MEASUREMENTS OF WOODY PLANT ATTRIBUTES FROM LARGE-SCALE AERIAL PHOTOGRAPHS

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(Received for publication 31 March 1995; revision 24 January 1996)

ABSTRACT

The use of low-cost, large-scale aerial photographs to measure woody plant attributes was assessed for a variety of early successional forest ecosystems. Two conventional 35-mm cameras were mounted on a boom and suspended from a balloon or tripod platform to obtain nominally vertical stereo photographs (contact scales ranging from 1:250 to 1:1000). Photo measurements of individual plant total height were generally unbiased and precise, with regression standard errors ranging from 3.4 to 10.6 cm for plants up to 4 m tall. Standard errors for individual crown diameter measurements ranged from 7.1 to 18.4 cm for crowns up to 3.1 m in width. Direct photo estimates of crown area were unbiased and consistent (standard error = 0.107 m^2, plants up to 6 m^2). With measurements being confined to the inner 70% of the overlap portion of each photo pair, relief displacement had no discernible effect on the accuracy of crown estimates. For all measurement variables examined, the relationships between ground- and photo-measured factors were generally unaffected by species but did shift in response to high levels of crown closure and/or discrepancies in ground- and photo-measurement protocols. The most precise photo estimates originated from the larger photo scales tested. Results suggest that evaluations made from large-scale aerial photographs may be used to augment field evaluations in surveys of early successional woody plant communities situated on level terrain.

Keywords: aerial photography; balloon platform; vegetation evaluation; community structure; competition.

INTRODUCTION

Vegetation surveys are conducted on newly regenerating forest sites for a variety of research and operational purposes. For example, researchers collect information on the dimensional changes of target and crop plants to evaluate and compare vegetation management treatments. Foresters collect information on stand structure and composition for silvicultural decision making (i.e., to determine whether or not a young plantation or natural regeneration area is progressing according to management expectations and, if not, what corrective action to take). Similar information is used by wildlife managers to assess quality and quantity of wildlife forage and habitat. Field survey, usually involving direct measurements of individual plant dimensions, is currently the only method used for these purposes. Invariably, such surveys are labour-intensive and expensive, characteristics which frequently manifest themselves in deficiencies such as insufficient sample sizes and bias (Borders & Shiver 1989; Zedaker *et al.* 1993).

Increased sampling efficiencies have been realised in some forestry-related applications of large-scale aerial photographs (LSP) (e.g., Lyons 1967; Needham & Smith 1987; Hall & Aldred 1992; Alemdag 1986). However, a search of the literature revealed only one study (Smith *et al.* 1989) where LSP was used to evaluate competition levels in young forest plantations. Though the accuracy of photographic measurements of the dimensions of mature trees is well documented (e.g., Allison 1956; Lyons 1966), similar information is not available for lesser vegetation.

Pitt & Glover (1993) introduced a low-cost aerial photo acquisition system and evaluated the quality and cost of LSP estimates of aggregate crown area (m^2/ha) on vegetation management research plots. The objectives of this paper are to (1) evaluate the precision and accuracy of direct measurements of individual plant height and crown dimensions made from similar low-cost 35-mm LSP, and (2) identify factors influencing measurement accuracy and precision. Results should be of direct interest to foresters, ecologists, and range managers, all of whom are concerned with maximising precision, minimising bias, and reducing the marginal cost of information obtained on early successional woody communities. This paper should also prove useful to forest managers who wish to expand the scope of existing regeneration surveys to include evaluations of non-crop woody vegetation.

METHODS

Field Studies

Six forest vegetation management studies, representing a variety of early successional vegetation communities, were chosen as subjects for this investigation (Table 1). Studies 1–3 represent comparative efficacy trials, characterised by woody and herbaceous communities typically present 2 or 3 years after clearcutting. Studies 4–6 represent mechanistic-type growth studies in which woody species composition and density have been highly controlled and herbaceous components excluded. Field-measurements secured as part of the original treatment evaluations were used, wherever possible, as ground-truth data for this investigation (methodological details are summarised in Appendix 1). Timing and measurement procedures differed somewhat from one field study to another (further details have been reported by Pitt 1994).

Aerial Photography

Stereo aerial photographs were obtained by mounting an identical pair of Nikon® EM* cameras on a lightweight aluminium boom (Pitt & Glover 1993). The cameras could be

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* Mention of trade names is for information only and does not imply endorsement or disapproval by the authors, the Canadian Forest Service, or Auburn University.

TABLE 1–Summary of forest vegetation management field studies used for the evaluation of LSP techniques (for specific evaluation methods and times, *see* Appendix 1).

Field study	Location	Vegetation conditions at time of assessment	Study type	Evaluation time(s)
1	Fredericton, New Brunswick, Canada	Varying densities of tolerant and intolerant hardwood coppice growth (<4 m tall). Crop trees were planted black spruce (<2 m tall). Light to moderate herbaceous cover in the understorey.	Chemical and manual site preparation and conifer release.	July '91
2	Auburn, Alabama, USA	Factorial combinations of three vegetation complexes consisting of planted loblolly pine (<2 m tall), volunteer south-eastern hardwood spp. (<4 m tall), and a variety of herbaceous spp.	Ecological: below-ground ecosystem processes.	Sept '92 Sept '93
3	North Florida, and south Georgia, USA	South-eastern non-arborescent species (<1.5 m tall) and moderate to heavy herbaceous cover. Planted slash or loblolly pine (<2.5 m tall).	Chemical and mechanical site preparation.	Sept '91
4	Shorter, Alabama, USA	Sweetgum planted at densities of 0, 1, 2, and 4 plants/m^2 (<3 m tall) around focal loblolly pine (<1.6 m tall).	Mechanistic competition study: Neighbourhood approach.	May '91 June '91 Sept '91 Mar '92 May '92
5	Shorter, Alabama, USA	Loblolly pine and sweetgum planted in restricted random patterns at ratios of 1:1, 1:2, 2:1, and 2:2 plants/m^2 (<3.5 m tall).	Mechanistic competition study: Addition Series design.	Jan '92
6	Shorter, Alabama, USA	Pure and equal mixes of loblolly pine and sweetgum at densities ranging from 0.27 plants/m^2 to 12.21 plants/m^2 (<3.5 m tall).	Mechanistic competition study: Nelder la design (Nelder 1962).	Jan '92

adjusted inward or outward along the boom to achieve a desired airbase (*B*). A bubble level, placed on the camera frame during installation, was used to orient each camera in a vertical attitude relative to the natural position of the boom. Guy lines, running from the four corners of the boom to the point of attachment, functioned to level and stabilise the boom and eliminated the need for gimbal mechanisms on each camera. When centred over a target area, the apparatus provided nominally vertical photographs. Two servos, operated by the same radio frequency, were used to depress the shutter release cables simultaneously.

A 25-m^3 Raven® helium-filled balloon provided a stable platform for the 5-kg camera system in wind speeds up to 8 km/h. The balloon was tethered to a single water-filled 20-ℓ container and moved from one photo station to the next by moving the container. A steering line was attached to one end of the boom and used to orient the camera axes relative to the plots being photographed. Field studies 1, 2, 5, and 6 were photographed with this system (Table 2).

