A MANUAL OF PERMANENT PLOT PROCEDURES FOR TROPICAL RAINFORESTS

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FOREWORD

This manual was drafted during a research project financed by the Ministry of Overseas Development from 1974 to 1977 at the Commonwealth Forestry Institute, University of Oxford. The results and conclusions of this project have now been revised for publication as Occasional Paper No. 10, Tropical Rainforest Silviculture: a research project report.

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Units of measurement

Most countries now use metric units for scientific work, although a wide variety of old and traditional units of length, land area and timber measurement are still used for management or marketing. It is strongly recommended that metric units should be used for all permanent plot measurements, particularly the restricted range in the Systeme International d'Unites, S.I. units. These units have mainly been used here.

Measurements recorded in other units can, if necessary, be converted to metric units by the standard data-processing computer programs. Some useful conversion factors are in Appendix 5.

Abbreviations

Where appropriate, this manual follows the IUFRO recommendations for the standardisation of symbols (25).

PSP Permanent Sample Plot
CFI Continuous forest inventory
TSP Temporary sample plot
SPR Sampling with partial replacement
LD Leading Desirable
TRF Tropical rainforest
SD Standard deviation
cm, dm, m centimetre, decimetre, metre
d diameter
dbh diameter at breast height (1.3 m)
CP crown position
CF crown form
CD crown diameter
CB base of crown, or height to base of crown
h height (often height to top of tree)
p.o.m. point of measurement (of d)
b.a. or g basal area
ha hectare(s)
Introduction

The purpose of this manual is to describe and recommend some of the most useful methods and techniques for permanent plots in indigenous, mixed tropical forests, for sample plots and for experimental and research plots. From accumulated experience and publications, many techniques developed in various countries and conditions have been collated to produce a standard recommended procedure with a number of options.

Important background material is discussed in references 11, 17, 19, 20, 23. Some of the methods recommended here are already widely used and described elsewhere (3, 4, 5, 14, 17, 45, 46). Others are an extension of previous practices and are based on more recent fieldwork and developments in methods of data-analysis. There are certainly many other suitable techniques which have been, and will continue to be, locally developed and which may be suitable for wider use.

The need for a manual of this kind became apparent during attempts to analyse and interpret data from sample plots and research experiments collected at Oxford from several countries. This work was carried out during 1974-1977 as a research project concerned with the management of tropical rainforests. It made clear the difficulties for analysis, comparison and interpretation caused by various and often incomplete measurements of similar situations by different methods. This suggested that a set of standard recommended techniques will help to ensure that results collected in different situations will be mutually comparable. It will also assist organisations which are starting work on rainforest plots and are wondering what methods are suitable. More important, the work of the project demonstrated the great difficulties caused by the absence of some kinds of data, and the advantages, for interpreting the results and for achieving the sampling and research objectives, of measuring a wide enough range of items.

The data to be collected for an adequate characterisation of the status of the trees and the stand, and of changes in status, are suggested in this manual, with suitable techniques. This should not discourage anyone from using or developing other techniques which may be more suitable locally, or for special purposes, and it will be very helpful if comments and suggestions are sent to the author of this manual for future revisions. However, it is hoped that this manual and the project report will help to ensure that the data collected in rainforest are better able to fulfill their purposes, and that results from different projects will become more reliably comparable, the usual advantages of standardisation preferably without the restrictive disadvantages.

The first part of this manual deals particularly with sample plots and the second with silvicultural research plots. Originally this manual was intended for publication with the results and conclusions of the research project. The project report has now been published as Occasional Paper No. 10 of the C.F.I. and it includes a description and discussion of the uses that can be made of suitably detailed measurements. There are several cross references and the list of literature references is identical for the two publications.
SAMPLE PLOTS

1. Objectives of sample plot program

A network of Permanent Sample Plots (PSP) in a Continuous Forest Inventory (CFI), if correctly laid out as representative samples of the forest and regularly assessed, provides the most reliable data for estimation of

(1) changes in the forest stand over time, in numbers, sizes and species,

(2) variations in composition and production with site (soil, aspect, initial vegetation and stocking) and treatment (various reductions in stocking and types of interference),

(3) the relationships between individual tree variables (diameter, height, crown position), stand variables (local basal area and volume stocking) and increments (in diameter, basal area and volume per tree or per plot), which may be used for predicting future stocking and production, and

(4) long term changes (improvements, degradation) in the site and its productive capacity.

CFI provides a system for monitoring the stocking and development of the stand and its rate of production which allows any unexpected or unfavourable developments to be measured. It also provides the data essential for constructing yield tables and growth models which may be used, together with current inventory data, for growth and yield predictions.

The objectives of CFI are different from those of inventory surveys or silviculture experiments. Growing stock inventories may make use of temporary sample plots (TSP), as well as plotless surveys and other methods, but in rainforest these give little or no information about dynamics and rates of production. Silviculture experiments may involve permanent plots for assessing the effects of interference and treatments on growth rates and production, and the data may be used for constructing growth models relating tree- and crop-increments to competitive status; such models alone do not provide quantitative information about the rest of the stand but they may be used with the data from more extensive sampling for extrapolation to other areas.

The results of treatment experiments and other studies of competition and survival are needed for a proper interpretation of CFI results; together they make it possible to understand the observed behaviour and performance of the stand and to forecast its future development. Relatively simple inventories, as from TSP, may be used with the appropriate growth and yield models, from CFI and experiments, to estimate current yields and to forecast future yields by species and sizes.

Ecological surveillance: PSP for regular management and treatment plots for silvicultural research are not usually expected to provide detailed information on long term changes in ground vegetation, fauna or
soil fertility. However, long term ecological surveillance is essential for detecting any possible deterioration in the productive capacity of the site which may outweigh the short term benefits resulting from treatment, enrichment or plantation. Such programmes are at present not practical for many tropical forestry departments, but at least some information can be gathered in descriptive form. The PSP system provides part of the information needed for long term surveillance (9, 20); more detailed monitoring can be initiated later in the same PSP layout, when practical.

2. Number of plots: sampling intensity

CFI is a sampling system, therefore the closeness of the results obtained from the CFI to the true values for the whole stand will depend on the sampling method, the variability of the stand and the number of independent samples; whatever the variability, it is more important to achieve an adequate number of plots than to aim at some pre-determined sampling intensity (cf. 16). "In fact the sampling fraction is a parameter of little account. What matters is the number of independent sampling units ...... Thus 50 one-hectare plots on a stratified random design will give almost as good estimates of a widespread species from 20,000 hectares of forest as from 5,000 hectares" (19).

At the start of a PSP program, there may be some information about the variability of the forest in terms of altitude, topography and forest-types in the management area. However, there may be no information about the variation, after exploitation, of the parameters which are the main subjects of the program, such as increments, stocking, recruitment and mortality for each species. It will be impossible to decide on the most efficient number of plots required in a management area, or in one site-type, until the variability of the stand with respect to these parameters has been assessed. The variability of some features such as stocking may be assessed by a pilot survey or inventory, or when 10-20 of the new PSP have been first measured, but the variability of dynamic features (increments, recruitment, mortality) can be assessed only after 2-3 measurements.

