2 INVENTORY DESIGN CONCEPTS

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2.1 Introduction

A forest resource inventory is

> *a qualitative and quantitative investigation of the location, ownership, extent, nature, condition, purpose and capacity of the forest estate on a broad scale.* (Carron 1968)

It involves a combination of textual information (the nature, condition and capacity) and spatial or geographic information (the location, extent and ownership-pattern) about the forest resource. Inventory design covers the methods of collecting, analysing and presenting such information. Selection of a particular design depends on the inventory objectives and various limitations of cost, time, equipment and personnel.

As it is impractical, indeed unnecessary, to measure every tree in a forest other than for its smallest units, various methods of sampling are used to estimate mean values per unit area (e.g. timber volumes) and then to expand these values to obtain estimates for the entire forest and/or its major sections. Simple random sampling, whereby samples are selected at random across the whole forest, is one of the simplest sampling methods. Alternatively, simple systematic sampling uses samples that are selected on a regular pattern, often a rectangular grid, to ensure that the resource is evenly covered by samples. The relative merits of systematic versus random sampling, together with other sampling designs, are discussed in most basic texts on sampling (e.g. Cochran 1977) and forest inventory (e.g. Husch *et al.* 1982).

Sampling efficiency is often improved by subdividing the forest into uniform strata followed by sampling within each stratum separately - called stratified sampling. Stratified sampling is effective in forest types where there are distinctive homogeneous subunits (i.e. strata) in which the variability is low compared with the variability between strata. Examples include forests consisting of a mosaic of even-aged stands of different ages; forests where pure stands of one species occur separated from pure stands of another or several other species. Even if the stratification does not improve statistical efficiency, the map produced in the process may have other benefits for management, such as priority for treatment (Kendall and Sayn-Wittgenstein 1961).

Double sampling (syn. two-phase sampling) is another method that can be applied, with or without stratification, in combination with either random or systematic sample selection to increase the sampling efficiency (Fig. 2). The method involves using a quick and cheap estimation

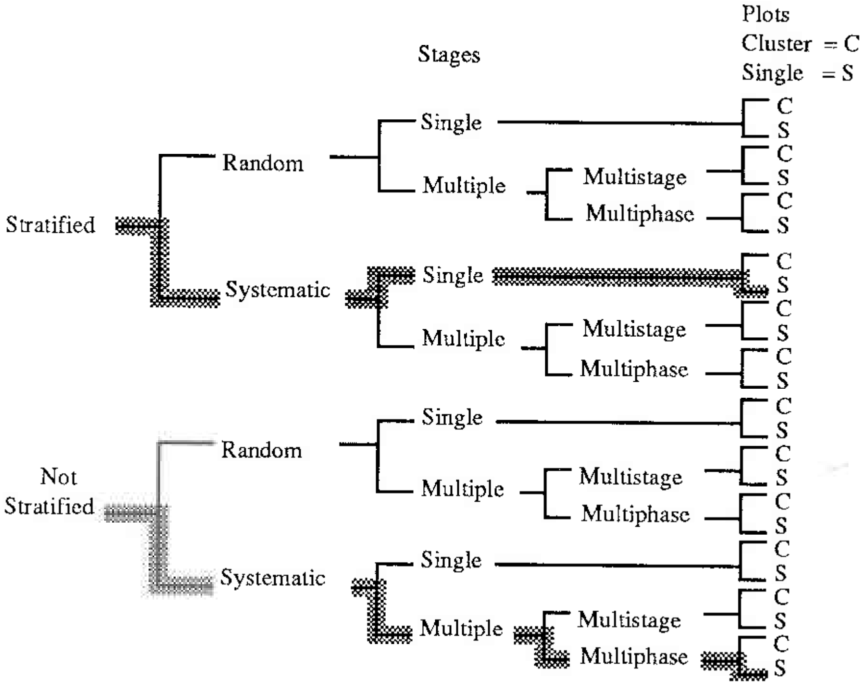


Figure 2

Survey-design options. In multiple-survey designs, alternatives shown are not necessarily mutually exclusive. For example, multistage and multiphase sampling (i.e. double sampling) can be and frequently are used together in large-scale photographic sampling programs. The stratified, systematic, single-stage sampling approach using single samples (e.g. plots) at each sample point is commonly used by ground-based forest surveys. The non-stratified, systematic, multiphase approach with single samples per sample point is the method selected for the jarrah inventory.

process, such as aerial photography, to obtain an intensive first-phase sample, supplemented by a second-phase sample to obtain more detailed and accurate measurements on a small percentage of the first-phase samples. The purpose of the double sample is to refine the first-phase estimates to correct for any bias and to provide more details, such as the apportionment of gross volumes into product classes. Normally this is done by establishing mathematical relationships between the two sets of data, usually by linear regression. A useful account of double sampling is given in Wear *et al.* (1966).