While the balloon proved to be a suitable camera platform for studies with large numbers of plots in close proximity and/or studies requiring large area coverage, a simple aluminium tripod was found to be more efficient for use on smaller plots (studies 3 and 4). With three 3-m sections of tubing per leg, the tripod provided a camera height of 7.2 m, weighed only 10.5 kg, and could be easily erected and moved about a forest cutover by three persons (Fig. 1). A plywood housing was used to fix the legs of the tripod together at the vertex and permit each leg to swing inward and outward, as needed, for deployment in the field. The camera system described above was raised and lowered using a cord and pulley system.

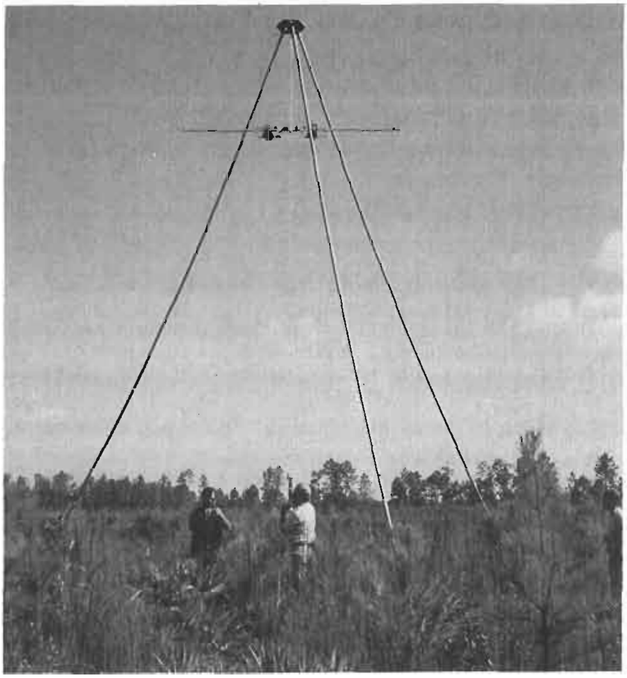

FIG. 1–Tripod used for photographing small plots (less than 3 × 3 m). Consisting of three sections of aluminium tubing per leg, the tripod provided a maximum camera height of 7.2 m and weighed 10.5 kg.

TABLE 2–Summary of photo specifications, by field study

Field study	Photo set	f* (mm)	H (m)	B (m)	B:H	Scale†	Film type	Platform	Foliage status	Date	Target size (m)	Number‡ photographed
1	a	67.1	29.1	2.54	1:11.5	1:94.8	Kodak Ektar 125	Balloon	Full leaf	July '91	¼ EU	23
	b	35.0	17.2	1.46	1:11.8	1:107.4	Kodak Ektar 125	Balloon	Full leaf	July '91	~9 × 7	8
2	a	35.0	12.5	1.00	1:12.5	1:78.0	Kodak Ektar 125	Balloon	Full leaf	Sept '92	EU	21
	b	67.3	24.3	1.90	1:12.8	1:78.9	Kodak Gold 200	Balloon	Full leaf	Sept '92	5.0 × 5.0	Repeated
	c	67.3	24.6	1.90	1:12.9	1:79.9	Kodak Gold 200	Balloon	Full leaf	Sept '93		Repeated
	d	67.3	24.6	1.90	1:12.9	1:79.9	Kodak Gold 400	Balloon	Leaf off	Mar '93		Repeated
3	a	28.8	7.2	0.60	1:12.0	1:54.6	Kodak Ektar 125	Tripod	Full leaf	Sept '91	SU 2.1 × 2.1	7
4	a	28.8	7.2	0.60	1:12.0	1:54.6	Kodak Ektar 125	Tripod	Full leaf	May '91	SU	32
	b	28.8	7.2	0.60	1:12.0	1:54.6	Kodak Ektar 125	Tripod	Partial leaf	Sept '91	3.0 × 3.0	Repeated
	c	28.8	7.2	0.60	1:12.0	1:54.6	Kodak Ektar 125	Tripod	Leaf off	Dec'91		Repeated
	d	28.8	7.2	0.60	1:12.0	1:54.6	Kodak Ektar 125	Tripod	Full leaf	May '92		Repeated
5	a	50.0	14.1	1.20	1:11.8	1:61.6	Kodak Ektar 125	Balloon	Partial leaf	Sept '91	EU	23
	b	50.0	14.1	0.60	1:23.5	1:61.6	Kodak Ektar 125	Balloon	Leaf off	Jan '92	4.8 × 4.0	Repeated
6	a	28.0	23.0	1.20	1:19.2	1:179.5	Kodak Ektar 125	Balloon	Partial leaf	Sept '91	EU	4
	b	28.0	23.0	1.20	1:19.2	1:179.5	Kodak Ektar 125	Balloon	Leaf off	Jan '92	13.8 × 13.8	Repeated
	c	28.0	28.0	0.60	1:46.7	1:218.5	Kodak Ektar 125	Balloon	Leaf off	Jan '92		1

* Actual verified focal length: nominal values are provided in text. H = height. B = airbase.

† Print scale at ground level after 4.576 times enlargement.

‡ Number of unique plots photographed. "Repeated" indicates that all initial plots were rephotographed.

SU = sample unit

EU = experimental unit

Kodak 125, 200, and 400 ASA films were used to maintain a minimum shutter speed of 1/250 of a second in diffuse light conditions (hazy or cloudy conditions). In the fall of 1991, the original cameras were upgraded to two Nikon® FM2 models, equipped with MD-12 motor drives. These cameras permitted the use of a fixed shutter speed (i.e., 1/250 of a second) as well as perfectly synchronised electronic shutter activation. This remedied problems encountered with the mechanical activation system, which was prone to maladjustment and mis-fires.

Identical pairs of Nikon® Series E 28 or 50 mm, or Nikkor® 35–70 mm lenses were used throughout this investigation. For each application, actual focal lengths (f) were verified by photographing a target of known size (S) and distance (H) from the perspective centre and relating the object image size (s) on the negative by (all units in millimetres):

$$f = H \times s / S \qquad [1]$$

In all tests, pairs of lenses deviated in a similar manner and the average value was used in subsequent calculations (Table 2).

In all photo sessions, f / H combinations were chosen to allow target areas to fall within the inner 50 to 70% of the stereoscopic portion of each photo pair (inner 50 to 70% of the overlap in each of the x and y directions). This was done to (a) ensure that measurements were not made along the edges of the photographs where relief displacement and lens distortion are greatest, and (b) allow a margin of error for capturing the target area on film. Sample unit (SU) centres were marked on the ground by 30 × 20-cm numbered cards (black lettering on white background) and white 20-cm diameter discs. A 2.4-m measuring stick was placed on the ground in a visible location near each SU centre to provide a check on photo scale (otherwise determined by f / H).

Photo Evaluations

Prior to print development, the geometric centre of each negative was pin-pricked so the position of the principal point would be visible on a paper print. Images were then enlarged by a factor of 4.576, to obtain 10 × 15-cm prints. Conjugate principal points were transferred stereoscopically and subsequently used to base-line the photos for stereo viewing (Paine 1981, p.56). All photo evaluations were conducted by a single interpreter.