There must always be a compromise between the requirements of embracing variability of site and treatment with acceptable precision and the need to keep fieldwork and expense to a reasonable minimum. The methods recommended here involve more detailed measurements of more trees than in most existing sample plot and yield plot procedures, allowing much more information to be calculated about tree and crop increments and responses to local competition. Tree and stand models are being developed to use the variability of increments and responses, within each plot, as measures of the stand variability, instead of using only the plot averages or totals for forecasts. By increasing the value of each plot it should be possible to reduce the number of plots required for any given level of accuracy.

Fox (23) examined the sampling errors for estimates of stocking obtained from Sabah yield plots; for one compartment he calculated the numbers of plots which would be required to achieve Standard Errors from 1% to 20% for estimates of total basal area, mean girth and stocking. Dawkins (19) has shown how the application of the Poisson distribution may be used for planning the number of sampling units, at any given level of
sampling error %, depending on the frequency of the population being
studied. However, for forest management, we require estimates of incre­
ments and, more useful, models of growth and response, not only estimates
of sizes and stocking, for each of the main species or groups of species,
over a range of sizes and crop densities. Cousens (14) and Baidoe (3)
showed that, at any given sampling intensity, the sampling error will
usually be lower for mean annual increments than for basal area stockings.
However, we do not know enough about the amount of data required to
characterise increments and to construct reliable models for many species
in a wide range of stockings, so the recommendations here are still
tentative.

Recommendation: As a rough guide, 50-100 randomly distributed plots
of 1 ha, established by the methods described in this manual, will prob­
ably be adequate for the normal management purposes of monitoring and
forecasting, with acceptable sampling errors, over areas of several
thousand ha or several compartments or coupes combined within one stratum.
In the initial stages, a rate of establishment of one plot per 150-200 ha
of forest (0.5-0.7 %) will probably be enough, depending on the intensity
of management practiced, the precision required and the uniformity of the
forest. In relatively uniform forest types, such as Mixed Swamp Forest
in Sarawak, an initial sampling intensity of 1 plot per 250-400 ha (0.25­
0.4%) may be adequate.

3. Plot size

In order to achieve a predetermined precision or sampling error from
a PSP programme, the larger the plots the fewer will be needed but, at the
same time, the larger will be the total area which must be measured in
samples. Therefore the labour of travelling from plot to plot and of
surveying and demarcating permanent boundaries and access lines can be
reduced by having few large plots, while the labour of detailed measure­
ments can be reduced by having a smaller total area of more numerous small
plots.

In large tropical forests, often with few all-weather roads, the
labour of reaching each plot may be very great and it is usually more
efficient, easiest and cheapest, to increase the work done in each plot,
and the value derived from it, and to reduce the total number required.
(In enumerations with TSP or in plotless timber inventories with no perm­
manent demarcation, it is usually more efficient to use very numerous
small plots, distributed more or less continuously along strips, in order
to reduce the quantities of measurements and the total area required.)

A decision about plot size is a compromise between the statistical
advantage of numerous small plots and the requirement to embrace minor
local variability and to minimise the numbers of plots, and hence the
expense of travelling and maintenance, by maximising the useful data
obtained from each plot (cf. 17, pp. 18, 48).

The most efficient plot size in a particular situation will depend
on the objectives, the precision required, the variability of the forest
and the present and future costs. The aim here is to recommend a stan­
dard plot size and measurement procedure for regular PSP programs so that
uniform methods of data processing, analysis and interpretation can be
used and results compared internationally.

Standardised 1 ha plots are widely used in many tropical countries and they have many advantages. Plot totals represent values per hectare with no problems of conversion, and they can be approximately compared with the totals from the plots of 2.5 acres (1.0108 ha) previously established in many countries. In addition, 1 ha plots can easily be subdivided into 25 subplots of 0.04 ha (almost 0.1 acre), or 100 subplots of 0.01 ha (c. 0.025 acre) so that these subplot totals may also be approximately compared with data from the 1/40 acre (half-chain square) plots used in many Linear Sampling Surveys of regeneration.

A plot of 1 ha is, in most cases, large enough to "absorb gross variation in stocking due to gaps" (17, p. 48), so that the variability of total stocking (basal area, volume) shown by a system of plots should reflect the broad variation of the stand and not the detailed variation between individual large trees and individual gaps.

During the analysis, the initial or final basal area stocking of the plot may sometimes be used as an indicator of its potential, on the assumption that the stocking of a forest which has not been disturbed for many years is close to the maximum that the site can develop and is an indication of the site quality or potential, the Limiting Basal Area (17, p. 60). The plot must therefore be big enough to ensure that the stocking is realistic for that locality and not distorted by a plot size too small in relation to the distribution of gaps and large trees. It is most important to lay out the plot accurately. Errors in area are proportional to the square of any errors in length. Correct angles at corners are particularly important; if the first two right angles are set up 5° too wide, the resulting error of the plot area is + 8.3% (32, p. 317).

**Recommendation:** 1 ha plots are recommended for PSP programmes. Rarely, smaller plots may be used in unusually uniform forest, in some short duration trials, or if access to large numbers of smaller plots would be relatively easy.

4. **Plot shape**

Several workers have discussed the factors influencing the choice of shape for rainforest plots (e.g. 23), and have used and recommended square plots for the following reasons:

(1) Squares have shorter boundaries than an equal total area of strips or rectangles, and thus reduce the expense of boundary demarcation and maintenance and the errors caused by uncertainties over trees standing on the boundaries.

(2) Square plots of appropriate size and distribution can achieve lower sampling errors than an equal total area of strips (16). Thus, to obtain a required sampling error with PSPs, which are more expensive per unit area than TSPs, it is cheaper to minimise the total area of samples and maximise their value by using square plots. (For surveys and inventories with TSPs, without permanent demarcation, the same sampling error may be achieved more cheaply with other shapes and distributions including strips and clusters, even if these cover a larger total area, but these are not appropriate for PSPs).

(3) Square plots are less likely to be interfered with by subsequent roads and tracks than strips, and are easier to site so as to avoid swamps, rock outcrops, etc. without introducing bias.
(4) Round plots of 0.1 ha are used in even-aged plantation sample plots (11, pp. 141, 213) where there is no recruitment and so plot boundaries need no demarcation and where all trees in the plot can be seen from the plot centre. Round plots cannot easily be subdivided into many subplots and it is practically impossible to lay out large round plots accurately in dense vegetation when trees near the perimeter cannot be seen from the centre.

Recommended: Square plots for all PSP.

5. Plot subdivisions

Small "recording units", quadrats, or subplots are required during field work so that each tree can be easily found and to allow checking and definition of each tree record and position. The subdivisions also allow subsampling or selection of "leading trees" to be distributed evenly over the plot.

This section deals with the size of the smallest subdivisions which are to be permanently demarcated with cut lines (here called subplots) and also with any further subdivisions within subplots which are the basic data-recording units, each individually numbered, temporarily demarcated with tape-measures at each assessment (here called quadrats).

