

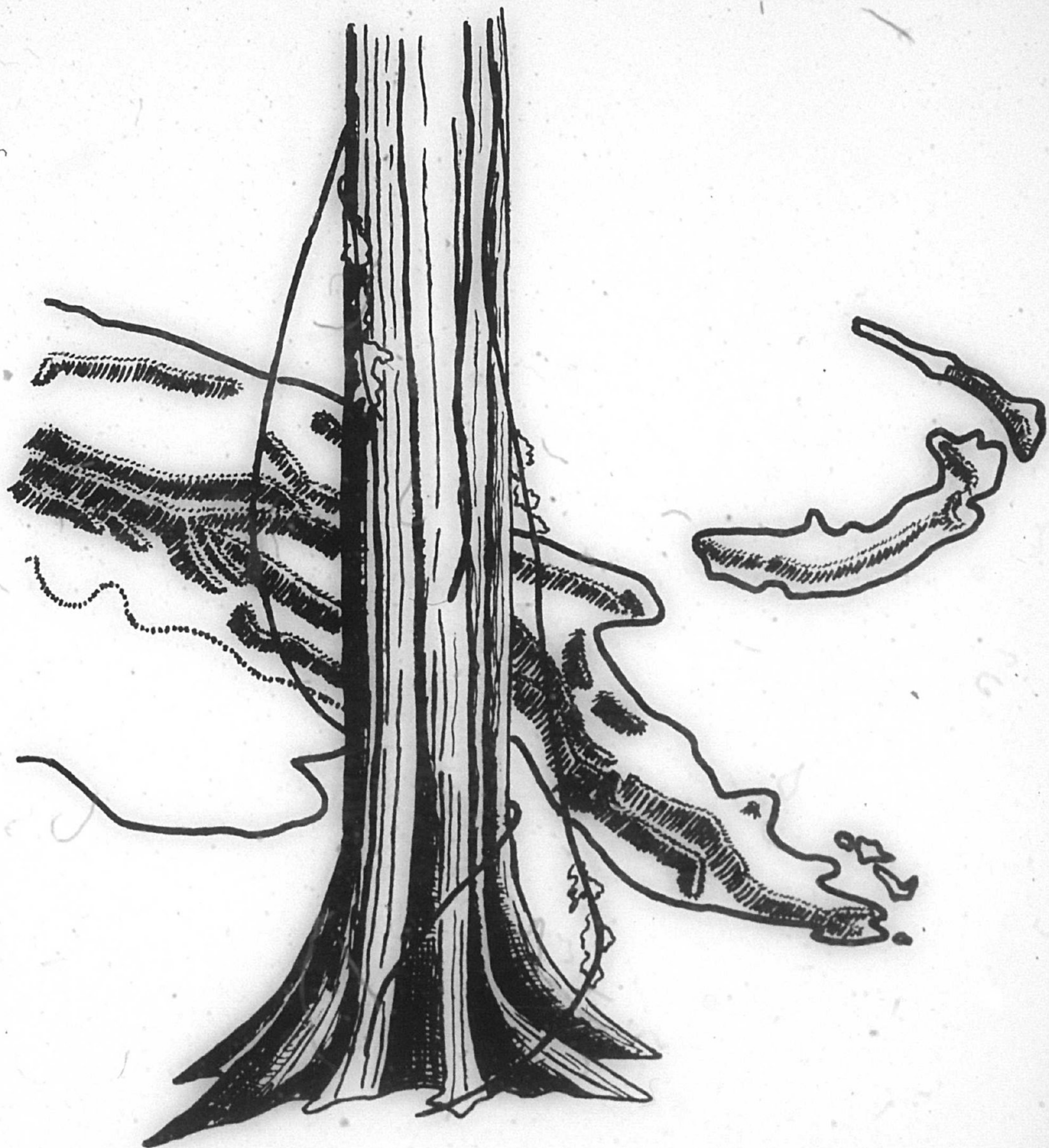
THESIS

THE APPLICATION
OF NEW
SAMPLING METHODS

E. D. SHIELD

1965

THE APPLICATION OF NEW SAMPLING METHODS TO
PREVIOUSLY INACCESSIBLE TROPICAL FOREST AREAS
WITH PARTICULAR REFERENCE TO PAPUA/NEW GUINEA



THE APPLICATION OF NEW SAMPLING METHODS
TO PREVIOUSLY INACCESSIBLE TROPICAL FOREST AREAS
WITH PARTICULAR REFERENCE TO PAPUA - NEW GUINEA.

A dissertation presented according to
the requirements of the Diploma in Forestry
University of Oxford.

by

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This paper establishes the need to evaluate the forest resource of developing countries as a preliminary to forest industry development. The purposes of forest resource inventory are defined as supplying information for -

- (i) long-term policy planning
- (ii) the evaluation of forest areas for exploitation investment
- (iii) direction of more detailed management investigation.

The requirements of a single inventory are to provide data on the physical, biological and economic aspects of a forest area. The biological and economic data requirements are of principal concern in this paper.

The application of forest resource inventory in Papua - New Guinea is reviewed in the light of existing and potential forestry development. The history of attempts at assessment of the forest resource of the territory has revealed that at no time have entirely objective methods been employed. It is contended that subjective methods have no place in extensive forest inventory.

Because it is necessary to use a sampling technique in inventory, the nature of the statistical populations which have to be recognised is discussed. These populations are based upon utilization requirements, although silvicultural requirements are not overlooked. It is established that populations based on species, size and form are essential to both requirements.

The necessity to delimit, within an inventory area, those areas of similarity of occurrence of particular populations, is demonstrated in the light of utilization and silvicultural requirements. Such demarcation is termed stratification.

A review is made of the methods of stratification of an inventory area by aerial-photo interpretation. Species identification, photo-mensuration and canopy-aspect mapping are the methods reviewed; the conclusion being that canopy-aspect mapping provides the greatest potential for achieving the ideal stratification based on species and size composition. It is established that there is room for

considerable improvement in the quality of photography for tropical forest interpretation. Some comments are made on the methods of such improvement from the point of view of the forester-interpreter.

Using photography designated as "multi-purpose", it is contended that an interpreter will be able to stratify only a small proportion of any inventory areas of tropical rain forest. In Papua - New Guinea, almost all inventory areas are remote from any point of conventional access. For these reasons, a multi-stage sampling procedure is recommended as most efficient, especially when helicopter transport is used. The possibility of extension of the multi-stage sampling technique to equally remote but more intensively stratified inventory areas is examined.

The impact of electronic data processing techniques on Volume Table construction is briefly discussed. Computer application to processing inventory data is indicated as a natural step towards efficiency and economy.

From data collected in Papua, the writer is able to make recommendations on efficient mensuration methods for inventory. Some of the problems associated with the measurement of rain-forest trees are outlined. The paper discusses the potential of the point-sampling by angle-gauge technique with the conclusion that, for extensive inventory practice, the use of small circular plots is superior.

The necessity to determine the influence of errors, other than sampling error, in the expression of total volume on an inventory area is discussed. The source and significance of these errors is indicated.

Finally, the paper refers to the major danger to inventory reliability as failure to appreciate the extent of hidden defect in standing trees. It is contended that there is much research to be done on methods of defect assessment.

1. INTRODUCTION

1.1 The Need for Forest Resource Inventory

(with acknowledgement to the preface of the proceedings of the Photo-Interpretation Symposium, Delft 1962)

Demographic statistics indicate a world population increase of 3.5 thousand millions by the year 2000 A.D. This figure represents an increase of 117% over the estimated 1962 population. Additionally, the bulk of this increase is to occur in less developed regions, where national governments will be involved in advancing living standards in addition to merely supplying sustenance.

A tremendously increased demand for raw materials must be met and, more importantly, must, in many cases, be met locally. Such local supply affords a saving on imported goods (assuming such are available) and ensures the development of sophisticated industrial processes essential to national development.

In the field of timber supply, it is not optimistic to expect the demand for industrial wood to double by the end of the century. Increased attention is thus being focussed on the tropical regions - currently estimated to contain some 45% of the world's forest area yet contributing only some 6% of the industrial wood supply.

The main explanation offered for this low performance is that economic exploitation of most tropical forest is hampered by the great variety of species found - only a small proportion of which are at present of value. However, with the emphasis shifting from timber, in the sense of logs, sawn products, veneers etc. to cellulose in reconstituted products (fibre-boards, pulps), in addition to the preservation of less durable timbers and the use of soft timbers in larger sections, it is contended that a much wider exploitation of the tropical forest may be expected.

The desirability of a sophisticated local forest industry, the potential use of a wider range of tropical species and the potential for export are now appreciated by many tropical governments. In addition, nearly all governments have adopted a forest policy recognising the full value of forests for production, protection and amenity.

Yet, the output of tropical forest areas has not shown any increase. Planning under forest policies aimed at the goals described has been hindered by inadequate knowledge of resource and hence, inadequate information on its value for investment. Much of this lack of knowledge concerning the forest resource may be attributed to the inaccessibility of the primary forest.

The inaccessibility referred to is economic rather than mechanical from the viewpoint of conducting an appraisal of timber resource. Most tropical countries are limited in the availability of finance, trained personnel and transport. The maintenance of forest appraisal teams in remote areas is difficult, consequently costly. Also, there is a deterioration in morale and efficiency of the personnel in long absence from their base.

This dissertation is directed at methods of appraisal of the timber resource of remote tropical areas. Such an appraisal may be termed "forest resource inventory" and has been defined by Harrison (1950) as "a record of the location, extent, nature, condition and productive capacity" of a forest.

1.2 The purposes for and requirements of Forest Resource Inventory.

In order to satisfy the need outlined above, forest resource inventory must supply information for three possible purposes. These are -

- (1) for the planning of a constructive forest policy, appreciating that forestry is a competition for land with other users e.g., agriculture, grazing etc.
- (2) for the evaluation of a forest area for investment aimed at its economic exploitation.
- (3) to provide data for detailed investigation of "management".

The distinction must be drawn immediately between "resource inventory" and "management inventory" - the latter implying a more detailed investigation and record of a forest area to be placed under "management". (Carron, 1961.)

The word "inventory" is originally a commercial term referring to the preparation of detailed stock-lists showing numbers, nature and value of each item. Foresters have adopted this term in the sense

given above.

To satisfy the purposes for a forest resource inventory, the inventory must provide data in an acceptable form. The provision of this data is here termed the requirements of forest inventory.

These requirements of a single forest inventory are to provide -

- A. Physical data on -
 - i geographic location
 - ii extent
 - iii physical features
- B. Biological and Economic data on -
 - i forest composition
 - ii the amount of forest produce available

The last two requirements are difficult to separate and are best described as the determination of a stand-table and utilizable volume in areas of similarity of occurrence.

The word "single" above has been emphasized as this dissertation is not directed at repeated, periodic or continuous resource inventories whose requirements are detection of changes in terms of A.ii and B.i and ii listed above.

The requirements listed are common to all three purposes of resource inventory. Only the amount of detail required by the particular purpose will vary. In general, development planning is a long-term activity and is considered at large-scale - nationally or at least regionally. Forest resource inventory for this purpose will thus be termed regional inventory and will require a lesser degree of detail than an inventory for evaluating the forest for investment or litigation, which will be termed local inventory. Included under investment or litigation considerations are -

- (1) determination of royalties
- (2) determination of capitalization necessary for exploitation
- (3) determination of the direction of utilization
- (4) determination of a value for the forest area either for purchase or for settling a claim.

Both regional and local inventories satisfy, to differing degrees,

the third purpose for resource inventory - that of providing direction for management investigations.

1.3 The Application of Forest Resource Inventory

Modern technology has provided the means of accomplishing an efficiency previously unknown in resource inventory and appropriate methods include -

- (i) aerial photo-interpretation and mensuration
- (ii) statistical method
- (iii) mensurational aids
- (iv) electronic computation
- (v) aerial transportation by helicopter.

All these techniques have been used in many places, some for a considerable period. The writer is concerned, however, with the application of these facilities and techniques to inaccessible tropical forests as he has experienced them in Papua - New Guinea. Some of these techniques and facilities are untried as yet, in these conditions.

The combined territories of Papua and New Guinea occupy 183,540 square miles of which about 36 million acres are estimated as exploitable forest. This area may be further sub-divided, dependent on locality and population pressure, into 26 million acres destined for local production only and 10 million acres so placed as to be suitable for export development.

Under the joint administrative arrangement, all land is considered to be owned by the indigenes (approx. 2 million people) unless purchased by present or past administrations or declared to be waste and vacant - tenure then being held by the administering authority. At present, some 97.5% of the total land area is indigenously owned - largely under the traditional clan ownership tenure. Such tenure is so complicated that this land is considered as being of indeterminant ownership.

Forest industry operates by the purchase of "timber rights" by the Administration. The area on which these rights are purchased is then available for utilization by private companies who tender for the grant of a timber permit. Local inventory is required for the determination of a price to pay to the indigenous owners and for providing prospective

investors with information on which to base their bids.

To develop more remote areas together with other forms of land use, the forest service is committed to the preparation of a national forest inventory. Such an inventory will allow decision on land-use alternatives - principally settlement on a combined cash-crop - subsistence agriculture basis. Thus the demand exists for regional inventory.

To ensure continued supply of timber for local consumption and for export the forest service is committed to the acquisition of a national forest estate. Such an estate is to be managed for the perpetual production of forest products. Both local and regional inventories can provide information on the suitability of areas covered by the inventories for more detailed investigation.

1.4 The history of forest resource inventory in Papua-New Guinea

Since extensive European settlement in Papua-New Guinea began in the latter part of the last century, progress in appraisal of the forest resource has been most spasmodic.

At the request of the Administration, forestry experts were sent to the territories in 1908 and again in 1923 but it was not until 1938 that a forest service was established. Shortly afterward however, a considerable part of the territories was occupied by the Japanese. With the defeat of their drive at total occupation, there began an unprecedented demand for forest products. Australian, American and New Zealand forces were all operating sawmills and a special unit was established by the Australian Army to assess forest potential.

This unit, led by the head of the former forest service, introduced air-photo interpretation in mapping 56,000 square miles of vegetative cover. Field work to assess timber volumes had just begun when the territories were handed back to a civilian administration.

Further inventory work was delayed until the forest service built an adequate staff - and this work, when commenced, was directed at timber supply for the service's own sawmills which were providing much of the necessary material for reconstruction.

During the decade 1950-1960, inventory work progressed only as fast as the demand for timber permits and staff availability allowed.

Production was entirely for the domestic market.

Since 1960 however, a greatly increased rate of urban and rural development, the establishment of an export market in Japan and the availability of trained local technical staff have boosted the rates of inventory enormously. Additionally, the use of small, high-powered helicopters since 1963, has enabled the forest service to attempt inventory over a total area of three million acres in 1965. (White 1965).

However, the writer knows of no single resource inventory carried out at any of the activity periods mentioned which was free from subjective methods. Such methods were used either in the selection or location of sampling units or in the estimation of the values assessed on those units. To a large degree, the science of statistical method has been ignored on the pretext of its retarding the operation. Such objection illustrates to the writer a lack of comprehension of the flexibility of sampling methods.

In addition to operating under conditions of extremely difficult access, the forest resource teams are containing an increasing number of technical grade indigenes. The limited experience and variable comprehension of the problem of this class of personnel demands that objective methods be made obligatory. Ideally, assessment of forest values should become a mechanical recording of measurements.

Only by utilizing the full flexibility of sampling methods and by adopting objective methods of assessment can forest inventory become a science making a contribution to better understanding of the tropical forest. Until such time, results obtained by subjective methods at any stage of the procedure will remain of dubious value and of no credit to the so-called science that produced them.

2. THE METHODS OF FOREST RESOURCE INVENTORY

It is proposed under this heading, to examine in greater detail the requirements of forest inventory listed previously, to appraise methods used to satisfy these requirements and to suggest those best suited to Papua - New Guinea. In some cases, it will be necessary to indicate the research which must be carried out before a method can be accepted. An outline of the research programme will be made in this event.

2.1 The Physical data requirements of Inventory

(i) The geographic location of forest areas.

A knowledge of the geographic location of those areas of forest of commercial significance is of immense value in forest development planning.

Implied in the topic is the definition of forest as being "of commercial significance". In Papua - New Guinea, forest having this attribute is the rain-forest or high-forest. Other forests such as mangrove, monsoon, savanna and secondary forest are excluded as are other forms of vegetative cover such as herbaceous and palmaceous swamps, grassland, shifting cultivation and agricultural crop land.

Naturally, what is regarded as forest of commercial significance will vary according to the development of utilization and the locality of the area in question. For example, lack of cheap transportation between Papua - New Guinea and the Asian markets prohibits utilization of mangroves in charcoal manufacture. For the time being the rain-forest or high-forest must be regarded as the only forest of commercial significance in Papua - New Guinea.

Also implied in the topic is a recognition of the impossibility of economic or, indeed, any removal of forest produce from certain areas. Such areas include tree-populated swamps and immense areas of steep country where the protective value of the forest is to be considered. At present in Papua - New Guinea, no exploitation is considered on those areas having a ruling slope of 30° or greater.

The most efficient method of delineating commercial forest is by aerial photo-mapping within the frame-work of a national mapping grid.

The recognition on aerial photographs of vegetation cover types

such as those mentioned is not difficult and has been widely practised (see later section). Demarcation of steep areas is less simple requiring a considerable field experience by the interpreter to match the exaggerated photo-image of the terrain with his experience of the difficulty and dangers of exploitation.

(ii) The extent of forest areas.

This requirement might have been logically included with (i) above but for the fact that the extent of a forest area changes with time - a change wrought by human interference through cultivation, conversion to plantation etc.

(iii) The physical features of the forest area.

Physical features within a forested area are important from the point of view of their effects on -

- (a) the biological and economic value of the forest through causing change in forest composition.
- (b) access by personnel involved in forest inventory procedure.
- (c) access by exploitation equipment.

Topographical maps of a forest area are essential for planning of field-work for the inventory. Similarly, maps indicating the major environmental sites are a possible guide to forest composition, which throughout this dissertation is used for size as well as floristic composition. Finally, maps exhibiting the various grades of access ease are essential to the planning of a utilization enterprise.

The above requirements are most economically met by mapping from aerial photographs. This assumes that satisfactory maps are not available and that the forest service is in a position to produce maps of the required specification.

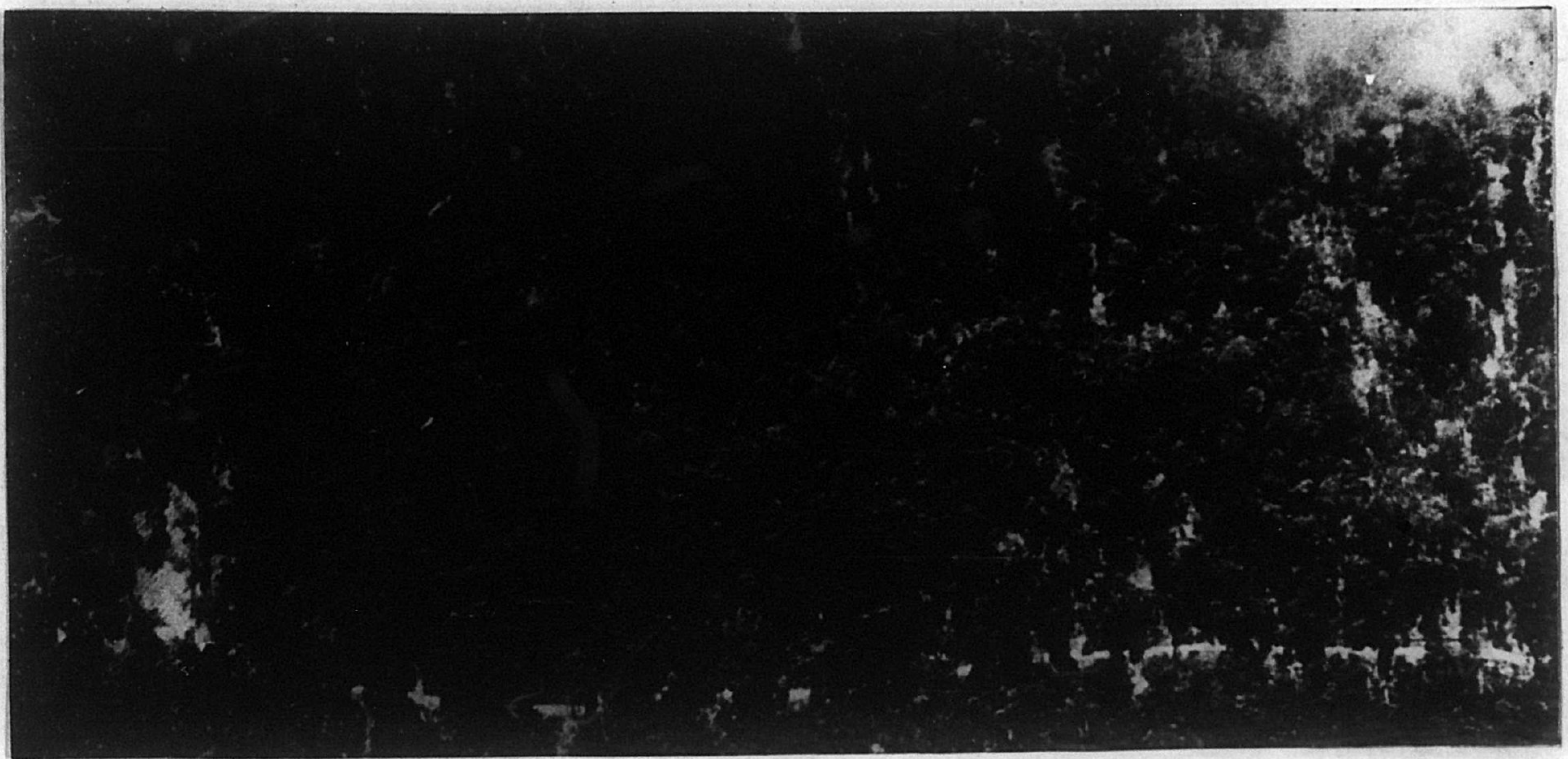
Aerial mapping techniques will not be discussed here, but, in a later section, the effect of the precision of map-derived area estimates on expressions of the total quantity of forest produce will be considered.

2.2 Biological and Economic data requirements of Inventory

As already stated, the object is to determine a stand-table and utilizable volume in areas of similarity of occurrence. The method employed is one of determination of areas of similarity and sampling

INTENSITY OF EXPLOITATION

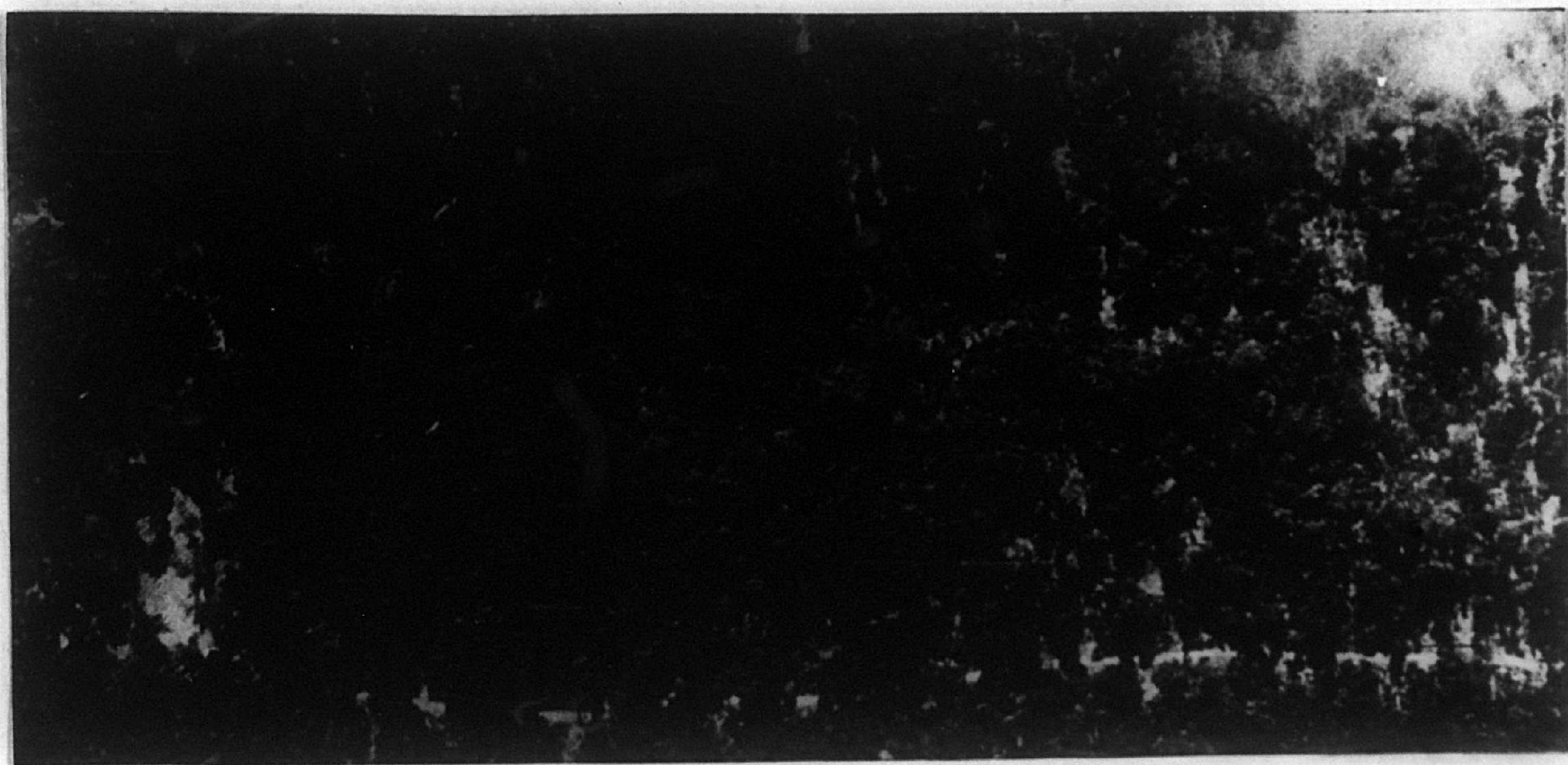
TRANS - BROWN LOGGING AREA [PAPUA]



In a sample taken near this area, a mean 15 trees per acre of mixed species over 5' girth were taken by the logger.

INTENSITY OF EXPLOITATION

TRANS - BROWN LOGGING AREA [PAPUA]



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within such areas.

The impracticability of performing a complete inventory over large areas of tropical forest - frequently unexplored, unmapped and almost impossible of access - is obvious. It is surprising, therefore, that complete inventory has been reported in Cambodia (Allouard 1944) and in Sarawak (Brunig 1963) by Loetsch and Haller (1964).

The speed and reduced cost of sampling as an alternative to total inventory are its most obvious advantages. Cochran (1964) contributes two others of possibly greater significance -

- (i) Greater scope - sampling permits use of highly trained personnel and specialized equipment - generally limited in availability - for the reason that sampling is done at greater speed.
- (ii) Greater accuracy - is assured by the use of better qualified personnel. Additionally, supervision is easier.

Sampling in tropical forests for inventory purposes remains a difficult task. The characteristics of such forests are generally unfavourable to sampling from the statistical point of view. The inventory must adopt a sampling procedure best suited to the individual forest concerned. This necessity is brought about by:-

(a) the distribution of the merchantable content within the forest area. Dipterocarp forest is generally "patchy" in distribution (Loetsch and Haller 1964). The bulk of lowland tropical forest has been described by Richards (1952) as a "mixed association". From the point of view of sampling, the level of utilization will determine the distribution of the commercial content of this forest. In Africa, this may involve as few as one or two trees per 50 hectare (Francis 1957). In certain operations known to the writer in Papua - New Guinea, up to 15 merchantable trees (over 5 feet girth) per acre have been removed (see photo). The distribution of the commercial content within the forest area is thus determined by the definition of what is commercial in terms of species and sizes and by the spatial distribution of these trees. Both factors have a considerable opportunity for variation dependent on locality as it affects utilization and the physiological requirements

of the species involved.

(b) the considerable variation in ease of access to tropical forest areas. In Uganda, access to many points about the periphery of the patches of high forest is possible by 4-wheel drive vehicle. In Borneo, navigable streams afford similar ease of access. In Papua - New Guinea access is primarily by walking - frequently establishing the route by cutting. The widespread use of small high-powered helicopters using village clearings and dry stream beds as landing sites has considerably reduced access time, however.

2.2.1 The objectives of sampling.

Cochran (1964) states the necessity for "a lucid statement of the objectives of the sampling procedure lest details of planning result in loss of sight of these objectives and decisions are made at variance to these objectives".

The objective of sampling as a method of supplying the requirements of economic and biological data has already been defined.

Numbers and volumes will be discussed in detail in a later section. Here, it is necessary to elaborate on the remainder of the definition.

(i) Utilization categories.

These categories are used to divide numbers and volumes into groups to suit the requirements of utilization of the forest produce.

Species are frequently grouped according to their timber properties. For example, in Papua - New Guinea, the following utilization categories are recognised -

- Group 1 - Highly valued veneer timbers
- Group 2A - Prime quality coniferous timbers
- Group 2B - Other coniferous timbers
- Group 3 - Timbers suited to decorative use as veneers or as
sawn timber
- Group 4A - Heavy construction timbers suited to external use
- Group 4B - Light construction timbers suited to internal
use only
- Group 5 - Marginal and non-commercial timbers

Each of the above utilization groups is entered by a knowledge of

the tree name - often a generic name will suffice e.g. Ficus spp.

in Group 5 though, frequently, a specific name is required e.g. Pometia tomentosa in Gp.4A; P.pinnata in Gp. 4B.

These groupings do not suggest that all species within a single group are of equal attraction to utilization or that species within a single group are unidentifiable to the trade. The "mixed association" forest is too diverse in its specific composition to allow such a grouping. It therefore remains essential that species do not lose their identity when placed in a utilization group.

However, a species must occur with sufficient regularity in the sample to retain its identity when placed in a utilization group. In a sample, the species A, B and C in a single group may occur at the rate of one or more trees per sampling unit; species D, E and F may occur at reduced frequency, say one tree to each ten sampling units. In such a case, the first three species would retain their identity whilst the remainder would be referred to as "other species" of the same group. The method of deciding the frequency of occurrence necessary to ensure retention of the individuality of a species will be discussed in a later section.

Another form of grouping involves division of numbers and volumes into size categories. Most frequently, these size categories are based on girths measured at the base of the log. An integrated utilization enterprise may require girth categories to have limits of one foot. The standards achieved in tropical utilization, however, are generally satisfied by wide categories such as three feet.

In Papua - New Guinea, girth categories required for the current standard of utilization are -

5' and 6'	} completed unit measure i.e. 5' and 6'
7' and 8'	
9' and over	

means from 5'0" to 6'11" inclusive.

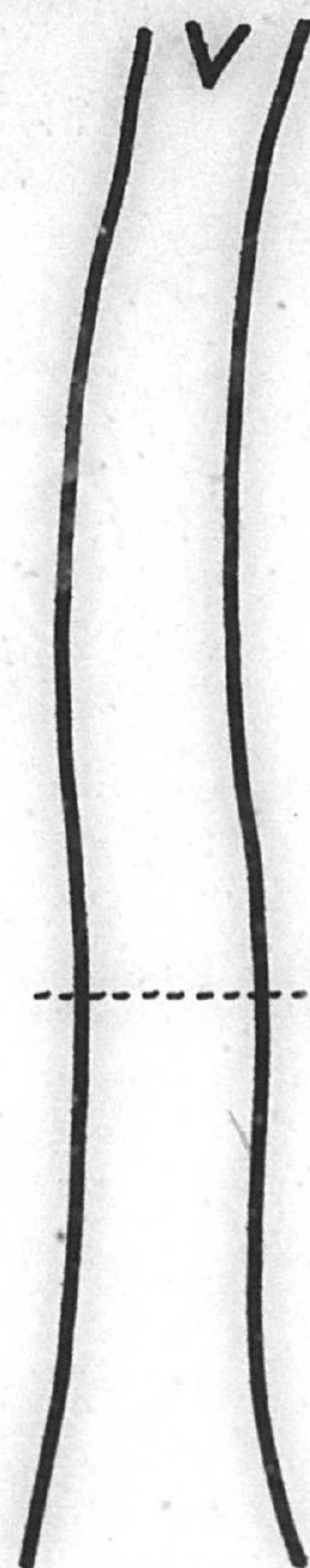
A more intensive degree of utilization may require a lower girth minimum - to include, perhaps, the class 3' and 4' or, perhaps, require numbers and volumes to be expressed in single foot girth classes.

Thus the standard of utilization will determine the girth classes

DEMONSTRATION OF FORM CLASSES



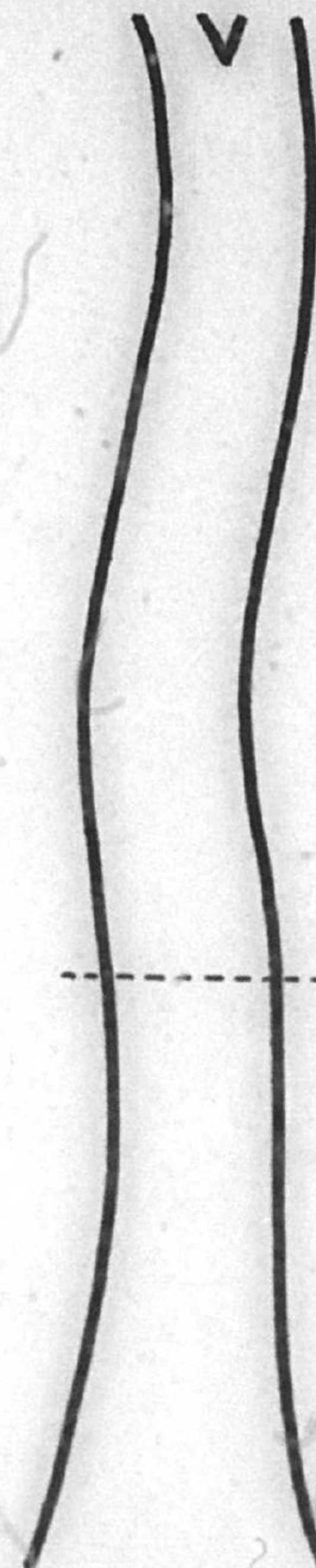
Form
Class
A



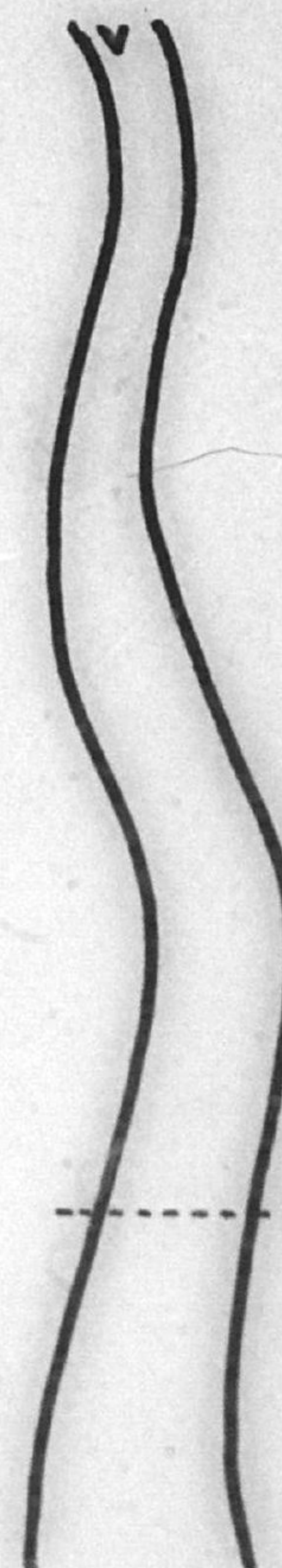
Form
Class
B



Form
Class
C



Form
Class
D



Form
Class
E

to be adopted. Ideally, the girth classes should represent similarity of end-use and of ease of handling.

The final utilization category is based on what will be termed the "form" of the trees.

Certain tropical species exhibit a considerable variation in form dependent on locality e.g. Pterocarpus indicus. Others are of consistently bad form e.g. Ficus spp. Some are of consistently good form e.g. emergent Anisoptera polyandra.

Form may be recognised on two bases - quantitative and qualitative. Quantitative log form is expressed as log grades having an objective basis in recovery studies. However, their application to standing trees is not easy and generally beyond the capability of the field staff employed in tropical inventory. The alternative is the subjective application of qualitative form classes which are applied to each tree encountered on each sampling unit according to external appearance. The following form-classes were suggested by the writer and have been adopted in inventory practice in Papua - New Guinea and in the Jengka project (Malaya):

<u>Class</u>	<u>Description</u>
A -	a "gun barrel" log; straight in length and circular in section; no apparent defect; suitable for rotary peeling over the entire log length.
B -	a log suitable for rotary peeling over extracted lengths; entirely circular in section; otherwise class A but for straightness; no apparent defect:
C -	a good saw-log; reasonably straight and of reasonable section; no apparent defect;
D -	a marginal saw-log on the basis of straightness and section; no apparent defect:
E -	not apparently suited to sawing; possibly useful for reconstituted wood; no apparent defect:
F -	useless; defect apparent; recorded for ecological purposes only.

The above form classes are applied irrespective of species and size since these factors are already included in other categories.

The application of such form classes is admittedly subjective. However, they do represent a valuable guide to possible utilization and are readily taught (see diagram) and speedily applied. Additionally, they represent field-collected data which may be modified at a later stage in computation ^f if the subjective application is considered too variable. Finally, they are superior to no information at all on log form.

(ii) Silvicultural categories.

As a guide to a more detailed investigation to determine fully the management of an area, resource inventory data may be presented in a satisfactory form with little additional effort.

The requirement of the silviculturist is a stand table showing the size distribution of each species in girth classes of one foot interval. By combining such individual tables, a total stand table may be derived.

Frequently, smaller size classes than involved in normal inventory practice are required e.g. girth classes 2' and over. Dealing with these classes involves a considerable increase in both numbers of stems and difficulty of species identification. Such identification is also of value to eco-botanical studies and generally requires a greater botanical ability than possessed by field-staff involved in inventory work. Assistance from a botanist can thus be of value or at the least, a specialist member of the team can be involved solely on botanical collection for identification.

(iii) Areas of similarity of occurrence.

Essential to all purposes of forest resource inventory is the delineation of areas within which numbers and volumes within the categories outlined are similar.

A most obvious example of the undesirability of not delineating such an area is when a particular species occupies a particular site within the inventory area. Sampling the area will reveal the numbers and volumes associated with this species. But unless the site it occupies can be defined, then the numbers and volumes must be regarded

as distributed over the entire inventory area. Such would have serious consequence for utilization and for management.

Such considerations lead to the concept of stratification of the forest area for resource inventory.

3. POPULATIONS INVOLVED IN INVENTORY SAMPLING

The objectives of sampling satisfying the requirements for biological and economic data demand recognition of more than one population which is to be sampled. Loetsch and Haller contend that "the accurate recognition and distinction of the population" or "of the multitude of populations, is evidently the first pre-requisite for the planning and execution of forest inventories".

In the previous section, the objectives of sampling were summarized and basic definitions given of the categories in which numbers and volumes were required. In addition, this information is required on an area-related basis - viz. per acre. There are therefore a multitude of populations to be recognised - for example:

Number of trees are required:-

- for each major species or group of species within each utilization category.
- in each girth class or group of girth classes.
- in each form class.

The populations associated with volume might be similarly listed. However, there is an added complication in that volume cannot be estimated directly except by guesswork.

Volume in tropical forestry refers to a log volume rather than a tree volume as normally used in temperate forestry or when considering plantation material. The sense used here is that each tree contains a single log whose volume is derived from a measurement of horizontal size (girth or diameter) at a fixed point, vertical size or log-length, and taper. A later section will be devoted to volume estimation. Here, let it suffice to say that volume populations can only be estimated from populations of girth or diameter, log length and taper in all the categories given above.

The population at which most interest is directed in forest resource inventory is that of commercial volume per acre. Commercial volume may be defined as the volume per acre of those trees -

- over a fixed minimum girth (in P./N.G. 5')
- of merchantable species (in P./N.G. Gps.1-4B)
- of acceptable form class (in P./N.G. Classes A-D)

In the sense of Freese's (1962) definition of a population, the "unit" is one acre and the "value" is the commercial volume. In the sense of the appendages to the definition of Loetsch and Haller, the individuals are of the same kind viz. commercial volume on a consistent unit and, from sampling unit to unit, will differ in respect to one feature - namely quantity - which is the variant.

This population of commercial volume per acre is, of course, a composite of the populations of volumes of individual species, in separate size classes in separate form classes. Such a composition of populations is frequently essential to providing a real meaning to sample data.

This has been demonstrated by Loetsch and Haller in the following example -

- for 18 sampling units, the mean volume of trees over 40 cms. diameter is shown with an appropriate precision:

<u>Population</u>	<u>Mean Vol. (cub.m./ha.)</u>	<u>Precision %</u>
All species	110.3	± 11.1
Timber Class I	22.5	± 17.4
Timber Class II	12.8	± 40.1
Belinga spp.	2.3	± 120.0

In this example, the precision measure required was ± 20 . This has been achieved by the stated number of sampling units only in the case of the first two populations. To achieve the required precision measure for the fourth population would have required an increase in the number of sampling units from 18 to 645.