For height and crown measurements, stereo pairs were positioned on a 30 × 43-cm Kurta® digitising tablet and viewed with an Old Delft® scanning stereoscope (under 4.5× magnification). Individual plant heights (HT_p, "p" denoting photo-derived) were measured using a Wild® parallax bar (for a description of the parallax bar and its use, *see* Paine 1981, p.145). Crown areas were estimated by digitising the plan (top) view of each crown, as seen in the three-dimensional stereo model. The area-by-coordinates method (Brinker & Wolf 1994, p.272) was used to compute crown area (CA_p) from the stream of x,y co-ordinates generated by each trace. Crown diameter measurements were conducted by digitising the endpoints of a line segment through the widest point of the crown ($CD1$; Fig. 2) and those of a similar segment, at 90° to the first, through the centre of the crown mass ($CD2$). The formula for the distance between two points in a co-ordinate plane (Anton 1988, p. 26) was used to compute the diameters ($CD1_p$ and $CD2_p$) of each crown.

To simplify measurements, both the digitising tablet and parallax bar were connected to a single 286 PC where a BASIC program read incoming measurement data and performed the necessary computations. Specific formulae used by the program to compute HT_p and CA_p

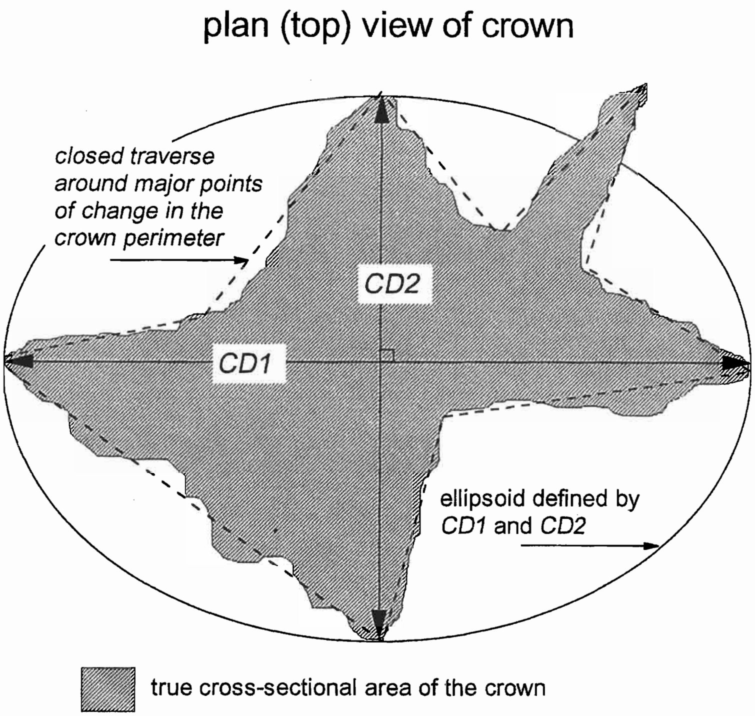

FIG. 2–Schematic diagram of the procedures used to measure crown dimensions. *CD1* and *CD2* are crown diameters taken through the crown at its widest point and at 90°, through the approximate centre of the crown mass. The solid ellipse depicts the crown area estimated from the two crown diameters (CA_{gD}, obtained from Equation 3). The broken line depicts the closed traverse used to estimate true crown area on the ground (CA_g; Appendix 1).

were adapted from Lyons (1966) and are provided in Appendix 2. The approximate height of the crown at its widest point ($HT_p(mid)$) and the radial distance from the centre of the crown mass to the centre of the photograph were also measured for each crown to compute *relief displacement* (d):

$$d = \frac{r \times HT_p(mid)}{H} \qquad [2]$$

where: r = radial distance from the centre of the photograph to the centre of the crown mass (same units as d),

H = camera height above the ground (m), and

$HT_p(mid)$ = the approximate height of the crown at its widest point (m), determined by parallax measurement.

Finally, each crown was allocated to one of three visibility classes according to its degree of openness on the photo. A class "O" crown was clearly defined and not overlapped by other vegetation. At least 50% of the margin of a class "P" crown was visible, the remaining portion being obscured by other vegetation. Finally, less than half of the margin of a class "F" crown was visible, causing the operator to actively "interpret" much of its perimeter. This classification permitted the study of relationships between ground and photo measurements of individual plants under varying degrees of interpreter confidence.

Data Analysis

Following the convention used to arrive at correction curves in problems of application, ground measurements were regressed on photo measurements (Allison 1956). The accuracy and precision of photo measurements were evaluated by studying the characteristics of these regression relationships. Specifically, information on bias in photo measurements is contained in the estimated regression intercept (expected to be 0 in the absence of bias) and slope (expected to be 1 in the absence of bias). Information on the precision of photo estimates is contained in the standard error of the regression (SE, or the square root of the residual mean square). Under large sample sizes, this value approaches the error with which a response variable of interest may be predicted from a given photo determination.

When differences between class variables were of interest (e.g., species), simple regression relationships between ground and photo determinations were expanded to include indicator variables for these factors (Draper & Smith 1981). If an F-test suggested that the expanded model accounted for greater variation than the simple model, attempts were made to group the class variables on the basis of meaningful *a priori* criteria (e.g., crown form), such that the expanded model could be presented in its simplest form.

RESULTS AND DISCUSSION

Observed Accuracy and Precision Levels

The relationship between ground- and photo-measured individual woody plant height was strong and generally consistent across the six field studies (Table 3; Fig. 3a). All relationships were linear and, with few exceptions, did not differ significantly ($p < 0.05$) from the expected line of equality (0 intercept and unit slope). Coefficients of variation (CV) were consistently below 10% and frequently below 5%, suggesting a high degree of precision.

As in height, the relationship between ground- and photo-measured maximum crown diameter ($CD1$) was reasonably strong and consistent across the five field studies where such determinations were made (Table 4; Fig. 3b). All relationships were linear and suggested slight photo-measurement bias in some instances. Standard errors and coefficients of variation tended to be larger than those observed for height, ranging between 7.1 and 18.4 cm, and 5 and 22%, respectively.

Detailed crown area estimates made by closed traverse on 91 hardwood crowns in field study 1 (CA_g, "g" denoting ground-based measurement) (Fig. 2; Appendix 1) provided sound evidence in support of the hypothesis that CA_p provides a true representation of actual CA (Fig. 3c). The relationship between CA_g and CA_p did not differ significantly from the expected line of equality (0 intercept $p = 0.104$ and unit slope $p = 0.450$) and exhibited appreciable precision (SE = 0.107 m^2, CV = 6.9%). Differences between photo sets 1a (n = 67) and 1b (n = 24) could not be detected ($F_{2,87} = 0.5064, p = 0.604$). Also, the relationship reflected the full range of crown sizes encountered in all six field studies where CA determinations were made.

This result is of particular importance, considering the difficulty and expense involved in the acquisition of accurate, direct crown area measurements in the field. Indirect estimations of crown area, based on two measurements of crown diameter, are commonly relied on in practice (Fig. 2):

TABLE 3—Summary of statistics for the regression of ground-measured tree height on photo-measured tree height, by field study (differences between crown visibility classes not significant ($p > 0.05$) except in study 6—*see* text).