The choice of the quadrat size used in PSP has been influenced by calculations of the area occupied by rainforest trees at maturity and hence of the area-units which should be assessed in order to determine the effective stocking and distribution of potential final-crop trees or Leading Desirables (17, p. 93). Plots of 0.01 ha or 1/40 acre (half-chain square) are used with further subdivisions during assessments of the silvicultural condition of regeneration by the methods of Diagnostic Sampling and Linear Regeneration Sampling (where $LS_{\frac{1}{4}}$, $LS_{\frac{1}{2}}$ and $LS_{M}$ correspond to linear sampling in $\frac{1}{4}$ chain square, $\frac{1}{2}$ chain square and milli-acre plots) (5, 45, 59, etc.). A subdivision of the 1 ha plot into 10 x 10 m or 20 x 20 m subdivisions will allow comparison with the results of 0.01 ha or $LS_{\frac{1}{2}}$ regeneration surveys.

A small quadrat of 10 x 10 m is most useful for assessing the potential stocking of final crop trees, since their development to maturity is dependent on their distribution and available space for crown development; a small size also helps to ensure that the quadrat can be thoroughly covered at each assessment with the minimum number of plants missed. However, permanent demarcation of 10 x 10 m quadrats with cut lines would cause much disturbance of the ground vegetation, making it unrepresentative of the rest of the stand. Subplots of 20 x 20 m involve much less labour and disturbance during demarcation and are suitable if only few trees are to be assessed in each plot (e.g. 4 Leading Desirables per 20 x 20 m subplot in Ghana (4), Sabah (23) and Uganda (5)), but it is more likely that some trees will be missed if many or all trees are to be assessed in plots of this size or larger. In practice, 10 x 10 m quadrats have often been found to be the minimum size for reliable finding and refinding of individual saplings. 10 m or $\frac{1}{2}$ chain quadrats have been a standard unit in most countries which have carried out rainforest silviculture.
Each quadrat should be numbered in the plot records to ensure that all data can be referred back to the appropriate quadrat on the ground and in the records; it is therefore essential that a standardised system for quadrat numbering should be adopted throughout any one country to avoid confusion in analysis. In practice, it will be possible to locate each tree from the tree position map and plot co-ordinates if recommendations below are followed so the choice of subplot numbering system is not vital so long as it is standardised and stated for each country.

Dawkins (17) and all subsequent Uganda work instituted 25 subplots, numbered serially clockwise, starting with the one in the NW corner; Baidoe (3, 4) arranged the 25 numbers back and forth along a NS axis for Ghana, while Fox (23) in Sabah labelled 25 subplots A-Y, arranged back and forth along an EW axis, with each subplot containing 4 units, numbered 1-100. The clockwise numbering of 25 subplots has an advantage if more detailed measurements are to be carried out in the central subplots: subplots 1-16 are always peripheral, 17-24 internal and 25 central.

Recommended: Each plot should be permanently divided into 25 subplots of 0.04 ha (20 x 20 m or c. 1 x 1 chain, c. 0.1 acre). During each assessment, each subplot is divided into quadrats of 10 x 10 m which are the basic areas for field records (recording units). The 100 quadrats are numbered from 00 to 99 from the plot co-ordinates (cf. Appendix 1).

**Sampling design**

The PSPs may be distributed entirely at random through the forest (unrestricted random) or in a restricted or stratified random design, or in a systematic design. Strictly, a random distribution is needed so that reliable confidence limits can be attached to the estimates. However, Dawkins and Field have examined this problem in relation to permanent plots in forest and have concluded that systematic sampling may be preferred to stratified random sampling for some purposes (20).

Systematic sampling may overestimate the sampling error but it is likely to result in means that are closer to the true value, and it is more efficient, for a given number of plots, than a random sampling at detecting phenomena such as differences in growth rates or rare populations. For some purposes, an ideal system may be a systematic layout plus subjectively located plots in particular areas with known unusual features. For measuring growth rates, stratified random designs are more efficient so long as the basis for stratification (such as vegetation type) does not change. A systematic distribution is probably satisfactory for PSP programs, but methods of randomisation are included in Appendix 1.

If a random design is chosen, the efficiency of sampling will in many cases be greatest (with smallest sampling errors for a given number of plots) if the plots are laid out in pairs, in a restricted or stratified random design rather than distributed in a simple and unrestricted random design.

If possible the forest should be divided, on a management map, into strata each of which is sampled independently. Each stratum may correspond to a whole logging concession, or to several concessions, or it may distinguish between major forest types e.g. swamp/dry land, or hillside/valley-bottom; or it may be much smaller, such as an annual logging coupe,
or an area of harvesting and treatment, within one vegetation or site type, within one Forest Reserve.

In each stand or stratum, the sampling can most efficiently be arranged within theoretical (undemarcated) blocks, based on the probability that differences within blocks and strata are likely to be less than differences between blocks or overall, by locating a pair of plots at random within each block. Since the sampling errors are calculated from differences between samples, which will be lower if the plots are closer together, this design will usually result in lower sampling errors.

Stratification on the basis of two plots per block is effective in reducing sampling errors only if differences between any two plots in one block are on average less than differences between any two plots in different blocks; in many areas of THF containing a range of different vegetation-, succession- and site-types, perhaps in a mosaic, the differences may be just as large within blocks as between them. Furthermore, the blocking may be completely upset by changes in the basis of the blocking, e.g. logging effects or new information about soils. Annual coupes may be used as blocks, because of the differences between them induced by differences in logging or silviculture, but such differences may be completely eliminated by the next logging or silviculture operation and a new pattern of differences may be superimposed. In such cases, stratified random sampling is no more efficient than unrestricted random sampling. In some cases, the whole sampling program may be stratified into different major forest- or site-types, e.g. swamp forest or dry land, hillside or valley bottom. These strata are less likely to be obscured by logging than are strata based on detailed vegetation types in the unlogged forest.

Sampling errors may be reduced by using the techniques of Sampling with Partial Replacement (SPR) (15, 19, 57). Normally, SPR involves discarding a proportion of the semi-permanent plots at each remeasurement and substituting an equivalent number of new plots. Because of the high investment of time and resources in PSPs, many Forest Services hesitate to discard them while they still yield useful results, in spite of the theoretical advantages of the SPR system. For some purposes, information from PSPs may be supplemented with measurements of temporary, unmarked plots chosen independently on each measurement occasion. SPR has not been applied widely in tropical rainforest, but when tested it may allow the numbers of PSP to be reduced still further for any required sampling error. SPR ensures that the PSP system is representative of the forest and does not become increasingly unrepresentative due to special attention, excessive impact of research workers etc. SPR is easier to impose on a systematic layout than on a random layout, but in reality the mistakes and disasters which overtake SPs, as a result of accidental losses, excessive logging damage or road building, result in an inbuilt replacement system whatever the layout.

If the forest is divided into strata of vegetation, site or management types for stratified random sampling, there is a risk that the efficiency of the design will be reduced if subsequent treatments cause changes in the vegetation or site characteristics. Systematic sampling avoids this problem, but runs the slight risk of coinciding with some periodic variation in the forest and tends to overestimate sampling
errors. The risks of initial stratification are reduced by using the restricted randomisation described here, involving two plots per block.

Whatever sampling design and method of plot location is chosen, it is essential that all sample plots should be representative samples of the forest, subject to no special treatment or interference except for the minimum needed for plot establishment; no tending, climber cutting or other interference should be carried out during the measurements.