For reasons of economy therefore, it is often necessary to group certain populations with a greater inherent variability into more universal populations in which the variability is reduced. Basically, the more individual populations that are absorbed into the composite population, the less will be the variability of this population and the greater the likelihood of small sampling fractions, as demanded by economy, meeting the required precision measures.

A compromise is frequently required between the amount of sampling and the desirability of recognising and obtaining reasonable estimates

for the more variable populations. An estimate of the commercial volume per acre, to a satisfactory precision level may be meaningless if utilization or silviculture is directed at a particular species of a particular form or size class required e.g. by the export market or as a seed tree. The advice of Loetsch and Haller to define the populations required for meaningful estimation of values cannot be too strongly emphasized.

3.1 Stratification.

Stratification in tropical forest inventory requires more than a division of the units of the population so that the value volume will be more homogeneous thereby requiring less sampling units to achieve the required precision.

If, for reasons of economy, the population of commercial volume per acre is the only population for which a tolerably precise estimate is required, then division of the units of the population may be made to satisfy the above requirement. Such stratification into classes of more homogeneous volume content has been long recognised as the most efficient for sampling processes estimating volume (Spurr 1952, Bickford 1953, Lawrence 1957).

However, in tropical forest, the purposes of inventory are not satisfied by such stratification. The variable attraction of species, sizes and form classes for utilization or silviculture demand that less general populations be recognised. Of these three, specific identity is probably the one worthy of most attention. Utilization and silviculture both require a knowledge of the distribution of attractive species. An ideal stratification would be one which delineates areas of similar floristic composition. Sampling efficiency requires, in addition, a further sub-division based on volume or, indirectly, on distribution within girth classes. Thus both purposes would be served if areas of similar stand tables, expressing both floristic and size composition might be grouped.

Strata must be delineated on a map of the inventory area to satisfy the purposes of the inventory. Methods involving recognition but not delineation of the strata fail to provide information on the physical

distribution of the strata.

For regional inventory such as was conducted by Loetsch (1957) in Northern Thailand, the arguments for non-delineation of forest strata are presented as:

(a) Stand (strata) areas are small, intricately mixed and of irregular shape requiring a large-scale map to allow accurate area assessments.

(b) Such large scale mapping, in conjunction with the difficulties of interpretation and the necessity for frequent field-checks make mapping very expensive.

These arguments may be overcome by specification of minimum areas for which individual strata will be recognised and by the recognition of fewer strata.

The size of minimum areas will depend on the nature of the inventory. Minimum areas of one thousand acres would probably be acceptable for a regional inventory covering upwards of one million acres and one hundred acres would be acceptable for a local inventory of approximately one hundred thousand acres.

Recognition of fewer strata could only be considered if strata differed so little from each other that the difference was not evident in the sample data.

Strata recognition will be more frequent in areas where the natural or artificial environment is less conducive to the forest acquiring a stable climax. The locality of such environments must be assumed to be at random over the total inventory area if strata recognition without delineation, a sampling process, is to be free from bias. For an entire region of many millions of acres, this assumption may prove of little consequence but over smaller areas, the nature of the distribution of anthropogenous influences alone, would make the writer hesitant of adopting such a method.

3.2 Methods of Stratification.

The ideal stratification has been described as a division and a mapping of areas of similar stand-table composition. To achieve such a stratification of so heterogeneous a population as the tropical

rain-forest would require a much more detailed knowledge of the forest than is generally available before a sampling procedure has been adopted.

This leads to the question of whether to stratify a forest area before or after sampling it.

The only sampling method suited to identifying and mapping strata is one of systematic transect samples. Such a method is not necessarily the most efficient method of estimating the values required from each strata. Additionally, more sampling units may be required for mapping the strata than are required for estimating the values to the required level of precision.

For efficiency therefore, it is necessary to stratify the forest prior to commencement of sampling. Aerial photography provides the means of approaching the ideal stratification through the interpreter's ability to recognise species, prepare volume estimates from photo-measured variables and to recognise differences in the canopy which is an expression of the floristic and size composition of that part of the forest of chief interest to utilization.

4. THE USE OF AERIAL PHOTOGRAPHS FOR FOREST STRATIFICATION

4.1 Introduction

Possibly the earliest application of aerial photography to the problem of forest stratification was made in Burma in 1924 (Sisam 1947). In this operation, some 1,400 sq. miles of mangrove forest was surveyed by means of vertical photography for the compilation of complete topographic and vegetation mapping.

Since that time, aerial photography has been adopted to a greater or lesser extent by almost every country. However, the bulk of literature attesting to the successful application of aerial photographs now comes from North America and to a lesser extent from Europe. In tropical countries, aerial photography has not had the same intensive use despite the fact that poor access is a major factor in the choice of aerial photography rather than other means of mapping topography, vegetation and forest strata.

The reasons for this are as follows:

(i) In general, tropical countries are less developed technologically and have not had the facilities or finance to experiment in photographic methods, materials and interpretation.

(ii) Interpreters of aerial photographs of tropical forests are presented with an unfamiliar (i.e. vertical) view of the most complex vegetation on earth. The heterogeneity of species and sizes and the considerable variation in composition from area to area present the novice interpreter with an apparently insoluble problem. This is especially true when he has been schooled in interpretation methods applicable to temperate regions.

(iii) Interpreters are frequently required to use photography flown for other-than-forest-interpretation purposes. This results in abnormally small scale and various standards of presentation of the photographic image, seldom the most suitable for forest interpretation.

4.2 Essential Characteristics of the Photo-Image.

The methods of stratifying mixed tropical forest fall into two distinct classes. Strata may be determined -

(i) Directly by identification of tree species or by the

measurement of forest produce on the aerial photograph.

(ii) Indirectly by delineation on the aerial photograph of areas of similar canopy appearance - here to be termed canopy aspect types which are an expression of the floristic and size composition of the forest.

The writer does not consider, however, that interpretation or measurement of forest produce quantities can fulfil the total requirements of forest inventory. It will be demonstrated that forest inventory is essentially a field-work operation.

Both direct and indirect methods of forest stratification make use of the same essential characteristics of the photo-image of the forest canopy. These will now be described:

A. Number (Density)

The attribute of number is of little significance to inventory unless related to area - therefore density. The determination of numbers of crowns - and therefore trees - on the aerial photograph - implies an ability to separate individuals. The accuracy of a count - or the likelihood of ability to identify an individual - is dependent on the following characteristics (adapted from Avery 1962)

- (i) the size and shape of the tree crown
- (ii) the scale and resolution of the photography
- (iii) the spatial arrangement of the crown
- (iv) the amount of tonal contrast between the individual crown and the surrounding vegetation.

Success in accurately counting individual trees on aerial photographs of the tropical forest has been small. Loetsch and Haller (1964) report an ability to count only 60-80% of the correct number of emergent Dipterocarp trees at a scale of 1:15,000 and only 33% of Dryobalanops spp. in dense stands at a scale of 1:29,000. Such under-estimation contrasts with the results of Pajmans (1951) working with photography of a mixed forest at a scale of 1:10,000. He reports that, for reasons of being unable to identify individual crowns accurately, the number counted "exceeds the number of trees marked as dominant on the ground and also exceeds the number of trees with a d.b.h. of 35 cm. (14 inches)

and over." The contrast in results indicates an attempt by the latter author to estimate the numbers of trees whose crowns are grouped so as to appear inseparable. Such an attempt was made by Swellengrebel (1959) who identified 421 out of a measured 557 trees over 10" d.b.h. using photography of a scale 1:10,000. This author reports a tendency for the crowns of three forest types in British Guiana to group together but that detailed study permitted recognition of the individuals with the degree of success indicated above.

B. Size.

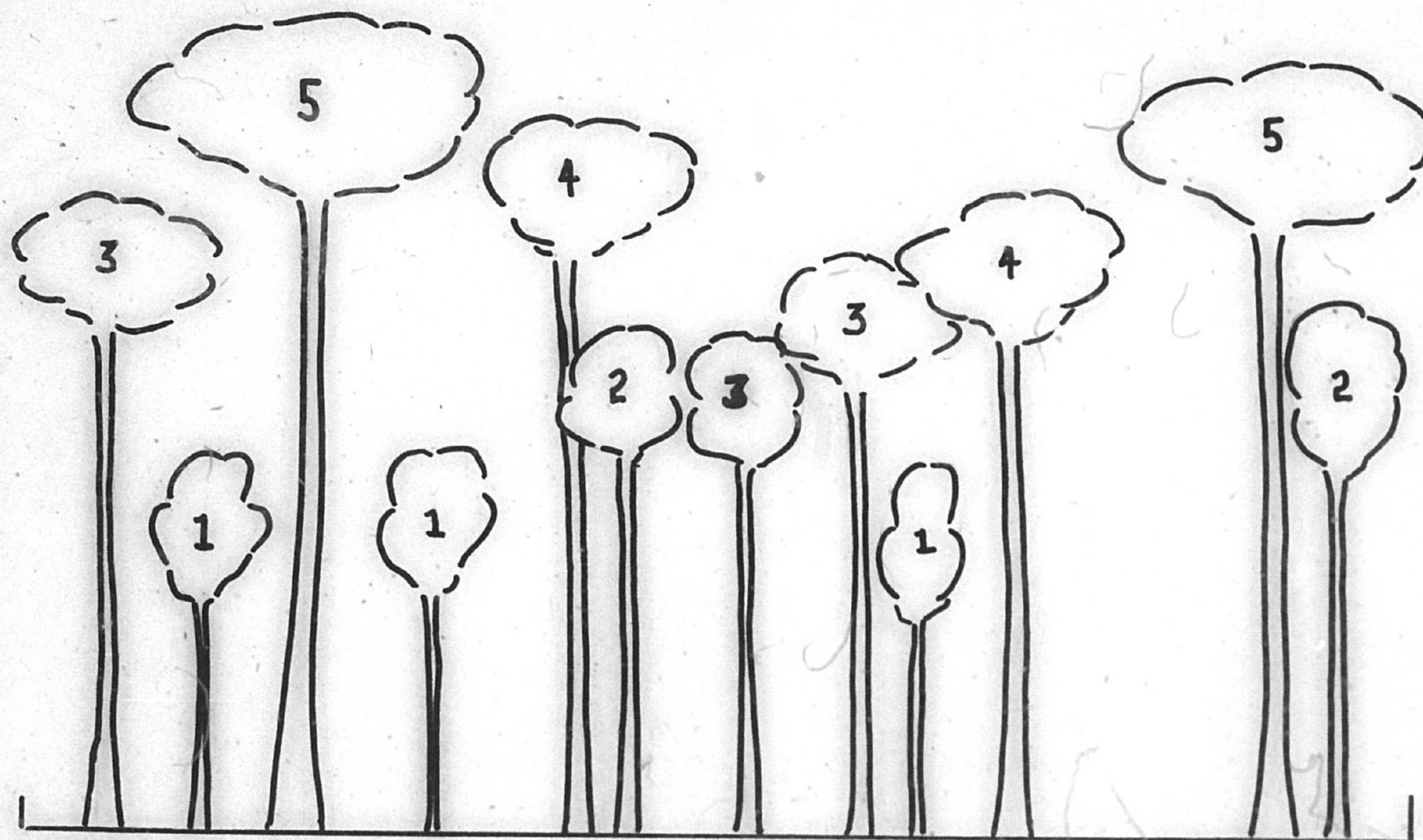
There are two measures of size to be obtained from vertical aerial photography.

(i) Height. In contrast to interpretation of boreal and temperate forests, the concept of total canopy height has little application to the photo-interpretation of tropical forests. Canopy height is not measurable in tropical forests because the ground level adjacent to the trees is not visible. Breaks in the vegetation cover do permit height estimation at such a point. However, such breaks are usually at stream-edges or are the result of limiting conditions for forest growth - where the canopy level has no real relation to that of the bulk of the forest.

Of more importance than total height is the concept of height advantage of one canopy over its neighbours. This value can only be measured in relative terms. More often, the impression of canopy irregularity or relief which is conferred by height advantage of a few individual crowns is of greater value. Height advantage also has important effects on tonal reproduction - an emergent tree tending to a lighter tone than another tree of the same species in the canopy (Swellengrebel 1960). Finally, the fact that a tree is emergent over its neighbours is important in associating this emergence with those species known to the interpreter to have this habit. The range of species having such a habit is small compared with the range of species found in the forest. (See section G below).

(ii) Diameter. The accurate measurement of crown diameter on aerial photography implies an ability to separate visually the required crown from the surrounding canopy. The factors governing identification

DEMONSTRATION OF CROWN POSITION CODES.



Code	Description
5	Emergent
4	Canopy (full overhead light)
3	Lower Canopy (some overhead light)
2	Upper Understory (some side light)
1	Lower Understory (no direct light)

of an individual crown listed above are therefore applicable here.

Assuming that a single tree crown is identifiable from the remainder of the canopy, then unbiased measurement will result only if the entire periphery crown is visible.

Dawkins (1958) has provided a classification of crown position which will serve to indicate those positions for which unbiased measurement is possible.

<u>Code</u>	<u>Description</u>
5	<u>Emergent</u> . Entirely exposed, free from competition for light, at least within the 90° inverted cone in which the crown lies.
4	<u>Upper canopy</u> . Exposed in entire vertical plan but in contact with other crowns laterally.
3	<u>Lower canopy</u> . Partly exposed and partly shaded vertically by other crowns.
2	<u>Upper understorey</u> . Entirely shaded vertically but with some direct side light.
1	<u>Lower understorey</u> . Entirely shaded vertically and laterally by other crowns.

The diagram opposite illustrates these definitions.

Trees whose canopy position can be described by Codes 1 and 2 will not appear on aerial photographs. Canopy position code 3 represents a tree whose crown measurement is liable to a considerable bias. Canopy position code 4 represents a tree whose crown diameter may be measured without bias only if the individual crown may be reliably identified. For complete safety from bias, only trees represented by canopy position code 5 should be estimated for crown diameter.

C. Shape.

Stereo-scopic viewing of photo-images will convey an impression of crown shape. Such viewing requires a re-orientation of normal perception which is horizontal or nearly so. As a characteristic of a particular species, crown shape has the disadvantage of changing with time and suffering modification by the environment in which it develops.

FACTORS INFLUENCING TONAL QUALITY.

[CORTEN 1962]

Tonal reproduction on the negative dependent upon +

- sun intensity and colour temperature of illumination.
- position and latitude on earth.
- time of day and year - sun's elevation.
- spectral diffusion and absorption characteristics of haze and its spatial distribution.
- spectral remission of object under prevailing conditions.
- non-spectral remission determined by shape and texture of object.
- shadow content of scene and of the details.
- wind strength and direction.
- state of humidity of the object.
- various soil conditions at the time of photography.
- flight altitude.
- filter characteristics.
- lens characteristics.
- exposure level.
- negative emulsion choice.
- H and D characteristic of emulsion chosen.
- position of various object brightnesses on this characteristic curve.
- developer choice.
- development time and agitation.

and for positive copies tonal reproduction is further dependent on +

- copying instrument.
- positive emulsion gradation.
- exposure level of positive copy.
- positive development.

D. Shadow.

Interpretation of photography of tropical forest uses shadow in two ways: Firstly, as conveying an impression of depth additional to that provided by stereofusion: Secondly, in contributing to the overall photographic texture of an area of the canopy.

Being the result of the angle of incidence of illumination relative to the angle of photography and the height advantage of emergent crowns over their neighbours, shadow content may be varied to suit the conditions required.

E. Photographic Tone.

"In black and white photographs, distinctions between colour hues are lost and objects are observed in tones of gray" (Manual of Photographic Interpretation A.S.P. 1960).

Such serves as a definition of tone. The value of tone as an identification characteristic is dependent on the fidelity with which an object of a particular characteristic tone can be reproduced, the consistency of the characteristic tone of the object and the consistency of recognition of the photographic tone.

Final reproduction of tone as an image characteristic is dependent on a great number of factors not all of which can be controlled to ensure fidelity of tonal reproduction of a single image on successive occasions. The table given opposite was adapted from a paper by Corten (1962) and demonstrates the multitude of highly variable factors on which tonal reproduction is dependent.

The consistency of the characteristic tone of a tree crown is dependent on the physiological state of the leaves whose differential reflection provides the basis for tonal variation. The majority of tropical rain forest species are evergreen and so little has been done to determine any variation in reflectivity with changing physiological conditions. However, the appearance of a characteristic flush has been noted in certain species and at least one author (Francis 1957) has indicated the value of photography at the time of this condition.

The consistency of recognizing a photographic tone has been assisted by the publication of a tonal scale of ten gradations from black to white

(Daehn 1949). However, these represent a small fraction of the total tones of gray (200) which are detected by the brightness sensitive nerves or rods in the eye (Heller, Doverspike and Aldrich 1963).

The use of tonal characteristics as a basis for identification of a tree species has been shown to be dependent on a great number of highly variable factors. Spurr (1960) summarizes his appreciation of the problem thus: "The complexity of factors determining tone are great enough so that photo-interpretation based upon direct tonal contrasts is highly subject to error."

F. Texture

"Texture in aerial photographs is created by tonal repetitions in groups of objects which are too small to be discerned as individuals." (Manual of Photographic Interpretation A.S.P. 1960).

On large-scale photographs, the texture of individual trees may be determined by the tonal repetitions of the individual leaves. On small-scale photographs individual trees can scarcely and certainly not accurately be identified as such. Tonal repetition and therefore texture is then produced by the crowns themselves.

Since texture is a composition of tonal elements, any factor influencing tone and hence tonal contrasts will influence texture.

G. Location and Association

As with identification of tree species in the field, identification from aerial photographs can be greatly facilitated by an understanding of the ecological characteristics of the species. In general, the characteristics will be more readily recognised and the interpreter should immediately become aware of the species which tend to possess that particular habit.

The first habit to consider is a geographic one. What species are known not to occur in the locality? The second habit is one of topographic site. What species occupy this particular site (- ridge-top, river terrace, swamp-margin etc.)? The third habit is one of position in the canopy. What species are likely to be emergent or to be clearly visible in the canopy? The fourth habit is one of association. What species are likely to occur in groups or pure stands?

Species identification [cont'd]

Nyyssonen 1961 (cont'd)	Merritt and Rangtunga Francis	1959	Ceylon	1:15,840	Dipterocarpus zeylanicus D. hispidus Doona congestiflora	Grouping tendency. " "
		1957	Ghana	-	Cieba pentandra Musanga smithii	In pure stands or as individuals. Neither of commercial value.
	Cahusac	1957	Uganda	-	Six species	Indicative of regenerating forest. Crown structure & tone - 2 species recognised as individuals 4 in "gregarious aspect."
	Heinsdijk	1952	Surinam	1:40,000	Eperva falcata Mora excelsa Groupia glabra Hymenolobium petraeum	Almost pure stands on sandy soils. Pure stands. Pure patches in upper-storey.
	Jaarverslag Swellengrebel	1957 1959	Surinam Br. Guiana	- 1:10,000	Virola surinamensis Mora excelsa Mora gonggrijpii Ocotea radiaei	Swamp localities: upper-storey occurrence with one other species. All species occur gregariously and are recognised on the basis of gregarious canopy appearance.
Literature (general)	Paelinck	1958	Belgian Congo	-	Terminalia superba	Gregarious habit: trees have characteristic crown shape.
P./N.G.				up to 1:50,000	Terminalia brassii Octomeles sumatrana 2 Araucaria species	Gregarious habit: characteristic site - respectively swamp forest and levée bank: characteristic tones - respectively light and dark. Emergents: characteristic crown shape: crown is moss-festooned at higher altitudes.

REPORTS OF ABILITY TO IDENTIFY SPECIES ON AERIAL PHOTOGRAPHY OF TROPICAL HIGH FOREST.

page 1

Source	Author	Date	Locality	Scale	Species	Remarks
Spurr 1960	Chapman	1947	Ceylon	1:9,000 1:7,200	Chloroxylon spp.	Used two filters and two seasons.
	Zahir-ud-Din	1954	Pakistan	1:20,000	Dipterocarpus spp.	Characteristic crown.
	Anon.	-	B. Honduras	1:15,840	Mangony	Characteristic flush.
Loetsch and Hallier 1964	Bergeroo-Campag	1955	Ivory Coast	1:15,000 to 1:20,000	A total of ten species	Frequent ground control was required.
	-	-	Thailand	1:20,000	Pinus merkusii + P. khasya	Recognised as individuals and in groups.
	-	-	Sarawak	-	Dacrydium beccarii	Pure stands.
	-	-	Thailand	-	Dipterocarpus intricatus	Light toned crown in high, open forest.
	-	-	Sarawak	-	Shorea albida	Compact light-toned crown: "cauliflower shape"
	-	-	Malaysia	-	Shorea curtisii	Glaucous crown tone: hill forest.
	-	-	-	-	Dryobalanops aromatica	"Feathery" crown appearance
	-	-	Sarawak	-	Dyera pneumatophora	Peat-swamp association: light toned crown with tufted appearance: individuals of irregular star-shape
Nyyssonen 1961	Paijmans	1951	Celebes	1:10,000	Anthocephalus macrophyllus Campnosperma spp.	Upper-storey tree: flat crown: star-shaped. Characteristic leaf aggregation habit provides unusual distinguishing texture.
	Hannibal	1962	Sumatra	1:40,000	Dryobalanops spp.	Occurring in pure stands
	Boon	1956	West Irian	1:40,000	Agathis spp. Araucaria spp.	Crown shape of emergents. Crown shape of emergents + moss growth in upper branches.
	Loetsch	1957	Thailand	-	Dipterocarpus alatus	Large crowns with "bright shiny leaves" appearing as light-toned photo-images
	-	-	-	-	Tectona grandis	In flowering season: July - August only.

Examples of the use of such a sorting technique are many and are demonstrated in the following section.

4.3. The identification of tree species in the tropical high forest by photo-interpretation.

In order to be of value to forest stratification, the identification of a tree species from aerial photographs must be reproducible over a wide area in which the species is likely to occur. Identification by virtue of local knowledge of a particular area does apply to that area but has little value if the same species cannot be identified from photographs of another area.

Those image characteristics, described in the previous section, which are used to identify species are -

- (i) height advantage (in conjunction with others)
- (ii) crown diameter (" " " ")
- (iii) crown shape
- (iv) tonal
- (v) texture of the individual crown
- (vi) location and association.

Presented in tabular form opposite is a summary of the positive results of species identification available in the literature and from the writer's experience.

Compared to temperate forests, tropical forest species identification is of a very low order (see Sayn Wittgenstein, Zsilinszky, Aldrich, Doverspike & Heller). Nor does aerial photo identification compare favourably with visual aerial reconnaissance by a skilled botanist. Thus, it must be concluded that failure to compare with the results from other climates is attributable to the unalterable heterogeneity and diversity of the forest itself while failure of photo-identification to compare with visual reconnaissance identification is attributable to the inability of the photographic system to reproduce with adequate fidelity the image of the forest canopy. The remedy for this is in the procurement of better quality photography.

The contribution of species identification to forest stratification should be carefully examined before the expensive investigation into

what constitutes better quality photography is begun.

Identification of groups of trees of a single species and of pure stands has considerable significance to stratification since these groups and stands may constitute a single strata. But as Richards (1952) has indicated, the bulk of tropical rain-forest is a "mixed association". The value of species identification in such forest will depend on how many species may be identified, the significance of a particular species as an indicator of its associates and the standard of utilization involved.

The present standard of identification in "mixed" forest is useful only if those few trees which can be identified happen to be those at which utilization is directed. In such a case, strata based on the density of crown of the particular species would meet the requirement.

The writer has found in the literature no single example of the identification of a single species being used to deduce forest composition through an appreciation of its value as an indicator species. The development of computer programmes to determine mathematically association between species may provide valuable information for this type of study in the future (Boon 1961 and 1962, Poore 1965).

Assuming that better quality photography were available the number of identifiable species would need to increase tremendously if a forest stratification were to be made on the basis of the identified species alone. This is especially true in view of the evolution towards utilization of a greater number of species.

Finally, the writer believes that too great an emphasis has been placed on the identification of tree species in the tropical forests. With the exception of the cited instances involving grouped trees or pure stands and involving low standards of utilization, species identification as a means of stratification would need a greater improvement even with the development of better photographic techniques than seems possible.

4.4 Measurement of Quantities of Forest Produce.

(Photomensurational Techniques)

There are three principal methods of assessing quantitative forest

data from aerial photography. They are:

(i) direct visual comparison of the photo-images with others on which the quantities of forest produce have been reliably estimated by field work.

(ii) compilation of Tree Volume Tables based on the relationship between crown diameter and stem diameter.

(iii) compilation of Stand Volume Tables based on a relationship between field measured volume and photo-measured independent variables.

4.4.1 Volume estimation by direct Visual Comparison.

An example of this method is available from a report by Swellengrebel (1965) concerning an area in West Irian (formerly Netherlands New Guinea). In this instance, the object was to determine whether the costs involved in a full inventory in an area of difficult access could be justified.

Using photographs at a scale of 1:20,000, Swellengrebel claimed the possibility of indicating four forest "quality" classes defined by their total round-timber volumes per hectare viz:

<u>Volume</u>	<u>Category</u>
0-860 cu.ft./ac.	5
860-1700 " "	4
1700-2550 " "	3
> 2550 " "	2

(Category 1 was reserved for Araucaria forest which did not occur)

No indication of tree species was involved. Additionally, it was claimed that such classification is possible even though the standard images for which volume had been accurately determined were of forest areas geographically removed from where the comparison was required.

The author admits having difficulty in defining methods of recognition of the quality classes stating that frequent reference to the standards was required. Even so, a gradual deterioration in interpretation is admitted particularly when associated with scale and tonal variation.

These variations resulted in Categories 2 and 3 being combined

into one class. Subsequent field assessment over "9 survey lines" representing 0.01% of the total area designated as belonging to the combined class revealed a mean round-timber volume of 2.825 cu.ft./ac. which is compared with a value of 2.550 cu.ft./ac. expected from the combined classification.

Swellengrebel has not defined the forests involved sufficiently well to enable the reader to determine if they were of the same floristic composition. However, the results of the single trial described are impressive despite the subjective nature of the comparison and the obstacles described by the author.

The method described is, in fact, a comparison of canopy aspects which reflect both the floristic and the size composition of the forest. The method should therefore be limited to areas of known floristic similarity. Particularly is this true when merchantable volume represents only a small proportion of the total wood volume. In these conditions, one or more of the commercial species may well not be represented in the canopy or be of smaller size, without noticeably affecting the canopy aspect.

Photographically, the method requires a considerable similarity between images particularly in texture. Texture will be the photo-image characteristic for the determination of similarity and any of the factors previously described affecting texture will need to be equated in the photography. Best results are likely therefore when the standard images are taken from the same photographic run as those on which the classification is being made.

One of the greatest difficulties with this method is in drawing a line of demarcation between two quality classes. Unless associated with a marked and rapid change in environmental conditions, a sudden change in volume content is unlikely. While comparison with standard photo-images at either end of the range of volume content would be relatively easy, a decision on the exact boundary separating two classes would be open to a considerable degree of subjective opinion.

It is considered that the method has many disadvantages - chief of which is an inability to determine if the standard and subject areas

have a similar floristic composition. Secondly, separation of categories is highly subjective. Finally, dissimilarity in canopy aspect can be mapped if not identified without introduction of a standard photo-image which has, in all likelihood, been produced under different photographic conditions.

As a method of stratification, the method has claims to dividing the area into classes based on volume content alone. Such a division has been described as only partially fulfilling the requirement of stratification.

4.4.2 Aerial Tree Volume Tables.

Aerial tree volume tables are based on an established relationship between crown diameter and stem diameter; the former being measured on the photograph to provide an estimate of the latter.

This is the inverse of the relationship between crown diameter and bole diameter first described by Duchaufour in 1903 (Dawkins 1963) who required an estimate of crown diameter from bole diameter as a measure of crop density for silvicultural purposes.

A great deal more attention has been given to the basic nature of the relationship by workers in the field of crop density (Curtin 1964; Dawkins 1963). Dawkins has examined six possible relationships of the regression of crown diameter (d.k.) on bole diameter (d.) and concluded "that the most practical interpretation over the normal range - - - - is a straight line $d.k. = a + (b \times d.)$."

The interpretation has been made that the value of the regression constant "a" is related to the tolerance of the species and to silvicultural treatment. Dawkins concluded that negative "a" values are found in evenaged crops after thinning or in un-evenaged crops when the criterion of air-photo visibility is applied.

From an array of data giving d.k. and d. values, it is possible to calculate either the relationship of d.k. on d. as the independent variable or of d. on d.k. dependent on the view-point of the worker. Once either relationship has been calculated, however, it is not permissible to calculate the inverse relationship by algebraic manipulation -

e.g. $d = a + (b \times d.k.)$

$$\therefore d.k. = \frac{d}{b} - \frac{a}{b}$$

- since the method employed in calculation of the original regression is based on the assumption of the independent variable being without error.

Determination of the true relationship between a regression of d.k. on d. and that of d. on d.k. will improve understanding of the basic nature of the regressions through adaptation of Dawkins theory.

A linear regression coefficient is calculated from:-

$$b_{yx} = \frac{SP_{xy}}{SS_x}$$

- here b_{yx} indicates the coefficient of "y" - the dependent variable on "x" - the independent variable; and SP_{xy} denotes the sum of products of the ^{deviations} ~~derivations~~ of x_i and y_i from their respective mean values and SS_x denotes the sum of squares of the ^{deviations} ~~derivations~~ of x_i from its mean value.

Now, where it is required to obtain the relationship from the opposite view-point, it follows that

$$b_{xy} = \frac{SP_{xy}}{SS_y}$$

Therefore -

$$b_{yx} \times b_{xy} = \frac{(SP_{xy})^2}{SS_x \cdot SS_y}$$

This latter is also the square of the co-efficient of correlation (r) - a frequently used measure of "closeness of fit".

Therefore -

$$r^2 = b_{yx} \times b_{xy}$$

+ Note: $xy + yx$ are
subscripts to b

Thus, if presented with a regression of, say d. on d.k. in the usual linear form and the correlation coefficient is given, it is justifiable to calculate the regression co-efficient of the inverse relationship. [It should also be noted, that in the event of a perfect correlation i.e. $r = 1$, then algebraic inversion of a relationship is valid.]

To determine fully the inverse relationship, it is also necessary to have the mean values of the variables since both relationships have a common point in the mean values of y and x.

CORRECTLY - INVERTED RELATIONSHIPS OF d. ON d.k.

AUTHOR	RELATIONSHIP	UNITS	INVERSE RELATIONSHIP	UNITS
Swellengrebel 1959	Wallaba forest	$\left. \begin{array}{l} d \\ 4'' \text{ units} \\ d.k. \\ 5' \text{ units} \end{array} \right\}$	$d.k. = 0.54 + 1.0415 d.$	$\left. \begin{array}{l} \text{as} \\ \text{before} \end{array} \right\}$
	Mixed forest		$d.k. = 1.1116 d. - 0.003$	
	Mora forest		$d.k. = 1.1131 d. - 0.080$	
	$d = 1.084 + 0.618 d.k.$			
Macabeo 1957	Pentacme contorta	d, d.k.		
	$d = 0.2893 + 0.04768 d.k.$	metres	$d.k. = 20.155 d. - 5.535$	d, d.k. metres.
Howroyd 1954	Dipterocarpus spp.			
	$d = 17.43 + 0.357 d.k.$	d. inches d.k. feet	$d.k. = 23.616 + 7.749 d.$	d, d.k. feet.

Of the many authors who have used the relationship of d. on d.k. (the photo-mensurationists), some have appended details of the derivation of their regressions. From these, it has been possible to calculate a statistically sound inverse relationship. (See Table opposite). Two of the inverted equations have resulted in positive "a" values and three are negative.

The theory proposed by Dawkins in support of his statement that photo-mensurationists generally provide expressions having a negative "a" value when inverted deserves consideration. The theory is that "the smallest of the visible crowns will tend to be the tallest in their d.k. class, consequently of exceptional d. and therefore of low d.k./d. in that class. ... Again, the largest of the visible crowns because they belong to a d.k. class which is entirely visible ... will consist of trees of maximum possible d.k./d. ratio for their d. class ... The result of this double bias, caused by the criterion of aerial visibility, would be a tilted d.k. : d. line, raised at the upper and depressed at the lower extremities relative to a line for all individuals of the given species in the community."

If an examination is made of the text of the papers presented by the authors listed, it is impossible not to concur with the theory presented by Dawkins.

Howroyd did not demand of his sample trees that their crowns be visible from above. A minimum girth of six feet was the only criterion applied. In the Dipterocarp forests of North Borneo, it is doubtful if the crowns of trees of six feet girth and over would all be entirely visible from above. Having not satisfied the requirement of aerial visibility, it is unlikely that the tilting effect described would have been encountered.

The other example of a positive "a" value occurring in a statistically correct inverted formula is that of the Wallaba forest in British Guiana supplied by Swellengrebel. Fortunately, this author has provided additional data permitting an explanation of the behaviour of this regression.

The Wallaba forest is composed of Eperua falcata to the extent

of 65% by numbers of all trees over 10" d.b.h.; crown diameters are small 10'-40' and canopy height relatively low 80'-120'. In all, it is hardly typical of wet tropical forests. However, more significantly, a greater proportion of the smaller diameter trees are visible on the photographs.

For comparison with the other forest "types" studied by Swellengrebel, consider the following table:-

<u>Percentage of Visible Trees.</u>			
<u>d.b.h.</u> <u>class</u>	<u>Wallaba</u> <u>forest</u>	<u>Mixed</u> <u>forest</u>	<u>Mora</u> <u>forest</u>
12"	73	26	38
16"	92	54	56
20"	100	77	67
24"	100	92	100
28"	100	93	83
32"	-	100	100
36"	-	100	100
40"	-	-	100
44"	-	-	100

For Dawkins theory to apply, only the largest trees are to be visible on the aerial photograph in order to ensure a tilting effect. The closer conditions favour an aerial view of the entire range of diameter classes, then the less is the tilting effect. On this basis, it would be expected that regression constant values for the inverted relationships would decrease (i.e. become more negative) from Wallaba through Mixed to the Mora forest. This, in fact, is illustrated as being so in the previous table.

Therefore, it is possible to conclude that the basic nature of the relationship of d. on d.k. is in the form: $d = + a + (b \times d.k.)$ when only those trees which are entirely photo visible are considered. An ability to recognise the crowns of trees of smaller size classes will result in smaller "+ a" values.

The basic requirement for establishing an unbiased relationship between d.k. and d. is that of ensuring the aerial visibility of the

tree crowns. This implies that the entire periphery of a crown be photo-visible and distinctly separable from its neighbours when photo-images are viewed stereoscopically.

Previously, it has been demonstrated that only those trees represented by Canopy Position Code 5 can be measured without fear of bias. Trees represented by Canopy Position Code 4 may be used to establish the relationship but at the risk of incurring a bias caused by the interlocking of crown peripheries even though optimum conditions of tonal contrast may exist between the crown concerned and its neighbours. In brief, from an aerial view alone, a distinction cannot be made between Canopy Position Codes 3 and 4.

A comparison of photo-measured and ground-measured crown diameters would serve as a means of judging the extent of interlock of the crown peripheries; and could provide a means of correcting the bias incurred if a single even-aged species were involved. Extension of such a method to a mixed tropical forest would have doubtful value in view of the complex structure in terms of species and sizes and of the competition within such forest.

Thus, to avoid bias through underestimation of crown diameter, only those trees represented by Canopy Position Code 5 should be considered for establishing the relationship.

The second requirement is that the interpreter be able to recognise the crown being measured as single or multiple. What is required is an ability to count crowns representing individual trees. The difficulties of so doing and the results of some workers have been previously given. For gregarious species particularly, the inability to separate individuals remains a barrier to the application of this technique.

The third requirement is one of statistical detail concerning the use of single species or multiple species regressions. Ideally, each species should have a separate regression calculated from purposively selected data covering the range of sizes of crown diameters which are photo-visible. Application of such a regression, however, would imply the ability to recognise the species concerned from its photo-image. The considerable difficulties, if not impossibility, of doing so on a

significant scale have been outlined.

The alternative is to prepare a regression for a combination of species and to apply such a regression to individual trees regardless of their specific identity. Such a combined-species regression would be made up from regressions for individual species after statistical tests involving comparison of residual variances to determine whether such combination is meaningful. Such comparison is facilitated by the use of the pro-forma Appendix I (Dawkins 1965). An inability to combine individual regressions in addition to an inability to recognise species is a barrier to the use of the technique.

Use of a successful combined regression is only satisfactory when applied to trees in the same proportion by species as was involved in its calculation. The application of a combined regression to a single constituent member cannot be recommended just as its application to a species not used in its construction would provide another source of bias. Ideally, therefore, regressions should be constructed for local usage only.

The final requirement for the satisfactory establishment of a regression of bole diameter on crown diameter concerns the shapes of the tree crowns involved. Hollerwoger (1954) and Loetsch and Haller (1964) have reported on the inability to accurately measure crown diameters of "stag-headed" overmature teak (Tectona grandis). Similar difficulty would be encountered with other species e.g. Terminalia superba (Paelinck 1958), Planchonia spp. and other species of deciduous habit. For accurate measurement, tree crowns should be entire and preferably circular since it is the relationship between crown area and bole area which is estimated by diameters. Trees represented by Canopy Position Code 5 will, in general, have more circular crowns and, unless senescent, suffer less crown damage.

Additionally, these trees may be assumed to have acquired a relationship between d.k. and d. which is characteristic for the species and site. Swellengrebel (1959) has referred to trees developing a crown out of proportion to their boles when first entering the forest canopy. The bias involved in such a phenomenon would be avoided in restriction

AERIAL TREE VOLUME TABLE ATTEMPTS

Paijmans	1951	Malili [Celebes]	All species	$d(\text{cms}) = 15.25 + 3.5 d.k. (\text{m})$	$r = 0.61$	Trees selected on ground as photo-visible.
Heinsdijk	1953 to 1961	Surinam and Amazon	Seperate species and Combined species	Linear and curvilinear relationships (both concave upwards and concave downwards). Combined regression for all species linear over 3m. d.k. (Surinam) and over 10m. d.k. (Amazon)		Only trees with "fully emergent crowns" were considered - called "upper storey" trees.
Howroyd	1954	North Borneo	7 Dipterocarp species	Linear relationships provide weighted equation $d(\text{ins}) = 15.71 + 0.400 d.k. (\text{ft})$		Selected trees over 6' girth.
Macabeo	1957	Philippine Is.	Pentacme contorta	$d(\text{cms}) = 28.93 + 4.768 d.k. (\text{m})$ (Stump)	$r = 0.961$	No information on selection methods.
Swellengrebel	1961	Surinam	Wallaba Mixed Mora	$d = 1.084 + 0.618 d.k.$ $d = 1.934 + 0.593 d.k.$ $d = 1.101 + 0.735 d.k.$ [d. = units of 4" diameter d.k. = units of 5' diameter]	$r = 0.802$ $r = 0.812$ $r = 0.9045$	Trees measured on ground for d. - attempted photo-identification of trees for measurement of d.k.

*The writer's own calculations from details provided by the author.

of interest to emergent trees which are intolerant (i.e. light demanding), probably pioneering species which have achieved equilibrium between crown and bole diameters.

Undeterred by these rather limiting requirements, or perhaps unaware of them, many workers have attempted to determine regressions in tropical forest conditions. The details of these attempts are summarized in the table opposite.

It has been established that a satisfactory relationship can only be determined for emergent trees of suitable crown form that are distinguishable as individuals. From this relationship, it is possible to obtain a measure of bole diameter with an appropriate precision of this estimate. The ⁱⁿfrequency of occurrence of suitable trees will mean that only a small fraction of the commercial content of the forest has been estimated for diameter.

In order to estimate the volume of those trees for which an estimate of diameter is available, there are two alternatives:-

(a) Application of the estimate of diameter to a single entry terrestrial volume table applicable to the species involved. Such a method involves two standard errors - the first resulting from the regression of d. on d.k., the second from the regression of volume on bole diameter. A combination of these errors is necessary to express the precision of the volume estimate. A more convenient but not necessarily a more precise method follows.

(b) Modification of the regression of d. on d.k. to give volume on d.k. with a single standard-error.

Neither method recognises the influence of log length or form factor on the volume estimate. If the relationship is established between crown diameter and bole diameter for local application only and if log length and form factor for the species involved are proved constant for the locality of application, then a satisfactory derivation of volume is made. Species of markedly different log lengths (as may be caused by excessively high buttress habit e.g. Alstonia spp.) or taper must be regarded separately. Such separation will involve an ability to recognise these species on the basis of their photo-images.

Examples of the relationship between crown diameter and volume are available as follows:

Howroyd, working with 4170 recordings of d.k. on volume for 15 Dipterocarp timbers, found the best relationship in the form of the exponential function -

$$\log_{10} \text{ volume} = 1.7108 + 0.0132 \text{ d.k.}$$

(hoppus cub.ft.) (3' classes)

Swellengrebel proposes the determination of a regression of volume on d.k. as a project for future activity in those forests where the "canopy is shallow and regular, allowing crown diameter measurement of the smallest crowns."