Field study	Photo set	*f** (mm)	*H* (m)	*B* (m)	Species complex	Max. height (m)	Mean diff.† (m)	Intercept	(se)‡	Slope	(se)	n	SE§ (m)	CV (%)	r^2	Theoretical precision (m)
1	a	67.1	29.1	2.54	North-eastern hardwoods	3.51	–0.001	0.0121	(0.014)	0.9904	(0.011)	172	0.090	7.63	0.98	0.049
	b	35.0	17.2	1.46	North-eastern hardwoods	3.51	–0.021	0.0252	(0.024)	0.9964	(0.017)	85	0.106	8.32	0.98	0.030
2	a	35.0	12.5	1.00	South-eastern hardwoods & loblolly pine	2.78	0.016	–0.0207	(0.010)	1.0048	(0.009)	277	0.076	8.23	0.98	0.023
	b	67.3	24.3	1.90		2.78	0.020	–0.0123	(0.009)	0.9915	(0.008)	276	0.069	7.47	0.98	0.045.
	c	67.3	24.6	1.90		4.00	0.002	0.0192	(0.009)	0.9881	(0.005)	301	0.057	3.25	0.99	0.047
3	a	28.8	7.2	0.60	Loblolly pine	2.44	–0.008	0.0170	(0.022)	0.9925	(0.016)	33	0.046	3.60	0.99	0.013
					Slash pine	2.32	0.016	0.0332	(0.032)	0.9686	(0.019)	16	0.046	2.94	0.99	0.013
4	a	28.8	7.2	0.60	Sweetgum	1.24	0.020	–0.0154	(0.012)	0.9944	(0.015)	334	0.038	4.87	0.93	0.013
					Loblolly pine	0.48	–0.003	0.2049	(0.056)	0.4748	(0.143)	24	0.034	8.83	0.33	0.013
	b	28.8	7.2	0.60	Sweetgum	1.27	–0.002	0.0208	(0.008)	0.9853	(0.006)	349	0.040	3.14	0.90	0.013
					Loblolly pine	1.08	0.043	–0.0599	(0.041)	1.0253	(0.061)	28	0.044	7.21	0.92	0.013
	c	28.8	7.2	0.60	Sweetgum	2.43	–0.184	0.2541	(0.030)	0.9322	(0.028)	357	0.154	12.61	0.76	0.013
					Sweetgum#	2.43	0.012	0.0006	(0.022)	0.9908	(0.016)	40	0.041	3.11	0.99	0.013
					Loblolly pine	1.11	0.042	–0.0339	(0.028)	0.9881	(0.042)	32	0.036	5.95	0.95	0.013
	d	28.8	7.2	0.60	Sweetgum	2.72	0.003	–0.0447	(0.010)	1.0264	(0.006)	368	0.043	2.79	0.99	0.013
					Loblolly pine	1.63	0.041	–0.0382	(0.046)	0.9972	(0.044)	28	0.053	5.45	0.95	0.013
5	a	50.0	14.1	1.20	Sweetgum	3.35	0.046	–0.0347	(0.013)	0.9944	(0.006)	151	0.041	2.00	0.99	0.024
					Loblolly pine	2.55	0.001	–0.0051	(0.013)	1.0026	(0.008	162	0.040	2.45	0.99	0.024
	b	50.0	14.1	0.60	Sweetgum	3.35	–0.029	0.0248	(0.036)	1.0021	(0.018)	151	0.116	5.70	0.96	0.048
					Loblolly pine	2.55	0.066	–0.0666	(0.016)	1.005	(0.009)	162	0.048	2.89	0.99	0.048
6	a	28.0	23.0	1.20	Sweetgum¶	2.95	0.106	–0.1355	(0.075)	1.0142	(0.036)	75	0.115	5.85	0.92	0.064
					Loblolly pine¶	2.46	0.046	0.1457	(0.071)	0.8980	(0.037)	96	0.105	5.73	0.86	0.064
	b	28.0	23.0	1.20	Sweetgum¶	2.95	–0.139	0.4434	(0.115)	0.8378	(0.060)	135	0.246	12.21	0.59	0.064
					Loblolly pine¶	2.46	0.161	0.1458	(0.064)	0.8451	(0.032)	113	0.108	5.94	0.86	0.064
	c	28.0	28.0	0.60	Sweetgum¶	2.95	0.507	0.6294	(0.531)	0.5954	(0.193)	28	0.315	14.09	0.26	0.189
					Loblolly pine¶	2.46	0.755	0.4572	(0.273)	0.5144	(0.108)	38	0.237	13.59	0.38	0.189

* Actual verified focal length; nominal values are provided in text.
H = height. *B* = airbase.

† Mean paired difference between photo and ground estimates.

‡ (se) = standard error of parameter estimate.

§ SE = standard error of regression (root mean square residual)

Trees with visible terminals only

¶ Crown visibility classes O and P only

TABLE 4—Summary of statistics for the regression of ground-measured maximum crown diameter on photo-measured maximum crown diameter, by field study (*see* text for definition of crown classes)

Field study	Photo set	Species complex	Crown class	Maximum diameter (m)	Mean diff.* (m)	Intercept	(se)†	Slope	(se)	n	SE‡ (m)	CV (%)	r^2	Theoretical precision (m)
1	a & b	North-eastern	O	3.13	0.052	0.012	(0.02)	0.934	(0.02)	78	0.017	11.6	0.98	0.04
		hardwoods	P	2.52	0.020	0.064	(0.03)	0.908	(0.03)	97	0.155	17.2	0.92	0.04
			F	1.49	0.017	0.083	(0.04)	0.861	(0.05)	82	0.142	20.2	0.77	0.04
2	c	South-eastern	O	2.07	0.011	0.068	(0.03)	0.916	(0.03)	77	0.111	11.9	0.91	0.03
		hardwoods &	P	2.27	0.028	0.104	(0.03)	0.879	(0.03)	107	0.140	13.2	0.90	0.03
		loblolly pine	F	2.32	–0.072	0.138	(0.04)	0.944	(0.03)	105	0.184	14.7	0.89	0.03
3	a	Loblolly &	O	1.80	0.127	–0.069	(0.11)	0.952	(0.09)	23	0.139	12.7	0.86	0.02
		slash pine	P	1.07	0.057	0.114	(0.11)	0.746	(0.15)	22	0.135	22.0	0.54	0.02
5	a	Sweetgum	O	1.90	0.160	0.077	(0.09)	0.811	(0.07)	17	0.088	8.0	0.91	0.02
		Sweetgum	P	2.02	0.149	0.145	(0.05)	0.743	(0.04)	68	0.114	11.5	0.83	0.02
		Sweetgum	F	1.56	0.115	0.115	(0.06)	0.750	(0.06)	66	0.137	17.0	0.69	0.02
		Loblolly pine	O	1.61	–0.023	0.243	(0.05)	0.791	(0.04)	34	0.071	6.6	0.92	0.02
		Loblolly pine	P	1.86	–0.065	0.187	(0.04)	0.871	(0.04)	62	0.089	8.8	0.88	0.02
		Loblolly pine	F	1.56	–0.044	0.293	(0.06)	0.742	(0.05)	66	0.130	12.9	0.74	0.02
	b	Sweetgum &	O	1.76	–0.022	0.159	(0.03)	0.860	(0.03)	96	0.092	9.1	0.89	0.02
		loblolly pine	P	1.89	–0.009	0.181	(0.03)	0.813	(0.03)	134	0.108	11.6	0.83	0.02
			F	1.83	–0.038	0.228	(0.05)	0.807	(0.04)	83	0.129	12.6	0.80	0.02
6	a	Sweetgum	O	2.05	0.345	0.228	(0.11)	0.636	(0.07)	38	0.121	9.9	0.71	0.07
		Loblolly pine	O	1.92	–0.086	0.552	(0.08)	0.637	(0.06)	69	0.133	9.7	0.62	0.07
	b	Sweetgum	O	1.76	0.037	0.290	(0.08)	0.736	(0.06)	91	0.143	11.9	0.61	0.07
		Loblolly pine	O	1.90	–0.047	0.416	(0.07)	0.720	(0.05)	78	0.118	8.6	0.70	0.07
	c	Sweetgum	O	2.13	0.060	0.900	(0.10)	0.349	(0.07)	20	0.076	5.4	0.61	0.08
		Loblolly pine	O	1.56	–0.109	0.341	(0.18)	0.810	(0.14)	26	0.157	11.8	0.58	0.08