Under normal circumstances, sample plots are best established shortly after major disturbances such as logging or major silvicultural treatment. If, as is usual, the plots will be used to monitor and predict the progress of the forest from one logging operation to the next, the state of the forest prior to a logging operation will give little information about the progress of the forest afterwards (except with the use of extremely complex stand-modelling programs not yet available for such purposes). This proviso does not apply to silviculture treatment experiments, where a pre-logging measurement is very useful. It is therefore recommended that PSP should normally be established as soon as possible after logging (or after treatment if this follows soon after logging) in order to make use of the logging access-roads and general clearance, but before dense regrowth makes access difficult.

Recommended: For random distribution, a stratified random pair system is recommended, to achieve lower sampling errors, by dividing the forest area (or each compartment or coupe in sequence, as the S.P. programme proceeds) into blocks of 300-400 ha of productive forest, and allocating 2 plots at random to each block.

For systematic distribution, a rectangular grid system is recommended, with each plot situated at (or a fixed distance from) the intersection of the grid lines used for national mapping.

7. Plot location

The location of each plot should initially be determined on a map and then identified in the forest.

The results will be used for estimating stocking and production within strata of productive forest whose areas will be determined from maps and aerial surveys; therefore, no plots should be established in vegetation or site types which will be excluded from the forest area under study, such as mapped unproductive vegetation (savanna, swamp, etc.), roads and big rivers. The stocking of each block or stratum can be more reliably estimated if such areas are excluded rather than by including them among the other sources of variation.

A plot position, selected at random, should be rejected in the office if it falls wholly or partially in a mapped (or easily measurable) unproductive vegetation type or within 100 m of the nearest edge of a previously selected plot. In the forest, a chosen plot position may be moved under some circumstances, which may arise from errors in maps, if it overlaps or falls too close to a road, railway, river, a forest boundary or a previously selected plot (Appendix 1). Loetsch et al. (32, p. 327) explain that some bias may be introduced by moving the whole
plot away from forest boundaries to avoid overlap, and other more complex solutions may give more reliable results, especially for inventories, but this method is recommended for PSP programs.

The plot position must not be moved merely because it happens to fall in a patch of locally poor forest, caused for example by windblow or locally poor drainage or shallow soil, unless the area affected is measured, mapped and deducted from the area of productive forest under study.

8. **Permanent demarcation**

It is essential that all plots can be exactly relocated even after a logging operation or several years of neglect; many carefully measured plots in tropical rainforests have been lost, sometimes within 5-10 years, because of impermanent demarcation and insufficient survey-data, rendering much of the work futile. The description and permanent demarcation of the start and end points of access lines and other reliable means of relocating plots, are among the highest priorities. However, it is also important to minimise the disturbance caused by ground marks and line cutting, and to avoid making the plots so conspicuous that they attract special attention during harvesting or treatment, thus making them less representative of the whole stand. This may be less of a problem in lightly managed rainforest than in intensively managed plantations, but in some regions it is an advantage if the plots and their demarcation are inconspicuous, so as to avoid attracting attention and interference from inquisitive people. In heavily used forests, the plot must be "difficult to recognise for those who do not know where it is, easy to find for those who do and are looking for it" (19).

On balance, permanent visible monumentation is of the greatest importance in most rainforest PSP programs.

**Recommended:** Mounds, direction trenches and corner trenches should be employed for demarcation of access lines and plot boundaries; they are less likely than posts to be obliterated or moved by animals, natural events, logging or other human activities, and they serve the double purpose of marking and pointing. In addition, but especially when trenches are unsuitable because of surface water or incipient erosion, permanent posts should be set up along the access line and plot perimeter. Numbered posts should anyway be set up at the start and end of the access line.

9. **Plot description**

At the time of establishment of each plot, an initial description of the plot and site should be made, including:

(1) Full details of the location and survey data of the plot and the access line to ensure that the plot can be found for subsequent measurements;

(2) a description of stable site features such as soil type, aspect, slope, geology and history which may be valuable for interpreting, comparing and classifying the results from the whole system of plots;
(3) a description of the initial state of the flora (and fauna) especially the ground flora, to provide a basis for estimating changes which may occur in the future. The more detailed the description, the more effective will the plot be for detecting long-term site changes.

A standardised PSP Description form, or a checklist of all items to be covered, should be used for recording the initial information and description, to ensure that each item required is recorded for each plot, with enough space for recording more details about unusual or locally important features. Each national forestry department may devise its own Description Form, appropriate to the resources available and the objectives and intensity of management. A sample TRF PSP Description Form is shown in Appendix 2, based on several examples (e.g. 5) and is recommended for general use or for modification to suit local circumstances.

Another example has been recommended for use in plantation sample plots of 0.1 ha (11). It provides for a lot of information about the local climate and site since the intensive management of plantations and the planning of production requires a detailed study of the correlation between production and site factors. Such detailed work is not always possible or necessary in TRF.

Dawkins and Field (20) have developed a system for describing forest plots for long-term ecological surveillance, suitable for detecting site changes rather than for measuring increments and production. These detailed assessments of vegetation and soil are too intensive for normal TRF management, but may later be grafted on to the PSP system.

It is especially important to record local observations and information if these are not well recorded in published or widely distributed reports. However, information which applies equally to all the plots in a PSP system, and which is available in full detail elsewhere (such as temperature, rainfall and other climatic data for each month and year, from local meteorological stations, or general information about the history and nature of the whole forest) need not be recorded for each plot. Similarly, if details of the yields and treatments of each compartment are recorded in a well distributed Working Plan or Annual Report or elsewhere, they can easily be found when needed, but not if they exist in only one report or compartment record.

10. Tree marking and location

10.1 In order to calculate tree-by-tree increments, plot-by-plot growth, recruitment and losses, it is essential to know the individual identities of each tree, so that each measurement can be allocated to the appropriate tree record. "Gross increment and time of passage cannot be calculated from repeated inventory unless the mortality in each size class is known. This mortality cannot be traced unless every measured tree can be identified with precise records" (17, p. 47; cf. also 20). Various attempts to calculate increments and predict stand tables from successive inventories, without individual tree identification, rely on a number of constraining and rather unlikely assumptions about movements of trees between size classes (47).

The identity of each tree may be determined (a) in the forest from plot maps showing the positions and numbers of all measured trees, and/or
10.2 Tree numbering

Labels or painted or scribed numbers are invaluable during remeasurements, especially when there is possible confusion between trees of similar sizes or species, when the relative sizes or statuses may change between measurements. It is recommended that the labelling or numbering should not be omitted even if plot maps of tree positions and numbers are drawn and regularly revised.

Numbered labels are best nailed to the tree at a standard height above the p.o.m., where they are clearly visible and help to define the p.o.m. However, they may be exposed to theft, and they may be lost if the tree is felled; it is sometimes an advantage to fix the nails near ground level.

Each tree number must be unique within its quadrat. If a tree dies, its number should never be used again within that quadrat; if a new tree grows up to the size of measurement, it should be allocated a new, unused number at the end of the sequence for that quadrat.

10.3 Mapping and measuring tree positions

Tree-position data define the position of each numbered tree in relation to other trees and the plot boundaries. This information is very valuable for relocating each tree for remeasurements, an essential requirement for all PSP programs. With appropriate computer programs, the data may also be used for calculating indices of individual-tree growing space and competitive stress and status, and for simulated relascope tallies, which may be needed for stand modelling, leading to more reliable production forecasts.