Double sampling differs from *multistage sampling* wherein increasingly detailed information is obtained by successively sampling from progressively smaller subunits of the population.

Spatial data in forest inventories depicting point locations, boundaries, routes, bearings, distances and areas have traditionally been recorded and displayed on hard copy maps. In modern inventories the evolving technology of computerized GIS now offers a much more efficient and flexible approach for the recording, analysis and presentation of spatial information. These GIS store and analyse spatial information as digital coordinate data that can readily be processed to produce a wide variety of outputs such as maps, graphs and tables. Such outputs may relate to single themes or multiple themes of overlapping spatial information (Burrough 1986).

2.2 System components and relationships

Major components of the inventory system are illustrated in Figure 3 and explained as follows :

Two-phase sampling was selected as the sampling scheme most likely to provide the required volume estimates in the given time frame, while giving the potential for flexible

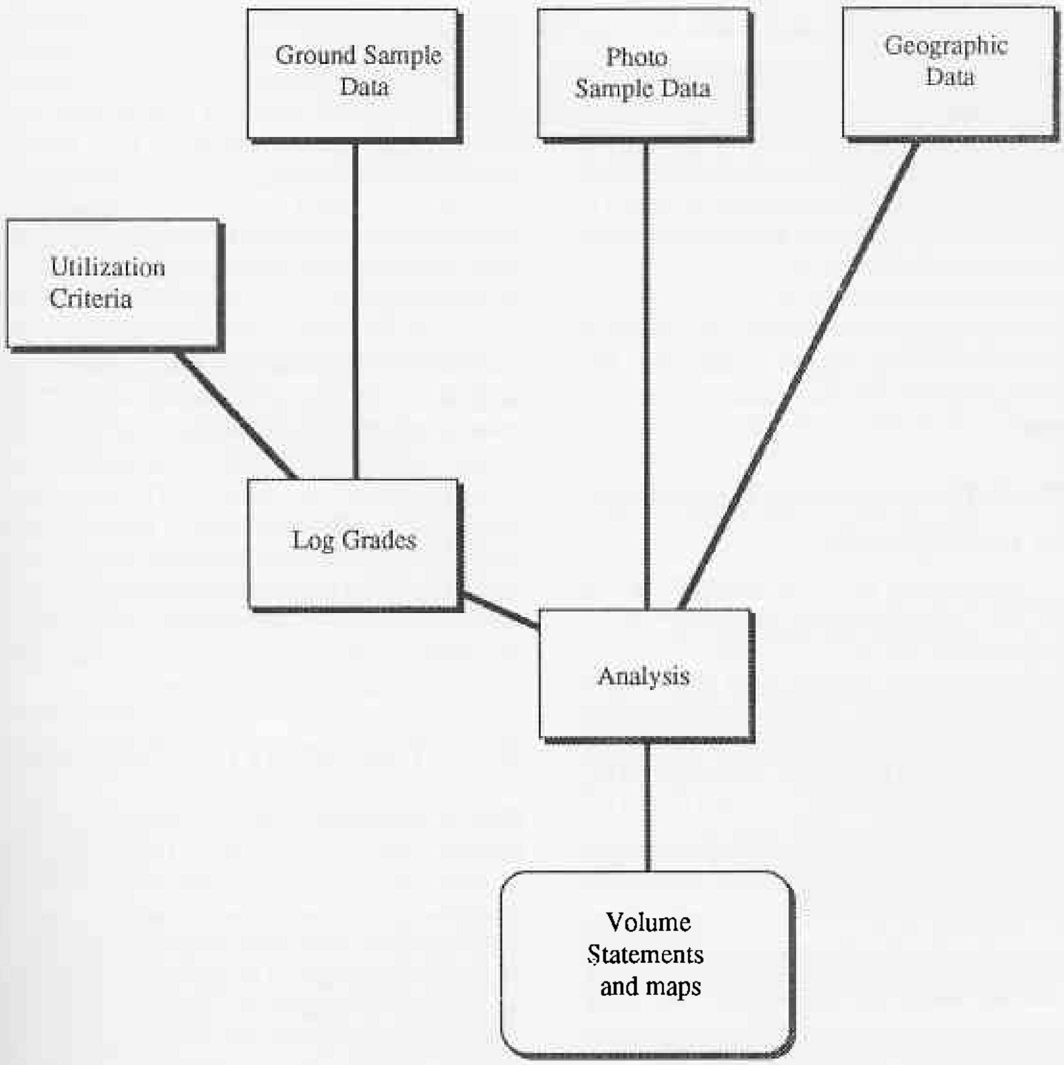


Figure 3
Major components of the inventory system.