* Mean paired difference between photo and ground estimates

† (se) = standard error of parameter estimate

‡ SE = standard error of regression (root mean square residual)

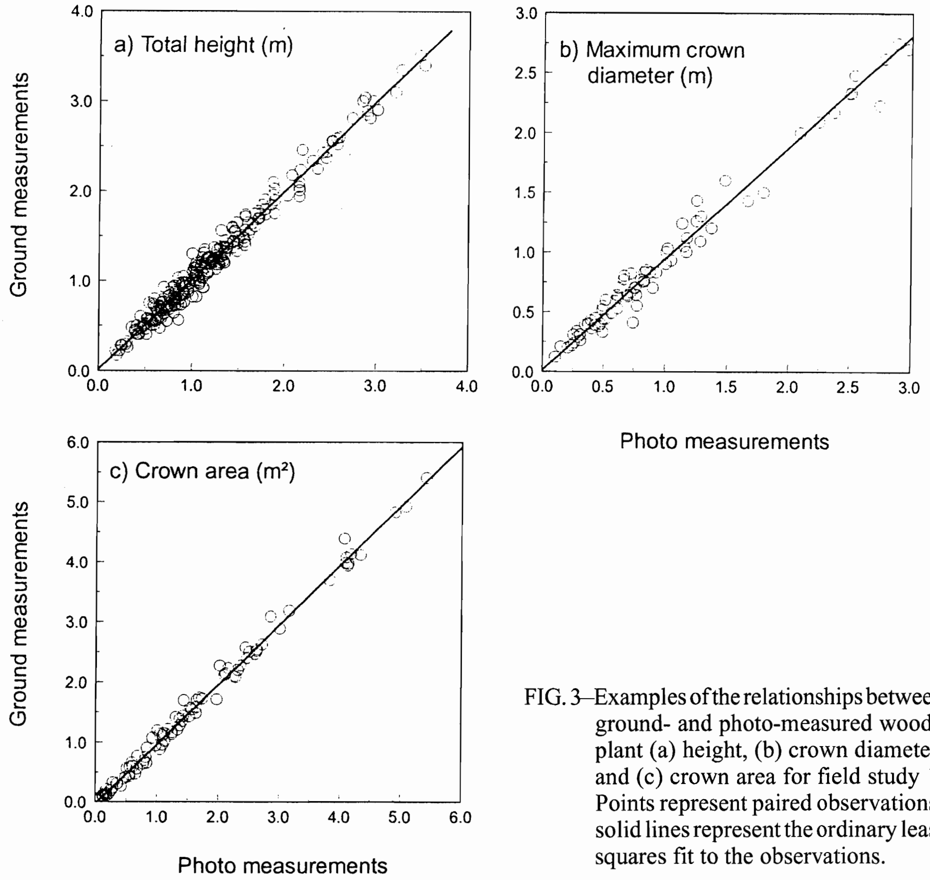

FIG. 3—Examples of the relationships between ground- and photo-measured woody plant (a) height, (b) crown diameter, and (c) crown area for field study 1. Points represent paired observations; solid lines represent the ordinary least squares fit to the observations.

$$CA_{gD} = \frac{CD1_g \times CD2_g \times \pi}{4} \qquad [3]$$

For the 91 crowns measured by closed traverse, CA_{gD} over-estimated true CA by widely varying amounts (mean difference between CA_{gD} and $CA_g = 0.23$ m^2, $p < 0.001$). In light of these findings, it would generally be undesirable to correct CA_p on the basis of CA_{gD}; correction curves for omission bias may need to be based on ground-truth measurements obtained by more accurate methods (e.g., vegetation charting described by Bonham 1989). Further, CA_p, which better approximates true CA, may provide a more sound index of plant competitive status than CA_{gD}. The comparatively poor representation of true crown area by CA_{gD} may also provide possible explanation for its lacklustre performance relative to other competitive indices in Knowe's (1991) study.

Effects of Photo Characteristics

The interrelationships between focal length, camera height, and airbase influence factors such as photo scale and relief displacement and therefore have a direct influence on the precision and accuracy of height and crown determinations made from LSP. Pitt (1994) outlined a simple means of computing the theoretical precision (TP) of tree height measurements from a given set of photographs taken under ideal conditions (i.e., perfectly vertical lens positions, each photo of the stereo pair having exactly the same scale, no image motion or lens distortion, etc.). These values are provided in Table 3.

Though observed regression SEs were slightly higher than TP values (because of variation attributable to sampling), there was a strong correlation between observed and expected values ($r = 0.89$). From these, it is apparent that as the $B{:}H$ ratio is decreased, precision is sacrificed. To a lesser extent, increasing the f/H combination, while keeping scale and $B{:}H$ relatively constant, also reduces precision.

These comparisons suggest that TP may be used as a guide for planning LSP applications. Since HT_p measurement precision will be greatest with large parallax differences, TP may be maximised by choosing an airbase that will produce large but comfortable levels of vertical exaggeration for the size of the vegetation being studied. To illustrate, in Fig. 4 TP values are plotted over B, for f/H combinations leading to a contact scale of 1:250 (target size = 3 × 3 m, vegetation height = 2 m). Each of the curves terminates when ΔP (the difference in absolute parallax between the top and the bottom of the plant) is approximately