The required information may be collected in the field either as hand-drawn maps, or as co-ordinates for each tree from plot boundaries, or as compass bearing and distances for each tree from two or more plot or subplot corners.

Accurate tree-position maps can be drawn by computer-plotters using existing programs (or by hand) from the measured co-ordinates or from bearings and distances; these programs can print a spot for each tree, or a circle in proportion to its size, plus the tree number and species, and numerous other options. Conversely, the co-ordinates of each tree can be measured by ruler from hand-drawn maps in the office, thus perhaps greatly reducing the fieldwork; these data can then be used in competition studies and for more complex plot-mapping using measurements of diameters, heights, crown dimensions etc. to represent various aspects of stand structure (1).

Hand-drawn plot maps can be drawn quickly and accurately by experienced field staff; they need to show only a spot or ring and the tree-number of each measured tree. They can easily be photocopied, and a copy can easily be brought up to date, showing mortality (with a cross) and recruits at each remeasurement. The maps give a better visual
impression of relative tree positions than co-ordinate data, and they are more useful in the field for relocating trees.

Compass bearings are less helpful than co-ordinates for quick checking and tree-finding, and they are subject to much greater errors which are troublesome to detect and correct, although they can be equally easily used by computer programs.

Co-ordinates can be measured quite quickly if 10 m tapes are first laid out along the sides of each 10 x 10 m quadrat in turn, with two tapes connecting the mid points of each side to form four 5 x 5 m squares; the co-ordinates of each tree, accurate to 10 cm, may then be read off by eye by members of the measuring team standing by the tape measure. If very many trees are measured in each sample plot, the labour of measuring co-ordinates will be very great, and it may be appropriate to confine the measurements of co-ordinates (and some other items such as heights, cf. section 11.3) to the larger trees.

Co-ordinates should refer to the centre of the stem at ground level, and it is reasonable to measure to the nearest decimetre. If the 100 quadrats are numbered i.e. 00-99 from their 10 m co-ordinates, then the first digit of the x and y co-ordinates will be the same for all trees in any quadrat; for example, in quadrat 89 one tree may have x and y co-ordinates 813 and 926, another may have 827 and 934 (cf. Appendix 1 for plot layout).

If it is expected that the tree-position data will be used mainly for locating trees for remeasurements, it is recommended that plot maps should be drawn by hand. They should be photocopied at least once, and then carefully checked, corrected and brought up to date and recopied at each remeasurement. Individual tree co-ordinates for each measurement-date may be obtained later from the maps if required.

If it is expected that tree-position data will be used for competition studies, association and nearest-neighbour analyses, and stand forecasts in the immediate future, co-ordinates should also be measured in the field. This will almost certainly be necessary if positions accurate to 1 dm are required; it is difficult to make hand-drawn maps so precise, and in fact it will be easier to measure the co-ordinates and make a less precise sketch-map and then rely on the computer for a more detailed map. It is strongly recommended that hand-drawn maps should be made and maintained in all cases.

10.4 Marking point of measurement

Small errors in successive measurements of diameters may cause large errors in the calculated rates of growth and production, especially in slow-growing trees or in old stands where measurement-errors may even exceed the true growth. Such errors may result in apparent fluctuations between rapid growth and stagnation or even shrinkage in successive intervals. It is therefore essential that successive measurements should be taken at the same point on each occasion, to minimise the sources of error. The only way to ensure this is to mark each tree so that the point of measurement (p.o.m.) can be fixed precisely (Appendix 1.5).

The p.o.m. should be marked on each measured tree at a standard height such as breast height, 1.3 m above ground level measured on the
uphill side of the tree (after removing accumulated litter). A consistent method should always be used for deciding on the ground level, or foot-point, for determining the p.o.m. (32, p. 82).

If the tree is (or apparently soon will be) buttressed, deformed or branched at 1.3 m, the p.o.m. should be at a higher standard point but not at some undefined and inconsistent height "above buttress" because buttress heights change with time. The appropriate standard heights should be chosen locally according to the buttressing characteristics of local trees, e.g. 2, 3 and 4 m in some regions or 3, 5 and 7 m in regions with extreme buttressing (cf. remeasurements, 13.2). Note that stem irregularities (flutes, buttresses and deviations from a true circle) cause the basal area and derived circle-diameter to be overestimated; it is important to avoid gross distortions of calculated basal areas and increments caused by the exaggerated size and radial growth of buttresses.

The most effective and reliable method of marking the p.o.m. is with a continuous painted ring round the stem; for greater accuracy, one edge of the painted ring is used for positioning one edge of the tape measure. A conspicuous (red or yellow), non toxic, weather proof paint should be used. The durability of painted rings varies enormously depending on the paint, the bark and the climate; on one plot in Uganda, many painted rings and numbers were still visible in 1976 on trees which had not been measured since 1952, but in some cases markings disappear within a few years. A ring of spots, e.g. from a tube of tree marking paint, may be used instead of a complete ring, but normally extra errors will be unavoidable unless the whole line of measurement is marked (except on fluted or buttressed stems where only the outer portions, in contact with the tape, need be marked).

For intensive and precise measurements, as for competition studies, various kinds of permanent girth bands, recording dendrometers and remote reading dendrographs are available, but these are unlikely to be feasible for sample plot programs.

If callipers are used for diameter measurements (not recommended for TRF) the p.o.m. may be defined by two (or four) paint spots on opposite sides of the tree. If a telerelascope or dendrometer is used, a single paint mark may be used, at the p.o.m.

The position of the p.o.m. may also be defined by a nail (e.g. the nail holding the tree number label) at a fixed distance e.g. 20 or 70 cm above the p.o.m., never on the exact line of measurement.

11. **Recommended tree measurements**

11.1 **How many trees to be measured?**

The tree-by-tree measurements carried out in a PSP, or in a system of PSPs, should be enough

(1) to characterise the stocking and composition of the existing stand by species and sizes,
(2) to enable the tree increments, crop production, mortality and recruitment to be calculated for each size, species and other categories of status, during the period covered by measurements, and

(3) to enable forecasts to be made of the future stand composition, by species and sizes, with forward projections of the recurrent measurements.

PSPs achieve the first aim in broad terms, but a detailed characterisation of current forest composition is best obtained by an inventory designed for the particular purpose. The second and third aims are the main ones; PSPs are designed for answering the questions: "How is the current crop growing and what will it produce in the future?"

PSPs are not designed to characterise the seedling and sapling regeneration; this information may be obtained by subsampling within PSPs or by Linear or Diagnostic Sampling in temporary lines appropriate to the sizes and densities of small trees, especially when needed for deciding on silvicultural treatments.

The terms seedlings, saplings and poles are used differently in different countries. The following are reasonable definitions for silvicultural purposes, although smaller subdivisions are needed for biological studies of regeneration.

- **Seedlings**: 0 to 150 cm high
- **Saplings**: 150 cm high to 5 cm dbh
- **Poles**: 5 to 20 cm dbh

It is suggested that all PSP programs, even rather intensive ones, will exclude seedlings (except, at most, on small subsamples or with written descriptions), and that all PSP programs, even rather extensive ones, will include some of the poles, perhaps only the larger poles of the most valued species.