spatial analysis of the data. Stratified sampling was rejected because it was not desirable to have volume estimates restricted to predetermined strata. It was also recognized that stratification in the jarrah forest may not have significant statistical advantage, given that the forest is uneven-aged and exhibits gradual changes in species composition. This means that the variability per hectare of volume within stands of jarrah that are defined as *uniform* may actually be quite high although the average volume may differ little from that of adjacent stands.

The use of photography in the two-phase sampling scheme gives the added advantage of providing a permanent record of each plot at the time of the initial measurement, which allows for further measurements to be made to check calibrations or to account for additional unmeasured variables.

Photo sampling was selected to provide the basis for estimating gross bole volume in the first phase because it allows for large numbers of samples to be obtained quickly and at low unit cost. Gross bole volumes are estimated from photo-measurements of heights.

Ground samples provide more accurate estimates of bole volumes and a breakdown into log volumes to serve as correction and conversion factors for the photo estimates. Using a new technique, the quality of each bole is described in terms that can be modified with computer programs to determine the volumes of different log grades under a range of utilization criteria.

Spatial analysis is arranged with the aid of a GIS, in which the sample data are linked with map information. The aim is to allow for the generation of volume statements for any areas of interest.

2.3 Methods for acquiring large-scale aerial photographs

Aerial photography has a significant, largely untapped, potential for reducing the time and cost of data collection in extensive forest inventories. Medium scale photographs (1:10 000 - 1:25 000) for example, are frequently interpreted to stratify large heterogeneous forests into smaller, more uniform areas that may then be sampled efficiently on the ground. Maps produced in this way provide a means for determining the size of different areas and they also represent a useful management tool for recording and monitoring other forest quantities and conditions.

Alternatively, timber volumes are sometimes estimated by reference to standard images (e.g. Stellingwerf 1967) or by estimating stand parameters such as stand height and crown cover, then using aerial stand volume tables to predict stand volumes (e.g. Meyer and Worley 1957). This method can be implemented successfully in uniform forests where the relationships are strong, but it is inadequate in more complex forest types where the structure of the stands cannot be adequately described, or where species cannot be identified.

Large-scale photographs (1:1000 - 1:3000) are required to estimate volumes in such forests. They enable species to be identified more accurately, smaller trees to be counted and the dimensions of individual trees to be measured. Their distinguishing characteristic is the provision of ground-quality measurements from aerial sampling independent of ground control.

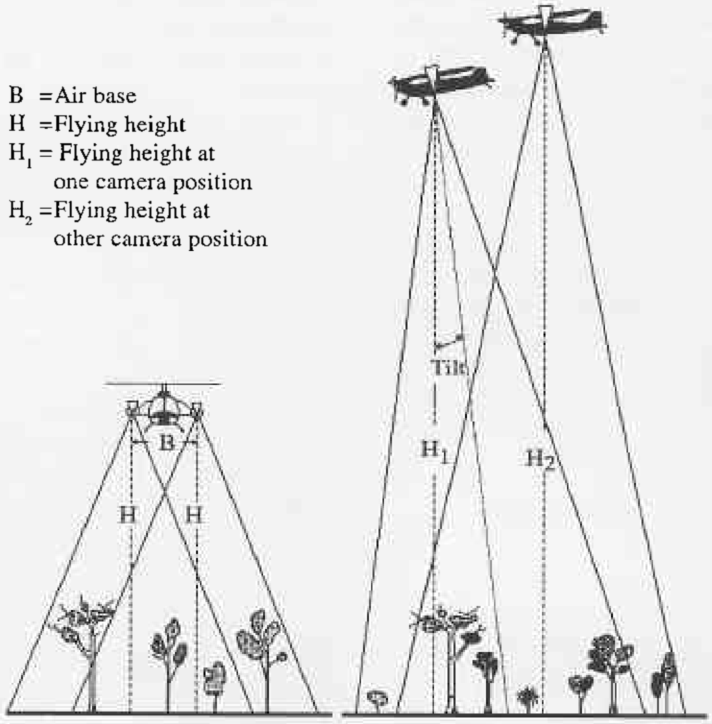
Progressive accounts of developments in large-scale photographic equipment and methods have been published by various authors, principally from Canada, over the past 30 years (Spencer and Hall 1988). The current work draws upon the Canadian experiences plus related research in the USA (Avery 1958, 1959), Australia (Spencer 1972, 1979) and Europe (Rhody 1977).