Macabeo obtained a simple linear regression -

$$\text{Volume} = 1.915 + 0.926 \text{ d.k.} -$$

(cubic metres) (metres)

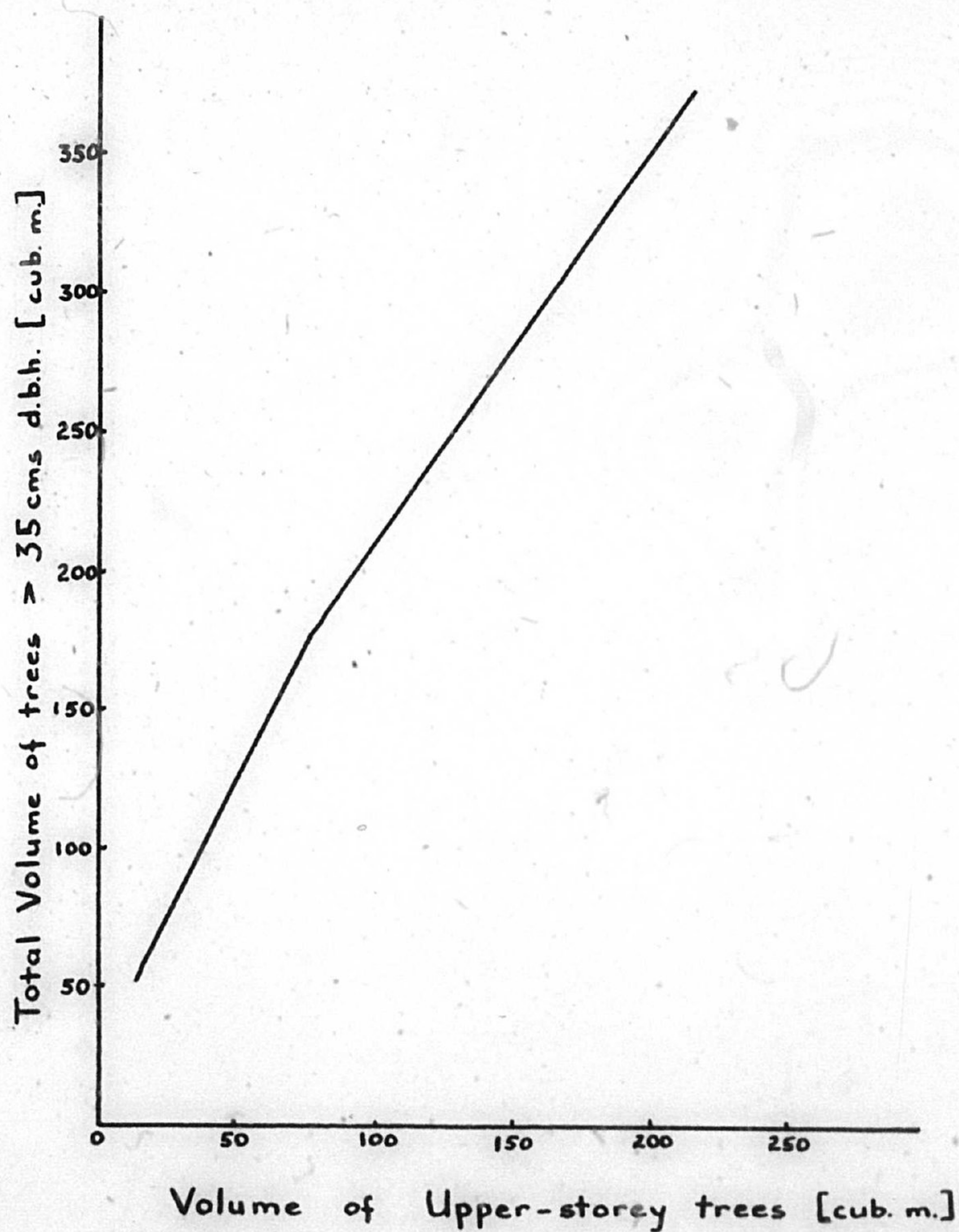
- with a correlation coefficient of $r = 0.967$.

On the other hand, Paijmans, working with a regression of d. on d.k. which provided him with a standard-error of the estimate of diameter of ± 5.3 inches, has made use of terrestrial volume tables prepared separately for three "quality" classes from a double logarithmic relationship between volume and diameter.

It is the writer's opinion that the authors quoted have attempted to obtain more from their measurements of crown diameter than the avoidance of bias will permit. Howroyd did not stipulate that crowns measured should be visible on the photographs. Swellengrebel attempted a diameter estimate of such small trees (10" d.b.h.) that it is difficult to imagine this author being aware of the bias involved if total crown periphery is not visible. Macabeo established his relationships in the anticipation of aerial photography becoming available at a later date. Paijmans has stated that aerial visibility was the criterion for selection of his sample and yet, has applied his regression to crowns which he admits are inseparable as individuals.

The remaining author, Heinsdijk was alone in stipulating that crowns be "fully emergent". His data on such crowns are as follows -

DEMONSTRATION OF THE RELATIONSHIP
BETWEEN UPPER-STORY VOLUME AND
TOTAL VOLUME FOR AMAZON FORESTS.
[HEINSOITK 1957]



<u>Locality</u>	<u>Stems > 25 cms.d.b.h. density</u>	<u>Upper-storey stems density</u>
Surinam	140-170/ha.	30/ha.
Amazon	100-120/ha.	20/ha.

Using war-time photography at a scale of 1:40,000, Heinsdijk developed a method of ocular estimation of crown diameter controlled by few measurements. Additionally, he subjectively divided the forest into two height categories - over and below a value of 25 metres. The result of these subjective assessments was a grouping into eight classes; the following table being duplicated for each height class -

	<u>Crown measure</u>	<u>Mean value</u>
Class I	3 - 12 m.	approx. 10 m.
Class II	13 - 17 m.	" 15 m.
Class III	18 - 22 m.	" 20 m.
Class IV	25 m.	" 25 m.

A linear regression for all species was obtained between bole and crown diameter. Bole diameter was entered into terrestrial volume tables to give a simple volume table -

<u>Vol. per tree (cub. metres)</u>				
<u>d.k. class</u>	<u>Low trees</u>		<u>High trees</u>	
	<u>A.</u>	<u>S.</u>	<u>A.</u>	<u>S.</u>
I	1.1	1.5	2.6	2.2
II	1.7	3.2	4.4	4.1
III	2.5	4.2	7.2	7.0
IV	4.3	6.0	12.0	9.6

(Heinsdijk states that upper-storey trees in the Amazon were, on average, 8-10 m. taller than in Surinam).

The most significant of Heinsdijk's contributions to the topic came with his putting the relationship between "upper-storey" tree volume and "total volume" on a quantitative basis. A reproduction of a graph representing the relationship is provided opposite.

According to the author, the proportion of the volume not measurable from the relationship of d. on d.k. via the volume tables, decreases with increasing measurable volume. Loetsch and Haller (1964) report a similar trend in the forests of Southern Sumatra. Nyssonen

(1961) obtained, in the same area, a linear relationship ($y = 0.79x - 15.5$: $r = 0.855$) between "commercial volume of trees over 42.5 cms. diameter ($= y$) and the total volume of trees over the same diameter limit ($= x$). This author concludes that "if the volume of all the trees above a certain size limit can be studied from aerial photographs, some indication can be obtained at the same time of the structure of the growing stock and, at least, of the amount of commercial wood."

What is obtained, of course, is gross volume indicating nothing of species and size composition nor of the form of the logs involved or of their defect. But as an aid to stratification of forest areas of similar floristic composition, the method offers interesting potential particularly if all subjective influences are eliminated through the use of better suited photography.

4.4.3 Aerial Stand Volume Tables

The third method of volume estimation is the preparation of Aerial Stand Volume Tables based on area-related information measurable on aerial photographs.

Greatest development in this field has been achieved in the forests of North America where the following represents a general outline of procedure:- A series of plots are examined on the ground to determine volume. These plots are usually purposively selected to cover as wide a range of volume content as possible. Photo-images of the same plots are then examined stereoscopically in order to determine suitable independent variables which are related to plot volumes by multiple regression analysis. The most frequently used variables are crown density - usually expressed as a crown coverage percentage and a measure of stand height. The introduction of a third independent variable - crown diameter - is also possible.

In tropical forests, it has already been indicated that height estimates from aerial photographs are impracticable. Crown diameter has been investigated in the previous section. Crown closure percentage remains worthy of investigation.

Paelinck (1958) used such a measure in his attempt at volume

estimation of *Terminalia superba* - a species with a tendency to aggregation in near pure stands. A classification of three degrees of crown cover representing 0-30%, 30-70% and 70-100% were associated with volume estimates 20, 100 and 200 cub.m./ha. respectively. However, the errors involved were too high to permit the use of such an association even for reconnaissance purposes.

Swellengrebel (1959) in deciding to use a d. on d.k. regression for volume estimation in British Guiana rejected crown closure measurement as "pre-supposing an incomplete crown cover which will hardly be found." Such a statement is, of course, dependent on what is being considered in the term "crown closure." This author was obviously referring to all trees whereas Paelinck was referring to a single identifiable species occurring in nearly pure aggregations which were apparently separable from crowns of other species.

In converting the volume of the individual emergent trees to an area-related "upper-storey volume" for use as the independent variable to assess total volume, Heinsdijk has used number of stems per unit area. This factor represents another possible expression of crown density viz. crown cover of "upper storey" stems.

Such an expression has been used by Francis in Sabah, Malaysia, as reported by Loetsch and Haller. Francis related extracted timber to the independent variable "visible crowns of upper-storey trees" per unit area to obtain a linear relationship -

$$y = 77.78 + 478.73x \quad (r = +0.69)$$

(cub.ft./ac. extracted) (no. of crowns per acre).

Included in this correlation are the effects of inability to separate crowns and of a variable defect percentage.

In summarizing their review of tropical forest photo-mensuration attempts, Loetsch and Haller indicate a promising line of research in the study of the regression "total timber volume" on the independent variables "number of visible emergent trees", "crown closure of the upper canopy trees" and "stand height classes" - the latter possibly in two or three broad classes.

The writer believes it is important here to distinguish between

CANOPY CLOSURE DETERMINATION



An area of natural rain-forest offering opportunity
for determination of the percentage of canopy closure.
(From original 2" x 2" negatives at approx. 1:25,000)

"number of visible emergent trees" - the factor surely used by Heinsdijk and "crown closure of upper canopy trees" which must refer to those trees whose crowns could be represented by Canopy Position Codes 3 and 4. The absence of a complete canopy closure by such crowns is impossible by definition unless the additional factor of relative height, as interpreted by stereo-viewing, is considered. The stereogram reproduced opposite would represent a suitable target for the determination of "crown closure of the upper canopy trees." Trees contained in the "depression" areas have canopies represented by Codes 3 and 4 but are separated from the higher forest by relative height interpretation. Only the higher forest has commercial interest.

Additionally, the writer believes that for the bulk of undisturbed tropical forest, the value for canopy closure of upper canopy trees would be 100% - a similar interpretation to that of Swellengrebel. At a later date (1961) that author used such an assumption to estimate the volume of a gregarious species (Greenheart - Ocotea rodiaei). In that study, he assumed that areas interpreted as stands of Greenheart contained a fixed volume per acre of that species. However, for disturbed forest, as represented in the stereogram, a measure of canopy closure of upper canopy trees has considerable importance.

The use of the independent variable "number of visible emergent trees" implies a disregard of crown diameter as a measure of bole diameter or volume. It could be interpreted that each emergent crown represents a fixed volume of timber. Use of this value as an independent variable would be suitable only for those forests where emergent trees were the same species or different species having the same relationship between crown diameter and bole diameter or volume. Similarly, the application of this independent variable would need to be limited to areas of similar environment to that for which the relationship was established. Dilworth (1956) has indicated that "as site quality decreased, visible crown diameter increased for a given d.b.h." Similar variations would be expected in tropical forests and would not necessarily be indicated by changing stand height which can only be assessed in broad classes.

4.4.4 Conclusions.

It is the writer's opinion that photo-mensurational techniques for the determination of some measure of volume in tropical forests does have a potential for aiding stratification. However, the methods do not enable an ideal stratification. Additionally, the methods have serious limitations as outlined and must be regarded as complementary^e to field sampling and not a substitute for it.

The direction for exploring this potential will vary according to forest types:

1. For a mixed tropical forest, a photo-sampling procedure for volume estimation would involve the following steps -

(a) Determination of a satisfactory relationship between volume as the dependent variable and crown diameter of emergent trees.

(b) Relation of the estimated volume of emergents to an area of productive forest i.e. exclusive of voids in the commercial canopy height. (Applicable to disturbed forest only). A count of emergent trees is required.

(c) Relation of the volume of emergents per productive acre to the total volume by regression analysis.

2. For individual species which may be recognised and which tend to aggregate in nearly pure stands. Such species are generally light demanding, have a relatively uniform canopy height and are difficult to separate as individuals. In Papua - New Guinea, Octomeles sumatrana (Erima) and Terminalia brassii are examples of this forest type. The procedure must involve the establishment of a relationship between the required volume and an area of canopy as exemplified by Swellengrebel (1961).

For any of the stages involved, it is essential that all relationships be established on a sound statistical basis permitting calculation of standard error. Only then can the effectiveness of the photo-mensurational technique be appreciated. Such an appreciation is essential to any decision regarding its application.

4.5 Canopy Aspect Mapping.

4.5.1 Definition and Method.

Identification of other than a few tree species from their photo-images appears to be impossible with the present standards of photography.

Photo-mensuration activities are limited to forests that have a sufficient density of emergent trees or are near-pure stands of a recognisable species.*

Neither method, even where optimum conditions for success exist, enables an ideal stratification as outlined.

Possibly the oldest method of using aerial photography for forestry purposes is what the writer has chosen to term "canopy aspect mapping." This method requires the interpreter to gain an overall impression of the photo-image of the forest canopy rather than to examine component parts in detail, as required by the other methods.

The photo-image characteristic involved is allied to texture - previously defined as created by tonal repetitions in groups of objects too small to be discerned as individuals.

Such a definition only partially satisfies the requirements of defining a canopy aspect. The many species of a tropical forest canopy each contribute an element of tone; dependent on the angle of illumination and the height advantage of emergent trees there will also be a varying content of shadow; different crown diameter sizes are represented as are the height advantages of some crowns over their neighbours when stereo-images are viewed. The effect of each of these elements conveys an impression of the canopy which has been termed "canopy aspect."

Just as a single sample plot of $\frac{1}{4}$ acre cannot reliably assess the floristic and size content of a tropical forest so a study of a limited area of a stereo-pair cannot provide a full impression of the canopy aspect. To gain an impression of canopy aspect, the writer prefers examination of stereo-images at a final scale of between 1:20,000 and 1:30,000. Larger scales tend to present too much detail - meaningless in view of the wide variation of tropical forest in terms of floristic and size compositions even within what might be termed a "type". Conversely, smaller scales tend to mask significant detail in terms of

size parameters of diameter and height advantage and in terms of tonal contrasts between crown images.

Since the elements creating the impression of canopy aspects are the product of the forest canopy and the photographic conditions, it is reasonable to expect any significant change in forest composition to be reflected in an impression of changing canopy aspect. Particularly is this true when photographic conditions are reasonably constant - as can be expected within the same "run" - possibly within a single mission.

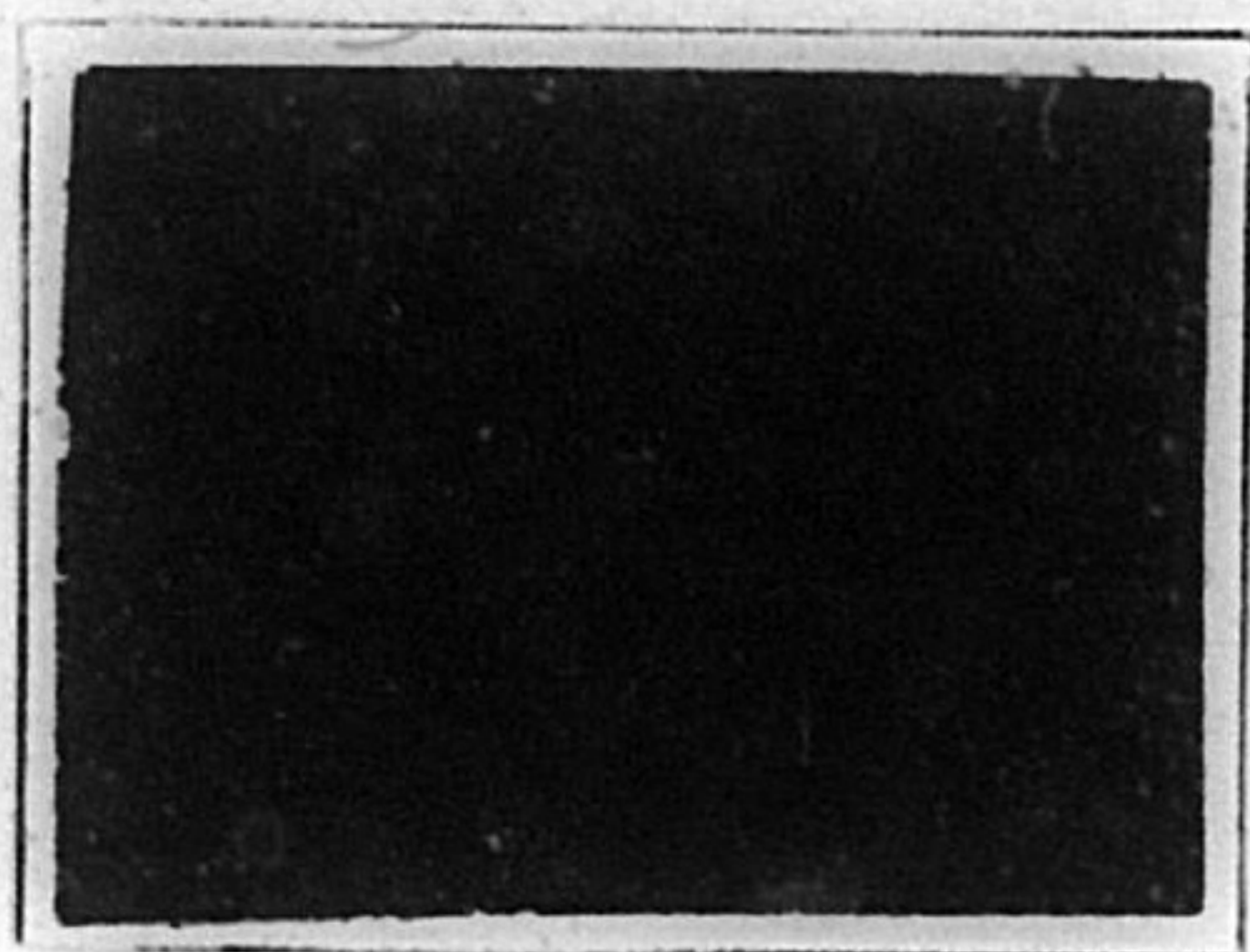
It has been through the recognition of canopy aspect changes that division of areas of tropical forest into so-called "types" has been achieved. Loetsch and Haller have made a most useful summary of the attempts at classifying tropical forests, quoting the work of Loetsch (Thailand), van Dillewijn (Surinam), Boon (Indonesia), Francis and Wood (Sabah, Malayasia), Rollet (Cambodia), Wheeler (Cambodia), Browne (Sarawak, Malayasia) and de Rosayro (Ceylon). To this already impressive list, the writer might add the names of Mason (Guatemala), Pajmans (Celebes, Indonesia) and Gregor (Fiji Islands).

Those authors quoted by Loetsch and Haller have made what is referred to as an "ecological-floristical classification". Additionally, reference is made to the use of quantitative methods to sub-divide such classifications e.g. by Loetsch who mapped three density classes of Dipterocarpus alatus on the basis of counts of this emergent; by Browne who sub-divided the Shorea albida community on the basis of crown diameters of individuals or groups and finally; by Francis & Wood who used crown cover percent as a measure of destruction to be superimposed on each "type".

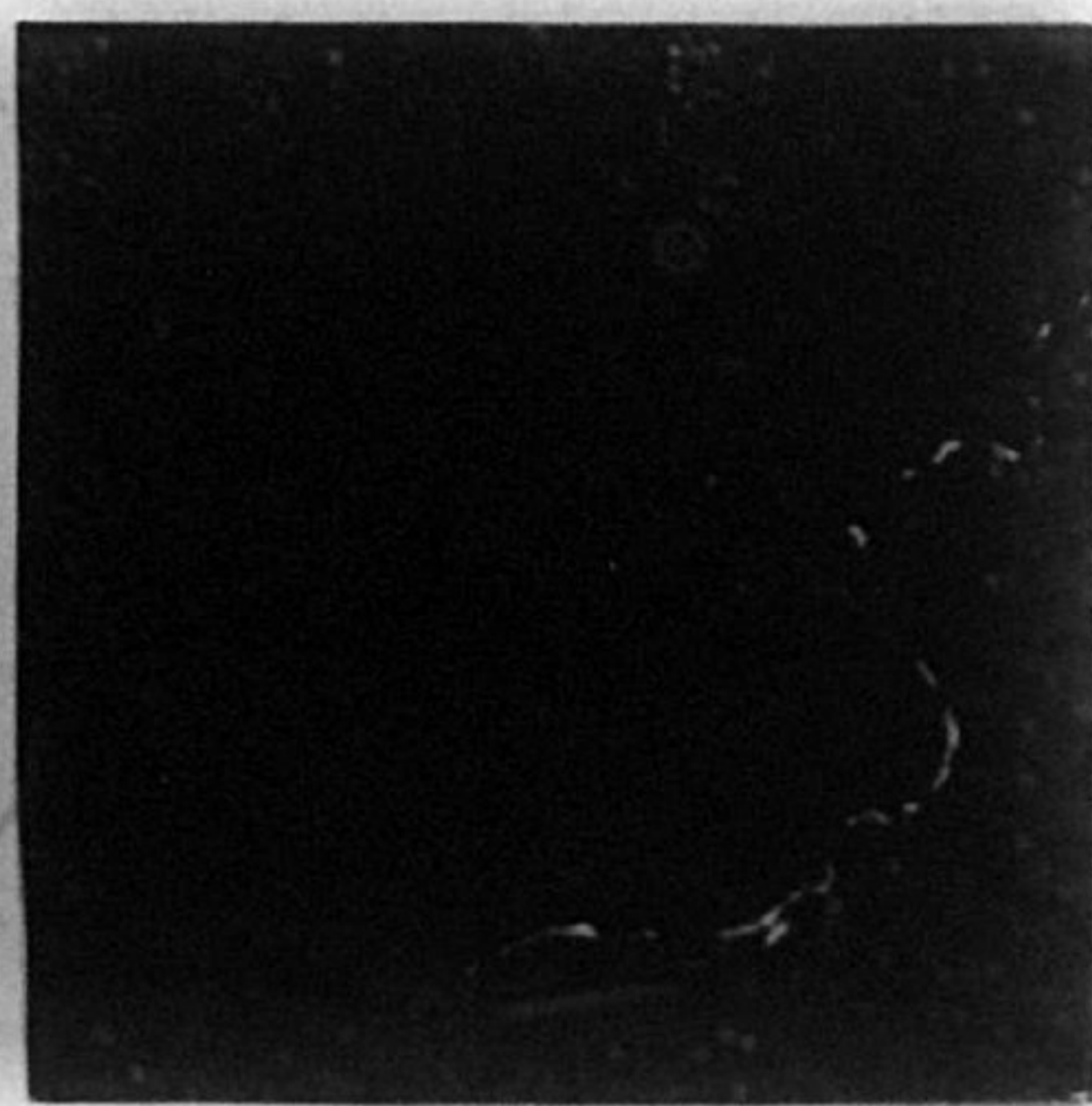
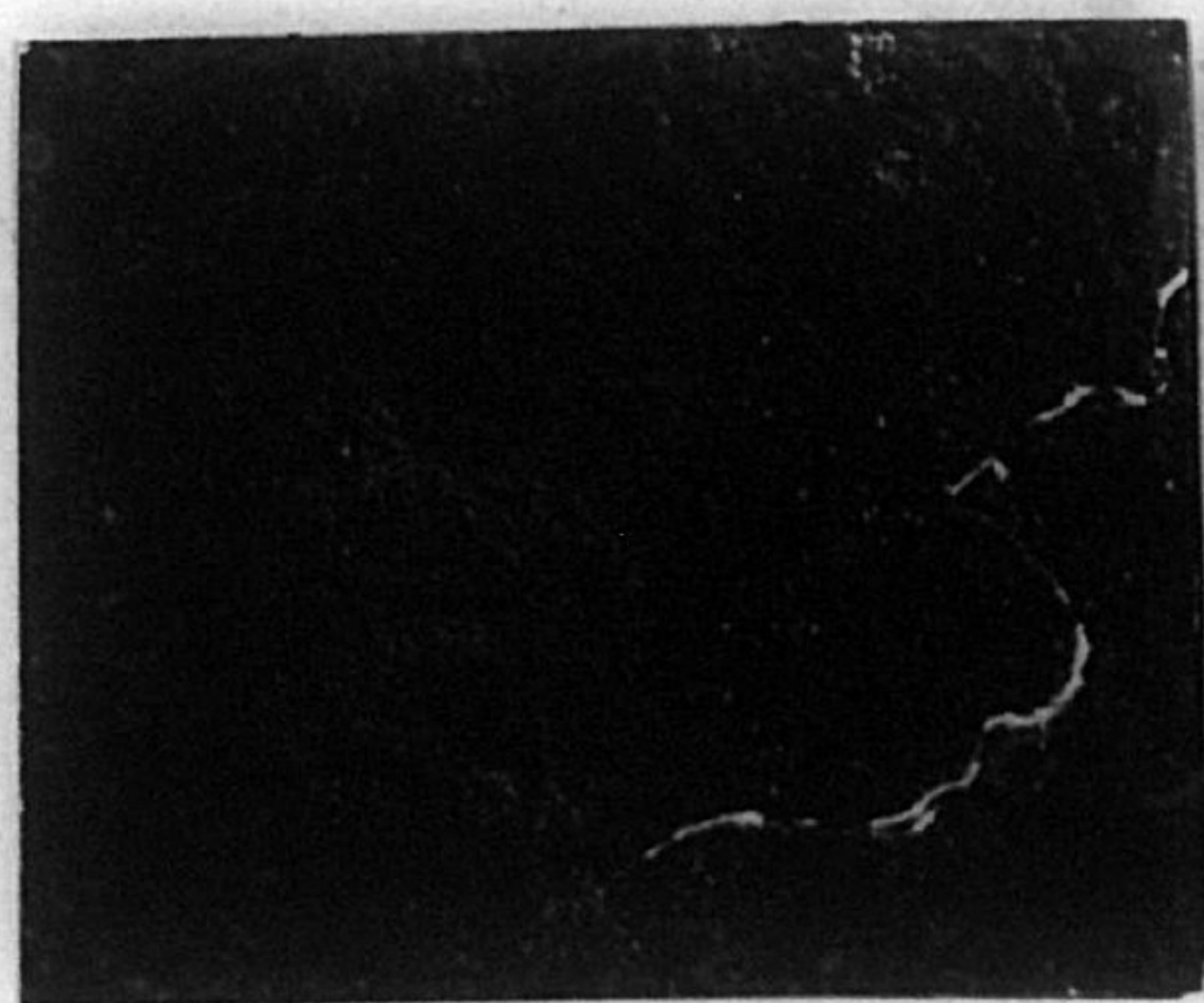
The writer believes that use of such methods is unnecessary and indicative of attempts to interpret what is already known from field observation. Such characteristics as those authors were seeking to establish should have been evident without a knowledge of the "ecological-floristical" detail, the density of emergents or crown cover percent.

It is contended that canopy aspect mapping can be performed by an interpreter having no knowledge whatever of the forest involved. Such does not imply that the interpreter need not be skilled. On the contrary

CANOPY - ASPECT MAPPING



- (I) An example of a simple canopy-aspect division in tropical rain forest (Papua).
(Enlarged from original 1:50,000)



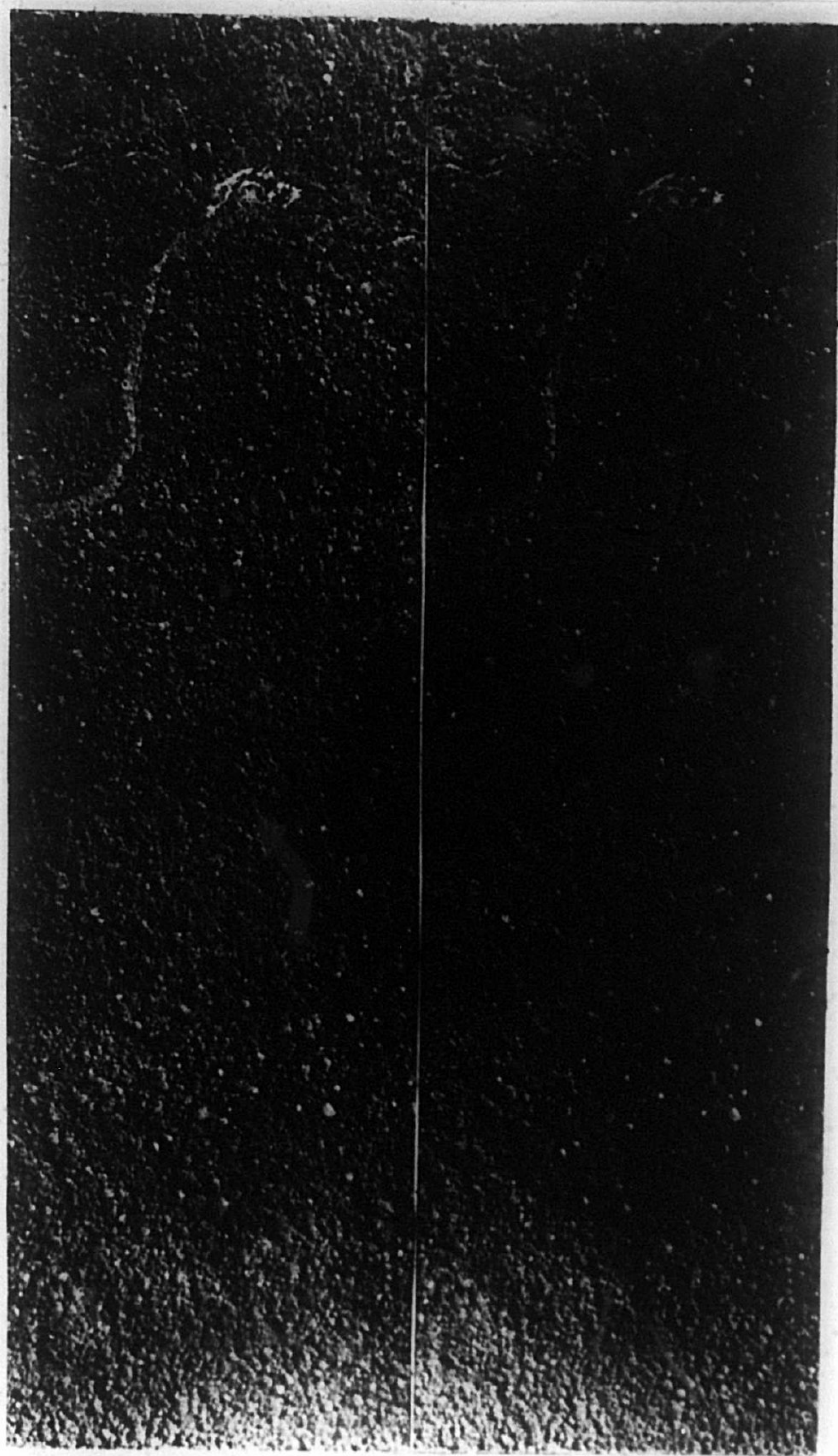
- (II) An example of a very difficult canopy-aspect division in tropical rain-forest (Papua). Divisions are highly subjective and those indicated proved unreliable.
(Enlarged from original 1:50,000)

a skilled interpreter may make divisions on this basis of canopy aspect which will represent the floristic and size composition of the forest inclusive of density, crown cover etc. Identification of such divisions will be made by field inspection. Francis (1957) has described a similar procedure of mapping "distinctive photo patterns" stating that "it is not necessary for" - the interpreter - "to have been in the field as the stratification is done purely on the basis of ocular identification. It is emphasized that, at this stage, the forester does not know if the photo-patterns he has identified are, in fact, forest types, vegetation associations or tree species...."

Success in canopy aspect mapping has not been universal. Loetsch reports being unable to sub-divide undisturbed forest in South Sumatra although aware of differences in vegetation type due to topographic features and the patchy distribution of Shorea and Hopea species. Gregor has reported difficulty in detecting photo-image differences "between two extensive areas, one known to have a good volume and one unworkable because of low volume per acre." Field exploration had established the specific composition of the two areas as similar and it seemed reasonable to the author "that the smaller sizes in the poorer area would be reflected in smaller crowns." In a similar situation to that encountered by Loetsch, the writer was unable to demarcate adequately small pure stands of Hopea papuana in the Papuan coast although the extent of the stands was known. See stereogram.

It should be appreciated that those authors claiming success in separation of canopy aspects and who have named the divisions have been concerned with broad vegetational "types". Such "types" may cover wide areas and tend to be zonal in occurrence. This type of division is invaluable to a regional inventory but offers little to a local inventory which demands greater detail of information. Additionally, it is contended that the identification of species groups and forest "types" is more easily accomplished in areas of environmental conditions least favourable to the development of the mixed tropical rain forest. A similar opinion has been expressed by Boon (1956). Indeed, a review of the literature reveals nothing on the subject of stratification

CANOPY - ASPECT MAPPING



An example of an area offering a considerable potential
for canopy - aspect mapping .
(From an original 1:18,000 scale)

within the mixed forest.

A strong case may be outlined for the detailed study of the division of canopy aspects suited to the requirement of local inventory. Boon (1961) has suggested the use of systematic sampling procedures, allied with statistical analysis of species occurrence and association, as a means of mapping areas of similar stocking by particular species. Such maps could then be compared with photo-images in order to reveal some hitherto unnoticed features. The writer would go further to suggest that the prepared maps should be compared with a series of photo-images representing different photographic techniques. Revealing additional information on a given set of photo-images would perhaps assist an individual interpreter to greater use of his subjective opinion. Selection of a technique best suited to exemplification of the additional information would ensure its more precise application by many individuals.

In conclusion, it is contended that examination of aerial photographs at a suitable scale will reveal certain differences in canopy aspect. Such differences are the result of changing forest composition in terms of species and size if photographic conditions are reasonably constant. A knowledge of the forest involved is not essential to an ability to demarcate canopy aspects since such information will be more reliably determined after interpretation. The interpretation is therefore one of detection not recognition. Given present standards of photography, demarcation of canopy aspects is most likely to be successful in areas unfavourable to the climax development of the tropical forest. Certain forest communities, demonstrably different on the ground, are not readily recognisable as such on the photographs. Research is necessary into photographic techniques for depicting such differences.

4.5.2 Canopy aspect units as statistical strata.

Assuming an ability to demarcate areas of different canopy aspect, as in the stereogram opposite, it would seem reasonable that each individual canopy aspect unit, as an expression of the floristic and size composition of the forest it represents, would be suited as a stratum for the purposes of sampling. Particularly is this so when photographic conditions are similar to the extent of preventing misinterpretation.

However, although an aerial view of the forest canopy generally depicts at least part of the crowns of trees of commercial size, inability to identify most species may mean that canopy aspect divisions have been made on the basis of the variable presence of one or more species of no commercial interest such as emergent species of Ficus and Planchonia. Recognition of such divisions as strata would involve more field work than necessary. Again, the effect of topography with relation to the angle of illumination on tonal variation and shadow content may cause the interpreter to make unnecessary or faulty divisions. For efficiency of field operations, therefore, it is essential that canopy aspects be evaluated before recognition of statistical strata.

Such evaluation must be made by field work prior to the design of the sampling procedure. It might thus be regarded as a reconnaissance. In addition to canopy aspect evaluation, such a reconnaissance provides other information essential to the efficiency of sampling e.g. the logistics of field-work may be studied; contact may be made with indigenous forest-dwellers.

The amount of detail to be collected for canopy aspect evaluation will depend on the extent of the differences that are required to be demonstrated. Ultimately, this could involve a detailed sampling to demonstrate statistically significant differences in numbers and volumes in required categories. In its simplest form, the evaluation could consist of a subjective observation at a few selected points within each aspect type. In order to be objective, however, quantitative data should be sought.

Since, in most sampling procedures a low sample-fraction is to be employed, differences between strata will need to be considerable before they become evident in the data collected in routine sampling. Therefore, the minimum of objective data should be sought in canopy aspect evaluation since only major differences are detectable in minimum data. This may involve the establishment of perhaps ten small plots in each aspect type. On each plot, the species and girth of commercial tree species over a minimum girth likely to be visible on the photos (suggest 3') should be recorded. Comparison of the stand tables available should

provide evidence of any difference in composition.

Under circumstances where an aerial view suggests a difference in canopy relief between canopy aspects, an additional factor of height measure could be included on a sub-sample of the trees in each plot.

4.6 Photographic Quality.

4.6.1 Introduction.

It has been observed that the identification of tree species from aerial photographs of tropical forests is less reliable than identification made by aerial observation. Small-scale photography has prevented objective methods of crown diameter measurement for volume estimation in the method demonstrated as likely to be most successful. Examples have been given of the inability of interpreters to differentiate canopy aspect variation for areas of known dissimilarity in floristic and size composition. Much of the fault in these failings must be placed on the quality of the photography available to the interpreter.

Most photography available to forestry interpreters in the tropics is of the so-called "general purpose" type. The scale is usually small, varying from 1:30,000 to 1:50,000. Flying and photographic conditions often appear to have been better suited to the convenience of the crew than to the quality of the product. Finally, processing has not generally been designed for the required interpretation.

As an example of the advantages to be gained by processing techniques alone, it is useful to consider the example given by Corten (1962). From original prints, an interpreter was unable to distinguish teak (Tectona grandis) from other species. Preparation of special prints showed a clear difference although the prints would be considered by others as of "very bad quality". Corten concludes that "the photo-interpreter should realize exactly what he needs and that he should express this in clear physical-photographic terms in order that the photographic organization may produce the optimum product for his requirements".

Another indictment of "general purpose" photography comes from a consideration of the trends in which this photography, intended primarily for mapping, is developing. The writer believes even smaller scales will be adopted in future. Small scale photography needs fewer ground controls

and involves less time in adjustment of photogrammetric machinery for a given mapped area. Further, the development of super-wide angle lenses offers the means of obtaining these small scales with adequate quality for mapping purposes.

However, scale should not be regarded as the sole factor governing photographic quality. Bovsky (1960) has referred to interpreters being in the practice of evaluating photography on the basis of scale to the extent that "scale has gained a significance in terms of interpretability never anticipated by its definition". Large scale photography is costly and such additional cost can only be justified by additional yield from the interpretation. Thus improved quality in terms other than scale is required.