PSP data analyses can reasonably handle data for all saplings down to the minimum size at which diameters or girths can be measured accurately with tapes; it is scarcely worthwhile to include trees of <1 cm dbh except in small subsamples or for special studies. Normally, a minimum measured diameter of 10-20 cm dbh will be appropriate for assessments of current production and forecasts of future yields. In some countries, seedling heights are measured, and converted to equivalent diameters by a regression equation or graph; this leads to many errors in calculations of diameter increments, and is not a recommended PSP technique although useful for particular studies of regeneration.

The survival rates of small, young trees in TRF is often very low, particularly when much regeneration becomes established and quickly dies during the first 5-10 years after logging or other disturbance. Nevertheless, there are many logged forests in which relogging will probably have to wait until some of the seedlings and saplings have grown to a usable size, i.e., the future crop will consist of trees which exist as seedlings and saplings after logging. The Malayan Uniform System and many of its derivatives are based on liberating adequate seedlings and saplings for the next crop in addition to the small numbers of surviving poles and
trees of 10 cm d and above. In order to monitor the developing crop, and to forecast the future crop, at least some of the smaller trees must be measured when they appear to represent the future crop.

In order to provide full information about current increments and production in the stand, and the most reliable forecasts of the future stand, all trees of all sizes and species would have to be measured. "Ideally, all species irrespective of desirability should be measured, as only by this means can a total increment be calculated .... In practice total measurement will rarely be possible, and limits of both size and species must be drawn .... It is therefore suggested that all desirable stems or at least the four leading desirables should be measured" (in 20 x 20 m subplots, >10 cmd) (17, p. 49). In order to reduce the burden of work for plot establishment, remeasurement and data processing, many PSP systems follow this suggestion by confining the individual numbering and labelling to a number of Leading Desirables, the best and largest individuals in each plot of the required or most valuable species; these are the trees which are thought most likely to form the next harvested crop, even if they are now small, in preference to trees which are smaller or defective or of an unwanted species. In Uganda, Sabah and elsewhere, up to 100 Leading Desirables (L.D.) per plot of 1 ha or 2.5 acres are measured. The L.D. measurements often include scores for their crown status and condition, and plot measurements often include counts of all other trees in the plot, above a certain minimum size, classified by species or desirability and size, as a measure of local competition.

This system is well able to achieve the basic aims of PSPs listed above, but the precision which can be achieved for estimates of production, mortality and future stocking, for the whole plot or the whole stand containing many plots will depend on the numbers and sizes of trees classified as LDs, their mortality and population turnover, and the extent to which their increments and survival can be correlated with the measures of tree-by-tree competitive status and of plot-by-plot competition. For example, a logged forest may contain a very variable, but often high, stocking of currently unsaleable trees of all sizes, but much less than 100 per ha of undamaged trees of the valued species. If these LDs are very small, their mortality and rate of replacement by new LDs will be high, and the data for the small sizes will be of little use for calculating increments and predicting future stocking. Among the larger LDs, mortality may be lower but they may represent only a small proportion of the total stocking and production, and the local competition may be characterised by nothing better than the total basal area in the subplot or quadrat.

Using new computer programs, PSP data can be used for constructing models of tree growth and stand production and for forecasting future stand tables in a way which takes account of tree-by-tree variability in increments and relates increments to any measures of tree status and stand competition; this is an improvement on earlier methods based on mean times of passage, which do not allow for future variability in increments and which are limited in the number of competition-variables they can include because of the very few trees likely to be found in any one closely defined category of status, size and species.
The new models (cf. Occas. Pap. 10) are expected to produce more reliable forecasts if based on more detailed measures of competitive status, determined by the individual tree status with respect to the sizes and distances of all competing neighbouring trees; in addition, the range of species, sizes and qualities which are saleable for timber is steadily expanding. Therefore there is now much greater justification for obtaining detailed measurements of trees of all species, although this will certainly involve more fieldwork within each plot and quadrat. The forecasting role of PSPs will then be served by a model and the reliability of the model will be improved if it is based on trees in a wide variety of competitive situations, such as are found if all trees from even a few varied plots are included; this is in contrast to the time-of-passage calculations based on LDs, which require numerous measurements from many plots, of the relatively few LDs in each plot, to obtain a reliable mean for each of the size and status categories of each species.

This introduction is designed to explain why more detailed measurements are now recommended for more trees per plot, and how the extra work can be justified by the anticipated better results and probably compensated by a need for fewer plots.

Summary:

Impossible to measure all trees of all sizes and species, and
Irrelevant to measure all seedlings and saplings since most will die, but
Desirable to measure all trees > 10 or 20 cm dbh to monitor production, and
Essential to measure at least the best individuals for an estimate of future composition and silvicultural status of the stand.

It is recommended here that all trees of all species above a certain minimum size (10-20 cm d) should be monitored in detail. Even defective trees of no commercial value are included, because their size, position and growth rates influence the growth of surrounding more valuable trees for which forecasts are required. In addition, any number of smaller trees or LDs of particular ecological or economic significance may also be measured, for example a small list of the most highly valued species for which long-term, even if less reliable, forecasts are required. The stocking of such seedlings or saplings may be a useful indicator of the potential supply of the most valued trees, but their mortality is likely to be very high and their growth rates highly variable so the data for their increments are unlikely to produce very accurate forecasts of their future sizes and stocking until they have reached a larger size.

All trees to be assessed will be individually numbered, with their p.o.m. marked (section 10.4).
11.2 Stem diameter, d

Diameters at the permanently marked p.o.m. can reasonably be measured to the completed mm (i.e. a diameter between 16.7 and 16.8 cm is recorded as 16.7 cm). A minor systematic error results from rounding down to 1 mm, but this can be ignored. The rounding error would be more important if completed 1 cm d classes are used, and this may be avoided by using a suitably marked tape, e.g. with marks at 24.5 and 25.5 cm for the 25 cm d class; however, measurements in 1 cm classes will not usually be sufficiently precise for the required calculations of increments and forecasts.

Tape measures are preferred for PSP work because they usually give a higher precision in use than callipers (32, p. 85). Linen tapes can quickly stretch and deteriorate when used in TRF. Steel tapes can easily crease when twisted during rough intensive use and the etched marks often become obscured rather easily by gum exudates. Fibre glass tapes are recommended since they are very stable and hard wearing, relatively cheap and easily produced to particular specifications (e.g. from Howard Wall Limited, Skelton Industrial Estate, Skelton, near Saltburn, Cleveland, U.K.).

A diameter tape of 2 m can be used for trees up to 60 cm d, usually the majority of trees measured. It is helpful if tapes have enough blank length at the zero-end to allow quick positioning of the zero mark; they should not have a hook on the end, since this can cause calluses when used repeatedly, except when used on large, thick-barked trees. An extra tape of 5 or 10 m will cope with the largest trees. Measuring diameters on very large trees, or at a p.o.m. well above breast height, often requires two people, sometimes with ladders or sticks for lifting the tape into position.

A positive bias will be introduced if the tape is held too loosely and if mosses and other epiphytes are not removed. Climbers near the p.o.m. should not be cut unless there is no room for the tape between the tree and the climber, because disturbance within the sample plots should be minimised.