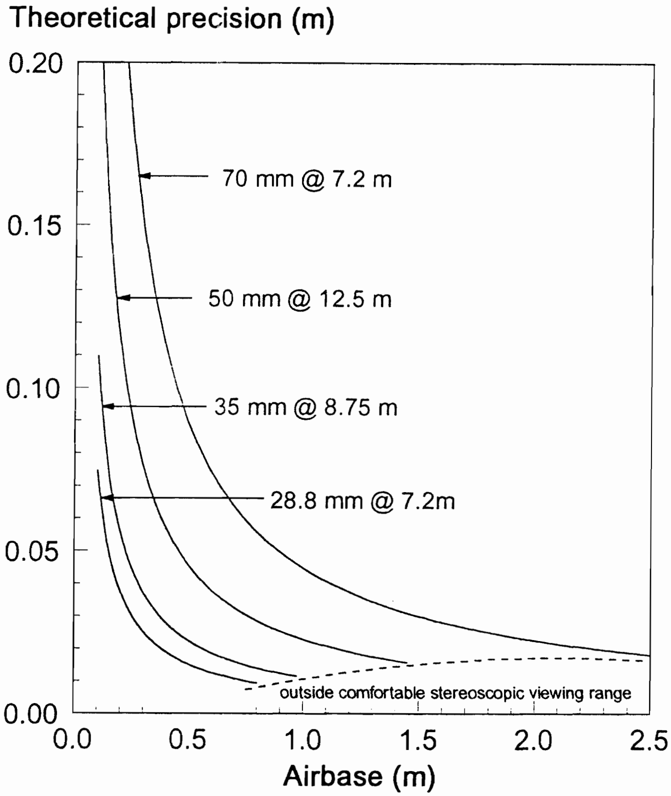

FIG. 4—Theoretical photo height measurement, precision plotted over airbase, for four different focal length / camera-height combinations leading to a contact photo scale of 1:250 at ground level (similar to that used in field studies 3 and 4).

5.5 mm (the upper limit of parallax for comfortable viewing). The TP level of 0.013 m that was attained with $f = 28.8$ mm, $H = 7.2$ m, and $B = 0.6$ m could also have been attained, in theory, with $f = 35$ mm, $H = 8.75$ m, and $B = 0.9$ m. Small sacrifices in precision would be required if larger f/H combinations were used; the combination of choice would depend on limitations of the camera platform being used and available equipment. A simple algorithm for balancing economy and precision in LSP applications has been provided by Pitt (1994, p.232).

Just as the limit of parallax perception defines the basic level of precision for height measurements on a pair of photographs, the resolution of the digitiser, relative to the photo scale, defines the basic level of precision for $CD1_p$ and CA_p determinations. The particular tablet used throughout this study had a resolution of ± 0.38 mm. This resolution can easily be translated into crown-diameter measurement units (m) for the various photo scales used in this investigation. For example, precision for the largest print scale used (1:54.6) was ±0.02 m at ground level (0.38 mm × 0.0545 m/mm); for the smallest print scale used (1:218.5) it was ±0.08 m (Table 4). These values represent maximum errors of approximately ±3.7% and ±14.8%, respectively, for a crown area equal to 1 m^2.

Photo characteristics play an important role in measurement *accuracy* as well (Appendix 2). Even small errors in the specification of f, H, B, or EF will lead to biased results. For example, if the nominal focal length of 70 mm were used in the calculation of plant heights on study 2c (instead of the actual 67.3), photo height determinations would be inflated by an average of 7 cm. The magnitude of bias would vary with plant size and therefore would be reflected in both the slope and intercept of the regression between ground- and photo-measured height.

Further, photo scale affects the accuracy of photo determinations of maximum crown diameter ($CD1_p$) and crown area (CA_p) through the way in which it is used in the calculation of these response variables. With LSP, plant heights can represent a significant fraction of the overall camera height and biased results are likely if photo scales are not adjusted to reflect the height at which crown measurements are made (i.e., $HT_p(mid)$; Appendix 2). For example, when CA_p was computed by adjusting photo scale for one-half of total plant height, the regression slope for the 91 crowns in field study 1 fell below 1 ($p = 0.004$) and the standard error increased to 0.125 m^2 ($p = 0.077$). Precision was even further reduced when no scale corrections were made at all (SE = 0.1615 m^2, $p = 0.006$). The extra parallax reading required to obtain the height of a crown at its widest point ($HT_p(mid)$) is worthwhile, particularly if "push-button" readings can be made.

Relief displacement is the shift in photographic position of an object, caused by its elevation above or below a selected datum (Wolf 1974). Relief displacement causes trees to appear to be leaning in the photographs and, although it is the very phenomenon that allows one to view stereoscopic photos in the third dimension (and measure height), it has the potential to introduce bias in $CD1_p$ and CA_p determinations. Concern is for over-estimation caused by inclusion of portions of the side view in the trace of the plan view of the crown.

When relief displacement (d) was computed for each crown (Equation 2) and related to crown measurement error (photo - ground), evidence of bias was not detected (Fig. 5). Under the null hypothesis that errors in photo-estimated crown dimensions are independent of d (at least within the range of r employed), data should be scattered about a line with 0 slope. If

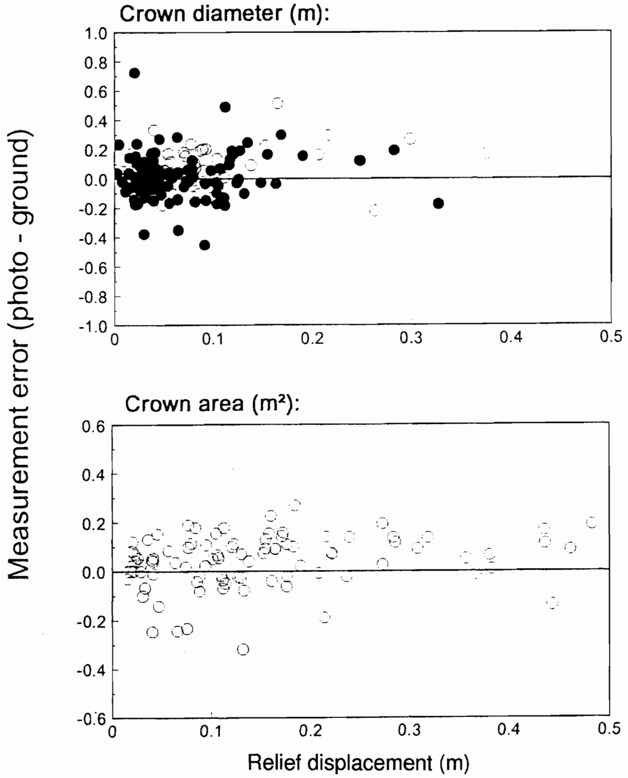

FIG. 5–Crown measurement error (photo - ground) *v.* relief displacement for trees in study 1. Points represent paired observations for crown visibility classes O (open) and P (solid); solid lines provide reference at 0 error. Observations for crown area represent the 91 rootstocks for which detailed crown area determinations were made.

d is significant enough to cause crowns to be measured more from the side than from above, both $CD1_p$ and CA_p values should generally be inflated and the trend in the errors should slope upward to the right with increasing *d*. Regression statistics for the lines in Fig. 5 suggest the presence of weak trends (slope = 0.362, $p = 0.038$, for *CD1*; slope = 0.197, $p = 0.041$, for *CA*). However, it appears that the proportion of variation in measurement error associated with relief displacement is small enough to be of little practical significance in either case. Scatter plots for the other studies displayed similar patterns.

Further substantiation of this conclusion comes from data collected for 168 plants in field study 4 that occurred on two or more photo pairs taken during the same session. Pairs of repeat observations (same plants, different photo pairs) were differenced, so that the observation with the smaller *r* was subtracted from that with the larger *r*. The mean paired difference for *r* was 0.643 m ($t_{167} = 17.465, p < 0.001$) and for CA_p, 0.007 m^2 ($t_{167} = 0.7097$, $p = 0.479$). Had *d* influenced CA_p through misinterpretation of plan views, the paired differences in CA_p ought to have reflected this. Thus, the general practice of confining measurements to the inner 70% of the stereo portion of the photographs appears to provide sufficient protection against bias due to relief displacement (at least at the photo scales and plant heights examined).