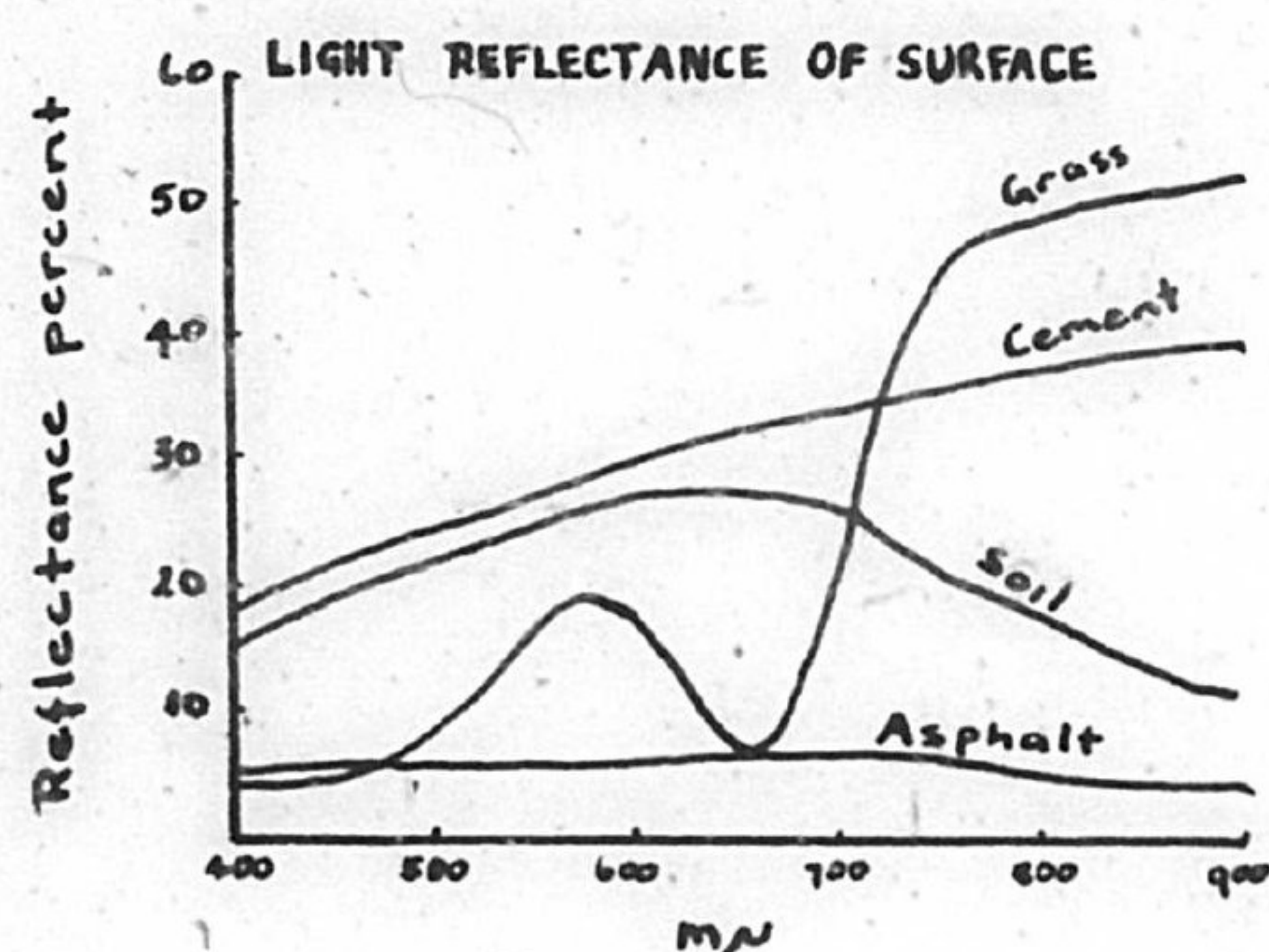
A final condemnation of general purpose photography comes with consideration of the different requirements of the photo-mapper and the photo-interpreter. Jackson (1960) considers an interpreter to be interested in identifying what he sees making "intensive and extensive examination of the detail and area involved.... The photogrammetrist, on the other hand, wishes to locate what he sees.

Corten (ref. cited) has expressed the need for interpreters to be able to express their requirements in "clear physical-photographic terms". Such may be the need but is only rarely going to become a reality. The number of influences involved in the determination of a very basic image quality characteristic - tone - have already been listed. It is the writers opinion that determination of the means of improving photo-quality is the responsibility of experts in that field. The responsibility of the interpreter lies in understanding the photographic nature of his target and in having a clear idea of the advantages to be gained from the alternative techniques available to him in contracting for aerial photography.

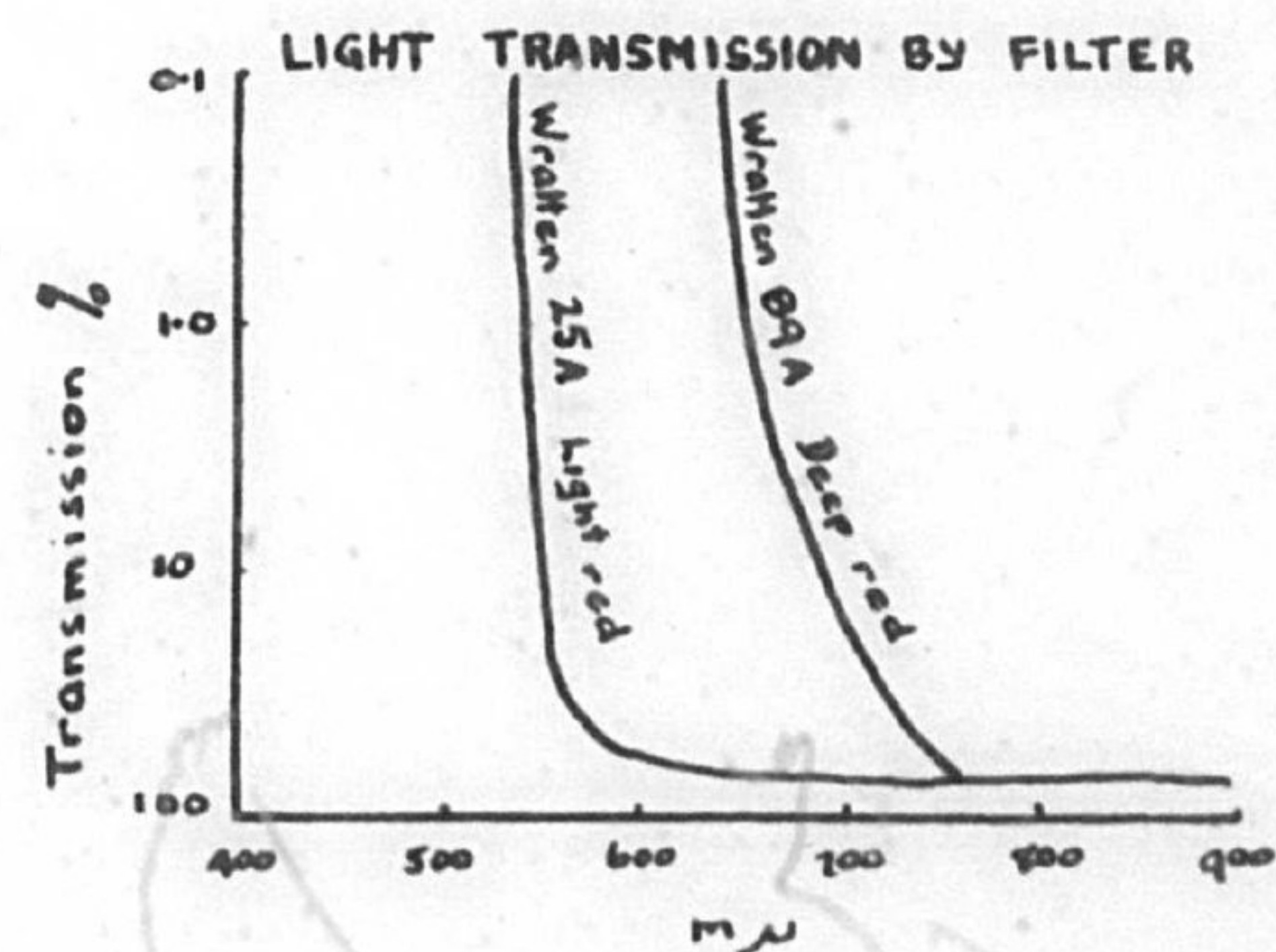
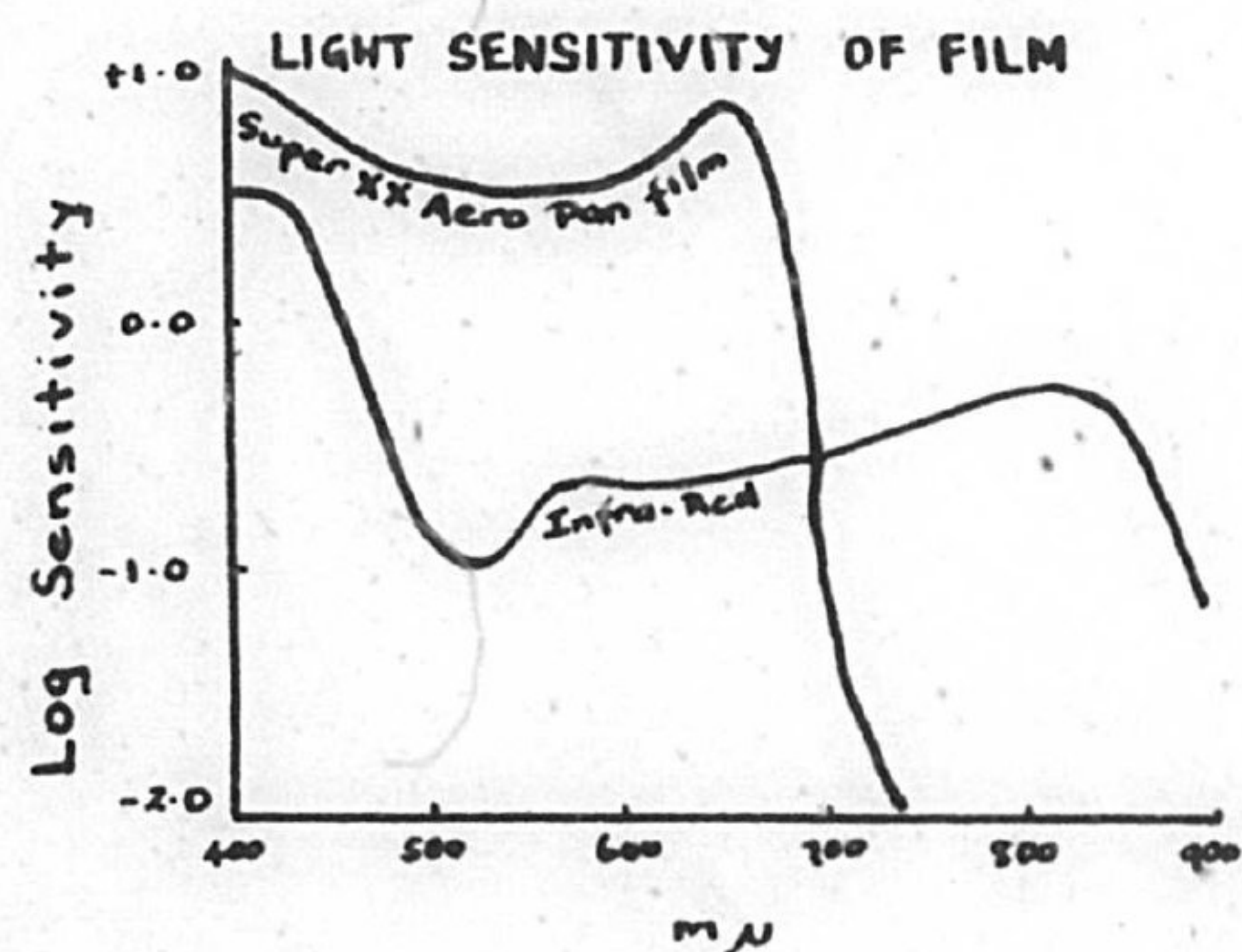
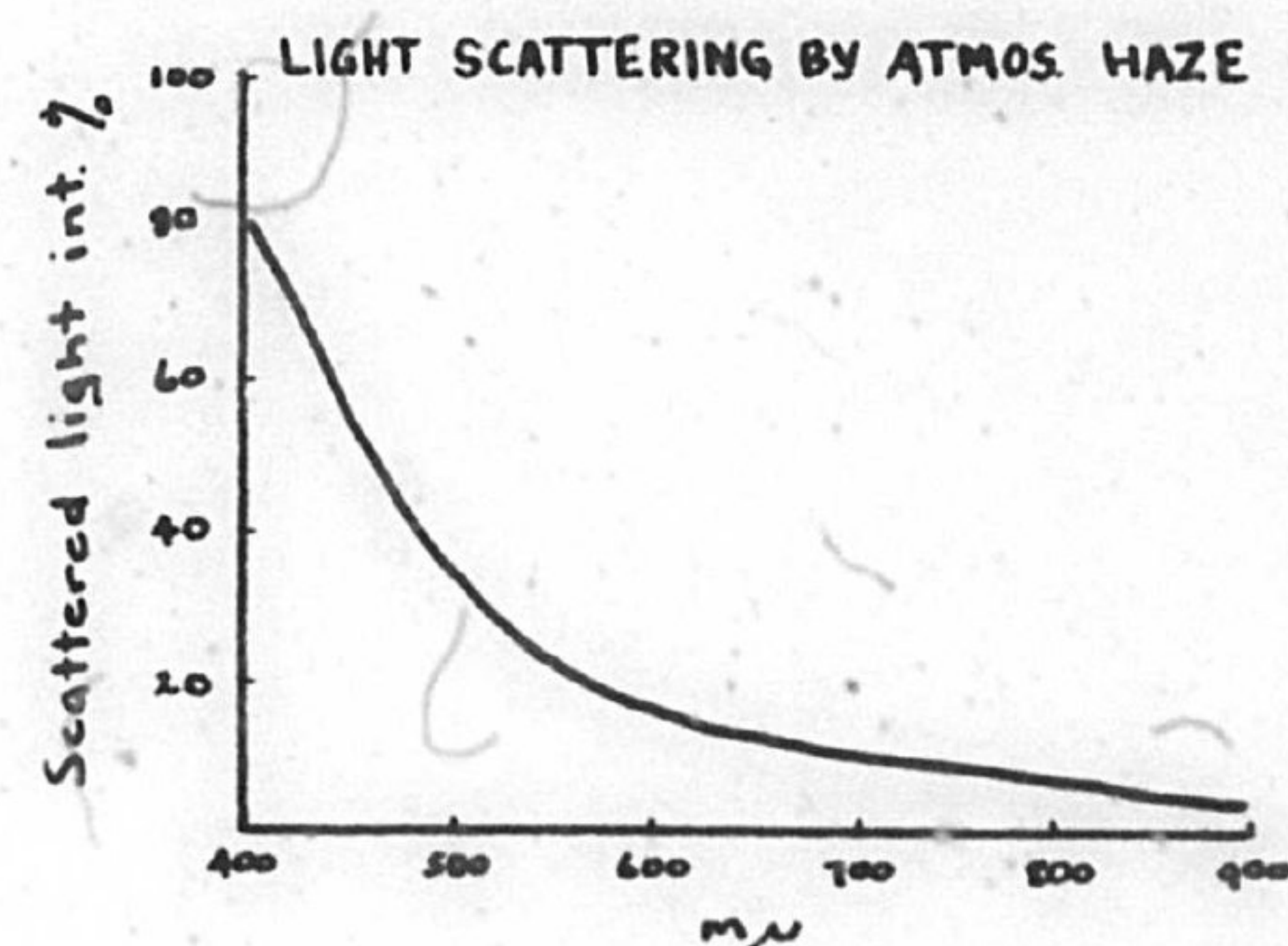
In the Manual of Photographic Interpretation (1960), the authors have stated that photographic images are dependent for quality on the following primary characteristics -

- (i) Tone or colour contrast between individual objects and their surroundings.
- (ii) Image sharpness characteristics.

DEMONSTRATION OF METHOD OF SELECTION OF FILM AND FILTER COMBINATION FOR OPTIMUM TONAL CONTRAST. [MANUAL OF PHOTOGRAPHIC INTERPRETATION]



400	VIOLET
	BLUE
	GREEN
600	YELLOW
700	RED
>750	INFRA RED



(iii) Stereoscopic parallex characteristics.

Jackson (ref. cited) has listed similar characteristics as the basis for his discussion of image quality.

It is intended to discuss the place of these characteristics in photography of tropical forests, to cite instances of application and to draw conclusions as to optimum requirements.

4.6.2 Tone or Colour Contrast.

For all purposes of interpretation of tropical forest areas, the interpreter requires the maximum differentiation of individual tones or colours within the forest canopy itself.

The forest canopy may be expected to have a reflectance of incident light of about 20% (Bovsky) and contrasts will be low in comparison with those of other targets.

In order to accentuate tonal contrast in so difficult a target, most attention has been focussed on the use of film and filter combinations. However, no results of objective investigations in tropical areas are available.

Variation in tonal contrasts in the images produced by different film and filter combinations results from the fact that tonal contrast is governed predominantly by these factors - (Manual of Photographic Interpretation 1960)

- (a) Spectral reflectivity of an object and its background.
- (b) Spectral sensitivity of the film.
- (c) Spectral scattering of the haze.
- (d) Spectral transmission of the filter.

Of these factors, items (b) and (d) are controllable to the extent of selecting alternative film and filter types best suited to the conditions imposed by items (a) and (c). (See diagram). Measurement of these items can be achieved by spectrophotometry and has been performed for many temperate climate forests (Spurr 1960). No information of similar measurement for tropical forests is available. Although such have been recommended by Nyysönen (1961), the writer believes the logistics of performing such an operation in a meaningful way would prove immensely expensive.

RECOMMENDATIONS FOR FILM AND FILTER COMBINATIONS.

Reference	Locality	Recommendations
Francis 1957	West Africa	Panchromatic film with minus-blue filter provides "greatest overall tonal rendering over most tropical rain forest areas": Colour photography represents "the most promising prospect for individual tree species identification in tropical forest areas": Use of colour film suggested by "coppery coloured flush of mahogany [<u>Khaya ivorensis</u>]" in Ghana: On infra-red + "pure infra-red photography has more contrast than modified infra-red and ---- the former accentuates tonal differences": Panchromatic film with red filter + "tonal quality of resulting prints showed this technique unsuitable
Miller 1960	General	Reports Belgians as using "a type of modified infra-red" for small scale photography of rural areas; more distinct tonal contrast evident in savannah vegetation.
Boon 1960	S.E. Asia	Reports no application of infra-red in the area and recommends early introduction on the basis of success elsewhere in tropical areas.
Nyssonen 1961	General	Warns of poor tonal differentiation in important green colour range with colour film. Recommends fast, good-quality panchromatic film for best reproduction of tonal differences.
Stellingwerf 1965	General	Prefers infra-red to panchromatic film for small-scale photography. Reports easier recognition of secondary forest with infra-red film in the Congo and Liberia; and better tonal contrast in the forest canopy in the Congo. Not as satisfactory as panchromatic film for man-made objects eg. villages, roads, etc.

The characteristics of film types - panchromatic, infra-red, colour and false-colour - and of filters - have been adequately discussed by Spurr (ref.cited) and in the Manual of Photographic Interpretation (A.S.P. 1960). It is intended to review their application to tropical forests.

Presented in tabular form are the reports of five workers on the subject. No author has had the opportunity to test the available alternatives on an area of forest from which quantitative data had been collected and for which forest associations had been mapped. The lack of such an objective test must place these reports in the category of opinion. Similarly, the following is only opinion.

By courtesy of Hunting Surveys Ltd., the writer was able to examine aerial photographs (taken in the tropics, but unfortunately not of typical tropical forests) utilizing a considerable range of techniques - panchromatic film with minus blue filter, infra-red film, colour negative film, black and white prints from colour negatives and false-colour film.

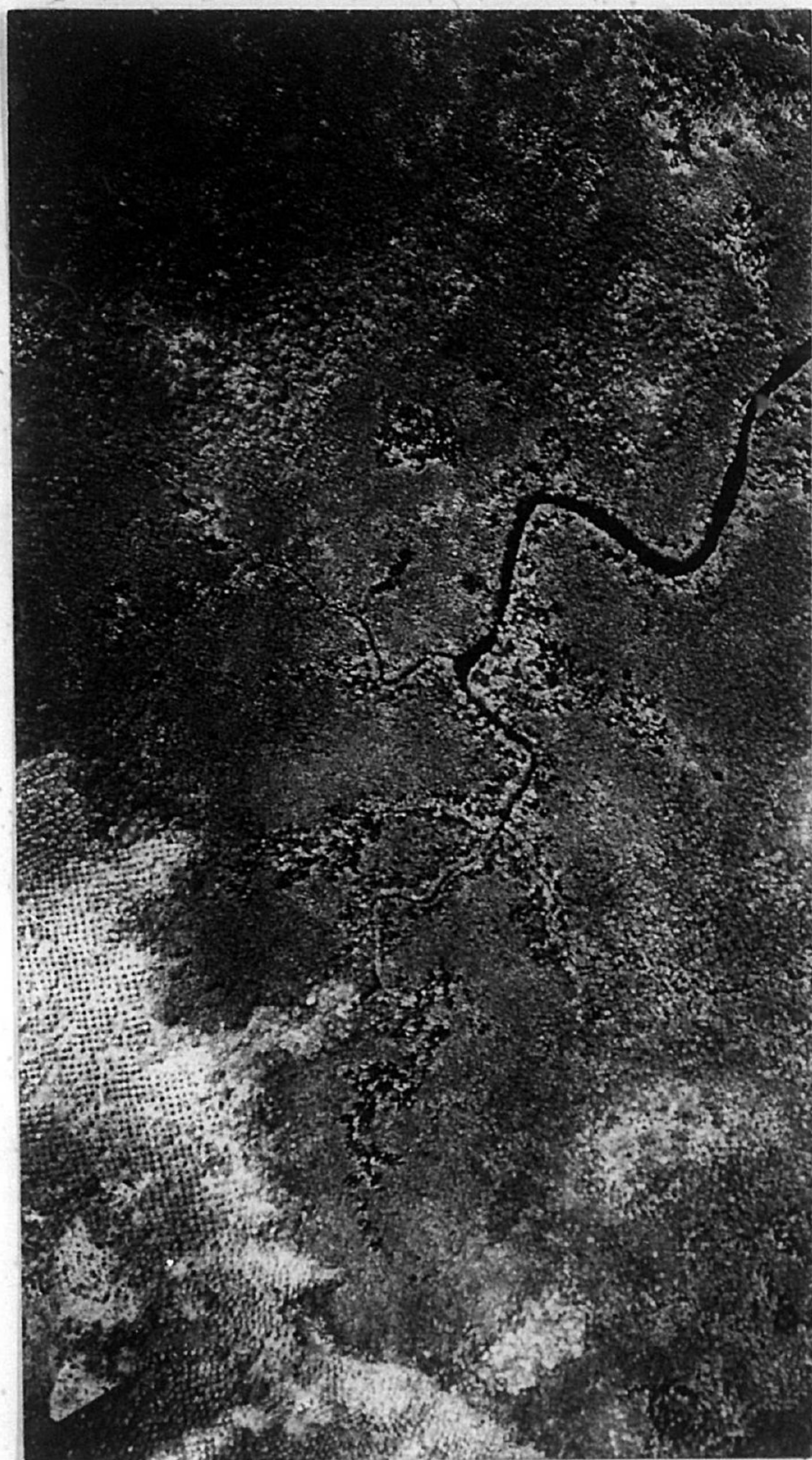
Colour negative prints proved most interesting in view of the wide range of overall print hue which could be achieved by various printing techniques from a single negative. Hues ranged from blue through greens and yellows to magenta, yet each print was equally clear and sharp. The opportunity is therefore available to print from a single negative a series of images from which a selection of the one affording best interpretation of the desired subject may be made.

False colour photography uses a colour infra-red film with three emulsion layers - sensitized to green, red and infra-red radiations. Foliage containing chlorophyll appears a bright magenta; dead vegetation a bright green and water a vivid blue. A reproduction of a false colour photograph of a mangrove forest in Sabah (Malayasia) is given.

The most impressive features of this photograph are the differences in the intensity of the magenta colour (tonal contrasts in the panchromatic film) and the ease with which water is detected. In other film types, water surfaces would have been lost in shadow. Additionally, the infra-red sensitivity of this film would probably allow haze-penetration - a serious barrier to quality photography in the tropics. The application

FALSE - COLOUR FILM

(ALSO CAMOUFLAGE - DETECTION FILM)



An area of mangrove forest and oil-palm plantation
in Sarawak (Malaysia).

by courtesy HUNTING SURVEYS LTD.
Boreham Wood
Herts. U.K.

of this technique to swamp forests - in particular the Terminalia brassii forests of the Solomon Islands - must have a considerable potential.

In addition to the techniques already mentioned, there is one other, known as spectro-zonal photography, which has been developed in the U.S.S.R. This technique employs a two-layered film producing an image in arbitrary, contrasting colours claimed to facilitate greatly the interpretation of detail (Mikhailov 1960). One layer is panchromatic, the other infrachromatic. The first develops to a light blue, the latter to a magenta. There is no known report of the use of this film in forest conditions outside its country of origin.

The need for objective testing of the variety of techniques available has already been stressed. Before the general application of whatever technique may prove best suited to the requirements of interpretation however, an evaluation must be made of the costs of any benefit gained.

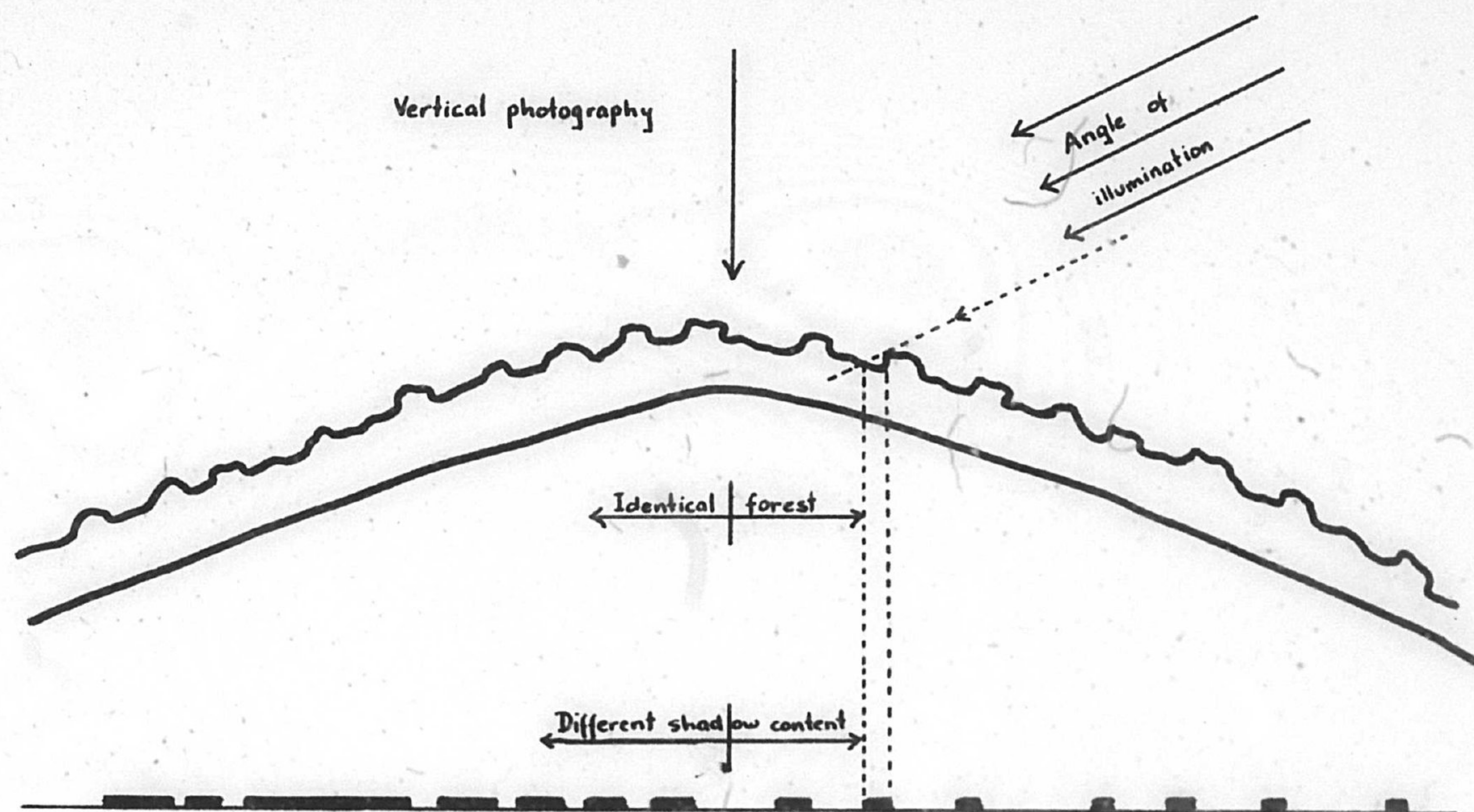
Panchromatic film is cheap because it is in such general use. Other film types vary considerably in cost. However, film and processing costs alone should not be the sole criterion of judgement. The placement and operation of the photographic aircraft will continue to represent a great proportion of the total mission costs. Thus, although colour film may prove three times as expensive as panchromatic film, the total mission cost using colour film may be only 20-30% greater than if panchromatic film is used. It is against such overall costs that the value of additional interpreted information must be measured.

Until such time as the experimentation outlined results in general acceptance of economic techniques, panchromatic film with a minus-blue (yellow) filter will continue to be used over large areas. There exists ample room for improvement of this technique to better suit forest interpretation.

To improve tonal contrast within the canopy itself, attention must first be given to the scale of photography. It has long been appreciated that small-scale photography tends to reduce tonal contrast between the individual tree crowns through poor resolution of these small images and through the effect of haze which increases with flying height. The new

SHADOW-CONTENT

VARIATION IN SHADOW-CONTENT DUE TO TOPOGRAPHIC ASPECT AS IT MAY AFFECT CANOPY-ASPECT DIVISION.



field of Contrast Transmission (International Archives of Photogrammetry 1960) has indicated that contrast reduction may begin with detail of a size between 0.5 and 0.2 mm. diameter in the photographic image. Equating the more conservative value of 0.5 mm. with a minimum tree crown size of 5 metres would require a scale of 1:10,000 to prevent loss of contrast between objects of this size. It has already been indicated however, that division between and determination of canopy aspects offers the greatest potential for stratification for inventory purposes. Larger areas than individual crowns are concerned. Thus, smaller scales are tolerated and indeed preferred - to a minimum of 1:30,000 which would ensure no contrast loss between objects of 15 metres (48.5 feet) diameter. Such a scale approximates with that recommended by Nyysönen (1961) in conclusion to his review of photographic scale used for tropical forest interpretation.

To facilitate canopy aspect mapping, attention to time of photography may provide an improved image. The amount of contained shadow in a canopy aspect is a function of the height advantage of certain trees and the angle of illumination. Photography at a time giving maximum shadow content would improve distinction between canopy aspects one of which has greater canopy relief. At the interval between 0° and 10° South latitude, photography between the hours 07.45-09.30 and 14.30-16.15 solar time would ensure an angle of elevation between 25° and 50° from the horizon. For such photography, care would be needed to avoid shadow-point through consultation of prediction tables (Sims 1961). For interpretation, care would be required that topographic attitude was not confused with canopy aspect. (See diagram).

Other measures to ensure tonal contrast within the forest canopy rest with the photographer and the film processing. The responsibility of the interpreter is to instruct that tonal contrast is required and to assess which method of processing is best suited to that requirement.

4.6.3 Image sharpness characteristics.

The Manual of Photographic Interpretation lists the following as major factors governing image sharpness -

- (1) Aberrations of the lens system.

- (2) Focus of lens system.
- (3) Image motion at the instant of exposure.
- (4) Characteristics of photographic materials.

The nature of interpretation will determine the significance of image sharpness factors in affecting image quality. Large-scale photography as might be used for crown diameter measurements may be taken at such a low altitude that image sharpness is impaired by image motion at the instant of exposure. Focus of the lens system for optimum image sharpness may involve a loss in small detail resolution. In either case, the solution is one of compromise best decided in discussion with an expert who is aware of the interpretation requirement.

4.6.4 Stereo-parallax Characteristics.

Normal aerial photography has a forward overlap of 60% and a lateral overlap of 20-30%. The stereo-model seen when the two images are correctly viewed has a vertical exaggeration tending to make buildings appear taller, slopes steeper etc. The degree of exaggeration perceived is governed by the following major factors. (Manual of Photographic Interpretation).

- (i) Altitude of photography.
- (ii) Height of object photographed.
- (iii) Length of air-base.

The physiological basis for stereoscopy has been a matter of dispute since first enunciated by Wheatstone in the 19th century. Original theories concerned a "convergence" of images and were elaborated with geometric diagrams from which interpretations were made that variation in viewing technique (magnification, image-separation etc.) could effect changes in the degree of vertical exaggeration perceived. (Spurr 1960). McGrath (1950) has indicated considerable differences in the interpretation of stereoscopy by four authors concluding that range finder theories were incorrectly applied to viewing photo-images. This author also demonstrated that a stereo-model could be perceived even with "divergent" vision. More recently, Julesz (1965) has indicated that a stereo-model was possible even under conditions where one image was out of focus and where one image was reduced 10% in size.

This author concludes that stereopsis "involves many cues and cannot be described by trigonometry alone". Jackson (1960) also rejects "convergence" claiming that depth is appreciated by "disparity in the field surrounding the point of attention".

Whatever the physiological nature of stereoscopy, any noticeable increase in the vertical exaggeration of the model can only be achieved by modification of those factors listed.

Jackson has also provided a measure of exaggeration. Reasoning that 10 inches (minimum distance of distinct vision) is the natural basis for expressing relative depth perception and that the relationship between this distance and mean inter-pupillary distance (2.5 inches) is in the ratio of 4:1, the author claims exaggeration to be expressed by the factor -

$$E = 4 \frac{B}{H} = 4 \frac{b}{f}$$

where -

H = flying height

B = air-base

f = focal length

b = photo-base.

Thus, in "normal" photography (9" square format, 60% overlap, focal length 6") $b = 3.6$ inches and $E = 4 \frac{b}{f} = 2.4 X$

Such an exaggeration value is constant for given photography regardless of the viewing technique.

The significance of exaggeration to the interpreter depends on the requirements of interpretation.

Jackson considered exaggeration a barrier to "seeing the object as it is" and suggested that a forward overlap of 80% would provide a more "normal" stereo-view yet still provide a 60% overlap from alternate photographs with a 2.4 X exaggeration.

The interpreter of a stereo-pair of the canopy of a tropical forest is presented with a view having relatively little relief. For the differentiation of emergent trees necessary for photo-mensuration techniques, vertical exaggeration is essential. As the differentiation

of canopy aspects is a technique based on the overall impression of texture and height variations with the canopy, the requirement is once again for vertical exaggeration.

Of those factors controlling vertical exaggeration, flying height and focal length also determine scale. This will most probably and correctly have been decided on the basis of other considerations. For smaller scale photography, there remains an opportunity to modify these factors and retain the same scale. For example, for photography at 1:20,000, a flying height of 10,000 feet with a 6" lens provides better exaggeration than 20,000 with a 12" lens. Use of wider-angle lenses and lower flying heights introduces two problems. The first is one of excessive radial displacement preventing stereo-fusion as experienced by Swellengrebel (1959) using a scale of 1:10,000. The second is one of atmospheric turbulence frequently encountered when flying at lower levels. For large-scale photography e.g. larger than 1:10,000, image motion characteristics must be considered.

Variation of the length of air-base is, in effect, variation of the interval between exposures for a given air-speed. Increased overlap results from shortened intervals or reduced air-base. Increased overlap means less exaggeration but also means more photographs per square mile and therefore greater cost. Corten (1962) has indicated that a reduction in the amount of forward overlap to 55% may result from improved flight execution. A considerable saving in cost of photography ($\frac{3}{4}$ of the number of photographs compared with the 65% overlap required for hilly areas under present navigation conditions) and interpretation time would result. Reduction of overlap therefore means greater vertical exaggeration and a saving in cost. However, there is a danger that too great a reduction, particularly for small scale photography, would again involve excessive radial displacement in taller objects and difficulty in stereo-fusion.

In conclusion, vertical exaggeration is necessary for tropical forest interpretation and the means are available for securing it. However, it should be achieved only without involving other factors such as turbulence, image-motion and excessive displacement which reduce photographic quality.

5. DEFINITION OF AREAS FOR SAMPLING ESTIMATES

Prior to commencement of sampling, it is essential that the areas for which separate estimates of numbers and volumes are required, be defined on a map.

Such areas may be required for utilization, silviculture or administrative convenience. Utilization will require details of forest produce in an area to be allocated to an individual permittee or which will represent a particular cutting period. Silviculture requires details of particular sites e.g. river terraces, lower slopes etc. For administrative convenience, particularly with regard to larger local and regional inventories, details may be required for individual catchment systems, forest districts or tenure categories.

With this information available before sampling commences, it is possible to obtain details of numbers and volumes to any desired precision level for any area defined. Super-imposition of these areas after the sampling process may reveal inadequate sampling to satisfy the purposes required. Additional units will have to be established involving the increased expense of returning to the inventory site.

6. METHODS OF SAMPLE SELECTION

To fulfil the objects of inventory, any sampling process must be within strata which are similar in floristic and size composition. The sampling process may therefore be termed a "stratified" sampling. Recognition of strata on aerial photographs will remain limited to areas least developed towards the climax forest until better techniques are developed. In Papua - New Guinea and in many other areas in which the mixed association forest is predominant, therefore, any area being considered for local inventory will have few strata imposed upon it as indicated also by Boon (1962). Larger areas requiring regional inventory will have strata representing major geographic floristic changes in addition to areas of vegetation disturbed by human agency. Such strata, particularly the former, will occupy considerable areas.

It has been indicated that volume cannot be estimated directly, unless by guesswork. Volume is estimated from measurements of diameter or girth, log length and taper. Such indirect estimation is known variously as double-sampling (Spurr 1952) and multi-phase sampling (Loetsch and Haller 1964).

A final term necessary to a sampling method for tropical forest inventory is "objective". The alternative to objective methods of location of sampling units is to rely on the ability of an individual to select "suitable" locations, either for convenience or because they are considered typical. In any event, a bias is invariably incurred and this cannot be estimated. Such a method is the Selected Line method proposed by Seely (1955; 1957 and 1961) for use in Canada and adopted by others for use in the tropics as reported by Nyssonen (1961). This author recognises its subjective basis but defends its application in stating "that personal bias can be avoided if the line is chosen without reference to the details of the stand either in the photograph or on the ground". Users of the method have gone as far as assuming that the individual plots along the line are at random and have calculated precision on the basis of this assumption. Another example of the use of the method is available from the forest inventory recently carried out on Mt. Kenya. A further example is the establishment of plots along

lines which had their origin in helicopter landing sites in dry stream beds, village clearings etc. and were directed to cross topographic features. This method has been used in Papua-New Guinea.

The unrepresentative nature of positions of convenience for the location of sampling units is obvious. Strata shape and orientation considerably affect a decision on the location of the selected line regardless of whether the individual refers to details of the stand or not. The result, particularly in dissected topography, would be a series of lines parallel with the strata margins but centrally positioned to avoid edge effects. The assumption of random location is completely invalid and cannot be substantiated.

As a method of reconnaissance to determine approximate floristic and size composition the method may claim the advantage of economy through the use of points of convenience. As a method of determining objective data, the selected line system places the results in the field^{of}/speculation.

To the writer, any enthusiasm for non-objective methods of sample selection serves to indicate a lack of comprehension of the versatility of objective methods to meet any requirement.

Objective methods of sample selection may be listed as -

- (a) simple random
- (b) restricted random
- (c) cluster sampling (either random or systematic)
- (d) systematic sampling.

Considerable variation is possible e.g. combinations of random and systematic and double systematic. In addition to this variation, there is considerable variation available in the selection of sampling units. Circular, rectangular or square plots, transects, line-plots of any shape and size may be adopted.

Whatever method of sample selection and whatever type of sampling unit used, efficiency demands that the required precision be achieved for all populations recognised at a minimum cost. The method meeting the requirements at minimum cost is the most efficient, provided the requirements have been set with a realization that their satisfaction

can be obtained at reasonable cost.

6.1 Precision

Originally defined by Finney (1947) as "the reproducibility of an estimate in repeated sampling", precision is used in the present context as the Standard Error of the mean of the required population. The requirement is made by those having interest in the results of inventory, and the level of Standard Error, usually expressed as a percentage of the estimated mean for a level of confidence of 95%, will depend on the attractiveness of the particular population being sampled.

A commonly accepted level of standard error for estimates of tropical forest produce is ± 20 percent at 95% confidence level. This error is derived entirely from the sampling procedure. The writer knows of no instance in tropical inventory where volume estimation derived from regression and therefore having a standard error has been considered as contributing an additional error of estimation. In addition to these two errors, there is a third derived from the area estimate of the stratum by which the mean value per unit area and its standard error must be multiplied to obtain a total quantity of forest produce. This error of estimate of the area of the stratum is also generally ignored. In addition to the mistakes and inaccuracies involved in inventory practice, there are therefore two additional standard errors which must be considered if the total volume and its standard error are to be meaningful to the end-use of the inventory data. It is the standard error of the expression of total volume which must be determined as a policy decision to provide this meaning.

The statement that total population volume can be expected to lie within the confidence interval of $\pm t \times \text{Standard Error}$ at a certain level of probability is of little practical value. A pre-investment survey to determine the economics of utilization alternatives would require an analysis of profitability based on three measures - total volume minus $t \times \text{Standard Error}$, total volume and total volume plus $t \times \text{Standard Error}$. Determination of a point of break-even for profitability for the various alternatives could have been made on the basis of the first measure alone. For poorer or less accessible forests,

the limit of exploitability is in part determined by the minimum volume reliably estimated as available. Such considerations led Dawkins (1958) to the calculation of R.M.E. (Reliable Minimum Estimate) as -

$$\text{R.M.E.} = \text{Estimated value} - t \times \text{Standard Error.}$$

The R.M.E. is a practical expression incorporating the necessary precision measures. Its use requires attention to the probability level applied. The required information is the probability at which it can be assumed that the true population value does not fall below the estimated value: This implies a disregard of the possibility of the true value exceeding that estimated. A probability of 95% ($p = 0.05$) that the true population value is greater than the estimated value is derived by application of a "t" value under the column $p = 0.10$ in the tables for the appropriate degrees of freedom.