Callipers are expensive, liable to damage and unwieldy to use in TRF. If the stems are eccentric they may give wrong values for tree sizes and increments. This source of error may best be avoided by measuring two diameters at right angles and recording the mean.

Various basal-area sticks and V and Y shaped devices (Bitterlich forks, etc.) are very convenient for inventories, and for counting trees into size-classes, but they are not sufficiently precise for measuring individual-tree sizes and increments. If smaller trees of selected species such as L.D.s are measured, their diameters can be measured if they are taller than 1.3 m; otherwise their diameter can be recorded as zero or a nominal figure such as 0.1 cm with their heights.

11.3 Tree height, h

11.31 Great precision in height measurements is not required since the calculation of tree-by-tree height increments is not feasible, and is relatively unimportant because volume is related to h but to the square of d. Reasonable precision is required for calculation of tree-by-tree
total wood volumes (0.5 gh) and volume increments and hence of volume production per plot. Height measurements may also be required for calculating the crown size, growing space and competitive stress and status of each tree, relative to the size and position of neighbouring trees.

It may be possible to estimate heights by eye, with an accuracy of 1-2 m, with regular checks to verify the accuracy of the estimates. Any instrument used for height measurements should be quick, easy and consistent in use, and should preferably have the height scale visible at the same time as the tree top (e.g. Suunto).

It is almost impossible to measure heights in TRF very accurately, since it is difficult to see or identify the exact top of the crowns of many of the large trees when in full foliage, so there is no need to record measurements with unrealistic precision. A suggested scale of precision would include:-

heights measured to the nearest m for all trees
or to 0.5 m for trees <5 m high
and to 0.1 m for trees <2 m high
and to 1 cm for trees <0.5 m high

11.32 Instruments for height measurements

11.321 Poles

Poles may be used for direct measurements quite easily up to about 15 m. Selectional fibreglass or aluminium poles, preferably with safety coupling, can be used for considerably greater heights under some conditions.

11.322 Graduated rulers

Graduated rulers or height sticks are cheap and simple and have often been used in inventories. They must be aligned on the top, base and a measured intermediate point on each tree. In TRF it may be impossible to see all three points from any one place, but they may be suitable for determination of merchantable height or crown base (seldom more than 25 m high). As discussed by Loetsch et al. (32, p. 120) the advantages are

a) they can be easily selfmade
b) no additional distance measurements are required
c) the required height is obtained with a single reading
d) the height measurement is not influenced by slope

and the disadvantages are

a) a steady hand and eye are needed to avoid serious misreadings
b) it is often very difficult to find suitable observation points.
11.323 Hypsometers on trigonometric principle

Useful optical instruments include the Abney Level, U.S. Forest Service hypsometer, Blume-Leiss, Haga, Suunto, Spiegel tele-relascope, Barr and Stroud dendrometer, and Zeiss teletop.

These instruments are capable of greater accuracy than the graduated rulers; if they have range finders, heights can be measured by one observer alone. A disadvantage is that separate readings have to be made (a) to the tree top, (b) to the base of the tree or to some measured height such as the p.o.m. and, on sloping ground, (c) to correct the readings for slope. Measuring the distance from the observer to the tree, either with a tape or optically, may be difficult in dense forest because of obstructing foliage or low light intensities.

11.33 Avoiding errors

If the tree is leaning, or if the crown is not vertically above the base of the stem, the line of sight of the observer should be arranged at right angles to the slant.

Great care is needed to sight on the top of the crown, not on an outer edge which may at first sight appear to be higher.

The moving parts of some instruments may stick, especially in high humidities. There is a danger of reading incorrect values, especially if the height scale is not visible at the same time as the tree top (e.g. Blume-Leiss and Haga).

Note that it is not necessary to use a "direct reading" instrument which reads the exact height, since the calculations can be made in the office using only the measured distances and angles.

11.4 Crown base, CB

The crown depth (from base of crown to top of tree) and the bole length (from base of crown to ground level) may be calculated if the height of the base of the crown (CB) is measured at the same time as tree height.

The purpose of measuring the depth and other dimensions of the crown is to obtain an index of crown size (not of course a true measure of crown volume) to be used in a growth model for forecasting the future tree size; the bole length is probably not so well correlated with competitive status and increment but it is a good measure of the potential timber yield (as distinct from total wood volume), and can be projected forward in the growth model to forecast possible future timber yields.

It is difficult to define the base of the crown objectively, and the significance of crown base probably varies between species. In different species, the measured crown depth may be strongly or weakly correlated with increment, but the calculated regression models take account of these differences. It is important that the definition of crown base (or crown point (32)) should be consistent, and a suitable choice may be the point where the lowest live branch joins the main stem, taking note of branch-swell at the crown base, and ignoring small epicormic shoots.
(In conifers it may be defined as the first green branch if no more than two branch whorls of dead branches are between it and the remaining crown.)

Dawkins (18, p. 12) defined crown base as the position of the lowest live foliage, ignoring small epicormics and suchlike, and he used a relascope sighted "on the point of intersection of the main stem with a horizontal plane tangential to the crown base, not difficult to estimate from a distance but unreliable when standing close to the tree". This measure is probably better correlated with the leaf-bearing canopy surface area or volume, especially when branches are strongly ascending or pendulous, hence with potential production, hence with increment, but we are aiming only at an index of crown sizes; the growth models for each species will allow for different degrees of correlation between increments and this index. Dawkins' measure has the disadvantage of being harder to define and locate accurately and consistently in the forest, and of being a less effective measure for determining bole length or merchantable length than the measure based on the junction of the stem and the lowest live branch.

11.5 Crown Position, CP

Irrespective of the size of a tree's bole or crown, some index is required for the position of each tree's crown relative to those of its neighbours, particularly neighbours of a similar or larger size, i.e. an index of dominance, competitive status or canopy exposure. Studies in plantations and in some homogeneous natural stands have shown that suppressed or subdominant trees, whether large or small, generally grow more slowly than exposed or dominant trees; a similar correlation between canopy exposure and increment doubtless exists in mixed TFR but is less easy to demonstrate. The index of crown position is believed to be most important for reliable growth models for forward projections of increment. Dawkins found that the CP score was more correlated with tree-by-tree increments than any other measure of environment, status or competition (as distinct from size) and was the only one of his environmental variables which was significant in his regression equations. He concluded (18, p. 46), that the CP scores could hardly fail to reflect the sensitivity of diameter increments to crown exposure if the species is actually sensitive to exposure.

A 5-point system for Crown Position scores was developed by Dawkins and has been used with little or no modification in many countries and reproduced in several reports (17, 23, 42, 45, 46, 60).

The diagram illustrating the Crown Position scores, Figure 1, and the definition of each category, are based on Dawkins:

"Emergent" Crown plan fully exposed vertically, and free from lateral competition at least within the 90° inverted cone subtended by the crown base. 5

Full overhead light Crown plan fully exposed vertically but adjacent to other crowns of equal or greater height within the 90° cone. 4

Some overhead light Crown plan partly exposed vertically but partly vertically shaded by other crowns. 3

Some side light Crown plan entirely vertically shaded but exposed to some direct side light due to a gap or edge of overhead canopy 2

No direct light Crown plan entirely shaded vertically and laterally 1
Figure 1. Crown Position Scores
(Reproduced from Silvicultural Research Plan, 1959-63, Forest Dept., Uganda.)
Earlier interpretations of the relation between CP scores and canopy strata are corrected by Dawkins and Field (20) who point out that a CP of 5 could apply to a seedling exposed in a wide gap as well as to a giant emergent; a CP of 1 could apply to a very tall subdominant under a closed top canopy as well as to a suppressed seedling.