Effects of Species Characteristics

In general, the relationship between ground- and photo-measured plant height did not vary with species ($p > 0.122$). However, certain crown structures, characterised by branchless terminal shoots containing small leaves (< 2 cm), caused bias and reduced precision of height measurements due to inconsistent visibility on the LSP. These included such species as spruces (*Picea* spp.) and firs (*Abies* spp.), and some non-arborescent species like *Vaccinium*. In study 1, for example, the height of some black spruce (*Picea mariana* (Mill.) B.S.P) crop trees could be accurately determined, while the vast majority were under-estimated on the photos (Fig. 6). If such species are to be evaluated on LSP, (1) species-specific height-correction equations may need to be developed, (2) photo scales should be as large as logistically feasible (i.e., ≥ 1:225 contact), and (3) increased ground-truthing should be planned. If the species in question is central to the investigation, evaluations may be more effectively conducted on the ground.

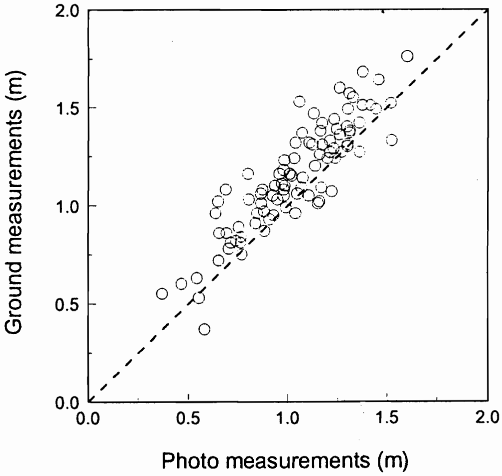

FIG. 6—Ground- *v.* photo-measured black spruce height for field study 1. Points represent paired observations; broken line shows a reference slope of 1 and an intercept of 0 (these data are not included in the regression statistics provided in Table 3).

Similarly, species differences were generally not significant in the relationships between $CD1_g$ and $CD1_p$ (e.g., field study 1, $p > 0.383$). Species differences in the relationship between CA_g and CA_p could not be thoroughly explored because of insufficient degrees of freedom for individual species (field study 1, 91-tree subset).

Effects of Crown Closure

As crown closure increases, parallax readings at the ground (base of the plant) are made with decreasing confidence. This is caused directly by foliage obstructing the view of the ground and (or) indirectly by shadows obscuring the ground surface. In studies 1–5, differences in the relationship between ground- and photo-measured height due to crown visibility (classes O, P, and F) could not be detected ($p > 0.05$; tests applied to individual species groups when differences between species were detected). This result was not unexpected, since all of the field studies were situated on relatively level terrain and none of the canopies was so dense that a representative base reading could not be obtained within a 2-m radius of a given plant.

In field study 6, beyond about 1 plant/m^2 (10 000 plants/ha), ground visibility became limited and there was a tendency to over-estimate plant height (Pitt 1994). This may be avoided, under level-terrain conditions, if a plane is generated from three parallax readings taken at representative locations in the target area where the ground is visible. Then, each plant's base reading can be interpolated from its x,y position on the plane (e.g., Aldred & Hall 1975). When this was done in study 6, bias at high crown closure levels was eliminated (Pitt 1994).

In study 2c, where f, H, and B were more representative of the values that might be used in practice, the use of plane-interpolated base readings resulted in a marginal loss in precision of individual plant height estimates (SE = 0.085 m *v.* 0.057 m). The more micro-relief within the target area, the less desirable this technique will be from the perspective of minimising precision.

As crowns appeared interlocked and overlapped, it also became increasingly difficult to distinguish the margin of one crown from another and the reliability with which crown diameter and crown area measurements were made decreased (Table 4). Individual-plant evaluations at high densities are extremely costly (and often questionable) on the ground. Depending on survey objectives, advantages may be gained by shifting focus from individual plants to groups of similar composition and structure. Then, LSP may be used to obtain accurate estimates of response variables such as average height, percentage cover, canopy area, and species composition for each such unit delineated.

Effects of Photo Timing

Several photo sets were taken in the deciduous leaf-off condition (Table 2—2d, 4c, 5b, 6b, and 6c). In practice, such timing may be used to advantage to enhance the visibility of conifers that would otherwise be obscured by taller deciduous or herbaceous vegetation. However, the extent to which hardwood species can be accurately evaluated in leaf-off condition appears questionable. In study 4c, representing the largest photo-scale tested for leaf-off measurement, sweetgum (*Liquidambar styraciflua* L.) terminals that were clearly visible on the photographs were coded so that they could be isolated for separate analysis (40 of 357 plants measured). Not surprisingly, the relationship between ground- and photo-measured height on these plants fell on the line of equality (0 intercept, unit slope, $p > 0.568$; SE = 0.041 m; Table 3) while the heights of remaining plants were under-estimated by varying amounts (SE = 0.154 m; Table 3) (typical of the results illustrated in Fig. 6). Similar trends were observed for hardwoods in studies 5b, 6b, and 6c. Increased variability was also observed for leaf-off $CD1_p$ and CA_p determinations (e.g., study 6b *v.* 6a; Table 4). Most of the hardwood crowns on photo set 2d could not be visually separated from logging slash, herbaceous vegetation, and other debris on the forest floor and measurements were not attempted.

Effects of Ground-truthing Characteristics

When primary response variables can be measured on LSP, identical ground- and photo-measurement procedures obviate corrections for "built-in" biases. As exemplified by the closed-traverse method used for CA_g determination, this may not always be practical or logistically feasible. In other situations, however, biases might easily be avoided by careful planning of ground-truth efforts. For example, in field studies involving pine (*Pinus* spp.) height measurements (studies 2–6), apparent species differences in the regression relationship between ground- and photo-measured height may be attributable to differences in the way pines and hardwoods were measured in the field (i.e., pines were measured to the tip of the terminal bud, while hardwoods were measured to the tallest leaf). Measurements on the photos were made to the top of the tallest visible portion of each plant; for pines this is often the tuft of needles 3 to 7 cm above the terminal bud. This discrepancy in methods was reflected statistically in field studies 4b, 4c, 4d, and 5b, with pine regression intercepts ranging from –0.03 to –0.07 and slopes not significantly different from 1 ($p > 0.421$; Table 3). Field studies 2a and 2b had intercepts not significantly different from 0 ($p > 0.394$), but slopes less than 1 (0.93 to 0.98), indicating non-constant over-estimation on the photos. Clearly, the photo measurements are sensitive enough to reveal minor procedural discrepancies. Further examples of bias caused by discrepancies in measurement procedures or times have been identified by Pitt (1994).