The inability to calculate a valid precision measure from a single systematic sample has been the argument applied by statisticians in favour of random methods of sample selection. (Freese 1962). Traditional use of systematic sampling as a means of mapping the forest concurrently with collecting quantitative data and the instinctive desire to see the sampling units spread over the entire area have led foresters to develop methods of estimating precision from systematic samples. Spurr (1952) has made a review of these methods, concluding that -

(i) "conventional random sampling formulae may be applied to systematic samples if it is realized that they tend to define the maximum sampling error rather than the average".

To many, this has meant that systematic sampling could be applied at a sufficient intensity to provide a sampling error satisfying the policy requirements for the individual populations. Comfort can be drawn from the fact that random sampling would probably but not necessarily have provided even smaller sampling errors.

(ii) Supplementary sampling may be carried out to provide information on sampling error.

Such supplementary sampling may involve random or systematic methods. For a trial inventory, both random and systematic methods may be used concurrently. From the random sample, a sampling fraction

providing the required error may be calculated. This sampling fraction is then applied to systematic samples in subsequent areas. The assumption is one of consistency in variability of all populations involved in the subsequent systematic sampling. Such a method has been used in Malaya for the so-called "big tree enumeration". A method involving supplementary systematic sampling has been suggested by Shiue (1960) and Shiue and John (1962) wherein interlocking systematic plots are established - each series having a random origin. Each series may be regarded as a single random unit for the calculation of a standard error.

Systematic sample selection cannot be condemned therefore on the basis of its inability to provide a valid estimate of precision. It must be considered along with other methods on the basis of its efficiency, provided the other major disadvantage of the method - when there is a coincidence between layout and the periodicity of a population trend - can either be ignored or overcome.

6.2 Application of Various Sampling Methods in Tropical Forest Inventory.

A most useful review of the sampling methods employed in tropical forests has been made by Nyssonen (1961). Loetsch and Haller (1964) have also made reference to tropical forest sampling methods while Brunig (1963) has made a useful historical review of methods applied in Sarawak (Malaysia) and Boon (1962) has provided indirect reference to methods employed in many areas.

In tropical forest inventory, all the methods referred to previously have been applied with the exception of unrestricted random sampling. There is also a preference for large plots, alternatively transects or line-plots as the sampling units. Both these preferences rise from the fact that the greater the proportion of total time spent on assessment of the forest compared to walking time, camp establishment and other overhead-cost activities, then the greater is the efficiency of inventory. Another reason for the use of restricted random sampling methods is that geometric or topographic block formation is considered to limit variability in an inventory area for which stratification is not available. Sampling within artificial blocks also satisfies the

instinctive desire to see sampling units cover the inventory area as uniformly as possible.

However, a review of the literature from which the reports of the above authors have been derived will reveal no comparative tests of the alternatives available. Guided by the single principle of efficiency outlined, various workers have described their methods without reference to the comparative efficiency of the many alternatives. There are two probable reasons for this -

(i) The alternatives are obviously suited to different conditions than those prevailing in the subject inventory area. e.g. Dawkins' method (1958) is most suited to those forests in which access to the periphery is easy, access within the forest is difficult (therefore, full use must be made of any access lines cut) and forest stratification in detail is not possible. However, comparative studies need not be limited to those methods outlined by other workers. The great versatility of objective sampling methods, coupled with a great number of possible unit designs, can frequently provide an alternative method satisfying the requirements of the particular inventory.

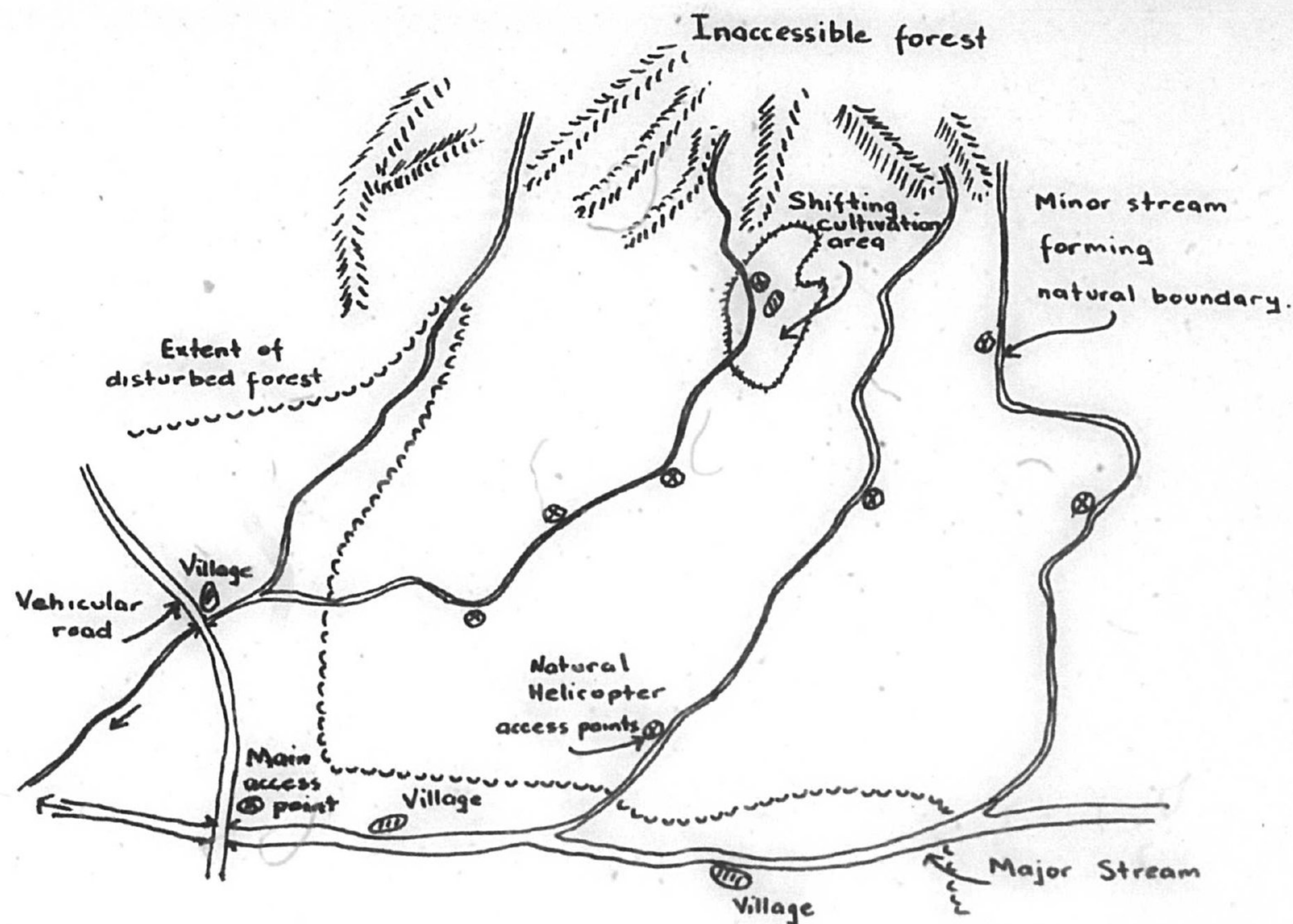
(ii) A comparative study of sampling methods and unit design requires a repetition of the procedure on the same inventory area unless areas of proven similar composition and variability are available. A comparison of sampling methods is therefore usually very expensive.

6.3 The conditions for inventory in Papua - New Guinea.

Access to peripheral points of an inventory area in Papua - New Guinea is limited. Roads are few and generally located in areas of intensive agricultural activity with little undisturbed forest. Airstrips are, of course, similarly located. Streams are mostly unnavigable and coastal vegetation has a long history of disturbance. However, it is generally possible to achieve access by road, air or water to at least one point at or near the edge of an inventory area. At such points, supplies and personnel for an inventory are discharged.

Access to further peripheral points and to the interior of the inventory area was previously by walking, frequently having to establish the track by cutting. The introduction of small, high-powered

A TYPICAL FOREST - INVENTORY AREA (approx. 102,000 acs of commercial forest)



helicopters made possible the use of dry-stream beds and distant village clearings as additional points of access.

As described, the largest proportion of any local inventory area is impossible to stratify with present photography. Stratification for regional inventory results in large areas allocated to a single strata.

The reproduction opposite would therefore represent a rather typical map of a local inventory area demonstrating access and forest stratification. In an attempt to attract well-capitalized industry which is prepared to utilize the forest resource to its maximum profitability, the forest service is directing attention to large areas which represent an adequate economic life for the industry in which to amortize this capital investment. Local inventory for this purpose will generally involve areas of in excess of 100,000 acres. To maintain the existing smaller industries and to encourage further investment by them, local inventory will also be required with areas of in excess of 25,000 acres.

Helicopter access points may be determined by airphoto interpretation but subsequent checks with the pilot are essential. Pilot-attitude to difficult landing sites has been found to be highly variable.

The distribution of helicopter landing sites is closely correlated with the distribution of larger, seasonal streams and with indigenous settlement. Poor distribution or inadequate numbers of landing sites can be overcome by cutting such sites. (The minimum requirements are indicated in Appendix II). Access to the required point may either be on foot, concurrently with a reconnaissance, or by air. Although the aircraft is not equipped with a winch, personnel may be lowered using a slow-descent device operated by the descending person. Descent is most safely carried out as a two-stage procedure - firstly into the crown of a tree, at the completion of which contact is broken with the helicopter and subsequently, by the same principle, to the forest floor. Cutting a landing-site at a point selected for the ease of such a job can be performed with a small chain-saw in one or two days by a party of two.

Technical details concerning helicopter use are given in Appendix II.

6.4 A sampling design for application in Papua - New Guinea.

Cluster or multi-stage sampling has long been appreciated as a means of reducing travelling-time overheads (Freese 1962; Loetsch and Haller 1964). "Cluster" sampling will be used to refer to the selection of secondary units in a systematic pattern while "multi-stage" sampling will imply selection at random at all stages as recommended by Freese.

An example of cluster sampling is available from Loetsch (1957). No example of multi-stage sampling is evident from the literature. This is surprising since multi-stage sampling offers a flexibility which cannot be achieved by systematic selection of sample units.

For the conditions outlined for forest inventory in Papua - New Guinea, multi-stage sampling has a most attractive potential.

6.4.1 Two-stage Sampling.

If n denotes the number of primary units selected from a total number N and each primary unit contains M secondary units of which m are selected, then the Standard Error of the estimated mean value, $\bar{y}$, is given as

$$S_{\bar{y}} = \sqrt{\frac{1}{mn} \left[S_B^2 \left(1 - \frac{n}{N}\right) + \frac{n}{N} S_W^2 \left(1 - \frac{m}{M}\right) \right]}$$

where -

- S_B^2 is the sample variance between primary units and is calculated as follows -

$$S_B^2 = \frac{\left(\frac{n}{\sum} (\text{primary totals}^2) \right) - \left(\frac{[\sum mn (\text{Secondaries})]^2}{\text{Total no. of secondaries sampled}} \right)}{(n - 1)}$$

- S_W^2 is the sample variance among secondary units within primary units and is calculated by:

$$S_W^2 = \frac{\sum mn (\text{Secondaries})^2 - \left(\frac{n}{\sum} (\text{primary totals}^2) \right)}{n (m - 1)}$$

The above expressions are taken from Freese (1962). Other expressions for the Standard Error are available from Cochran (1964) and from Loetsch and Haller (1964). These expressions appear different but are, in fact, equivalent. The alternatives are used to demonstrate the effects of multi-stage selection.

The first of these effects is that, for a fixed number of sample

observations, two-stage sampling is usually less precise than simple random sampling (Freese). The second is that two-stage sampling is less precise than comparable restricted random sampling (Loetsch & Haller). The advantage of the method is that, by reduced cost per unit, the desired precision can be obtained at lower cost.

Additional calculations permit the optimum number of sampling units at each stage to be determined. These optimum numbers are specific to a pre-determined unit size and, of course, to the population being assessed. The following has been adapted from Freese:-

From a preliminary sample to estimate population variabilities and costs, the following are established:-

σ_1^2 - population variability between primary units which is equated to $\frac{S_B^2 - S_W^2}{m}$ from the preliminary sample.

σ_{11}^2 - population variability within primary units which is equated to S_W^2 from the preliminary sample.

C_p - costs of locating and establishing a primary unit.

C_s - the additional cost of getting to and assessing a secondary unit after the primary unit has been established.

Given this cost and variance information, the optimum number of secondary units per primary is available from:-

$$M \text{ opt.} = \sqrt{\left(\frac{\sigma_{11}^2}{\sigma_1^2}\right)\left(\frac{C_p}{C_s}\right)}$$

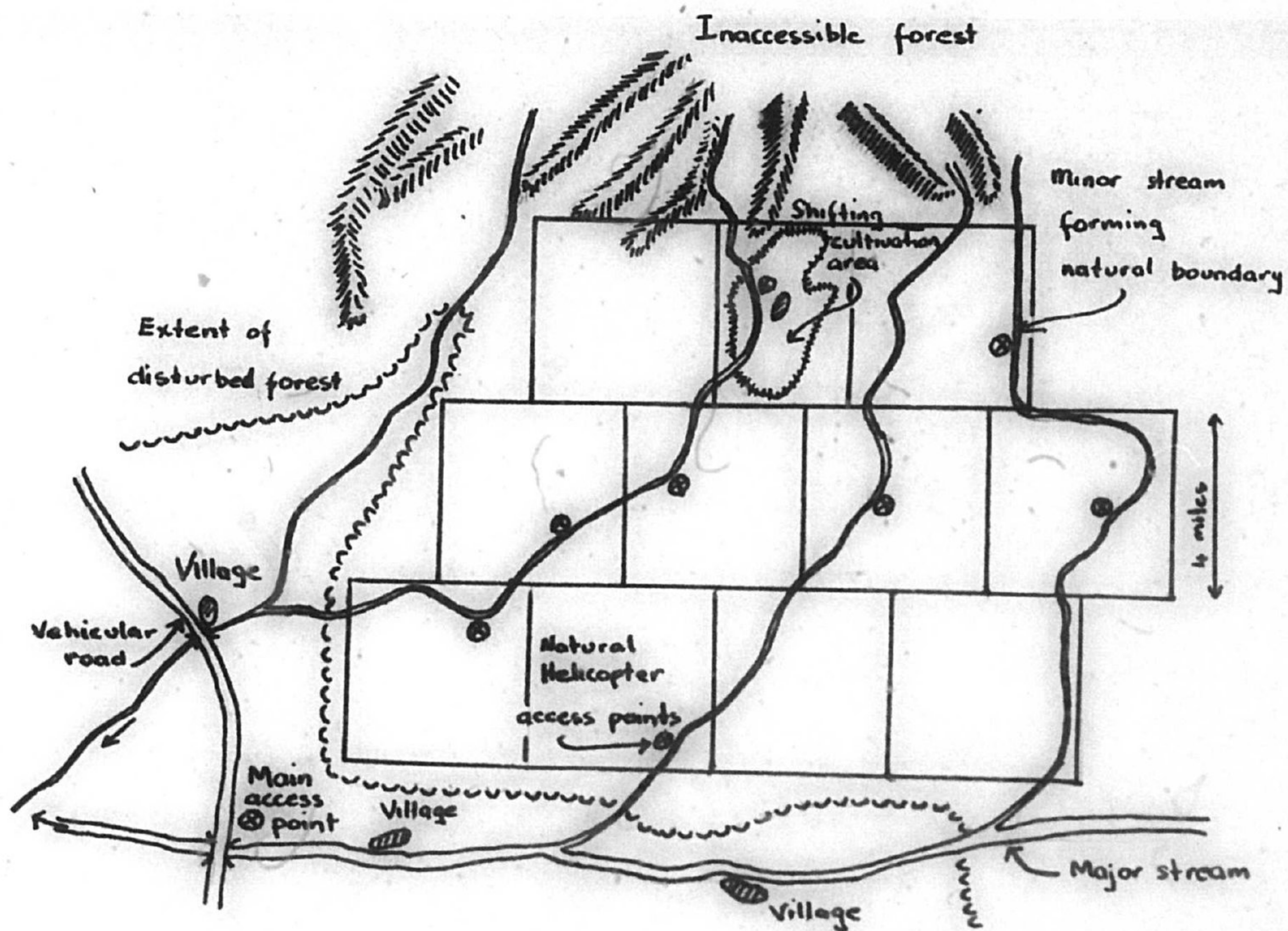
- and the optimum number of primary units with M opt.

secondaries per primary for a specific standard error (D) is available from:-

$$n = \frac{\left(\sigma_1^2 + \frac{\sigma_{11}^2}{M \text{ opt.}}\right)}{D^2 + 1/N \left(\sigma_1^2 + \frac{\sigma_{11}^2}{M}\right)}$$

The unlikelihood of any such information being available from remote tropical forest areas demands use of the preliminary sample. Such a preliminary sampling need not be in reconnaissance form; rather the calculation of optimum numbers should be made during the actual inventory after a certain amount of data has been collected. This method avoids a return of inventory parties to primary units if additional secondary units need to be established. The requirement is, of course, that several primary units need to be established simultan-

DEMONSTRATION OF PRIMARY UNITS.



ously. The method therefore demands a large number of field parties which is convenient since the requirements for economic use of costly helicopter transport are similar.

It is important to realise that optimum sample numbers so calculated are specific to the units adopted as primaries and secondaries. The optimum type of unit at either stage can only be decided by comparison of total costs of repeated inventories of the same population using the alternatives of unit size and shape adopted. The adoption of particular units may be made on non-statistical consideration of their efficiency.

For a two-stage sampling process in Papua - New Guinea conditions, it is recommended that primary units 4 miles square be superimposed on the inventory map in such a way as to provide as complete a cover as possible of the unstratified forest. Artificial boundaries can, of course, be ignored in this process (Spurr 1952). To avoid bias, no reference should be made to access points in the application of this framework. (See diagram opposite).

From a camp situated at the centre of such a square, most points within the square will be within one hour's walking distance. This is the principal criterion for selection of a primary unit of this size.

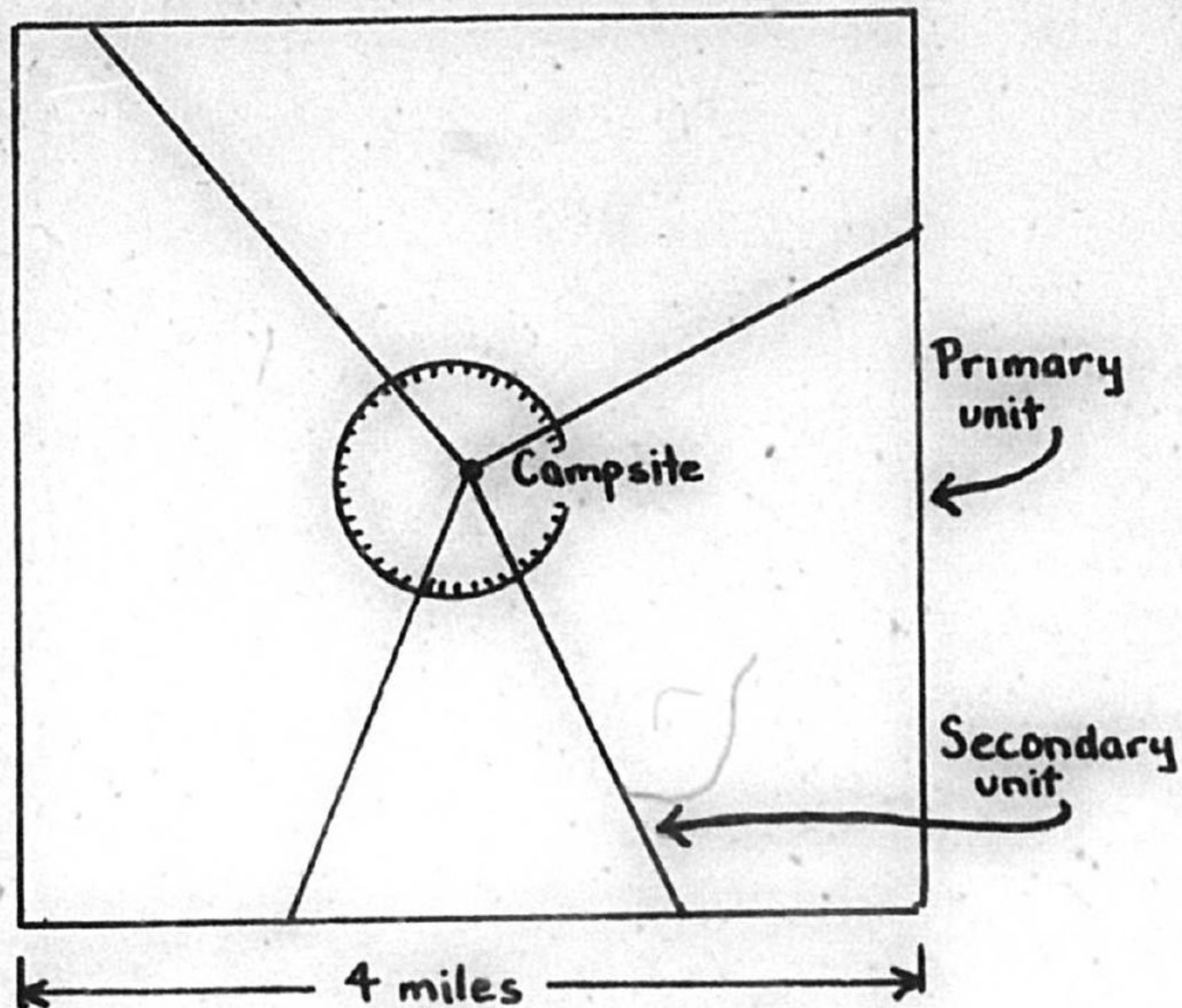
From primary units so established, a random selection is made of those required for further sampling. A preliminary requirement to any field-operation is the establishment of points of access as near as possible to the centre of each selected primary unit. A density of one natural access point per 10,000 acs. is not unlikely. However, additional points may be established as required.

As secondary units, it is recommended that a sampling unit consisting of circular plots of 58'10.5" radius (0.25 acs.) distributed systematically along a line at intervals of 5 chains unreduced distance be adopted. Access through the forest is moderately easy; a party of two, with a compass, can establish such a line and assist another two in assessment of the plots, at a rate of approximately two miles per day with adequate walking time allowed.

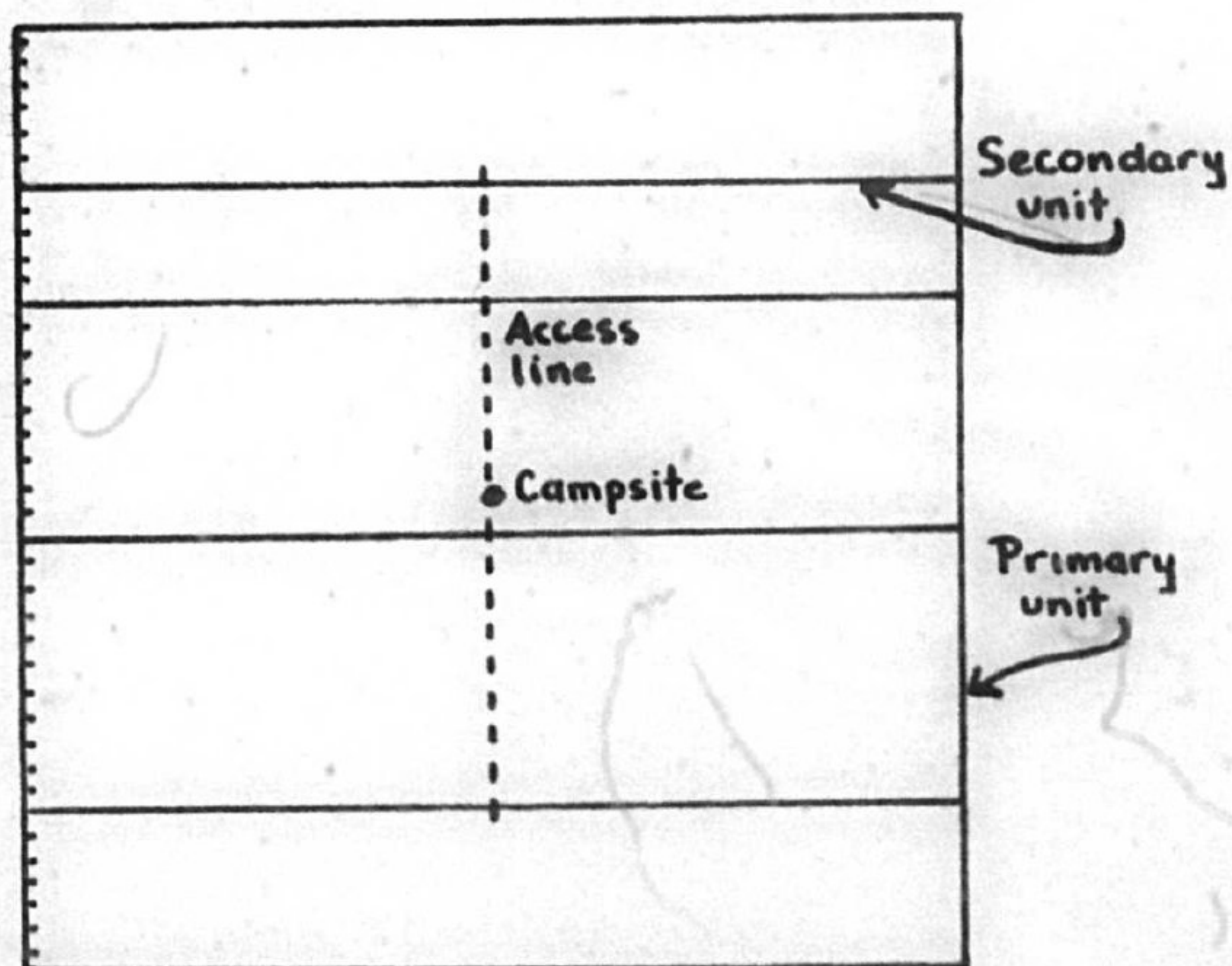
Circular plots of this size need rarely be demarcated - only

TWO - STAGE SAMPLING

POSSIBLE ARRANGEMENT OF SECONDARY UNITS.



(I) Radiating secondary units



(II) Parallel secondary units

Note: At this scale it is not possible to indicate circular plots arranged on secondary access lines.

marginal trees need be checked for distance from the centre point. Plot size is consistent as, in steep areas, a stepping procedure can be used to establish the distance of marginal trees. Since sample size (no. of plots x plot area) is consistent, there is no need to reduce distances between plots to a horizontal equivalent. A five-chain steel band can therefore be used with minimum clearing necessary only for human access.

Used in lengths of one mile or more (4 acres per mile), the units are sufficiently large to express the variability of most populations under consideration. Loetsch and Haller have indicated that the coefficient of variation will "differ very little whether sampling is done by line-plots or continuous strips..... Accordingly, the standard errors will also be about equal in spite of the very much smaller sampling fraction of the line-plot strip sampling". A similar indication is given by Chacko (1962).

From both the economic and statistical point of view, the line-plot described is a most attractive proposition as an ultimate sampling unit. Administratively, it has been found easy in instruction and precise in application.

For application as a random sampling unit, the entire length of the line-plot system must be considered as a single sampling unit. Location of the first plot at a random position within the first five chains of the line introduces a total randomization into the use of the unit.

The first possibility for the subsequent sampling process within each selected primary could involve unrestricted random selection of angles along which line-plots are established. Walking-time to begin work on each line would be nil. However, radiating line-plots must be rejected because of the possibility of such a unit following a valley bottom, ridge top or similar topographic feature. (See diagram).

The second possibility is to randomize the units along the edge of the primary-unit selected so that the units cross topographic features. (See diagram). Access to the units (each 4 miles long) could be established by cutting an access line perpendicular to the direction

of the units and passing through the centre of the primary unit. Each half-unit could conveniently represent a day's work for a single party.

For this type of secondary unit, the sampling fraction $\frac{m}{M}$ within primaries must be calculated as an area proportion. Circular plots provide a difficulty in this respect e.g. along the edge of a square of 4 miles, there are approximately 180 positions which a circle of 58.875 feet radius can occupy without overlap; yet a line-plot unit 4 miles in length contains a sample area of 16 acres giving, for a single unit, a sampling fraction of $1/640$. Randomization of the position of the first circular plot along the line will increase the chance of any point in the area being sampled thereby partly justifying the calculation of the sampling fraction as an area proportion.

6.4.2 Three-stage sampling.

Primary units of approximately 10,000 acres offer a considerable potential for variation within selected units. Topographic as well as forest composition changes are likely within such a large area. Use of the formulae will permit calculations of the optimum requirements for a two-stage sampling procedure based on predetermined units. But, because of the possibility of considerable variation in population estimates within each primary unit, the total cost of the operation must be weighed against that of the alternative methods.

The first alternative is a reduction in the size of the primary units. The results of so doing would be -

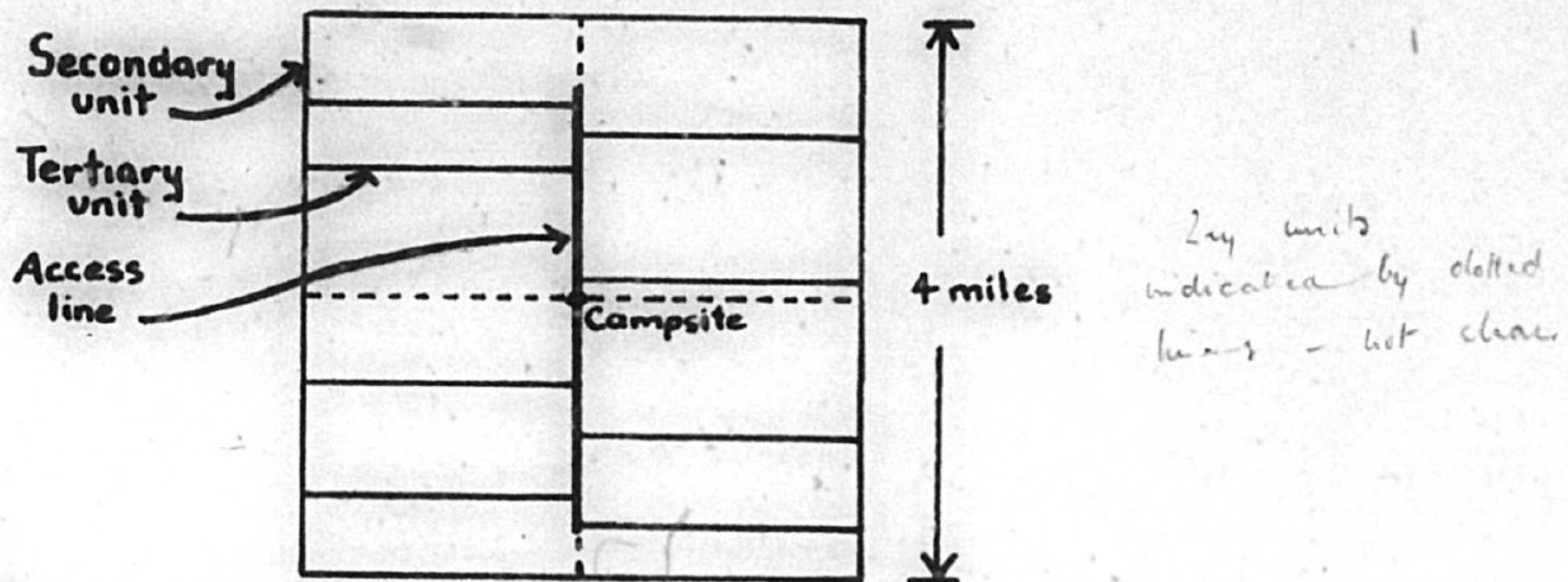
- (i) a probable reduction of variability within primary units
- (ii) a probable increase in variability between primary units resulting in the need to sample more primary units i.e. to establish more landing sites.

The second alternative is likely to prove less expensive in avoiding the necessity to establish more landing sites. It is to adopt a three-stage sampling procedure by dividing the existing primary units into secondary units of smaller size - recognised since Hasel (1937) as a means of reducing variability. Within a minimum of two randomly selected secondary units, tertiary units are selected, also at random and also with a minimum of two units per secondary.

THREE - STAGE SAMPLING

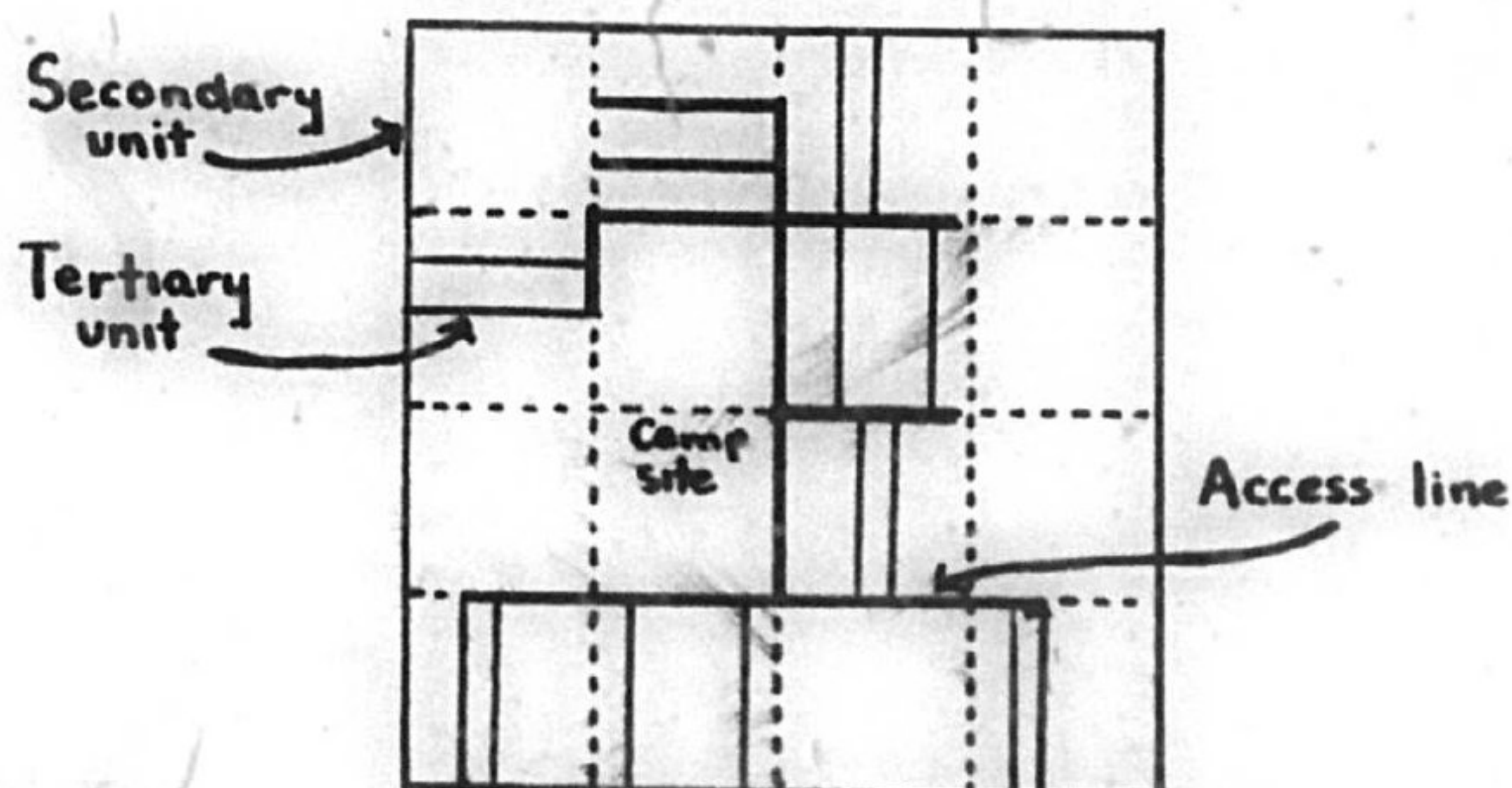
POSSIBLE ARRANGEMENT OF UNITS WITHIN PRIMARIES.

(I) Constant topographic aspect.



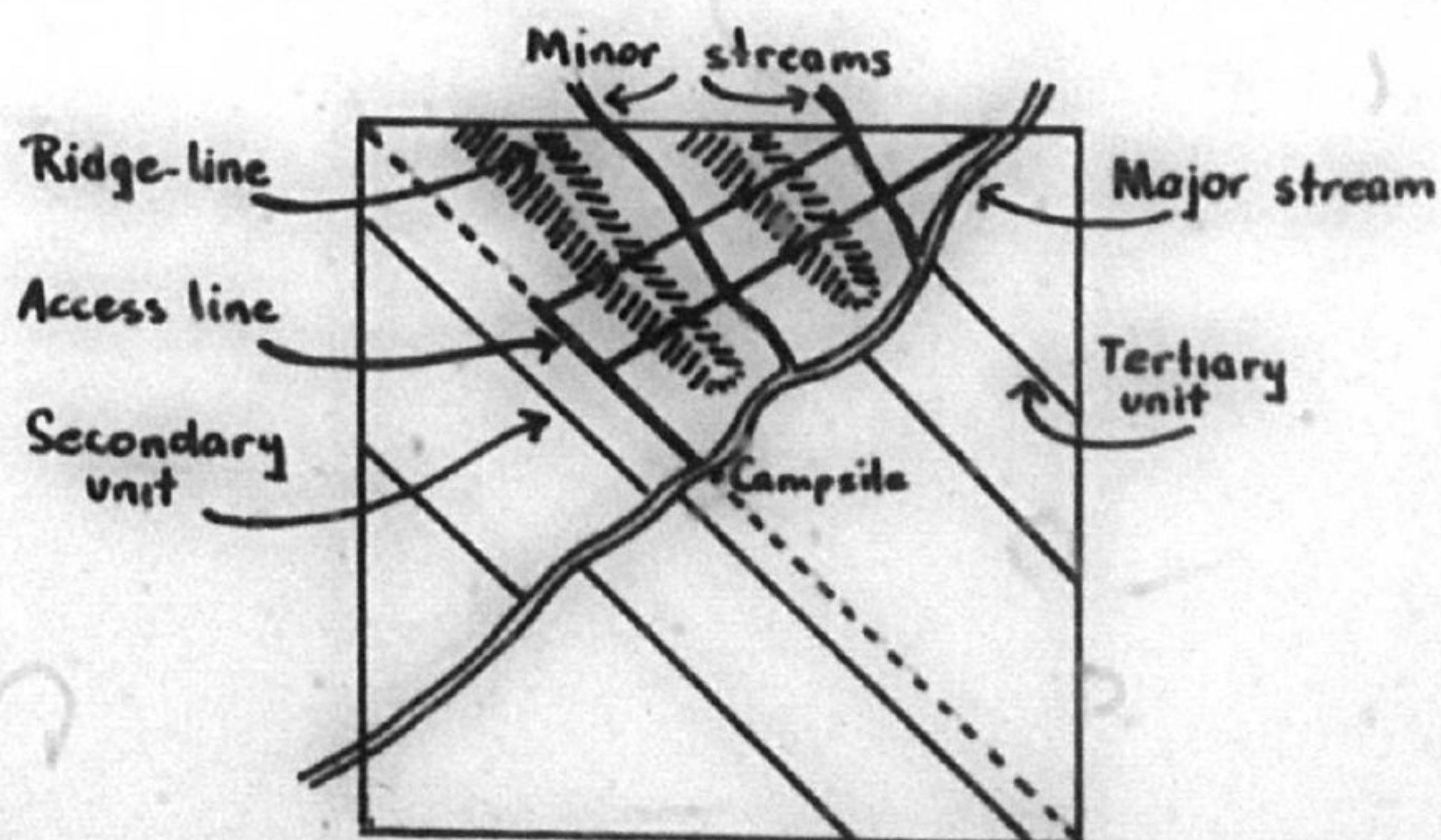
Minimum time required for access line establishment.

(II) Variable topography - equal-sized units.



Recognition of a greater number of secondary units involves greater expense in access-line establishment.

(III) Variable topography - unequal-sized units.



Tertiary units within any secondary may be directed to cross topographic features within the secondary. Ease of access is highly variable.

A considerable flexibility is possible in the design of secondary units. These units need not be of identical size or shape and need not be sampled by an equal or proportional sample fraction. Computation of results may be made more difficult; but, with electronic computation widely available, economy of field operations should not be sacrificed for computational ease. Examples of the necessity for flexibility in the design of secondary units are given in the diagram opposite.

As in two-stage sampling, the number of primary, secondary and tertiary units to be selected to meet the requirements of achieving a given precision at minimum cost may be calculated for each pre-determined design of all three types of units.

