressed, or sub-dominant, trees from the classification of tree crowns, as was mean DBH, using the crown area model, for the same reason. Nevertheless, the ortho-image estimations for stand parameters (basal area, net volume and biomass) fell between the abbreviated tariff (higher) and random plots (lower), and the approach based upon ortho-photographs estimated tree top height with an accuracy acceptable for most forestry applications (Hart, 1991).

4. Discussion

Measures of stand tree height are one of the most essential and difficult stand characteristics to assess in forest management. In this study, two expressions of stand height were used, mean height and top height. Mean height is the average height of all trees within the stand, and stand top height represents the height of the 100 largest trees per hectare.

The difference in the estimation of top height in the present study was less than 1 m from the true top height, which demonstrates the ability of the methodology to predict this essential stand characteristic. This is probably due to the fact that top height is influenced by dominant trees only, which are not affected by the errors in omission. The over-estimation of mean tree height of 2.2 m was expected since a number of suppressed or sub-dominated trees were omitted from the count.

Total tree volumes, estimated from calibrated tree height and predicted diameter, were larger than the volumes calculated from field-measured tree height and diameter (Table 6). The relationship between volume estimates was high with adjusted R^2 of 0.76 and standard error 0.16 m^3, and furthermore, the residuals plot, histogram and normal probability plot all indicated that the prediction of tree volume appears to be random and unbiased. Due to the small sample size that was used in the current study, some caution must be exercised for the height, DBH and volume models developed.

Estimated top height was used to determine the tariff number. The tariff number was equal to, or slightly under, that derived from the ground measurements of stand top-height. Estimates of mean DBH, average volume per tree and average biomass per tree were over-estimated significantly due to the omission of suppressed or sub-dominated trees. This over-estimation had a range of 2-3 cm for DBH, 0.173 m^3 to 0.193 m^3 for average volume per tree and 0.079 tonne to 0.099 tonne for average biomass per tree. Over-estimations of volume per hectare ranged from 4.0% to 7.4%, and basal area per hectare ranged from 3.3% to 9.2%. These values are within accepted accuracy intervals of ±10%. The prediction of total biomass per hectare, however, ranged from 9.7% to 18.0% and is slightly outside the generally accepted accuracy intervals. These results are similar to results derived from manual interpretation of aerial photographs.

5. Conclusions

Increasing demands for the inclusion of basic and value-added information in forest inventories, and the increasing costs of field surveys, have resulted in experimentation with digital photogrammetry in combination with crown delineation techniques as a method for data acquisition. The results reported in this paper suggest that the combination of these techniques can be used as alternative operational method for the derivation of stand parameters such as stand height, stand basal area, stand volume and stand biomass for Sitka spruce plantations in Great Britain. The reliability of the proposed method depends on the quality of the aerial photographs (*e.g.* acquisition conditions), their products (*e.g.* DEM resolution, relief distortions) and the accuracy of the terrain surface used.

The estimates of volume and biomass (749 m^3/ha and 301 tonnes/ha) are closer to the abbreviated tariff values (704 m^3/ha and 267 tonnes/ha) than the estimate from the random survey plots (839 m^3/ha and 329 tonnes/ha). Variations of these magnitudes are within acceptable limits and similar variations appeared in the ground inventory surveys depending on several factors such as cartographic boundaries of the stand, sample spacing, unit size, and type (Johnston and Lowell, 2001) or survey crew mistakes.

However, ultimately, the value of digital photogrammetry in assessing forest stand parameters not only depends on accuracy but also cost. An assessment of the start-up and operational costs of the approach described in this paper is the subject of ongoing work.