Application of large-scale photographic techniques requires specialized equipment and methods for managing major problems associated with image-motion, scale-determination, and camera tilt. Owing to the small coverage per frame, it is impractical to use ground control to determine photo scale for operational inventories. Therefore, alternative approaches have been developed for obtaining and scaling large-scale photographs without reference to ground control: twin-camera fixed-based systems (Fig. 4a) and single-camera sequential systems with and without a radar or laser altimeter and a tilt recorder (Fig. 4b).

Large format cameras are generally not well suited for very large scales because of limitations with camera cycling rates, image motion, and higher costs (Spencer and Hall 1988). Consequently, small format cameras, in particular 70 mm cameras, are common. The twin-camera fixed-base system and single camera sequential system use different methods for photo scaling and photo orientation for measurement purposes. Different designs are also used according to choice of aircraft, camera mountings, air-base orientation, and application. The two basic systems are described in the following sections.

2.3.1 Twin-camera fixed-base systems

Early developments of this system for Canadian forestry (Lyons 1961, 1964, 1966, 1967) were based on recommendations from the USA (Avery 1958, 1959). The method uses two identical, synchronized cameras mounted a set distance apart with their principal axes parallel (Fig. 4a). Stereopairs are obtained by simultaneously firing the two cameras, thereby providing a means for determining photo scale based on the ratio of photo-base over actual air-base (i.e. camera separation). The relationship between this scale and focal length of the cameras then provides a simple method for determining flying height that does not require ground control.



(a) Twin-camera fixed-base aerial photography

(b) Single-camera sequential photography.

Figure 4.
Methods of large-scale aerial photography.

The fixed-base method provides stereopairs of photographs of known relative orientation and freezes dynamic scenes, such as tree crowns swaying in the wind. A disadvantage of the method is that the fixed-base controls the amount of overlap at each scale, thereby affecting differential parallax, and, consequently, the accuracy of photo height-measurement (i.e. less stereo effect at smaller scales because of reduction in the base-to-flying-height ratio).

Based on Lyons' early work, the Ministry of Forests in British Columbia, Canada, developed a twin-camera system with a boom mounted longitudinally on a helicopter and twin Hasselblad MK70 photogrammetric 70 mm cameras (Bradatsch 1980).

Other workers (Spencer 1972, 1979; Rhody 1977; Rivest 1980) have investigated the use of transverse booms, which enable photographic scales to be calculated more precisely because minor mis-synchronization of the cameras does not change the effective length of the boom, as is the case with a longitudinal orientation.

Adaptation of the twin-camera concept to fixed-wing aircraft offers the potential advantages of a longer air-base, lower operating costs, and greater flying range (Williams 1978). Conversely, it suffers disadvantages owing to the adverse effect of higher aircraft speeds on image motion, as well as the lower manoeuvrability and reduced ground visibility with fixed-wing aircraft. The system may also suffer from instability owing to wing flexing. This can be reduced by using aerodynamic camera pods and mechanical compensation to the camera mounts, although not to the extent that is needed for rigorous photogrammetry (Spencer and Hall 1988).

A variety of cameras are suitable for fixed-base photography because each stereopair is acquired from simultaneous firing of two cameras, which means that the recycling speed of the cameras is not a major concern.

2.3.2 Timed-interval large-scale photographic systems

This method uses sequential photographs from a single camera to obtain stereo coverage through forward overlap of the photos. Scale can be determined from ground reference points, a foliage-penetrating radar, (Aldred and Hall 1975) or a rapid pulse laser altimeter that provides for discrimination between canopy and ground signals (Aldred and Bonnor 1985). Relative orientation of stereopairs is usually determined from direct measurement of camera tilts, or photogrammetrically when the photo-base-to-flying-height ratio is large enough (Williams 1978).

Timed-interval photography offers greater latitude in scale because the air-base can be varied for different flying heights to maintain an acceptable base-to-flying-height ratio for parallax measurements. This makes it suitable for a wide range of applications at different scales, including regeneration surveys at 1:500, volume estimation at 1:1200, and disease detection at a scale of around 1:5000 or smaller. Other advantages are that it can readily be used in fixed-wing aircraft, resulting in lower costs and, if the cameras are mounted internally, it allows for access to cameras and film magazines during flight.