Using k and K to refer to the selected number and total number respectively of tertiary units per secondary, then the Standard Error of the estimated mean value of $\bar{y}$ is given as -

$$SE_{\bar{y}} = \sqrt{\frac{1}{nmk} \left[S_B^2 \left(1 - \frac{n}{N}\right) + \frac{n}{N} S_W^2 \left(1 - \frac{m}{M}\right) + \frac{n}{N} \frac{m}{M} S_{WW}^2 \left(1 - \frac{k}{K}\right) \right]}$$

(Cochran 1959)

- where S_{WW}^2 is the variance between tertiary units within secondary units and is estimated by -

$$S_{WW}^2 = \frac{\frac{nmk}{\sum (\text{tertiaries}^2)} - \left[\frac{\sum (\text{secondary totals}^2)}{\text{No. of tertiary units sampled per secondary}} \right]}{nm(k - 1)}$$

- and S_W^2 is the variance between secondary units within primary units and is estimated by -

$$S_W^2 = \frac{\frac{\sum (\text{secondary totals}^2)}{\text{No. of tertiary units sampled per secondary}} - \left[\frac{\sum (\text{primary totals}^2)}{\text{No. of tertiary units sampled per primary}} \right]}{n(m - 1)}$$

- and S_b^2 is the variance between primary units and is estimated by -

$$S_b^2 = \frac{\frac{\sum (\text{primary totals}^2)}{\text{No. of tertiary units sampled per primary}} - \left[\frac{\sum (\text{tertiaries}^2)}{\text{Total number of tertiary units}} \right]^2}{(n - 1)}$$

A preliminary sample may be used to establish these variance

estimates and the costs associated with collecting data from tertiary, secondary and primary units.

If C_1 , C_2 and C_3 represent costs for primary, secondary and tertiary units respectively, the next step of the procedure is to estimate population variance for all stages of the sampling process.

S^2_{WW} as calculated above is an unbiased estimate of the population variance σ_{111}^2 which may be equated with the value obtained.

However, the population variance σ_{11}^2 between secondary units is estimated by -

$$\sigma_{11}^2 = \frac{S^2_{WW} - S^2_{WW}}{k}$$

- and the population variance σ_1^2 between primary units by -

$$\sigma_1^2 = \frac{s_b^2 - S^2_W}{mk}$$

(adapted from Cochran 1959).

Optimum number of sampling units for the tertiary (k opt.) and secondary (m opt.) stages are given by -

$$k \text{ opt.} = \frac{\sigma_{111}}{\sqrt{\sigma_{11}^2 - \sigma_{111}^2/k}} \sqrt{\frac{C_2}{C_3}}$$

and -

$$m \text{ opt.} = \sqrt{\frac{\sigma_1^2 - \sigma_{11}^2/k}{\sigma_1^2 - \sigma_{11}^2/m}} \sqrt{\frac{C_1}{C_2}}$$

(adapted from Cochran 1964).

An economical three-stage sampling process for the conditions pertinent to Papua - New Guinea, requires use of the same primary units as were discussed for two-stage sampling; the line-plot unit described previously as a secondary unit is suitable as a tertiary unit in the present discussion. The possibilities for secondary units have been briefly outlined in the previous diagrams. It is obvious that the greater the number of secondary units arbitrarily adopted, the greater will be the cost of establishing lines of access and orientation for the tertiary units within these secondary units.

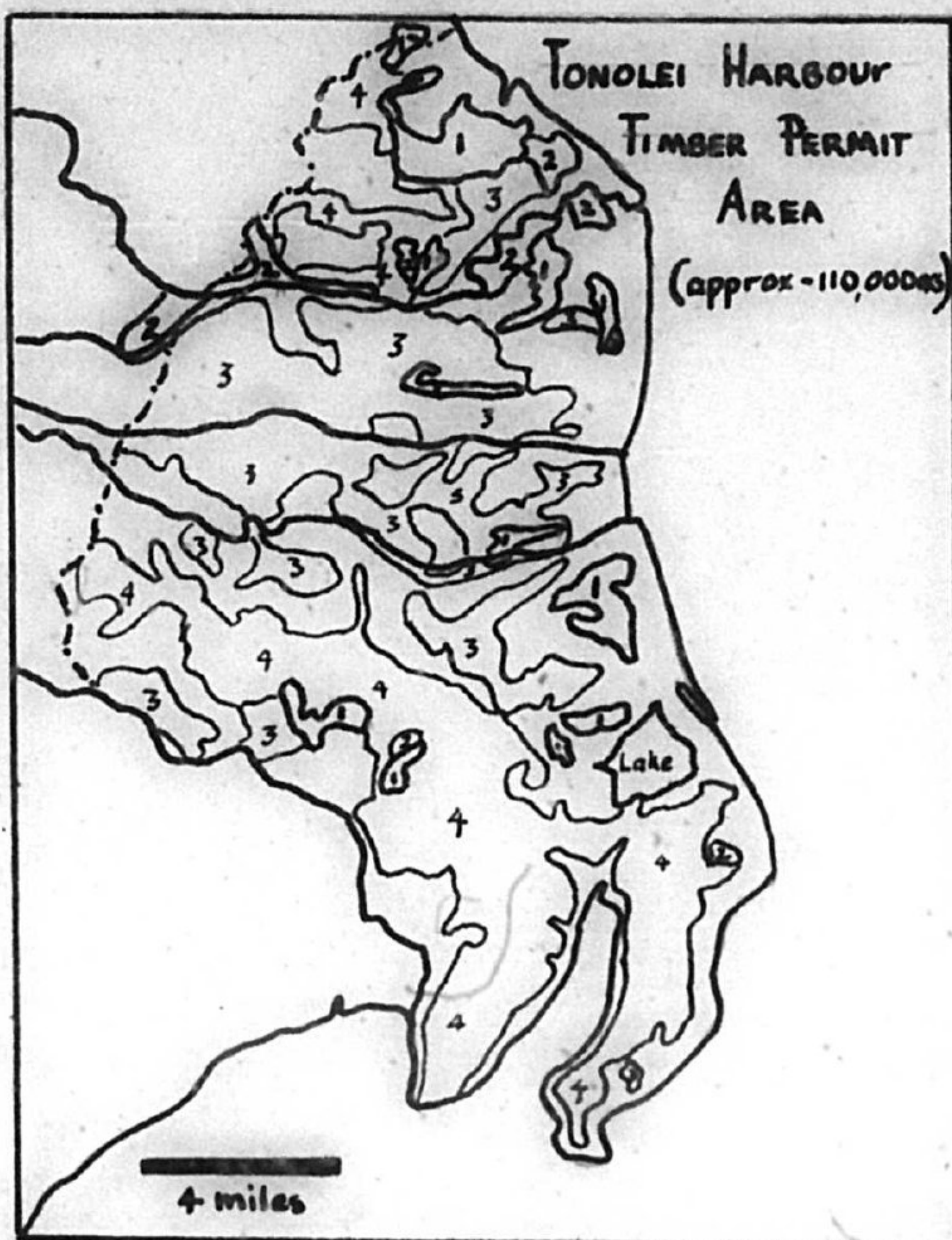
As a basis for experiment, it is recommended that the primary units be divided into four secondary units. Methods of doing so under conditions of varying topography are indicated in the diagrams. In

flat terrain or in areas of consistent topographical aspect, costs involved in providing access to tertiary units are minimal since a single access line is required. Changing topographical aspect or the presence of a major stream as indicated in the diagrams involve additional access costs. It is recommended further, that all four secondary units be sampled, each with three tertiary units. Except in the unusual circumstance of a major stream forcing the division of the primary unit as illustrated, this will involve a sampling fraction of 0.9375% (15/16%) per selected primary unit.

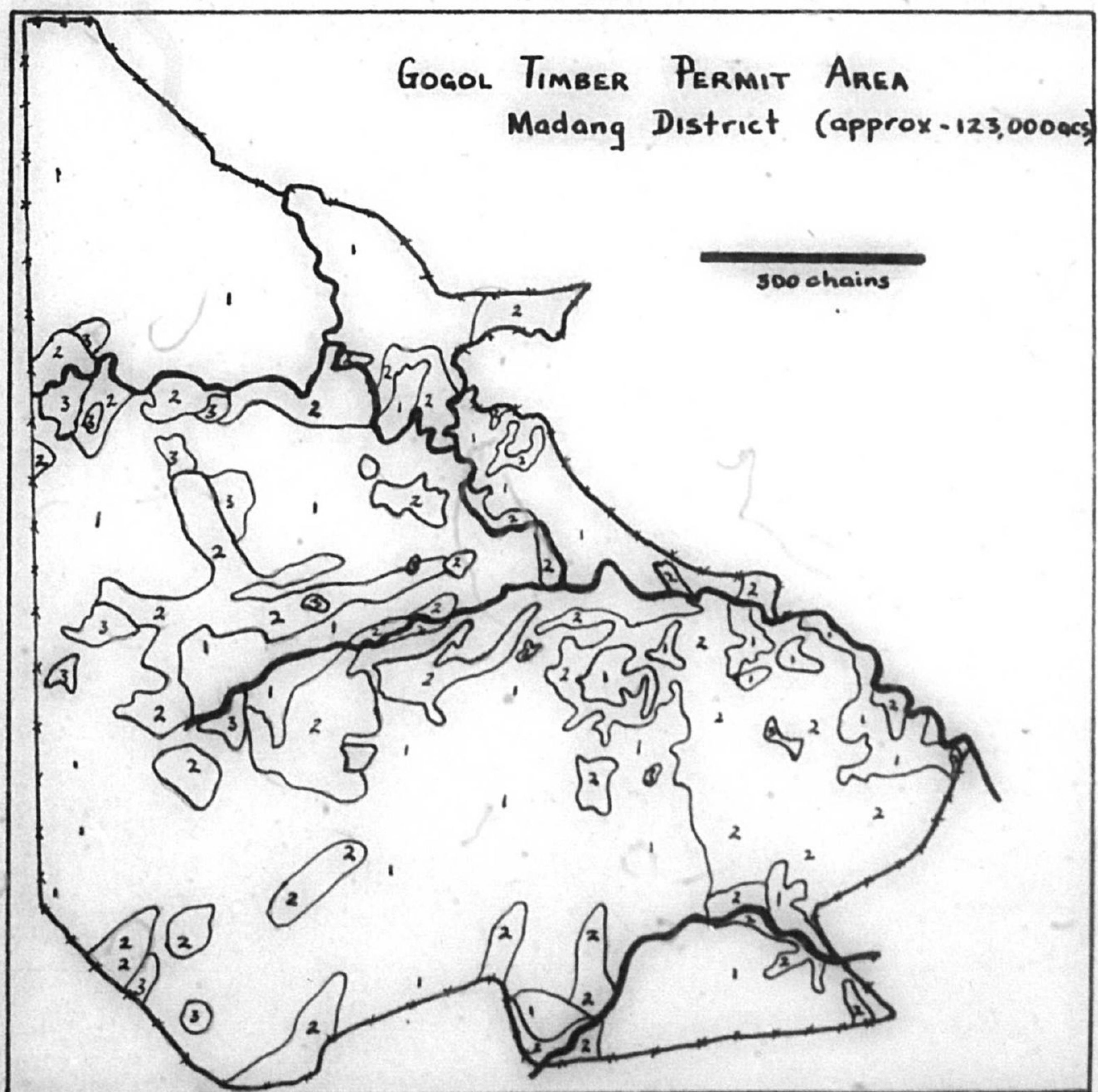
For inventories of areas of less than 100,000 acres, it is recommended that all primary units be selected. For areas greater than 100,000 acres, it is recommended that, initially, one half of the primary units be selected by random process. This will involve a sampling fraction of slightly less than one-half of one percent - below the minimum recommended by Dawkins (1956) and endorsed by Boon (1962) but satisfactory for experimental purposes.

The effect of selecting all secondary units will be to reduce the finite population correction for the "between secondaries" expression of variance to zero thus eliminating this contribution to the standard error. However, the formula for the calculation of the standard error remains valid. An alternative view is to regard the process as a two-stage sampling in which a restriction has been placed on the possible distribution of secondary units by dividing selected primary units into blocks. The formula for two-stage sampling is applicable provided it is recognised that division into blocks removes $(\ell - 1)$ degrees of freedom (where ℓ is the number of blocks recognised) in the calculation of the sample variance between secondary units.

For smaller inventories, where it has been recommended that all primary units be sampled as well as all secondary units, the method is equivalent to restricted random sampling with three units per block. Although the formula for standard error estimation by three-stage sampling remains valid, it may be easier to consider the formula for restricted random sampling, again recognising the loss of one degree of freedom for each block imposed.



Numbers indicate four strata of commercial interest.



Stratum 1 only is of commercial interest. 2 + 3 provide helicopter access

It must be emphasized that the size, shape and type of units of all stages that have been recommended and the sampling fractions recommended at all stages have been arbitrarily decided on the basis of economy and the overall sampling fraction deemed necessary. They represent an experimental approach only - to be modified when field trials provide more information.

6.4.3 The remaining commercial forest.

The methods outlined above are directed at large areas of undifferentiated forest. Smaller areas of different strata will be present in most inventory areas in those environments in which no climax has yet developed. A reconnaissance, as recommended, will have established the value of photo-differentiated areas as strata and determined, in part, their commercial significance.

Sampling of these smaller areas demands recognition of the same principles as those involved previously. Any objective sampling method may be employed, the criterion of selection of method being again one of meeting a given precision at minimum cost.

From the statistical point of view, the sampling process for each stratum^{um} should be discrete. Methods of proportional or optimum allocation of units for a fixed cost have no place in forest inventory practice. Each stratum^{um} must be sampled to provide the precision required. Combination of results from each strata to express a total quantity of produce is performed as a last stage in computation.

6.4.4 The extension of multi-stage sampling.

Multi-stage sampling has been described as an attractive proposition for the larger unbroken and unstratified forest areas. On these areas, primary units representing areas of easy access from the central point and of equal size are easily superimposed. Although almost all the areas at which resource inventory is directed in Papua - New Guinea can be so described, occasionally there are areas containing valuable timber in patches interspersed with shifting-cultivation or secondary forest areas but equally remote from any point of access. Such an area is the Gogol Timber Area represented in the map opposite. Again, aerial-photo stratification may be possible over larger areas resulting in strata

distributed in unequal and uneven-sized areas. Such an example is the Tonolet Timber Area also represented in the map opposite. Again, there is no access within the inventory area.

Obviously, equal-area primary units of the type discussed previously cannot be applied. Equally obvious is the potential for economy through the use of multi-stage sampling.

Two-stage sampling with unequal-sized primary units is less difficult in forest inventory than in other sampling procedures since the size of each area of forest is generally available from a map or may be approximated from aerial photographs and there is unlikely to be a relation between forest area and mean volume per acre.

In the case of the Gogol Timber Area, there is only one stratum of interest i.e. the commercial forest. The choice between the techniques which may be applied in this case is dependent on the range of area size of these patches of timber. If the individual areas can be grouped into area-strata so that areas of forest within each stratum are equal, or nearly so, then two-stage sampling may be applied to each stratum as a discrete process. The two-stage computation methods outlined previously are applicable to each stratum; total estimates being obtained by combination of stratum estimates as a last stage of computation.

If the individual areas of forest are such that many area-strata must be recognised, then there is the alternative of selection of primaries with probability proportional to size (p.p.s. sampling).

In this technique, each individual area of forest is given a serial number and its area and cumulative total is obtained e.g.

<u>Area No.</u>	<u>Actual area (acs.)</u>	<u>Cumulative total</u>
1	120	120
2	240	360
3	1160	1,520
.	.	.
.	.	.
21	830	27,650
22	420	28,070

From a table of random digits, numbers varying from one to the cumulative total for the last forest area are selected. A particular

area is included in the sample when a random number is drawn which is equal to or less than the cumulative total for that area and greater than the cumulative total for the preceding area.

Selection of primaries by this method must be with replacement. However, selection of secondaries within primaries is with equal probability and without replacement. A new set of secondary units is drawn on each occasion that a given primary unit is selected. (The above has been adapted from Freese).

Computation procedure is as given previously with the exception that the finite population correction is dropped from the "between primary" part of the standard error estimate - the selection of primaries being with replacement.

The third technique is a combination of area-stratification and sampling with probability proportioned to size. Such a method overcomes the bias involved where a selected area is smaller than the majority in the same strata but is unlikely to result in improved precision as compared with p.p.s. sampling since there is unlikely to be a relationship between forest area size and mean volume per acre.

Weighting is required where unequal sized secondary or tertiary units are involved. To facilitate this weighting, it may be more appropriate to consider computation on the basis of the mean values estimated at each stage e.g. - (as indicated by Cochran 1959)

- for two stage sampling

$$S^2_b = \frac{\sum_{i=1}^n (\bar{y}_i - \bar{\bar{y}})^2}{n-1}$$

and
$$S^2_w = \frac{\sum_{i=1}^n \sum_{j=1}^m (y_{ij} - \bar{y}_i)^2}{n(m-1)}$$

- for three-stage sampling

$$S^2_b = \frac{\sum_{i=1}^n (\bar{\bar{y}}_i - \bar{\bar{\bar{y}}})^2}{n-1}$$

and
$$S^2_w = \frac{\sum_{i=1}^n \sum_{j=1}^m (\bar{y}_{ij} - \bar{\bar{y}}_i)^2}{n(m-1)}$$

and
$$S^2_{ww} = \frac{\sum_{i=1}^n \sum_{j=1}^m \sum_{z=1}^k (y_{ijz} - \bar{y}_{ij})^2}{nm(k-1)}$$

An example of weighted calculations is given in Appendix III.

The extension of these methods to inventory areas for which large strata have been differentiated is possible by performing either a sub-stratification of each forest stratum on an area basis or by sampling with p.p.s. within each stratum. In effect, this extension involves discrete sampling processes for each photo-interpreted stratum recognised.

7. VOLUME CALCULATION

Before discussing methods of estimation of the data to be recorded on each sampling unit, it is essential to establish a method of volume estimation since this method will, in part, determine what is to be recorded.

The methods of calculating relationships between volume, measured by some standard procedure, and readily estimated log-size parameters, have developed so rapidly with the more general use of computers that the subjective graph or desk-calculator approaches are things of the past. The computer can readily calculate the coefficients for a great number of mathematical models, and print out a table based on the chosen model.

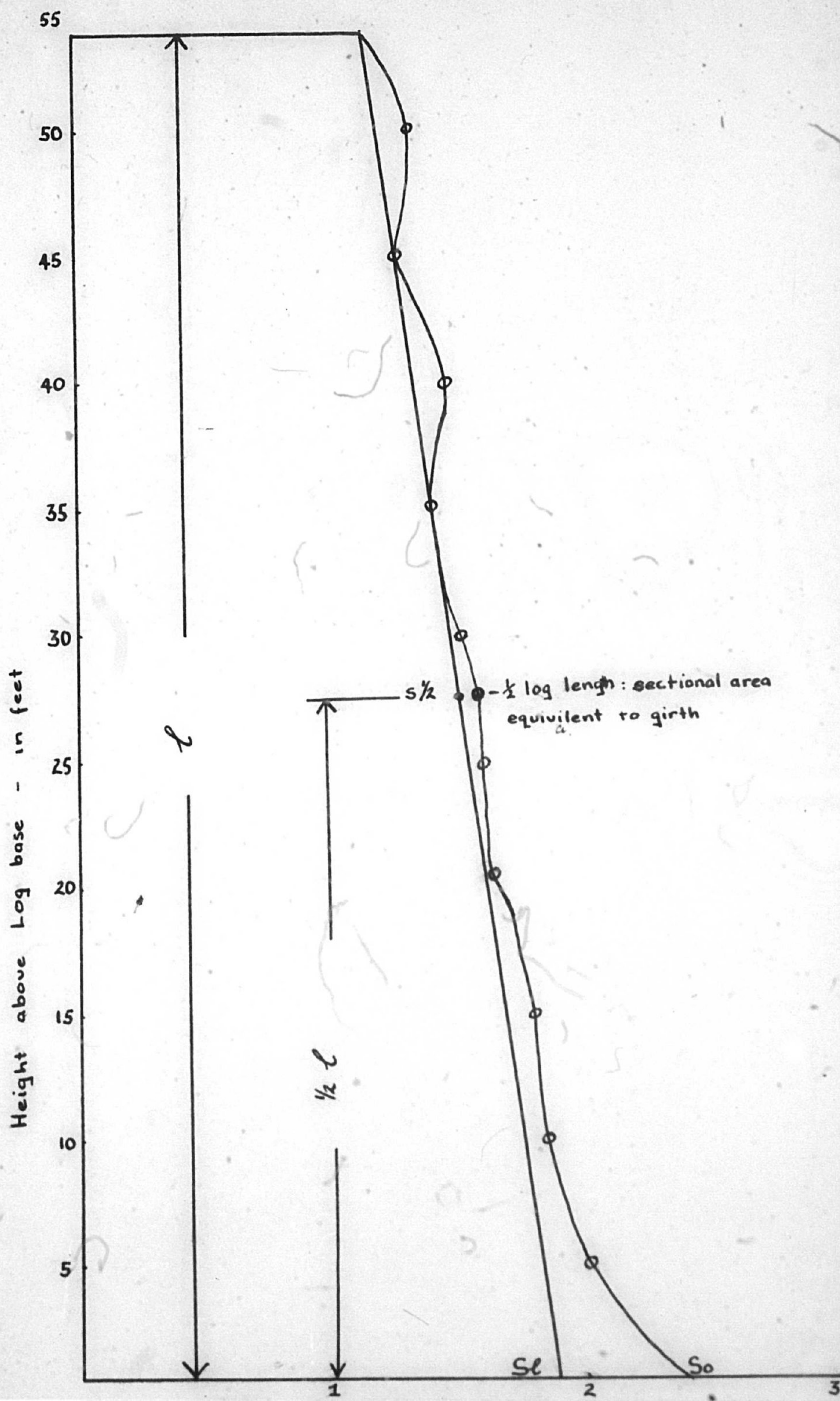
As an example, Appendix IV indicates the fourteen mathematical models against which volume data for Papua - New Guinea species were tested. These models represent most of those established in pre-computer days (Spurr 1952) in addition to more refined models using weights directed at overcoming the frequently occurring increase of variance with larger sizes (Cunia 1964 and Wright 1964). The model selected as providing the "best-fit" was based on an index developed by Furnival (1961).

Although the volume estimator from the writer's data was multi-specific and its application not confined to any one locality, the question of whether a particular model selected as best for a single species from one locality is suitable for other species from the same locality, the same species from different localities or other species from different localities may also be decided by a computer technique for analysis of variance similar to that outlined in Appendix I.

However, such refinement of techniques does not imply that volume estimating equations need no longer concern the field forester. There remain the questions of what standard volume to adopt, whether to use single species volume estimators or composite estimators, what parameters of log size to use and whether the derived equations should be for general or local application.

A further development from the more sophisticated data processing

A TYPICAL TAPER-LINE GRAPH DEFINING TERMS AND THE "INSIDE" LINE.



methods is that volume estimators based on two parameters of log size (viz. sectional area and length) invariably provide "better fit" than those using only one i.e. sectional area (Wright 1965).

However, there remains with the forester the responsibility for determining the method of calculation of the standard volume which is to be used for subsequent computation.

In Papua - New Guinea, log volume as accepted by the trade is calculated by multiplication of log length and sectional area one half log length. Since this is Huber's formula, a second degree parabaloid shape is assumed resulting graphically, in a straight taper-line (Gray 1956) when length as ordinate is plotted against sectional area as abscissa.

In the volume estimator prepared for Papua - New Guinea (as quoted above and detailed in Appendix IV) this standard volume was used as the dependent variable. Independent variables were girth at the base of the log (a more concise term than "above buttress") and log length, the latter being the difference between log height (from ground level to break of crown or major defect) and buttress height (from ground level to the base of log). These independent variables are readily measured in practice.

As a measure of standard volume, centre-girth volume has two serious defects -

(i) From the statistical point of view, centre-girth volume can vary for the same parameters of log size.

(ii) From the utilization point of view, centre-girth volume invariably over-estimates recoverable volume.

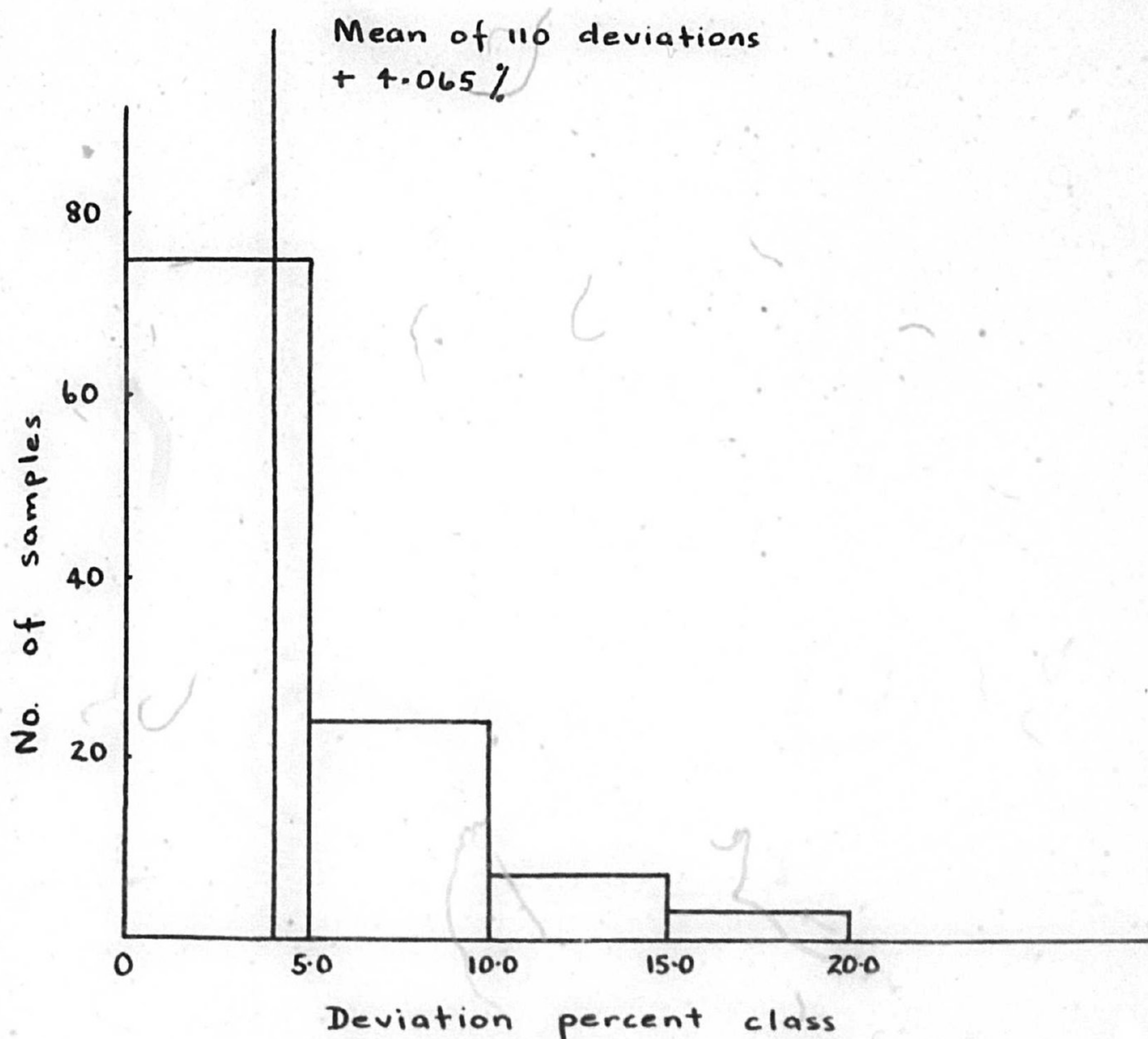
Both defects of centre-girth volume arise from the fact that, in tropical forest conditions, centre-girth is liable to considerable variation not associated with meaningful estimates of volume.

The figure opposite represents an actual taper-line graph for a tropical species.

Since, the strong curvilinear trend introduced by butt-swell even above the buttress is more apparent than real due to occasional concavity of section not being estimated by the girth-tape, any method of

COMPARISON OF CENTRE - GIRTH AND LIMITING VOLUMES

$$\frac{\text{C.G. Volume} - \text{L. Volume}}{\text{L. Volume}} \times 100\%$$



estimation of standard volume must ignore this effect.

What centre-girth volume estimation or any other popular methods (Graphical Volume, Taper-line Volume and Sectional Method Volume) do not ignore is effect of irregularity from the near-linear relation above the buttress influence attributable to occluded branch stubs as observed in saw-mill break-down by the writer.

A more suitable alternative to any of the above methods of determination of a standard volume is the concept of the area under the straight-line (equivalent to volume) joining all "inside" points i.e. all graphed points lie either on this line or outside it. This concept of log volume has been termed "limiting volume" by the writer in the sense of limiting variation in volume for given log size parameters - with advantages for both statistical computation and recovery studies.

This concept of Limiting Volume is an extension of an approach adopted in Tasmania (Lawrence 1960). The relationship between Centre Girth Volume and Limiting Volume has been examined for 145 logs of various species. In this study, it was found that Centre-Girth (C.G.) Volume exceeded Limiting (L.) Volume in 75.9% (110) of the samples with an average excess of 4.1% of L.V. For the remaining logs, C.G. volume equalled L.volume. Alternatively, it might be considered that mean excess of C.G.V. over L.V. for all 145 logs was 3.1%. A histogram showing the distribution of these excess values is given.

Rather than considering L.V. radically different from C.G.V., it should be regarded as a refinement of the same concept.

The C.G.Volume may be obtained by a single measurement of girth at a point one half of log length; and, in so doing, the operator must be prepared to accept that this point may be removed from the straight line by virtue of a swelling (in fact, the sample shows that this is true in 75% of the cases) which in the writer's experience is not readily recognizable as such.

Alternatively, the L.Volume is obtained by taking several girth measurements about the point of one half log length, plotting these and determining the intercept of the straight line so formed on the one half log length point.

It should be noted that the majority of points so taken should be above the mid-height point since it is not unknown for apparent buttress influence to extend to one half log length. In general sufficient points should be taken to achieve a reliable straight line. The writer suggests four or more each separated by five feet. It is important not to measure within five feet of the top of the log since frequently, pre-nodal swelling is to be found a few feet below the point of cross-cutting.

Most of the mathematical models used for relating volume to log-size parameters have no real application to the tropical forest concept of volume. The traditional formulae as outlined by Spurr (1952) have all originated from temperate conditions where the size parameter height refers to some measure of tree or stand height. In tropical forests, volume estimates use length of log as one parameter of log size. More recent formulae represent an endeavour by mathematicians to discover "the elusive formula of best fit" to quote Grosenbaugh (1958). The actual relationship between volume and log-size parameters is ignored while empirical attempts are made to establish a formula.

Adoption of the concept of L.V. permits calculation of a theoretical relationship from first principles.

From measurements of 145 logs, data was processed to give:

(a) Limiting Volume, as defined, calculated as : $L.V. = S_{\frac{1}{2}} \times l$
 - where $S_{\frac{1}{2}}$ is sectional area (in square feet) on the straight line joining "inside" points at one half log length and l is log length as defined.

(b) Slope of the straight line joining "inside" points - measured as the rate of loss of sectional area per unit increase in height.

(c) S_1 and S_0 - defined as the sectional area at the base of the straight line joining "inside" points and the sectional area equivalent to girth as measured at the base of the log.

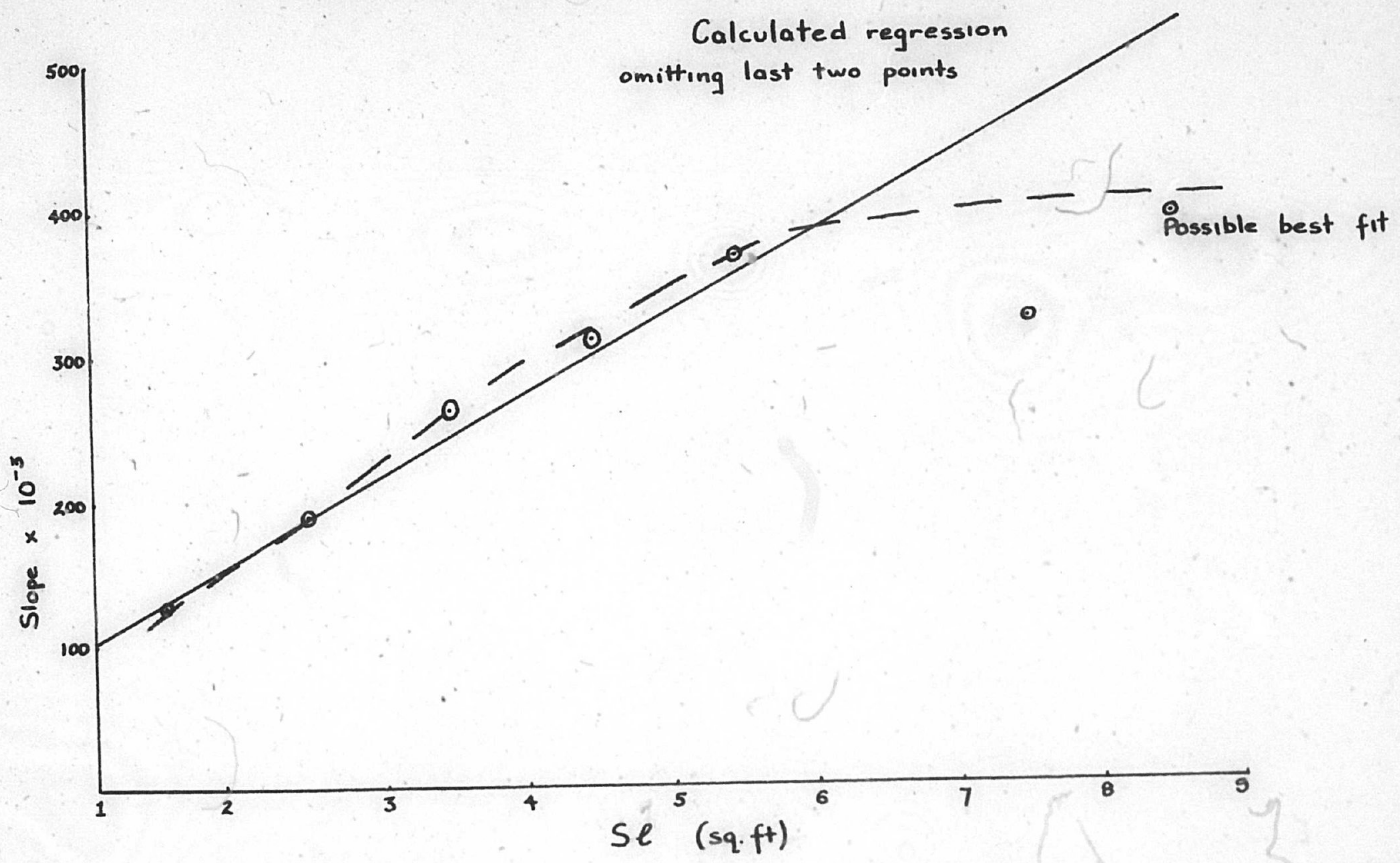
From these data, the first equation established is that -

$$S_{\frac{1}{2}} = S_1 - (\frac{1}{2} l \times \text{Slope})$$

- this is obvious from the definition of Slope given above.

RELATION BETWEEN Sl AND SLOPE.

Calculated regression
omitting last two points



An investigation was made into the relationships between Slope and 1 and between Slope and S_1 .

Slope was determined as being independent of 1 but related to S_1 in near linear form. The data was grouped into classes of one square foot of S_1 and the corresponding average slope for the class was calculated -

<u>S_1 class (sq.ft.)</u>	<u>Number of Samples</u>	<u>Mean Slope for Class</u>
1 - 2	20	0.0125
2 - 3	46	0.0186
3 - 4	35	0.0257
4 - 5	18	0.0308
5 - 6	11	0.0367
6 - 7	11	0.0388
7 - 8	2	0.0321
8 - 9	3	0.0383

Classes 7-8 and 8-9 were ignored in the calculation of the relationship in linear form -

$$\text{Slope} = 0.0043 + 0.0058 S_1.$$

While such a relationship served to illustrate the present approach, it is realized that more data is required in view of the possibility of a curvilinear relationship considering classes 7-8 and 8-9.

Returning to the equation -

$$S_{\frac{1}{2}} = S_1 - (\frac{1}{2} 1 \times \text{Slope})$$

- the alternative expression for slope may be substituted -

$$\text{i.e. } S_{\frac{1}{2}} = S_1 - 0.00215 1 - 0.0029 (1 \times S_1)$$

To express this relationship in terms of a measurable quantity S_0 , S_1 was regressed against S_0 - again using grouped data. The relationship was obviously linear -

$$S_1 = 0.528 + 0.708 S_0$$

Further substitution gave -

$$S_{\frac{1}{2}} = 0.528 + 0.708 S_0 - 0.00368 1 - 0.00205 (S_0 \times 1)$$

and since -

$$\text{L.V.} = S_{\frac{1}{2}} \times 1$$

then

the L.V. = $0.528\ l + 0.708\ S_0l - 0.00368\ l^2 - 0.00205\ S_0l^2$

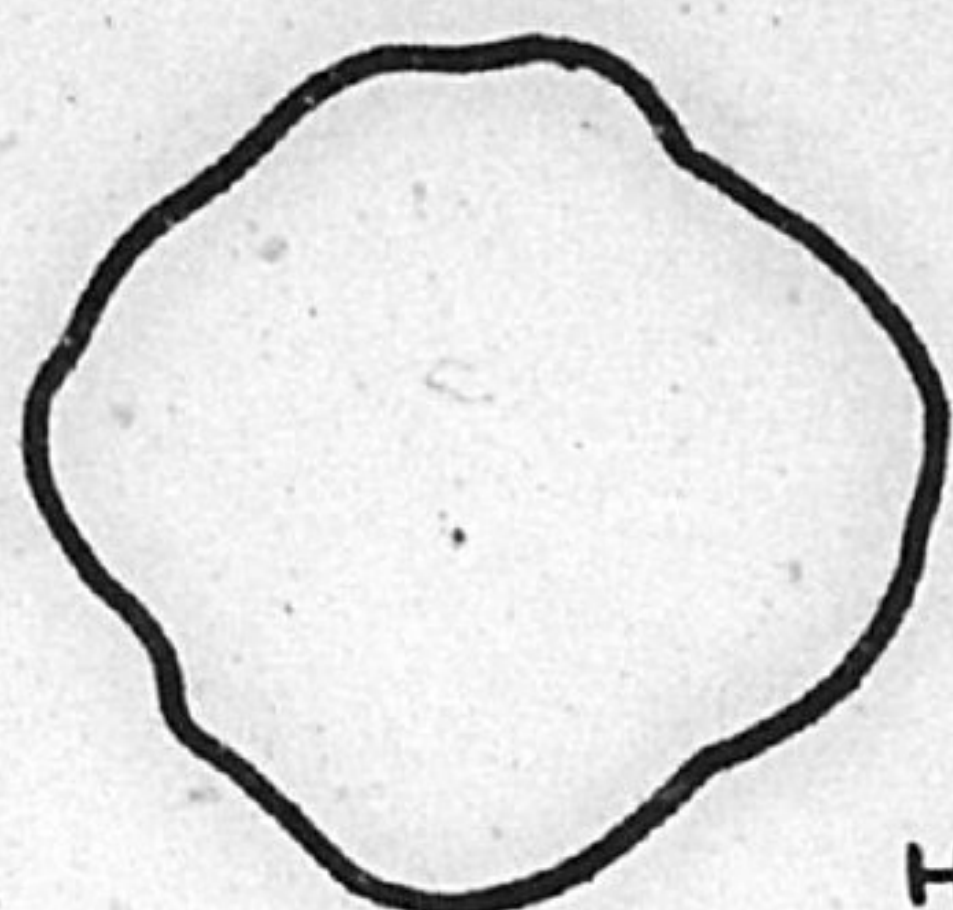
or, in general terms -

$$L.V. = m\ H + n\ D^2H + p\ H^2 + q\ D^2H^2$$

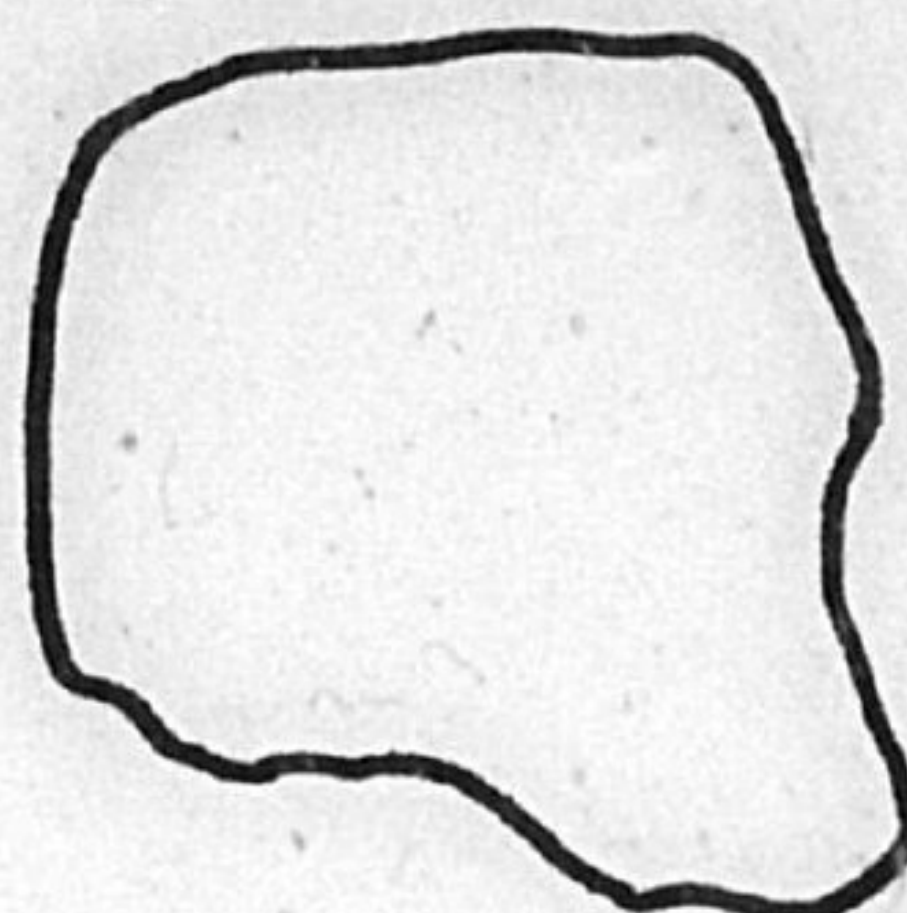
This model is unusual in that it includes H^2 components. It is, however, derived from first principles and has a basis in a more acceptable expression of standard volume.