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7. References

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Figures

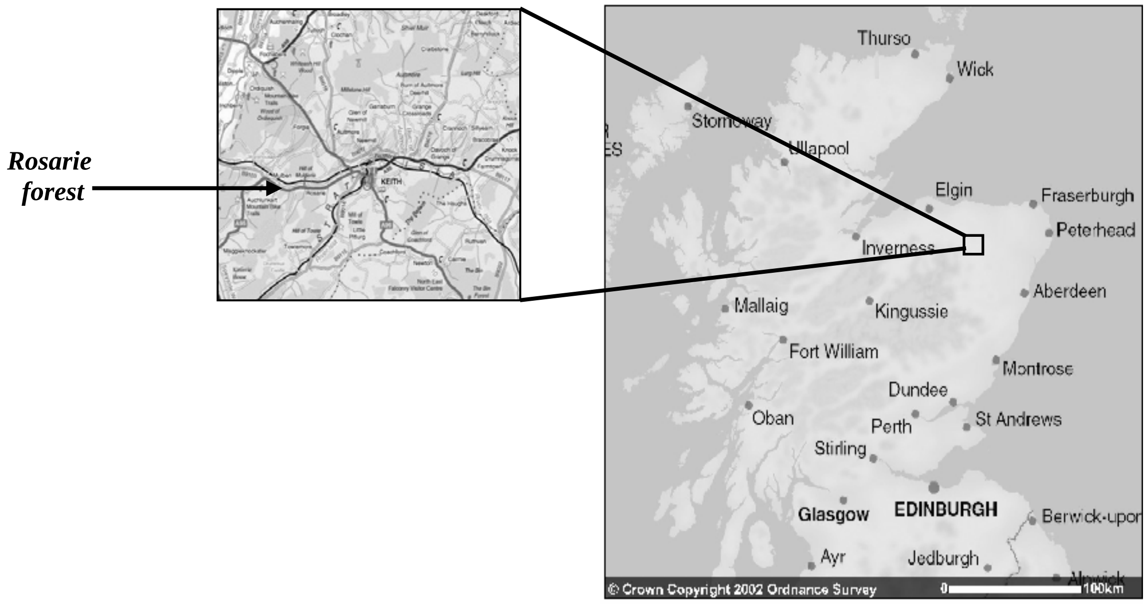

Figure 1. Location of Rosarie forest study site in north-east Scotland.

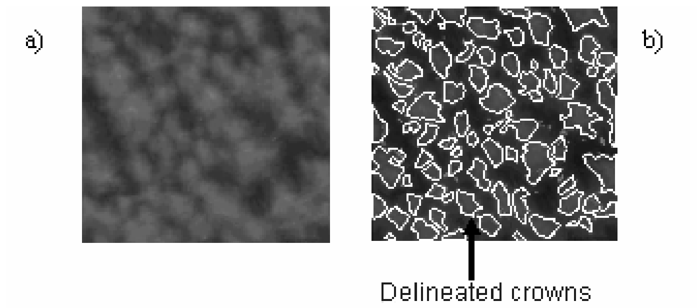

Figure 2. Part of the ortho-photograph: a) original, b) with the delineated trees.

Tables

Table 1. Overall accuracy of the Digital Elevation Model

DEM accuracy					
X (m) mean	X (m) RMSE	Y (m) mean	Y (m) RMSE	Z (m) mean	Z (m) RMSE
0.60	0.65	0.53	0.66	0.30	0.34

Table 2. (a) Details of ground measurements of 60 Sitka spruce trees from traverse survey. (b) Relationship between ground-measured tree heights (dependent variable) and tree heights which were derived by subtracting the DTM from the DEM at Rosarie Forest.

(a)

	Mean	**Standard deviation**	**Range**
Dbh (cm)	29.9	5.8	18 to 43
Height (m)	24.3	1.6	19.8 to 26.6

(b)

Tree heights	**Adjusted r^2**	**RMSE of height differences (m)**	**Model**
Ground measured tree heights vs DEM - DTM	0.607	0.98	1.11 + 0.989 X

Table 3. Regression statistics of DBH (diameter at 1.3 m) predicted from tree height (H) and tree crown area (CA) derived from ortho-photographs at Rosarie Forest.

Equation	Adjusted r^2	Standard error (cm)	Regression significance	Regression coefficients (T-value and probability)		
				a	b	c
DBH = a+bH+cCA	0.787	2.67	P < 0.000	-0.053 (0.958)	13.144 (0.000)	2.654 (0.011)

Table 4. Relationship between ground based tree volume (Vg) and estimated tree volume (V_{est}) at Rosarie Forest.

Independent variables	Adjusted r^2	Standard error (m^3)	Regression significance	Regression coefficients (T-value and probability)	
				a	b
$Vg = a + b V_{est}$	0.759	0.16	P < 0.000	0.355 (13.682)	0.724 (0.000)

Table 5. Comparison of the results from the abbreviated tariff (most accurate measure), random plot survey and digitised aerial ortho-images at Rosarie Forest. Volume calculations were made by the three methods using a tariff number of 36.

	Survey method		
Tree and stand parameters	Abbreviated Tariff	Random Plot	Digitised aerial ortho-photographs
Number of trees/ha	1479	1600	1129
Mean Height (m)	21.4	-	23.6
Top Height (m)	-	25.1	24.7
Average DBH (cm)	23.0	25.0	28.0
Average vol./tree (m^3)	0.48	0.52	0.66
Mean biomass/tree (tonnes)	0.18	0.21	0.27
Total biomass/ha	267	329	301
Basal area/ha (m^2/ha)	66.6	79.8	70.2
Net vol./ha (m^3/ha)	704	839	749