The instruments required to determine scale and tilts with this system are expensive and require careful calibration and operation to achieve good results. Furthermore, a reconnaissance camera may be required to achieve the rapid recycling rates needed to obtain sufficient overlap for satisfactory stereo-viewing of large-scale photographs taken from low altitudes.

2.4 Photo measurement concepts

2.4.1 Variable selection

Two of the most important parameters required for a forest inventory are stand volume and the size class distribution of individual trees, usually expressed as diameters. Tree volumes cannot be measured directly on aerial photographs and direct measurement of diameters is either impossible or unreliable. Therefore both parameters must be estimated indirectly from other parameters that can be measured on photographs, such as tree height, crown diameter, crown area, stocking, or measures of competition with neighbouring trees.

Volume estimates based on photo-measurements imply the use of either aerial stand-volume tables or aerial tree-volume tables. Aerial tree-volume tables imply the use of photographs at scales large enough to show individual trees in open stands.

For most species, total tree height has the strongest correlations with both bole volume and diameter (Sayn-Wittgenstein and Aldred 1967; Spencer 1972; Aldred and Lowe 1978; Hall *et al.* 1989). This is followed by measures of crown size (often crown area) and measures of competition with neighbouring trees. However, Hall *et al.* (1989) have shown that the extra cost of measuring crown area may not be justified by the additional small benefit to be gained from its inclusion in the volume or diameter estimating function. Aldred and Sayn Wittgenstein (1972) concluded that '*measures of relation to neighbours*' would not prove to be very useful for estimating volume except in special cases.

Initial studies in the jarrah forest attempted to estimate stand volumes from 1:4500 scale photography. It was found, however, that the correlations between stand volume and the usual parameters, stand height and crown cover, were too low to be cost effective. The structure of the jarrah forest was too complex for simple stand volume estimates. Stands of equal height and crown cover could have different volumes depending on the structure of the forest, but insufficient detail could be seen on the photos to be able to count trees or interpret the structure with sufficient accuracy.

It appeared that estimation of timber volumes in the jarrah forest from aerial photography would have to be based on estimates derived from individual trees.

To test this theory, approximately one hundred jarrah trees were measured near Collie to determine the relationship between gross bole volume and tree height. Crown dimensions were not investigated at this stage, because they are difficult to estimate from the ground and ground estimates vary considerably from estimates made on photographs. It was also anticipated that the crown dimensions would be of secondary importance to height because many of the old trees have degenerate crowns that bear little relationship to their current standing volume (Fig. 5).

A strong exponential relationship was found between bole volume and total height, indicating that stem volumes could be estimated from measured tree height as long as suitable photographs could be obtained that showed individual trees (Fig. 6). The derived relationship is :

$$\ln V = a + b \ln H$$

where $\ln V$ = natural log of bole volume (m^3)
$\ln H$ = natural log of tree height (m)
a and b = constants

Test photographs at 1:1000 - 1:1500 scale were taken over the Collie forest using a Hasselblad 70 mm camera from a Piper Super-Cub aircraft. A combination of slow camera recycling and a high aircraft speed resulted in a small stereoscopic overlap, i.e. there was a very large base-flying-height ratio. This made it difficult to measure tree-heights accurately, nevertheless, it demonstrated that individual trees could be identified and measured. Based on a further review of Canadian experiences and parallel research at Melbourne University (Spencer 1972) it was decided to implement a twin-camera, fixed-base photographic system.

2.4.2 Measurement of tree heights on large-scale photographs

There are three approaches for determining tree heights from aerial photographs; measurement of shadow-length, measurement of displacement on single photographs, and measurement of stereoscopic parallax. The wider application and greater accuracy of the parallax method has led to its exclusive use in large-scale photographic programs. Therefore, it is the only method discussed here.