The co-efficients for this model may be readily computed using existing programmes; and an evaluation may be made of it in comparison with other models through use of the Furnival Index.

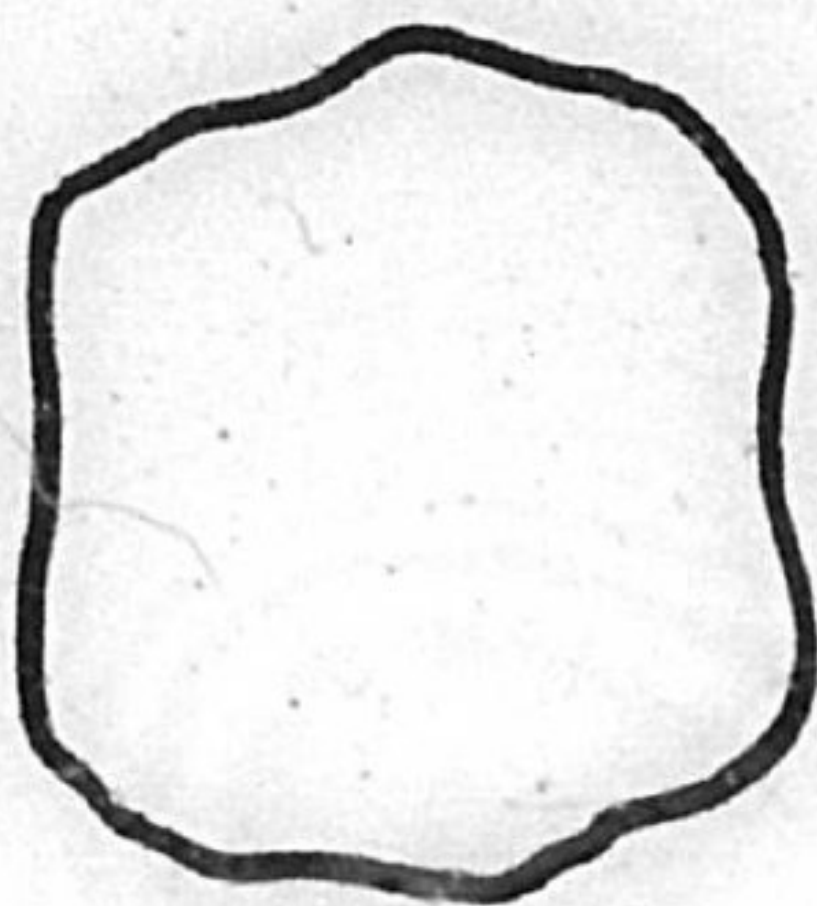
SCALE DRAWINGS ($\frac{1}{12}$ ORIGINAL) OF SECTIONS OF P. TOMENTOSA LOG.



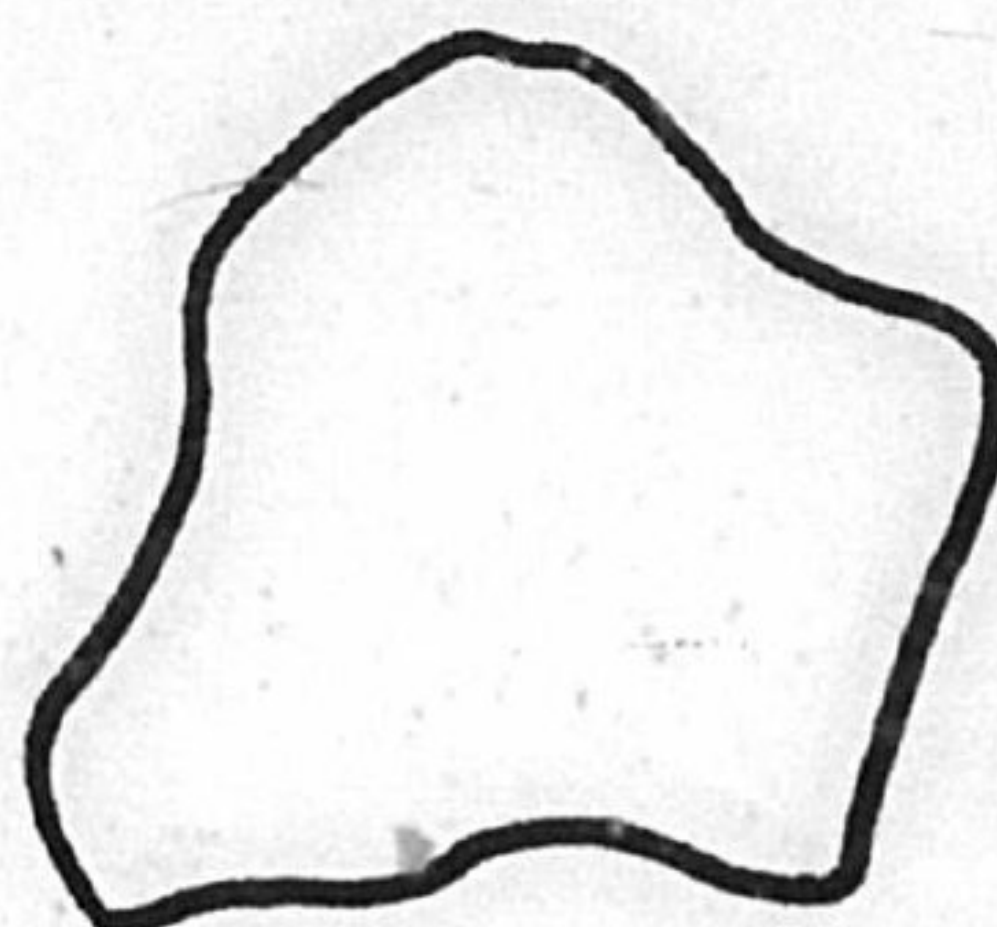
Ht = 0



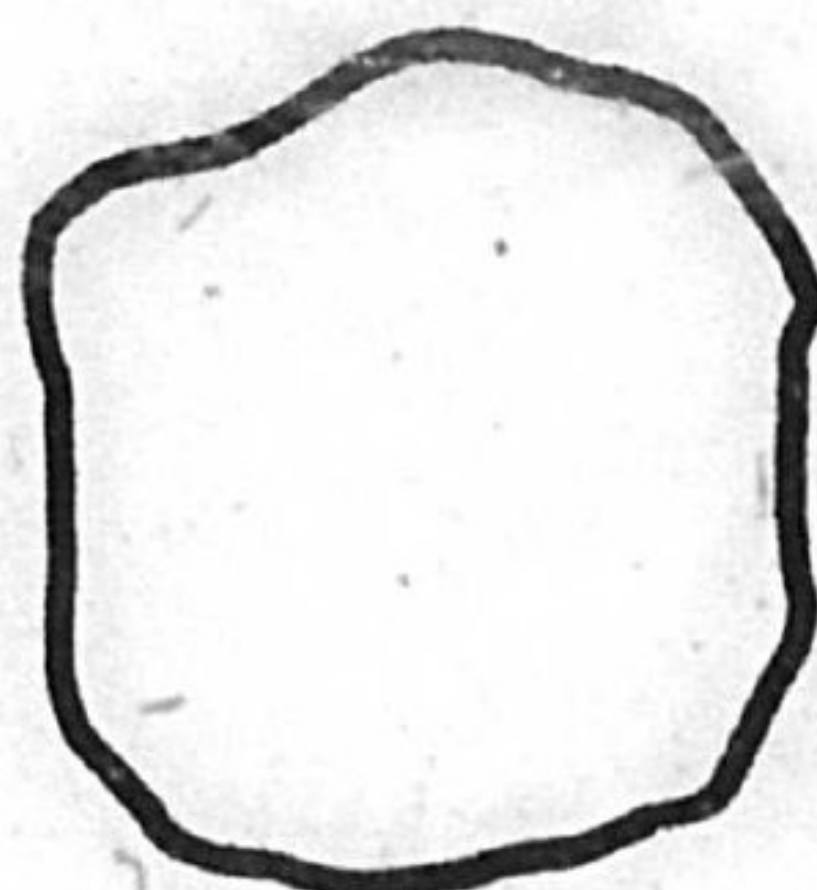
Ht - 12'



Ht - 2'



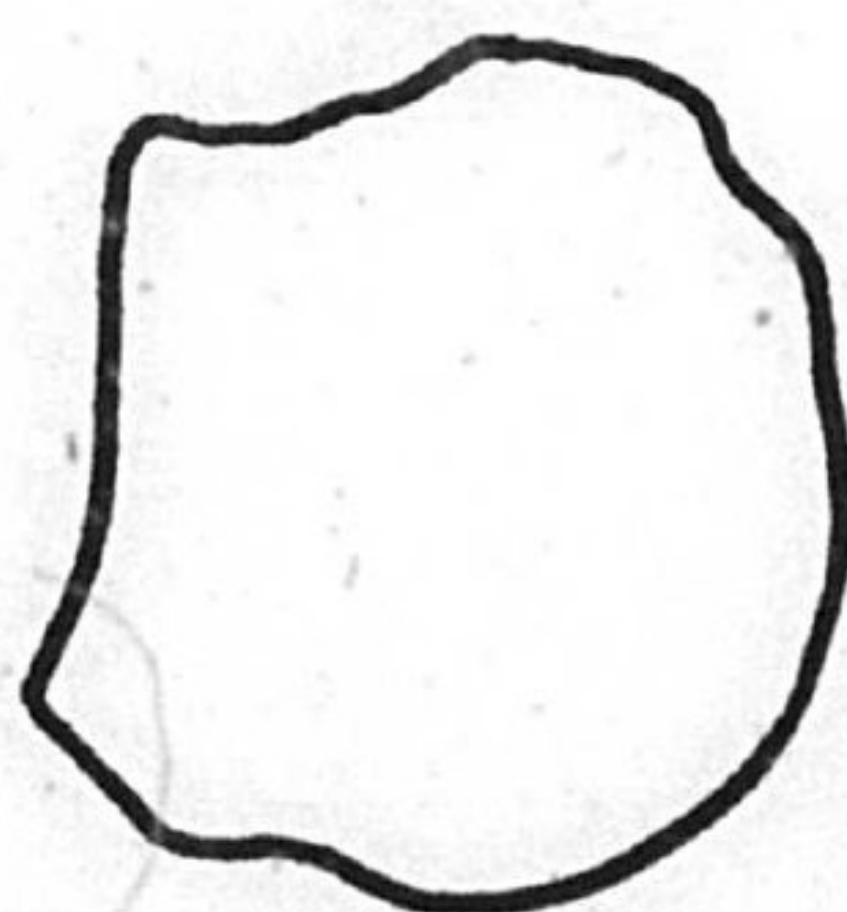
Ht - 13'



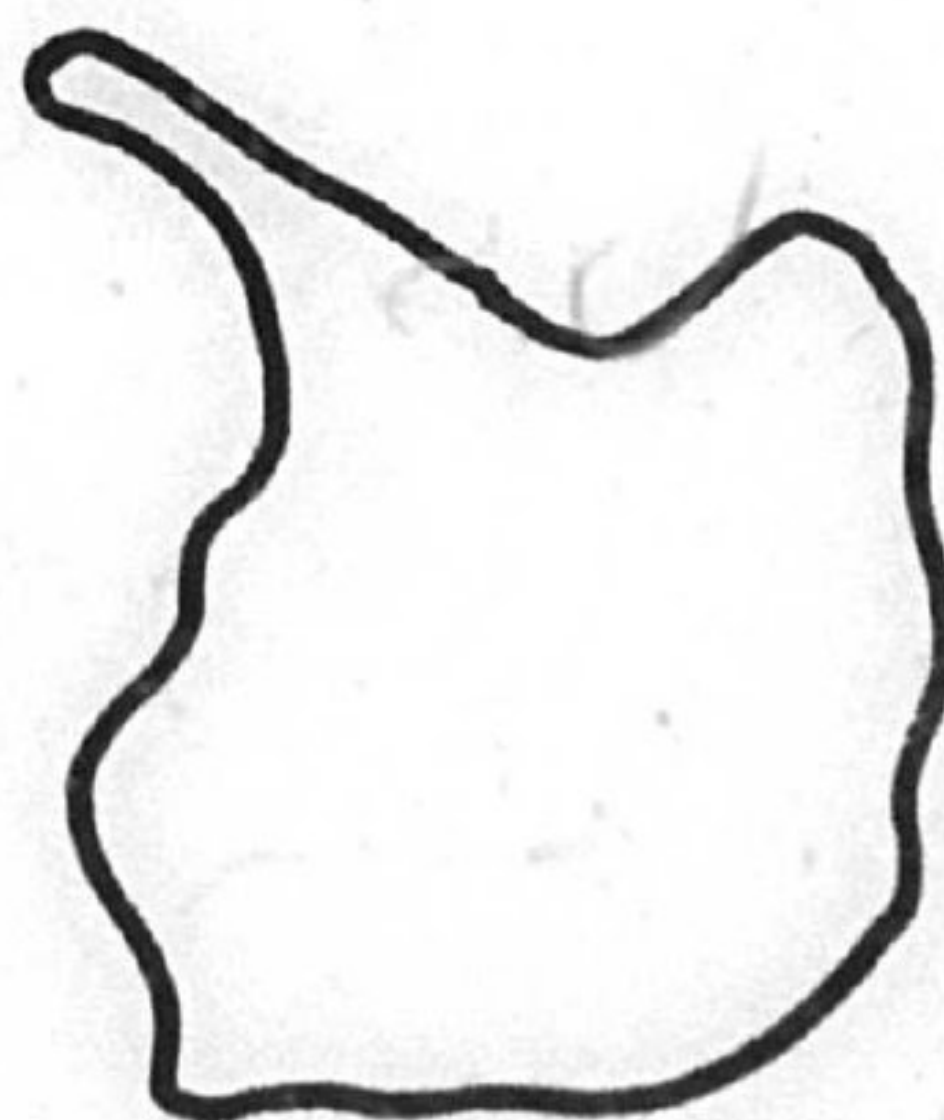
Ht - 4'



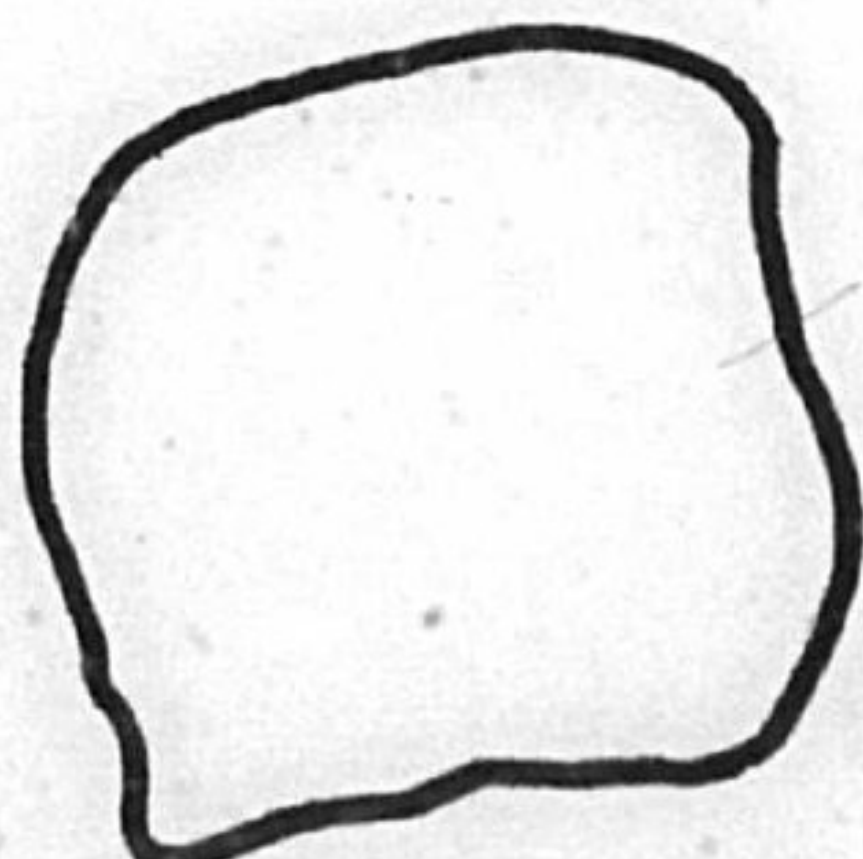
Ht - 15'



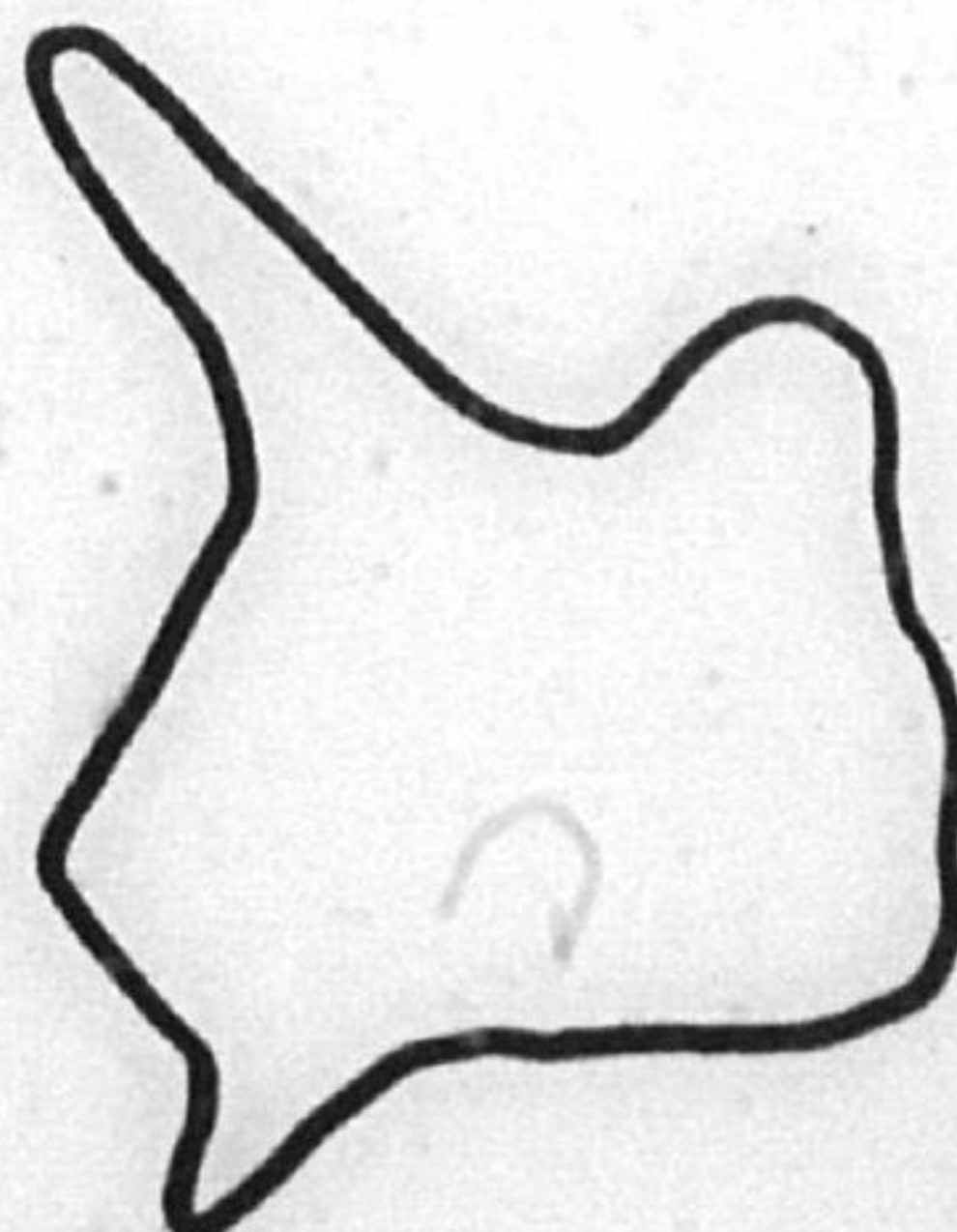
Ht - 6'



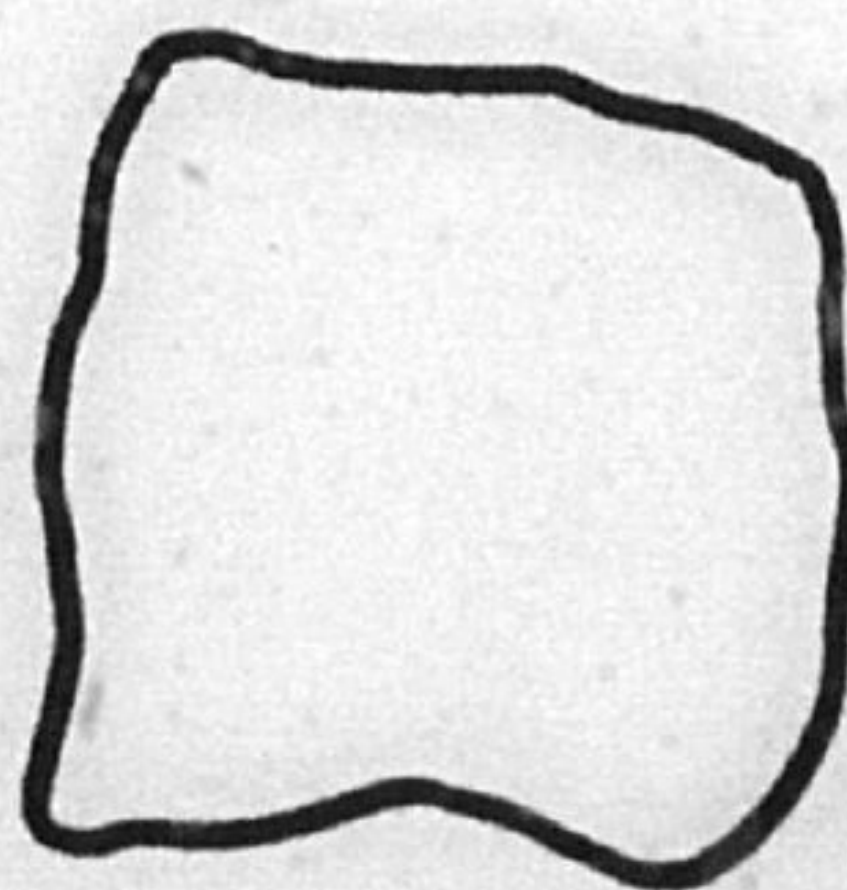
Ht - 17'



Ht - 8'



Ht - 18'



Ht - 10'

Scale equivalent to $\frac{1}{12}$ actual.

8. SOME MENSURATION ASPECTS OF TROPICAL FOREST INVENTORY

The estimation of girth at base of log and of log length in tropical forest conditions is not easy. However, in view of the standard of personnel employed in inventory, it is essential that objective methods be used. It is not intended in this section to make an exhaustive review of the methods of estimation used throughout the tropical world. Not a great deal has been published on this aspect of inventory, reflecting perhaps, the degree of the problems associated.

8.1. Girth at base of log.

As indicated previously, the writer prefers this term over the more nebulous "girth above buttress". The selection of the point at which this estimate is to be made must remain subjective. However, the principles for selection of the point may be defined and evidence cited of likely errors associated with poor selection.

The guiding principle for the selection of the point of measurement must be the extraction of the maximum merchantable volume of log from each tree. Incorporated in this principle, there must be an understanding of how the tree is to be cut. Axe-felling invariably involves a greater butt-height than chain-saw felling and a greater depth of butt-end waste. One standard or the other must be adopted in view of this variation. It is recommended that the chain-saw standard be adopted as this method alone ensures the extraction of the maximum merchantable volume from each tree. With a chain-saw, an operator is able to cut lower to the ground in the case of non-buttressed stems; and, on buttressed stems, can cut through the flanges at a height convenient to the operator, subsequently cross-cutting the log to remove the irregular butt section.

The figures opposite represent scale drawings of the cross-section of the butt end of a log extracted under the writer's supervision. An axe-felling crew indicated that they would cut at the point Hto. The writer felled the tree with a chain-saw 18 feet below this point and subsequently cross-cut the log at a point 13 feet below Hto. The volume saving as a result was 88 cubic feet - valued, in royalty in the case of this species, at in excess of £8.

DEMONSTRATION

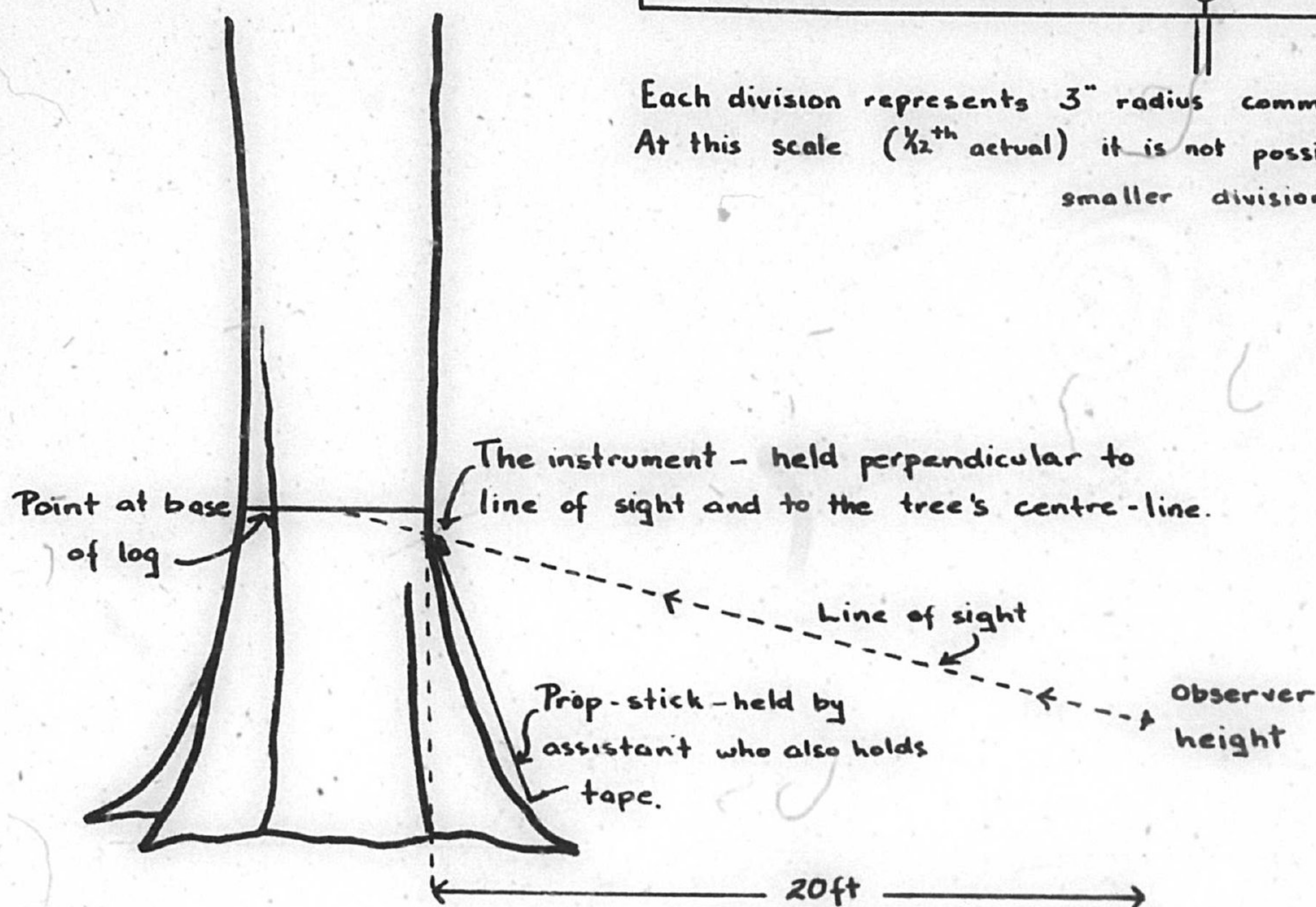
MODIFIED

BILTMORE

STICK



Each division represents 3" radius commencing at 9" on either side.
At this scale ($\frac{1}{2}$ th actual) it is not possible to indicate numerals or smaller divisions.



In selection of the point at base of log, it is unnecessary to require a convexity of section at that point. This is evident from the previous diagrams. The writer believes that efficiency of logging in the rain-forest, a difficult task at any time, can be improved by recognition of this standard.

Any other point selected for girth measurement will, most likely, by definition, be above the point recommended. By preparation of an estimate of the mean rate of taper from the selected point at base of log to the point 2.5' above this standard, an appreciation was gained of the errors involved in faulty selection.

For 115 sample trees of all commercial species, the mean taper rate, apparently independent of girth over this range, was estimated at 1.56 inches girth per foot of height or alternatively -

<u>Height above recommended point.</u>	<u>Error associated (negative) Girth"</u>	<u>Diameter"</u>
0'6"	0.780	0.248
1'0"	1.560	0.496
1'6"	2.340	0.745
2'0"	3.120	0.993
2'6"	3.900	1.241

It is essential that, having adopted a guiding principle as above for volume estimation for regression purposes, the same principle be applied in estimating girth for substitution in the resulting formula.

However, in assessment procedure, the use of a steel-girth-tape is uneconomic in view of the necessity to climb a considerable proportion of trees to reach the required point and to remove vines, canes etc. from about the circumference at this point. Estimation of girth using a non-circumferential comparison is essential.

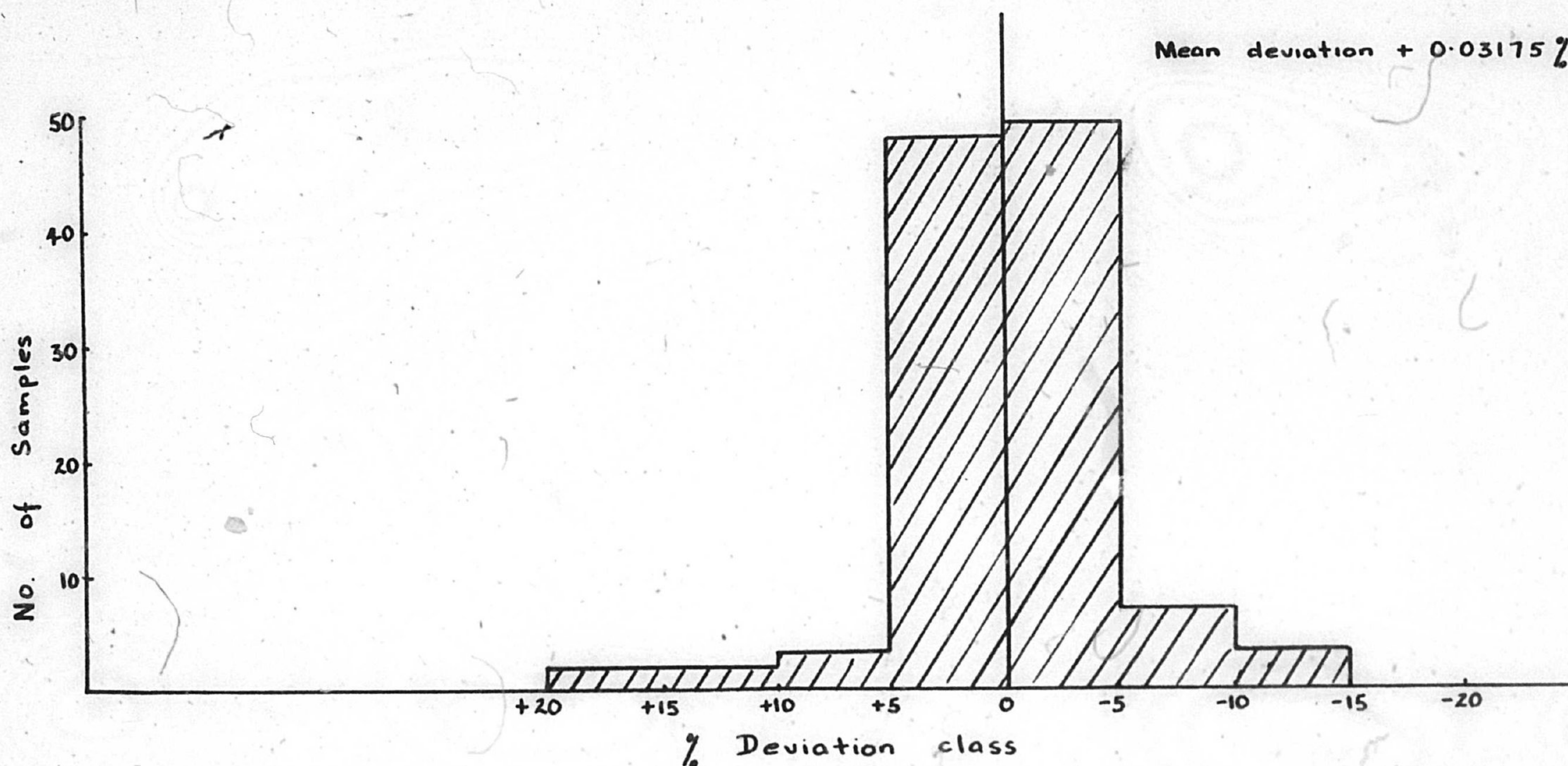
A method of achieving this aim was suggested by Finlayson and Archer (1964) in modifying the principle of the Biltmore Stick to give estimates of "radius" on both sides of a central zero point according to the formula -

$$m = r \sqrt{\frac{q}{2r + q}}$$

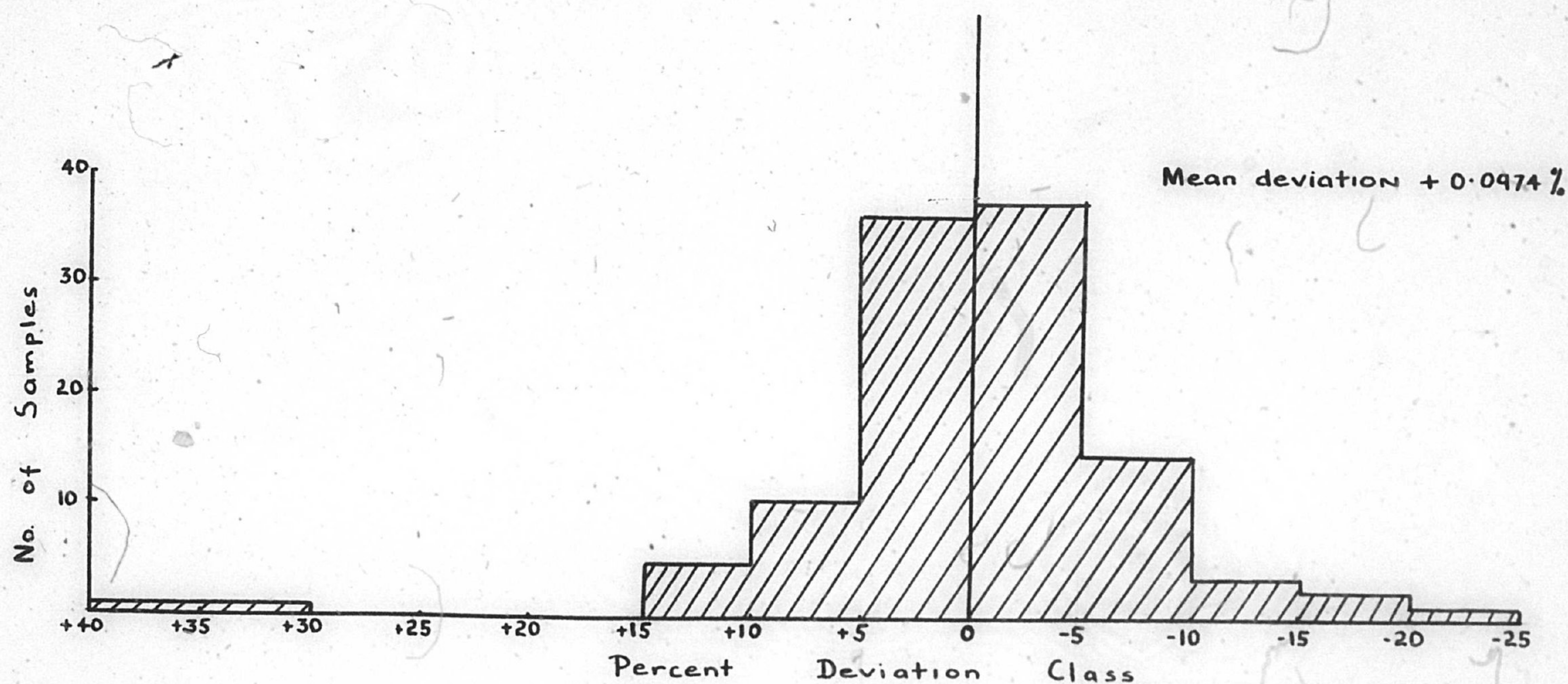
where m = calibration

and q = distance - set, for convenience at 20'.

DEVIATIONS [%] OF π x MEAN OF THREE SYSTEMATIC ESTIMATES OF DIAMETER FROM GIRTH.



DEVIATIONS [%] OF $\pi \times$ SINGLE RANDOM DIAMETER FROM GIRTH.



The writer first constructed this simple instrument and found the results of its use entirely satisfactory in Papua - New Guinea. (See diagram opposite for method of use). The method was also introduced to Malaya for use in the ^eJangka project by the writer.

Graduation of the instrument may be either in units of diameter (as used in Papua - New Guinea) or girth (as used in Malaya).

Such is the variation in shape of the section of trees at the selected point of measurement that doubts may arise as to the value of a non-circumferential estimate of girth or diameter.

From scale drawings of the butt sections of 115 logs using a spoked-wheel device and a plotting sheet (see Appendix V), it was possible to measure any required diameter and compare this estimate with the steel tape estimate of girth.

Since it may be considered that in normal assessment procedure, estimation of diameter or girth, as above, would be made on a particular face at random, on each drawing a point was selected at random and the diameter estimated. In addition, two more points were estimated for diameter; these being systematically placed 120° away from the random point on either side.

A list of results was prepared in the following form -

<u>Girth-tape estimate</u>	<u>Diameter at random point</u>	<u>Mean of 3 diameters</u>
-	-	-
-	-	-

Hence columns two and three were multiplied by pi (taken as 3.1416) and the results compared with column one. The deviation was expressed as a (+/-) percentage of the column one value.

A plot was prepared of percentage deviation against girth for both the single random diameter and the mean of 3 systematic diameters. Taking the distribution of the girth values into account, it was readily seen that percentage deviation was independent of girth.

The next step involved the accumulation of all deviation percentages associated with each series into distribution classes.