CONCLUSIONS

This paper has explored the extent to which low-cost large-scale aerial photographs (LSP) might be used to augment field evaluations of woody plant attributes in vegetation surveys of newly regenerating forest sites. Stereo LSP was acquired by suspending a standard 35-mm camera system from a balloon or tripod platform. The balloon was suitable for large areas containing several sample plots in close proximity or where large camera heights (> 7 m) were required. The tripod was successfully used for photographing small plots ($\leq 3 \times 3$ m) and was found to be more portable and less costly to own and operate than the balloon. Photo evaluations were conducted on 10 × 15-cm prints enlarged from images captured on 125, 200, or 400 ASA print film. A BASIC computer program streamlined photo data collection by recording height and crown measurement data, graphing stem maps of plants in research plots, and performing all necessary calculations.

The primary dimensions of visible individual woody plants (total height, maximum crown diameter, and crown area) could be estimated to within 10% of their mean values on the LSP obtained. Photo measurements of these response variables were generally unbiased and consistent. For most purposes, the levels of precision and accuracy obtained are likely to be within acceptable limits. For crown area, direct photo measurements were more accurate than traditionally used indirect estimates based on two field measurements of crown diameter. This result suggests that photo estimates of crown area may provide a more sound index of plant competitive status than traditional field estimates.

For the response variables examined, LSP precision and accuracy can be ensured or enhanced by adhering to the following guidelines:

(1) Use the largest photo scales that logistics will allow.

(2) Optimise camera separation relative to camera height (base-to-height ratio) to provide adequate vertical exaggeration in the stereo model (a differential parallax of 2 to 5.5 mm should provide results similar to those reported),

(3) Confine measurements to the inner 70% of the stereo (overlap) portion of each photo pair.

(4) Correct photo scale, on an individual-plant basis, for the actual height at which measurements of crown dimensions are made.

(5) Use the most precise values of camera height, focal length, airbase, and print enlargement factor available in all calculations.

(6) Personnel should plan on spending 15 to 30 hours in training before reaching measurement precision levels similar to those reported (Pitt 1994). Proper use of the parallax bar requires particular attention.

(7) Avoid using LSP for evaluations of (a) tree height on species with tall slender terminal leaders, (b) tree height on very uneven terrain, (c) deciduous species in leaf-off condition, and (d) vegetation with high levels of crown closure.

(8) In (7d), where micro-relief is minimal, use the co-ordinate plane method for interpolating base parallax readings. Also, consider shifting focus from individual plants to vegetation groups of similar composition and structure, for which average height and percentage cover values can be obtained.

(9) Avoid "built-in" biases by striving to synchronise ground truthing and LSP measurements in terms of timing and procedures. When corrections for bias are anticipated or suspected, a minimum of 30 individuals, representing the entire range of variates in the population of interest, should be considered for adequate statistical power.

This investigation has demonstrated that reliable measurements of individual woody plant attributes can be obtained directly from low-cost LSP. LSP may be effectively employed in a two-phase or double sampling design, which will permit correction for bias associated with the omission of smaller plants hidden in an understorey and enhance sample distribution and intensity (Pitt *et al.* 1996).

ACKNOWLEDGMENTS

The authors are indebted to Robert Tufts (Auburn University) for his assistance in computer programming, Dick Crabbe (National Research Council) for loan of the balloon, and the staff of Camera Graphics (Auburn) for their patience and quality photo finishing. Bruce Zutter, Dwight Lauer, and Robert Jones (all of Auburn University) are recognised for their assistance in the acquisition of some of the photographs and ground-truth data used in this investigation. Evert Johnson, Greg Somers, Ralph Meldahl, and Dean Gjerstad (all of Auburn University), Robert Fleming, and Richard Sims (of the Canadian Forest Service), and two anonymous referees provided many helpful comments to improve this manuscript.

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APPENDIX 1

SUMMARY OF FIELD MEASUREMENTS CONDUCTED BY FIELD STUDY

(1) Two growing seasons after treatment (July 1991), woody plants included in the study's variable-radius sample units (SUs) were measured for total height (HT_g; "g" denoting ground measurement) to the nearest centimetre and crown diameter ($CD1_g$ and $CD2_g$, leaf tip to leaf tip, Fig. 2). Within 372 randomly selected SUs, the position of all hardwoods and crop trees included in the original efficacy evaluation was also recorded by measuring the distance and bearing from the SU to the centre of each crown. (Study reference: Pitt *et al.* 1993).

A subset of 91 stem-mapped hardwoods were selected for detailed crown area measurement. Selected crowns were not interlocked or overlapped by other crowns and included the full range of crown size observed in the original sample. Crown area (CA_g) was determined by projecting on to the ground the major points of change in a crown's perimeter and then conducting a closed traverse (with compass and metre stick) around the projected points (Fig. 2). Depending on the cross-sectional shape of the crown, between 5 and 10 legs were measured for each traverse.

(2) Two and three growing seasons after site preparation (September 1992 and 1993), broadleaved woody plants and crop trees falling within SUs (0.5-m radius plots) were measured for HT_g, $CD1_g$, and $CD2_g$, in the manner described for field study 1, above.

(3) Two-growing seasons after treatment (September 1991), crop trees situated in 2.1 × 2.1-m SUs on bedded surfaces were measured for HT_g, $CD1_g$, and $CD2_g$, as described for the two previous studies (except that crown diameter measurements were bud tip to bud tip).

(4) Sweetgum in 1.5-m radius neighborhoods centered on 32 pines were measured for HT_g, $CD1_g$, and $CD2_g$ on 21 May, 19 June, and 23 September 1991, and 12 March and 18 May 1992. Focal pines were also measured at these times. With the exception of the March sweetgum measurements, all crown diameter measurements were leaf tip to leaf tip. Distance and bearing were also available for each sweetgum relative to each focal pine on a plot.

(5) Measurements of HT_g, $CD1_g$, and $CD2_g$ (leaf tip to leaf tip on pine, bud tip to bud tip on sweetgum) were conducted in January 1992. The position (*x,y* co-ordinates) of each plant was also available. (Study reference: Mitchell *et al.* 1993).

(6) Measurements of HT_g, $CD1_g$, and $CD2_g$ (leaf tip to leaf tip on pine, bud-tip to bud-tip on sweetgum) were conducted on all plants within each Nelder plot in January 1992.

APPENDIX 2

EQUATIONS USED FOR PHOTO MEASUREMENTS OF PLANT HEIGHT AND CROWN AREA

(*see* Pitt 1994 for derivations)

$$HT_{\mathrm{p}} = \frac{H \times \Delta P}{\dfrac{f \times B \times EF}{H} + \Delta P} \qquad [4]$$

where: HT_{p} = photo estimate of plant height (m),

H = camera height above the ground (m),

ΔP = difference in absolute parallax between the top and bottom of the plant (mm),

f = actual focal length of the lens (mm),

B = airbase (m), and

EF = print enlargement factor (4.576).

$$CA_{\mathrm{p}} = CA_{\mathrm{p}}(raw) \times \left(\frac{H - HT_{\mathrm{p}}(mid)}{f \times EF} \right)^2 \qquad [5]$$

where: CA_{p} = photo estimate of crown area (m^2), adjusted for photo scale at $HT_{\mathrm{p}}(mid)$,

$CA_{\mathrm{p}}(raw)$ = crown area, unadjusted for photo scale, and

$HT_{\mathrm{p}}(mid)$ = approximate height of the crown at its widest point, computed via Equation 4.