Parallax is the displacement of one image with respect to

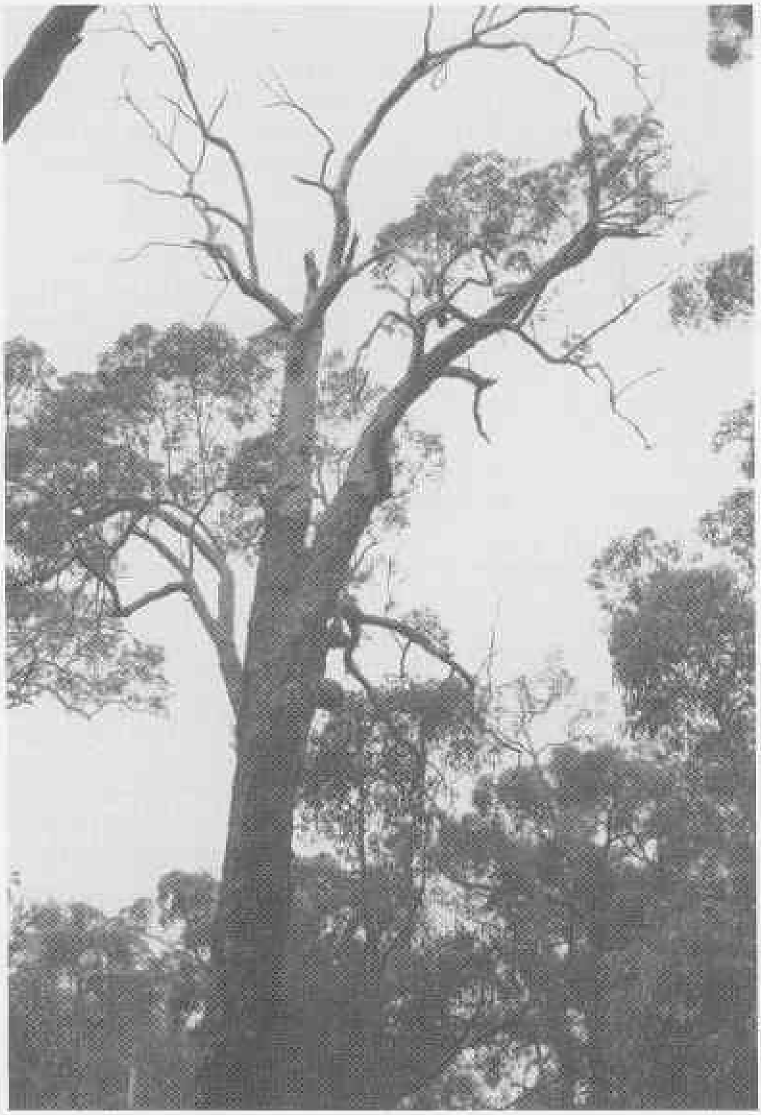


Figure 5

Degenerate marri crown. Many old trees have degenerate crowns that bear little relationship to their current standing volume.

another that arises when two objects at the same planimetric position but at different elevations are viewed obliquely. For measurement of heights, parallaxes parallel to the air-base are of most interest.

Requirements for reliable tree-height measurements with the parallax method are :

(i) accurate flying height;
(ii) large differential parallaxes and accurate measurement;
(iii) absence of, or adjustment for, differential tilts;
(iv) absence of wind-sway of tree crowns;
(v) good resolution of tree tops;
(vii) good photographic *penetration* below canopy to facilitate parallax readings at or near the base of each tree or at sufficient ground points to develop a digital terrain model.

With fixed-base photography the flying height (H) can be determined accurately from the photographic airbase; differential parallax can be made large by careful selection of H; differential tilts are eliminated or minimized by preflight alignment of the two cameras; and wind-sway is not a problem because of the simultaneous exposure of the two cameras which *freezes* dynamic scenes. Requirements for resolution of tree tops and photographic penetration below the canopy are essentially the same for both fixed-base and timed-interval photography, and depend on choice of scale, camera, film, lighting, exposure and film processing.

The parallax formula for height determinations is usually stated in the form:

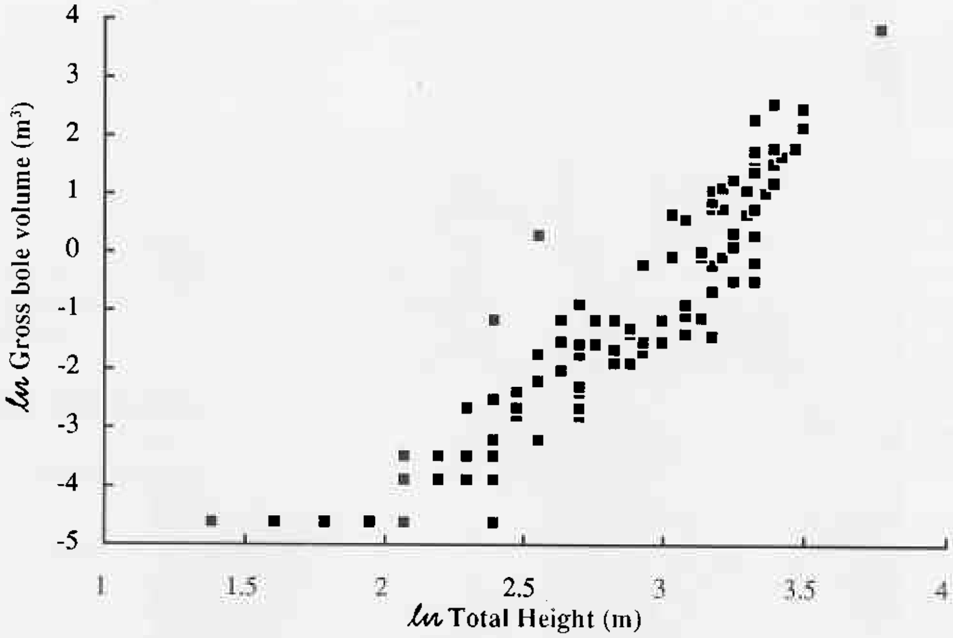


Figure 6

Jarrah gross bole volume / total height relationship; 112 observations, $r^2 = 0.8439$.

(1) $$h = H_b.dp/(P_b + dp)$$

For flat country P_b is equal to the photographic air-base (b).

(2) Thus $$h = H_b.dp/(b + dp)$$

Making the alternative substitution

$$P_b = f.B/H_b,$$

gives the following equation which can be used for fixed-base photography:

Thus $$h = H_b.dp/(B.f/H_b + dp),$$

which transposes to give

(3) $$h = H_b^2.dp/(H_b.dp + fB)$$

where h = height of tree (m)
H_b = height of the camera stations above the base of the tree (m)
dp = differential parallax (mm)
B = distance between the two camera stations, syn. air-base (m)
b = photographic air-base(mm)
f = focal length of camera (mm)
P_b = absolute stereoscopic x-parallax of the base (mm)

The above three formulae are exact in theory and under perfect conditions of photography and measurement would give the same results (Schut and van Wijk 1965). However, because perfect conditions rarely apply, results will vary.

By transformation of parallax equation (2) it is seen that :

$$dp = h.b/(H_b - h)$$

For conventional small-scale photography where object-heights (e.g. trees) are generally small relative to flying heights, this equation may be approximated by

$$dp = h.b/H_b.$$

Substitution of

$$b = B. f/H_b$$

gives $$dp = h. (f/H_b).(B/H_b).$$

This approximation does not apply with large-scale photography because the heights of objects cannot be assumed to be small in comparison with flying heights, hence

$$dp = h. (f/H_b).(B/(H_b-h)).$$

Because of this difference it is apparent that differential parallaxes can be large on photographs of very large scales, even when the air-base is very short and air-base to flying height ratio is small relative to values in conventional photography.

With fixed-base photography, increasing flying height increases overlap and consequently reduces differential parallax for objects of given heights. This is a constraint of the system in contrast with the single-camera system where flexibility in the choice of air-base allows for parallax conditions to be maintained over a range of flying heights, hence scales of photography. The latter system, however, requires very fast recycling of the camera at low flying heights to obtain desired overlaps. Thus, neither system is optimal for all requirements.

Other factors affecting both types of photography include film characteristics, image quality, distortions in the image, and the skill of the interpreter. Focal plane shutters cause distortions in the image which may be significant over the whole photograph, although their effect on tree-height measurement at a point on a photograph appears to be small. The type of film, transparency or print, colour or black and white, also has an influence on the accuracy of height measurements but differences between interpreters make this difficult to quantify.

2.5 Sampling design

The sampling design had to meet the objectives of a relatively intense sample over a large area in a short time. Two-phase sampling met this requirement, while providing flexibility as demanded by other constraints.

An important objective of the jarrah inventory was to provide valid volume estimates for any portions of the production forest zones, therefore samples were required at uniform intensity over all areas. Systematic sampling ensured such a uniform distribution and maximized the efficiency of flying, although it was recognized that random sampling would have provided more valid estimates of sampling error. This requirement for uniform coverage, plus the difficulty of obtaining random photo samples, amply justified the use of systematic sampling.

Various assumptions were made regarding the variances and costs of the two phases when estimating the required sampling intensities. Based on existing ground inventory data, it was expected that the coefficient of variation (CV) of gross bole volume from the photo samples would be approximately 70 per cent (i.e. the standard deviation is 70 per cent of the value of the mean). The required number of ground plots depended on the strength of the relationship between the two phases, and this was unknown for jarrah forest. Chehock (1981) stated that the ratio of ground estimate/photo estimate should be predicted to a CV of less than 20 per cent. It was expected, however, that ground estimates of sawlog volume would be less well correlated with the photo estimates of gross bole volume, so it was assumed that the CV of this ratio could be as high as 50 per cent. As the objective was to estimate sawlog volume to ± 25 per cent at 95 per cent confidence for areas of 10 000 ha, it was this figure that was used to determine the appropriate sampling intensity.