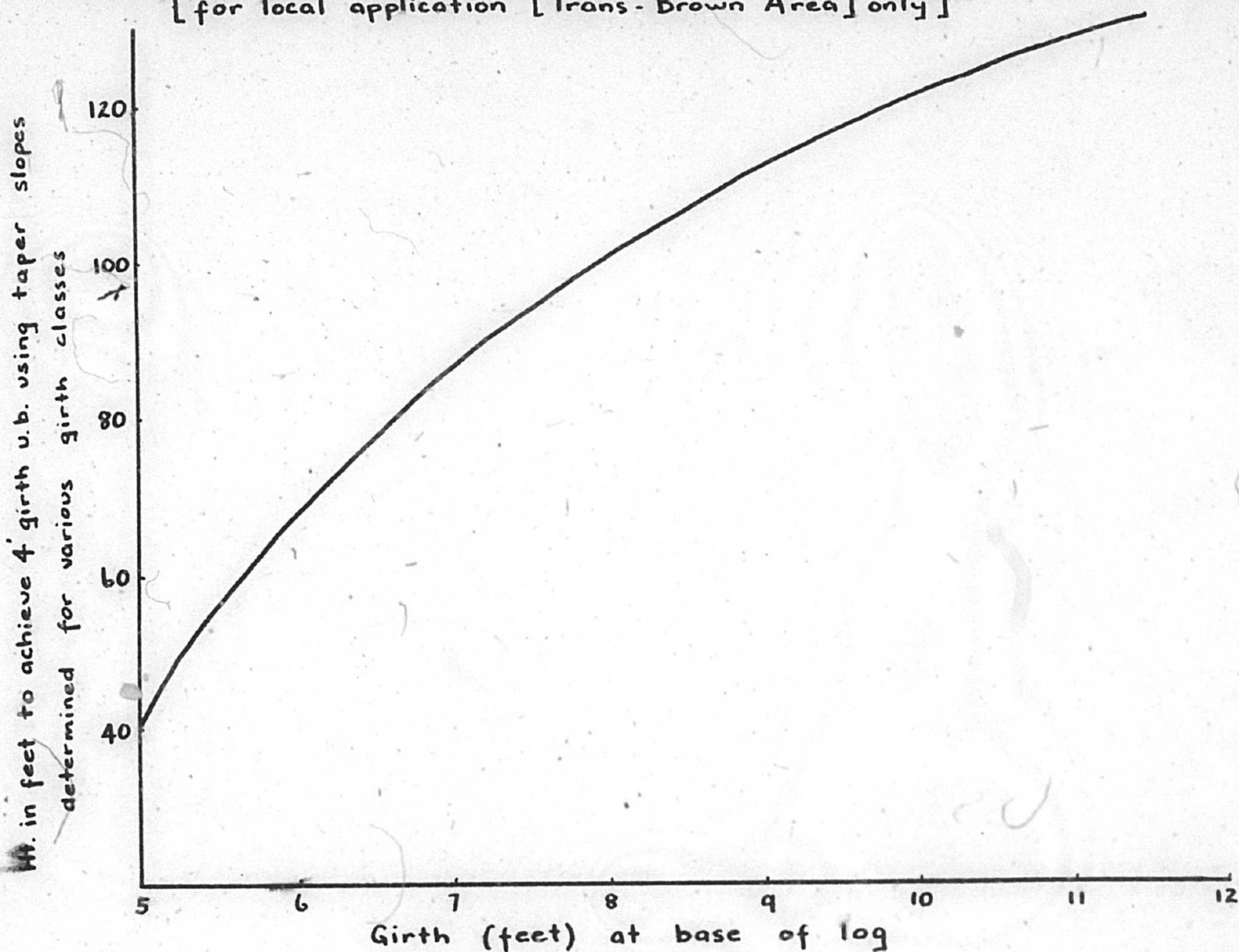
Mean values of deviation percentages were found to be -

For single random diameter : + 0.0974%

For mean of 3 systematic diameters : + 0.0318%

DETERMINATION OF LOG-HEIGHT FOR NON-BRANCHING TREES.

[for local application [Trans-Brown Area] only]



Of the two series, the mean of 3 systematic diameters provided the best mean deviation and its distribution had stronger central tendency. However, the improvement over the values for a single random diameter was not considered sufficiently high to warrant adoption of this more time-consuming method unless special accuracy was required.

A subsequent test was made of the ellipticality of section; but, it was found that an assumption of elliptical section was less justifiable than one of circularity.

8.2. Log-length Estimation.

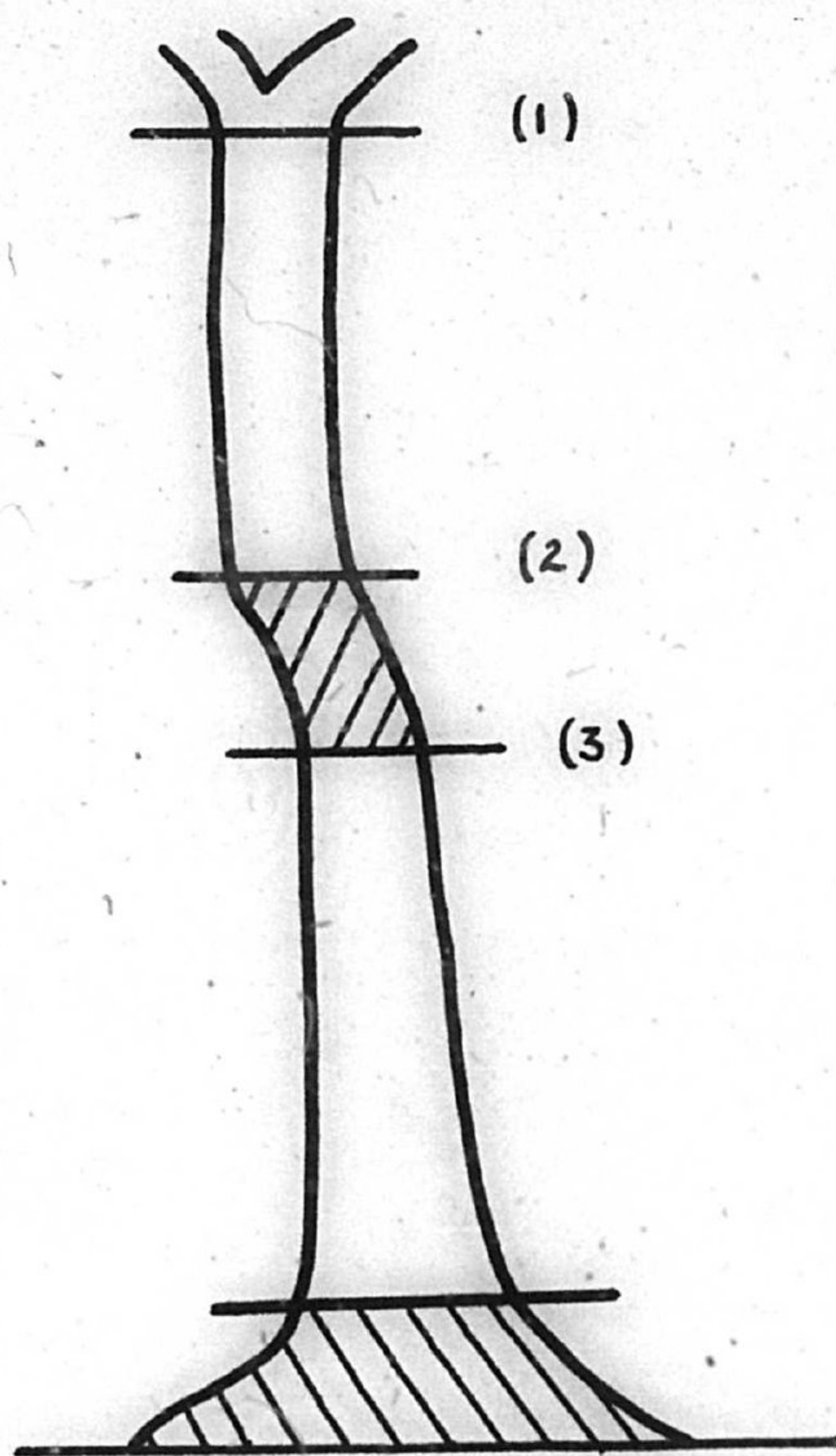
Log length is defined as the interval between height from the ground to the top limit of merchantability (as determined by branching or visible defect in form or wood quality) and height from the ground to the base of log. Hence -

$$\text{Log-length} = \text{Log height} - \text{Butt Height.}$$

Although readily estimated with any of the usual types of altimeters (Blume-Leiss, Haga etc.) by a method of ratio between actual base-line and that on the instrument, Log Height has some inherent difficulties - the chief of which is variable interpretation of the top limit of merchantability.

Trees exhibiting definite branching, obvious defect or poor form provide little difficulty in this respect. Certain trees do not, however, exhibit any form of top limit of merchantability other than what can only be an unmerchantable girth. Selection of the height at which girth becomes unmerchantable is open to wide interpretation even when given, as in Papua - New Guinea, the criterion of a top girth limit of four feet. In such a case, it is recommended that no instrument reading be made of Log Height. As an alternative, it is recommended that prediction tables be established to provide an estimate of Log Height to this girth limit. An example prepared from 145 logs is given opposite. The wide variation in height at the point of four feet girth between species and between sites demands that the relationship be established for groups of species of known similarity in taper and for local use only. The application of a Relascope to preparation of such prediction tables is obvious.

TREE VOLUME ESTIMATION FOR TREES. WITH NONMERCHANTABLE SECTION



$$\text{Merch. Vol.} = V_3 + V_1 - V_2$$

The second problem is associated with those trees which at some point in the log have an unmerchantable section as illustrated opposite. Estimation of Log Height (1) and subtraction of the interval Log Height (2) minus Log Height (3) will provide an underestimate of the volume in the two logs. The correct method involves derivation of three estimates of Log length viz.

$$\text{Log length (1)} = \text{Log Height (1)} - \text{Butt Height}$$

$$\text{Log length (2)} = \text{Log Height (2)} - \text{Butt Height}$$

$$\text{Log length (3)} = \text{Log Height (3)} - \text{Butt Height}$$

Consultation of the volume estimation using one estimate of girth at base of log will provide three estimates of volume. Merchantable volume may be estimated by calculation -

$$\text{Merchantable Volume} = V_3 + V_1 - V_2$$

This method is applicable only where the unmerchantable section does not involve any abnormal taper in the section from point (1) to point (3). Should the defect consist of a large branch or branch stub, then this calculation may provide an overestimate.

Although log length estimates may be derived with a satisfactory level of precision, the estimation of this parameter for each tree on the sample is most time consuming. An objective alternative is to sample for log length estimates within the units being assessed for species name, girth and form-class. The strata in which log length estimation is required are - by species (possibly to be combined into groups) and by girth classes. Sufficient information should be collected to provide mean log lengths, with a satisfactory measure of precision, for each species or species group in each girth class.

In the Jengka inventory currently being conducted in Malaya, sub-sampling for height data is at a fraction of 1/10 of the sample for other information. Insufficient results are available at time of writing to determine the effectiveness of this rate of sampling.

For any particular species or species group in which log length is similar, there is a likelihood of girth being related to log length in a particular manner which may afford a saving in time spent in height estimation. For 145 logs, measured in Papua by the writer, it was found

that for girths greater than five feet, log length was independent of girth. Similar indication is available from the Celebes (Indonesia: Pajmans 1951) and from Surinam (Heinsdijk 1953). The sample used by the writer to establish this fact contained a mixture of species all of which were of similar log length habit. In another locality, however, the possibility on encountering species of consistently shorter log length e.g. Vitex cofassus or of consistently longer log length e.g. Anisoptera polyandra would prevent species being grouped in this manner. The trend does indicate, however, that for species or species groups of proven similarity in log length, it may be possible to minimize the amount of data required if a relationship between girth and log length can be established.

Given mean log length for each species and each girth class on a sample of all the trees assessed for species and girth, there are two methods of volume estimation from regression.

The first is to enter a two-entry (viz. girth and log length) volume table with the sample data and to extract information to permit construction of a volume on girth relationship into which would be entered all estimates of girth, including those for which height data was available. In so doing, a measure of the precision of the volume estimate would be available from the regression of volume on girth alone. The measure of precision from the original two-entry table would have to be ignored.

The alternative is to regard each tree sampled for girth alone to have a log length equal to the mean of log lengths from the sub-sample. The tendency for log lengths to be normally distributed about this mean value has been demonstrated by the writer. Therefore, this alternative is likely to produce equally reliable results in addition to permitting expression of a Standard Error from regression.

8.3 Grouped data.

The methods described permit precise estimation of log-size parameters. Multiple-regression analysis by computer provides a mathematical model for estimation of volume from these parameters. A measure of precision of this volume estimate is readily available. These improved

techniques overcome a great part of the argument frequently presented in support of grouping data into classes e.g. estimation of girth into six inch or one foot classes, of height into classes of five or ten feet. Such grouping is employed because it is believed that more precise results cannot be obtained. However, it invariably involves errors in the less populated size classes, where the mean value rarely approximates to the class mid-point.

A further argument in favour of grouped data is that data processing is simplified. Such may be true of manual processing but the necessity to use electronic processing for data collected by helicopter-assisted inventory proves this argument false.

Appendix VI shows a comparison of the times taken for conventional and helicopter-borne inventory. The sampling methods outlined previously will yield higher sampling intensities than those shown - therefore more data. Computer processing is essential for economy, speed and accuracy of data output if field work is to be related to the results obtained, as it must be, until more is known of the populations being assessed.

8.4 The Application of Variable-plot techniques to tropical forest inventory.

Bitterlich's principle of the angle-gauge has been attempted in tropical forest with varying reports of success. In Ceylon, optical-wedge prisms were used (Merritt & Ranatunga 1959) as in Kenya and currently in Nigeria. In Sabah (Malaysia), research has been carried out into the use of this instrument. (Nicholson 1964). In Papua - New Guinea, the writer modified a constant form-factor volume estimating equation -

$$V = 0.00485 g^2 h$$

where "g" is girth at base of log (inches)

and "h" is log length (feet)

- to provide a direct estimate of volume from a sweep with an optical wedge prism with a Basal Area Factor of 20 so that -

$$\text{Volume per acre} = \text{B.A.F.} \times 8.7767 \times \sum \text{log length of tallied trees.}$$

For this B.A.F., plot radius limits for trees of various girth classes were determined to assist in checking marginal trees. All

tallied trees were estimated for girth class (one foot intervals) using a rough diameter-stick. Stand table factors were prepared as follows -

$$\text{S.T.F.} = \frac{\text{B.A.F.}}{\text{Basal Area of Class Mid-Point}}$$

<u>Girth Class</u>	<u>S.T.F.</u>
5'	8.313
6'	5.951
7'	4.470
8'	3.480
9'	2.786
10'	2.280

The number of trees per acre by species and size class was available by multiplication of the number of tallied trees of a particular species by the S.T.F. for the particular girth class into which it was placed by the approximation of its diameter. Thus in one operation, volume per acre by species, by size classes was available in the field within a few minutes of completing the sweep.

However, it was found that job of correcting for slope of the line of sight to the point at base of log was tedious, and required considerable skill. (An Abney-level was used to determine the angle and subsequently to set the prism at the same angle from horizontal in a vertical plane perpendicular to the line of sight).

The use of a Relascope would overcome this difficulty of slope correction; and, used in conjunction with caliper mounted torches as suggested by Edwardson (1965) would also overcome, in part, the necessity of clearing a line of sight to the more distant trees. Calipering high-buttressed trees is, however, a time-consuming task.

But the Relascope is an expensive instrument requiring the application of skill and patience by the operator. The number of operators demanded by helicopter-borne inventory, and therefore the standard of personnel, and the infrequency of supervision make its use of doubtful value.

A third variation of the same principle would involve dispensing with any form of instrument. From an assumption of the B.A.F. likely

to give best results (i.e. to provide 7-10 tallied trees per point), calculation could be made of the distances from the centre-point that trees of required girth class limits would have to be in order to be tallied if an instrument were used. Assessment would therefore involve a rough check, as previously, to determine girth class, and a measure of horizontal distance (by stepping procedure if necessary) of the tree from plot centre. Trees close to girth class limits or close to distance limits would have to be checked by more detailed measurement. From prepared tables, a stand-table could immediately be derived; and, as before, volume estimates could be immediately calculated. Alternatively, a computer could be programmed to process the girth class and distance information alone along with necessary height information and a volume estimating regression.

This method would, in fact, be more expensive than the conventional technique of naming, measuring girth and assessing form on a circular plot of 58.875' radius. As described, only a few trees need be checked for distance from the centre of a plot of this size. The "plot-less" technique described would require the same information and in addition, the horizontal distance of each tree from plot centre.

9. SAMPLING FOR FORM CLASS

Calculated mean values of numbers and volumes within classes of species or species groups and within size classes will be the primary aim of inventory. The inability, for financial reasons, to recognise ultimate divisions such as individual species and girth classes may be overcome by grouping into sufficiently large populations that a tolerable estimate of precision may be attained at reasonable cost. Allocation of trees in such a population to one of the six suggested sub-populations on the basis of form will again result in excessive cost if a satisfactory estimate of precision is to be attached to e.g. species group in size class M in form class A. As the least important population into which number and volumes are placed, form class may tend to be omitted despite its obvious attraction to utilization.

An alternative is to regard each form class defined as an attribute to be applied to the number of trees in each species group - size class population recognised. Taking each form-class in turn, the proportion of the total number of trees in the population belonging to a particular form class may be calculated.

For a particular population e.g. species group 4A, size class 7'-8' girth, the number of trees observed on each sampling unit is going to vary considerably as is the number belonging to a particular form-class e.g. form class A. A method involving a ratio of means estimator is required, as indicated by Freese who calls such sampling "Cluster sampling for attributes - unequal-sized clusters". The method will be unbiased since there is no conceivable relationship between the proportion of trees in each unit being of form-class A and the size of the unit.

From a list as follows -

<u>Unit No.</u>	<u>No. of trees in population</u>	<u>No. of trees form-class A</u>
1	15	7
2	24	12
.	.	.
.	.	.
.	.	.
n	x	y
	$\bar{x}$	$\bar{y}$

- the ratio-of-means estimate of the proportion of trees of form-class A is -

$$\bar{p} = \frac{\bar{y}}{\bar{x}}$$

- and $\bar{p}$ has a standard error estimated by

$$S_{\bar{p}} = \sqrt{\frac{1}{\bar{x}^2} \left(\frac{S_y^2 + \bar{p}^2 S_x^2 - 2\bar{p} S_{yx}}{n} \right) \left(1 - \frac{n}{N} \right)}$$

where -

S_y^2 = Variance of individual y values

S_x^2 = Variance of individual x values

S_{yx} = C-variance of y and x

n = Number of units observed

and

$$S_y^2 = \frac{\sum y^2 - \left(\frac{\sum y}{n} \right)^2}{n - 1}$$

$$S_x^2 = \frac{\sum x^2 - \left(\frac{\sum x}{n} \right)^2}{n - 1}$$

$$S_{yx} = \frac{\sum (y \cdot x) - \left(\frac{\sum y}{n} \right) \left(\frac{\sum x}{n} \right)}{n - 1}$$

The above procedure may be repeated for each form-class and subsequently, for each population.

10. THE PRECISION OF RESULTS

It has been indicated that inventory results contain a number of errors which are not to be confused with mistakes caused by carelessness, casualness or inattention. Those errors already indicated, include - a sampling error, an error from regression for volume estimation and an error arising from area estimation of strata. These are the major sources of error. Others may include - the error associated with use of diameter measurement as an estimate of girth and the error associated with use of an estimated mean log length for each species or species group and/or each girth class. These minor sources of error may be ignored in the present discussion - it having been established that a single random diameter is a satisfactory estimator of girth though a more precise result, to be applied in the case of larger trees, entails the use of the mean of these diameter estimates systematically distributed around the tree; and that the individual estimates of log length are closely grouped about the mean value in a normal distribution.

Of the major sources of error, sampling error is frequently the only one considered. A commonly accepted limit is $\pm 20\%$ of the mean at 95% confidence level. This error should, in fact, be applied to Basal Area since this is the quantity generally estimated by measurement of girth or diameter on the sample units. However, volume estimates from Basal Area are frequently assumed to be without error and so a mean volume per unit plus and minus a standard error of 20% or less is obtained. This mean value and its standard error is then multiplied by the area of the stratum involving, in tropical inventory, an expansion factor of up to and frequently greater than 500. This factor, the inverse of the sampling fraction, is calculated from the tolerance of the stratum, frequently measured by planimeter from a map and assumed to be without error arising either from the map or the planimeter, and the total area of the assessed units which, in all probability, have been carefully established to an exact dimension.

With computers so readily available with proven programmes for volume estimating regressions and for assessment data processing, there is little excuse for ignoring the error associated with volume estimation

from regression. The error associated with the expansion factor represents more of a problem, being allied to the standard of mapping and the method of strata area measurement.

The methods of strata area determination not involving the production of a map i.e. by a sampling process, are adequately discussed by Loetsch and Haller (1964). For large regional and national inventory, these methods are acceptable in that they provide an estimate of stratum area to which a measure of precision may be attached. Adjustments for faulty interpretation of strata and for scale variation are possible. For local and smaller regional inventories however, a map showing the extent of all recognised strata is essential for the reasons outlined previously.

The first error involved in stratum area determination from a map is due to the map itself. The ideal of a professionally produced topographic map at nationally accepted standards of point tolerance (indicated by Stellingwerf (1961) as the measure of planimetric accuracy) will seldom be met in tropical forest areas. The production of maps for inventory is likely to remain the concern of the forest service which must make do with aerial photography and a minimum of photogrammetric equipment. As a further hindrance to mapping, control points in remote forest areas are generally not available. The first possibility in such a situation is the preparation of a "photo-scale map" or uncontrolled mosaic - the scale of which at any point is indeterminable and is also liable to considerable variation. A preferred alternative is to prepare a slotted-template map for which, although actual scale remains unknown, the bulk of scale variation due to radial displacement will have been overcome. As an alternative to actual scale, the scale equal to flying height above mean terrestrial altitude divided by focal length may be used.

The second error arises from the subjective determination of stratum boundaries. The writer has found that boundaries selected on one occasion may differ considerably from those drawn at a subsequent occasion using the same photography and viewing technique. Between interpreter variation is likely to be even greater. Until better photography permits better strata identification, this problem will not be overcome in total.

It may be partially overcome by - interpretation by a single interpreter under similar conditions, frequent ground checks simultaneously with strata identification by reconnaissance and possibly, by use of a systematic sampling of the smaller or more difficult strata to determine their limits.

The third error arises from methods of estimation of strata area from the map. The most common method using a planimeter is readily adaptable to calculation of an error by consideration of the distribution of repeated planimeter readings - each being considered as a sample. Methods employing dot-grid counts are more apparently adaptable and have been discussed by Loetsch and Haller.

For tropical inventory generally, strata area estimates are going to represent the least reliable element in the expression of total volume. So long as this is recognised, then the expensive methods of obtaining more reliable estimates may not be required. Particularly is this true when recognition of the potential error involved results in the requirement of a smaller error in the mean volume per unit expression. In this regard, it is recommended that a sampling error of $\pm 10\%$ at 95% confidence level be adopted for estimates of mean basal area in Papua - New Guinea. With such a decision, it is possible after some initial sampling to calculate the effectiveness of an arbitrarily adopted sampling fraction and to adjust this fraction if required on the remainder of the sample. No tedious volume computation is required and the calculations may be made in the field. In this connection it is appropriate to quote Dawkins (1958) reminder that it is impossible to recover expenses of a too excessive sample but it is always possible to increase the sample when sampling errors prove too great.

11. DEFECT ASSESSMENT

No forest resource inventory can be considered complete without an evaluation of the defect percentage in the assessed volume. Particularly is this true of local inventory required for investigation of exploitation potential.

Division of trees encountered on sample units into five categories with no apparent defect and one with apparent defect, as in recognition of the writer's form-classes, does not fulfil the requirement since defect is most frequently hidden.

In tropical areas, defect assessment methods are too frequently neglected; often with disastrous results when the trees are cut.

A considerable amount of research is required into methods of defect assessment as an integral part of forest inventory. Defect is most obviously associated with topographic site, tree size and species and these three factors may well be suitable strata in which to sample for defect. However, other unidentifiable conditions such as proximity to a source of infestation or damage to the tree crown or bole considerably effect the variability of the defect percentage.

12. THE PROCEDURE OF FOREST RESOURCE INVENTORY

It is intended, in this concluding section, to indicate the sequence of operations involved in forest resource inventory.

(i) Maps, Aerial Photography and Reports.

The first requirement is to obtain these items and to extract all pertinent information. This may involve mapping from the aerial photography and will, without exception, involve interpretation for vegetation types, access and canopy aspect types.

Any reports whatever on the subject area are of some value. Particularly valuable are reports regarding climatic conditions, access and population frequently available from District Administration officers.

(ii) Data to be collected.

The next requirement is to obtain a decision on what statistical populations are to be recognised for sampling purposes and in what areas separate estimates of these populations are required.

Recognition of populations for which an acceptable standard error cannot be calculated within the financial resources available is meaningless. Therefore, the criteria for selection of populations will be - total permissible expense, locality of inventory area with respect to markets - existing and potential, the type of inventory - regional or local and whether any interest exists for exploitation of the area.

Any sub-division of the inventory area for utilization, silvicultural or administrative purposes must be known prior to design of the sample.

(iii) Sample Design.

Prior to a reconnaissance, it is necessary to plan a sample design for the unstratified area of forest. The small strata that may be recognised have yet to be evaluated and therefore sample design for them is not justified at this juncture.

(iv) The Reconnaissance.

As time spent on planning is seldom wasted, a reconnaissance by one or two individuals can frequently save a great amount of time in the sampling operation which must involve considerable numbers of expensive personnel. The objects of a reconnaissance are to -

- (a) evaluate canopy aspect types
- (b) assess landing-sites and, perhaps, establish new ones as necessary or improve existing sites
- (c) test the applicability of volume estimating equations in the locality and to additional species that may occur
- (d) establish the identity of less well known species that may occur and prepare descriptions for the instruction of staff on the subsequent assessment.
- (v) Final Planning.

With the reconnaissance completed, it is possible to:-

- (a) Revise strata map on the basis of canopy aspect evaluation.
- (b) Make a decision regards volume estimating equations.
- (c) Prepare an operations plan based on this design by organizing field-work schedules, movement details and helicopter hours.

(vi) Field-operations.

When parties are established in the field and assessment work is begun, computation must begin to determine -

- (a) the adequacy of the pre-determined sampling fraction
- (b) the adequacy of the log length information which provides entry to the volume table.

Separate computations are required, of course, for each stratum or inventory area recognised.

In addition to the collection of statistical data, field operations involve a study of accessibility of the area to exploitation equipment.

Information considered necessary includes -

- (1) prevailing slopes
- (2) sub-soil conditions with respect to roading
- (3) availability of road-surfacing materials
- (4) stream-flow of major water-courses
- (5) stream-bank height of major water-courses
- (6) likelihood and frequency of flooding (from debris incidence and information from locals).

Additional information is frequently required on land-ownership patterns and the tenure system in the subject area. This information

requires consultation with local indigenes. .

Finally, a study is necessary to evaluate timber defect.

(vii) Computation of Results.

When sufficient sampling units are established to provide satisfactory precision estimates of Basal Area for the required populations, computation of volume estimates may begin.

(viii) Report preparation.

The final step for inventory is the preparation of a report on the forest resource of the area. In Papua - New Guinea, as elsewhere, this report is made under standardized headings which ensure that no information relative to knowledge of the forest resource and its exploitation or management is omitted.

Comparison of Linear Regressions of form $y=a+bx$

(after calculation of individual regressions, eg. Statform 7)

Regressions are of y :-

on x :-

No. of regressions to be compared, $Nr =$

Total no. of pairs of observations, all regressions, $N =$

Comparability of residual variances.

Largest resid. MS = _____ } F ratio = _____ with { DF =
Smallest " " = _____ } DF =

Table F at P.05 for above DFs is :

If table F exceeds F-ratio, combine all N data into single overall regression, eg. on Statform 7. If F-ratio is the larger, regressions should not be combined.

Calculations for analysis of variance, (lines 22-26)

$\sum$ (individual regression SS) = _____ = $\sum$ (SS regr)

$\sum$ (" " SSx) = _____ = $\sum$ (SSx)

$\sum$ (" " SSy) = _____ = $\sum$ (SSy)

$\sum$ (" " SPyxc) = _____ = $\sum$ (SPyxc)

DF and SS for overall regression and total are obtained from overall An. of Var. (Statform 7; 16 & 18)

Between coefficients; $DF = Nr - 1 =$

$SS = \sum (SS regr) - [\sum (SPyxc)]^2 / \sum (SSx) =$

Between constants; $DF = Nr - 1 =$

SS; by subtraction in An. of Var. below.

Residual; $DF = \sum$ (individual regression DF) =

$SS = \sum (SSy) - \sum (SS regr) =$

Analysis of variance of differences between regressions.

	Source	DF	SS	MS	F-ratio	Sig.
22	Overall regression :					
23	Betw. coefficients:					
24	Betw. constants:					
25	Residual :					
26	TOTAL :					

If F-ratios for coefficients and constants are less than table F, the overall regression is valid for the N data.

If F-ratios (coeff. or consts) exceed table F, diffs. between coeffs. or consts. must be tested individually.

APPENDIX II

Technical details - helicopter transport.



A Bell 47G3B1 super-charged helicopter showing 2 passengers alongside the pilot and the litters on either side to which cargo is strapped: At the feet of the left-hand-side passenger is a knotted rope (approx. 12' long) on which passengers descend into grass, garden areas or water-logged places on which the machine could not alight safely.

Appendix II (Cont'd.)

Technical details - helicopter transport

Aircraft: Bell 47G3B1
(super-charged, flat six aircooled aero engine).

Size: Overall length - approx. 24'
Rotor diameter - 34'

Working details: Total load - 900 lbs.
- or 2 passengers + 500 lbs.
Fuel requirements - 15 gals./hr. of 100/130 Av.gas.
- 4 gals. oil/25 hours.

Performance: Maximum altitude - in excess of 20,000'
(though no engine restart possible over 11,000')
Cruising speed - up to 75 knots.
Mean calculated speed including passenger
discharge - 60 knots.

Governing regulations: Pilot hours - a maximum of 30 hours in any
period of seven days.
Overhaul - at 600 hours requires a Certificate
of Airworthiness.

Landing/Take-off requirements: - approx. 250' x 80'

APPENDIX III

An example of weighting for unequal-sized secondary units in two-stage sampling.

If w_{ij} is the area of the j^{th} secondary unit within the i^{th} primary unit, then the mean square between primary units is estimated by -

$$s_b^2 = \frac{\frac{\sum_i \sum_j w_{ij}^2}{m} - \frac{(\sum_i \sum_j w_{ij})^2}{mn}}{\bar{w}_{ij}^2 (n - 1)}$$

- and the mean square between secondary units is estimated by -

$$s_w^2 = \frac{\sum_i \sum_j w_{ij}^2 (y_{ij})^2 - \frac{(\sum_i \sum_j w_{ij} y_{ij})^2}{m}}{\bar{w}_{ij}^2 \cdot n(m - 1)}$$

The above is based on the following -

$$\text{Sum of Squares} = \sum (y - \bar{y})^2 = \sum y^2 - \frac{(\sum y)^2}{n}$$

When an area weight w is applied to each value of y then the sum of squares is derived as -

$$\frac{\sum (wy)^2 - \frac{(\sum wy)^2}{n}}{\bar{w}^2}$$

or

$$\frac{\sum (wy - \bar{wy})^2}{\bar{w}^2}$$

That this is true may be tested by calculation sums of squares for which unit size is equal and then assuming an equal weight to be applied to all unit data. The answer, using the above formulae, will be identical with that derived in the first instance.

APPENDIX IV

Models used to derive a satisfactory volume estimating equation for Papua/New Guinea species.

I. All species 461 samples.

	<u>Model</u>	<u>Furnival Index</u>	<u>Order of Merit</u>
1.	$V = d^2$	868.3	
2.	$V = d^2h$	370.7	
3.	$V = d^2 + h$	556.1	
4.	$V = d^2 + dh + d^2h$	361.8	
5.	$V = d^2 + h + d^2h$	361.8	
6.	$\log V = \log d + \log h$	237.4	4
7.	$\log V = \log d^2h$	242.5	5
8.	$V = d^2$ - weighted by d^2	642.8	
9.	$V = d^2h$ - weighted by d^2h	237.4	3
10.	$V = d^2 + h$ - weighted by d^2	437.0	
11.	$V = d^2 + dh + d^2h$ - weighted by d^2	250.2	
12.	$V = d^2 + dh + d^2h$ - weighted by d^2h	231.3	2
13.	$V = d^2 + h + d^2h$ - weighted by d^2	250.2	
14.	$V = d^2 + h + d^2h$ - weighted by d^2h	230.9	1

II. Anisoptera polyandra 62 samples

The same models were used - the order of merit being 6, 14, 12 and 9.

III. Pometia spp. 211 samples.

The same models were used - the order of merit being 9, 12, 14, 7 and 6.

Regression constants and coefficients are assumed.

Appendix V

LOG ECCENTRICITY

LOG N°

SPECIES

LOCALITY

DATE

G.U.B. S.A.U.B.

S.A.U.B. (planimeter)

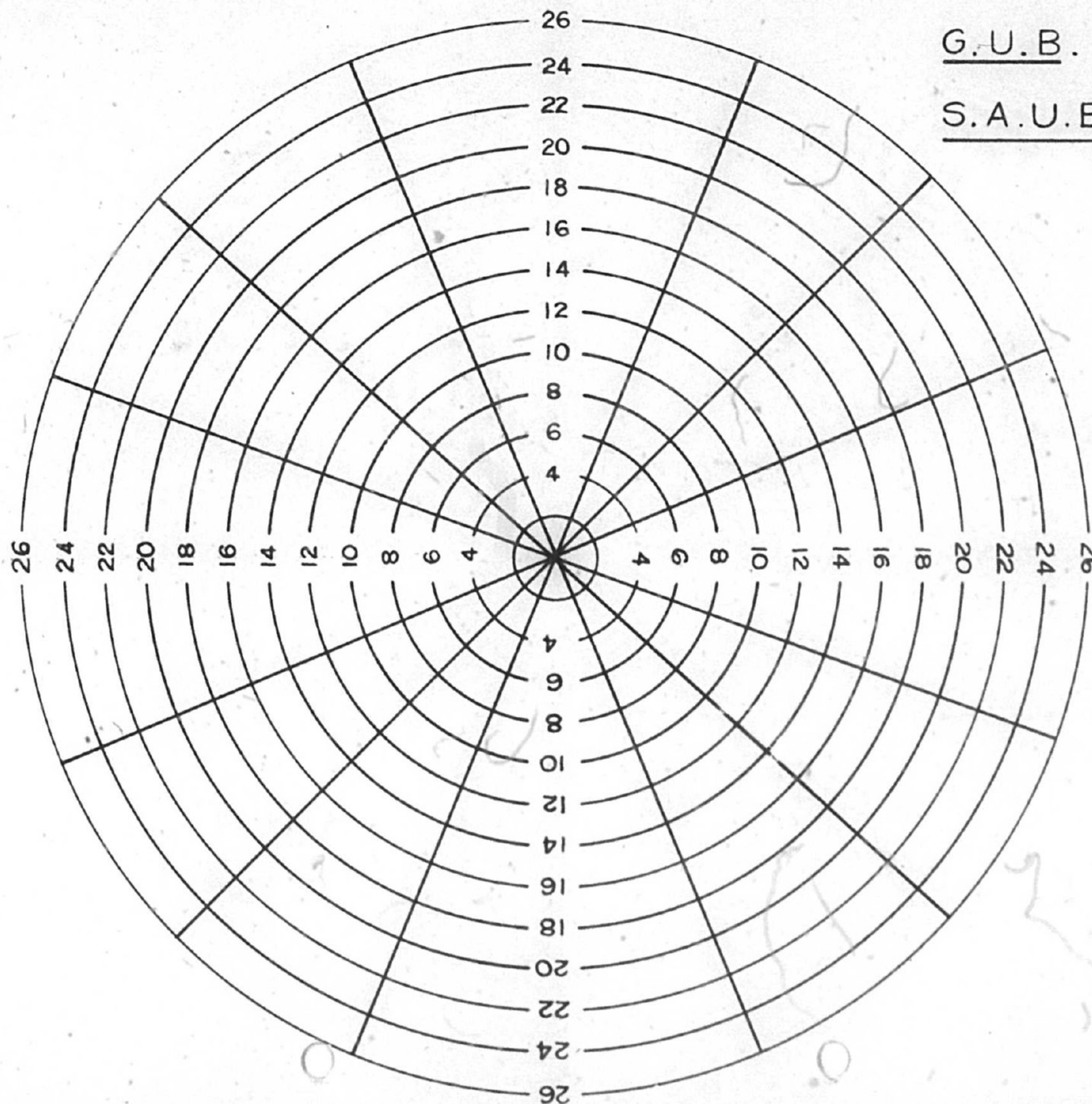


Diagram $\frac{1}{4}$ scale.

1/88

Rosengren
31-7-88

(III)

APPENDIX VI

COMPARISON OF SURVEY COSTS - CONVENTIONAL VS. HELICOPTER TRANSPORT.

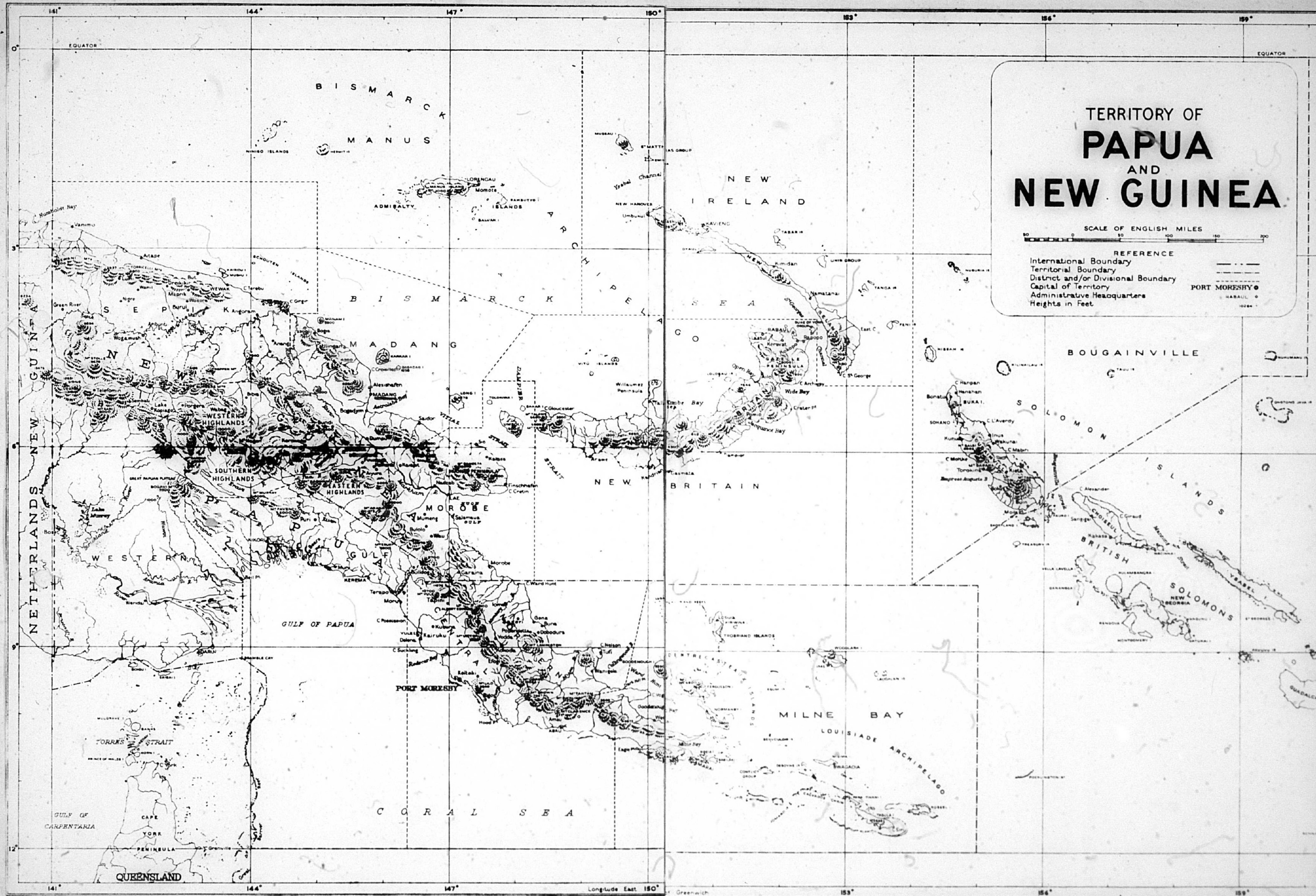
Source: Dept. of Forests files.

Area	District	Duration	Area (acs)	Sample Plots			Sample Intensity	Computed Cost	Av. cost per ac.	
				No.	Size	Acres			Sample	Tot. area
<u>CONVENTIONAL</u>										
Kulu Dagi	New Britain	5 Months	93,000	⊙ 56	2 acs.	112	% ·12	£ A 4,000	£ A 35·7	£ A 10·3
Tonolei	Bougainville	9 "	107,000	71	2 "	142	·13	5,000	35·2	11·2
Gogol	Madang	6 "	130,000	125	2 "	250	·19	5,000	20·0	9·2
<u>HELICOPTER</u>										
Gogol	Madang	10 Days	130,000	⊙ 608	$\frac{1}{4}$ "	152	·12	3,200	21·0	5·9
Pual River	Sepik	21 "	400,000	1642	·31 "	547	·13	8,000	14·6	4·8
Imila River	Central	14 "	112,000	855	·31 "	272	·24	2,810	10·3	4·6
Sagarai River	Milne Bay	18 "	130,000	1222	·31 "	384	·29	4,860	12·7	8·9
Torokina	Bougainville	31 "				462		7,158	15·5	

Writer's Note

- ⊙ Independent plots
- ⊙ Circular plots systematically established on access lines subjectively located.

(X)



**TERRITORY OF
PAPUA
AND
NEW GUINEA**

SCALE OF ENGLISH MILES
0 50 100 150 200

REFERENCE
International Boundary
Territorial Boundary
District and/or Divisional Boundary
Capital of Territory
Administrative Headquarters
Heights in Feet

PORT MORESBY
HABAU
10264'

Longitude East 150°

2

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