From Chehock (1981), the total relative sampling error can be calculated from the two phases as

$$E = \sqrt{E_1^2 + E_2^2} \quad (1)$$

where E = allowable sample error
E_1 = sample error from the first phase
E_2 = sample error from the second phase

The sample errors E_1 and E_2 can also be defined as

$$E = \frac{t.SD}{\sqrt{n}} \quad (2)$$

where SD = standard deviation
n = sample size
t = value of student's t at the appropriate confidence level (= 2 at 95%)

Substituting equation 2 into equation 1 gave

$$E = \sqrt{t^2SD_1^2 + t^2SD_2^2}$$

Using SD_1 = 70% and SD_2 = 50%, there was a wide range of combinations of sample sizes which could have been used to obtain a sampling error of 25 per cent for areas of 10 000 ha. It was expected from the literature that the cost of photo plots could be as little as one tenth the cost of ground plots (Lyons 1964), but this was untested in the local conditions. Also, costs were not the only factor in deciding the relative intensities of the two samples. It was desirable to maximize the use of the photographic systems once they were established, and also to ensure that the distribution of the first phase samples was adequate to meet the demands of the later geographic manipulation.

It was determined that an intensity of one photo plot per 50 ha and one ground plot per 500 ha would meet all these requirements. This corresponded to 200 photo plots and 20 ground plots in each 10 000 ha. (Fig. 7). It was planned to alter this intensity, if necessary, based on analysis of early results.

The efficiency of aerial photography is greatest when sample points are arranged densely along flight-lines that are spaced far apart. This, however, produces a very clumped sample and would have compromised an important objective of the inventory. As a compromise, flight-lines were selected at 1000 m intervals, with photo samples at 500 m intervals along each line. This involves 40 per cent less flying time than the same number of sample plots at 700 x 700 m spacing.

Ground samples were then selected as every fifth photo sample on every second line, giving a spacing of 2000 m x 2500 m, which closely approximated the desirable square configuration for maximum uniformity.

Fixed-area plots were chosen in preference to point samples because they are easier to define on the aerial photographs and they facilitate close matching of the ground and photo samples. Circular plots were selected as they involved only the matching of one point, and for a given area involve the smallest perimeter along which mismatches can occur between the two phases.

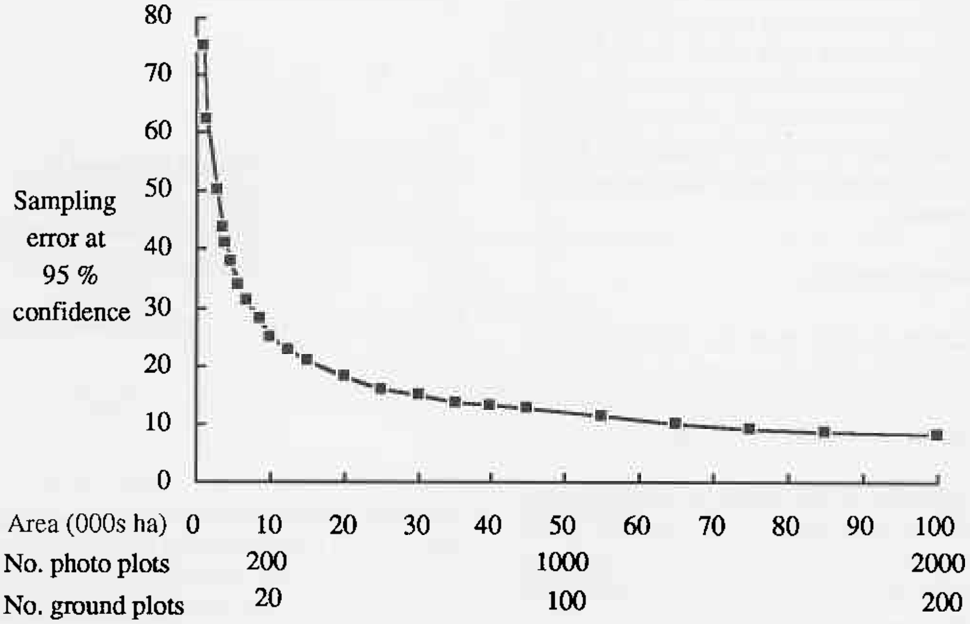


Figure 7
Forecast sampling errors for volume estimates derived for discrete areas of forest, assuming systematic plot locations, one photo plot per 50 ha, one ground plot per 500 ha and coefficent of variation as explained in Section 2.5.