11.6 Crown Form, CF

Within a population of any one species, the shape or quality of a crown in relation to the size and stage of development of the tree is correlated with the increment and potential increment. Dawkins (18, p. 12) explained his CF score "as an index of quality, its value being dependent on past history and perhaps indicating future potential". He explained (17) that they are inevitably more subjective than the CP scores but he had found them of even greater value in interpreting growth rates. (CF scores were not included in his 1963 analyses.)

As for CPs, the 5-point scoring system for CF was introduced by Dawkins and has been widely used. The definitions of CF given here should be interpreted and applied in accordance with the characteristics of each species and the stage of development of each tree (cf. Figure 2). A CF of zero is a useful way of confirming that a tree is found dead.

Perfect

The best size and development generally seen, wide, circular in plan, symmetrical

Good

Very nearly ideal, silviculturally satisfactory, but with some slight defect of symmetry or some dead branch tips

Tolerable

Just silviculturally satisfactory, distinctly asymmetrical or thin, but apparently capable of improvement if given more room

Poor

Distinctly unsatisfactory, with extensive die-back, strong asymmetry and few branches, but probably capable of surviving

Very poor

Definitely degenerating or suppressed, or badly damaged, and probably incapable of increasing its growth rate or responding to liberation

(Dead

0)
Figure 2. Crown Form Scores

(Reproduced from Silvicultural Research Plan, 1959-63, Forest Dept., Uganda.)
11.7 Impeders

If a tree is affected by overhead competition, the nature of the impeding plant may be important in determining its effect on the tree's increment - for example, dense multilayered canopies, pioneer monolayered canopies, nitrogen-fixing leguminosae and climbers may all have different impacts on the trees they are shading. However, the nature of the impeder is probably not as important as the amount of cover, as indicated by the CP score, and much data would be needed for assessing the correlation between increments and the nature of the impeders; it is not expected to be an important factor for inclusion in growth models for forecasting increments.

However, the nature of the impeders is a most important factor for assessing the silvicultural status of any particular category of tree species or sizes, such as the most valued timber species, and for assessing the need for silvicultural treatment. The PSP stand table can show the stocking of any particular category, and the degree to which they are exposed or suppressed, but extra information is needed to show whether suppression is caused by climbers, by large unwanted trees or by valued trees.

If silvicultural treatments are considered, the nature and intensity of treatment can best be assessed by some form of Linear or Diagnostic Sampling at an appropriate intensity, particularly if the smallest sizes of trees are to be assessed. However, PSPs provide a more permanent way of monitoring changes in the silvicultural status of any particular category.

The amount of information recorded about impeders will depend on the management options and requirements. For a simple assessment it may be enough to characterise the impeder which is casting most of the shade on the subject tree as

- a desirable timber tree
- or, if defective or damaged
- an undesirable or unwanted species of tree
- a shrub
- a woody climber or liane
- a herbaceous climber or other plant

Alternatively or additionally (as in (20) and (46)), the species name of the main impeder or of all impeders may be recorded; this has the advantage that a suitable computer program could be written to characterise the status of any chosen category of trees in terms of the species, sizes and statuses of their impeders. The less informative system of code letters has the advantage that a visual inspection of the
data and a hand calculation can characterise the selected trees in terms of the silvicultural treatments required to release them from impeders e.g. climber cutting, shrub cutting, thinning or selective removals.

11.8 Cause of death

During the initial measurement, it may in some cases be important to measure all standing dead trees. In any case during remeasurements it is always necessary to inspect every numbered tree which was measured on the previous occasion and the opportunity should be taken of recording the apparent cause of death.

This information has many potential values, particularly in the growth models and stand forecasts, since different causes of death may be correlated with different competitive situations. It has already proved valuable in sorting out discrepancies in some sets of data.

The causes of death can be recorded in a column for comments on the field-sheet, or else codified by numbers so that they can easily be processed by computer programs and used for growth models.

Local codes may be developed to suit local circumstances, and they should be clearly described, perhaps on a point system. The following is an example of a code for causes of mortality:-

<table>
<thead>
<tr>
<th>Cause of Death</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logged or felled for timber</td>
<td>1 T</td>
</tr>
<tr>
<td>Felled for use as a non timber product</td>
<td>2 F</td>
</tr>
<tr>
<td>Killed by falling tree or branch</td>
<td>3 K</td>
</tr>
<tr>
<td>Killed by silvicultural operation, e.g. poisoning, thinning</td>
<td>4 P</td>
</tr>
<tr>
<td>Killed during road building or log extraction</td>
<td>5 E</td>
</tr>
<tr>
<td>Broken by climbers or lianes</td>
<td>6 C</td>
</tr>
<tr>
<td>Killed by physical agent such as windblow, lightning, landslide</td>
<td>7 L</td>
</tr>
<tr>
<td>Killed by visible mammal damage</td>
<td>8 M</td>
</tr>
<tr>
<td>Killed by insect and/or fungal disease</td>
<td>9 D</td>
</tr>
<tr>
<td>Apparently killed by shade or competition</td>
<td>10 S</td>
</tr>
<tr>
<td>Killed by waterlogging</td>
<td>11 W</td>
</tr>
<tr>
<td>Dead or disappeared from unknown cause</td>
<td>12 U</td>
</tr>
</tbody>
</table>

11.9 Borderline trees

Borderline trees are those which are growing on the boundary of a plot, subplot or quadrat. The decision about whether or not to include borderline trees within the PSP, as each case arises, has an important effect on the calculated plot totals for numbers, basal area and volume and hence on the accuracy of the results as samples of the whole stand. The decision about which subplot a tree is standing in, when it stands on an internal boundary, is less important, unless the total quadrat basal area is used as a measure of the local competition for stand models and growth projections. Tree growing space and simulated angle-gauge (ruler) counts for models and forecasts can be calculated from tree co-ordinates, so the allocation of individual trees to internal quadrats is important only for the organization of field records, but the inclusion of trees on the main plot border is still a critical factor.

When a tree grows on a boundary, the decision should be based on the position of the tree centre at breast height, 1.3 m. Clearly, the trees
with their centres outside the boundary will be exerting an influence on trees inside the plot, and vice versa, but it is assumed that these influences balance out in the PSP system as a whole; trees which are judged to be outside the boundary will not normally be measured in a PSP program, although they might be if a special effort is being made to characterise the full competitive status of all the trees in the plot by measuring the trees in a surrounding area as well.

When trees have irregular cross sections or large buttresses, it may be difficult to decide on the central point of the stem. This problem can best be met by examining the crown distribution. An alternative is to include such doubtful trees, or indeed all trees which touch the boundary, along alternate boundary lines (e.g., N & S, or E & W) or in alternate plots; this produces less accurate plot-by-plot results, but would probably balance out without bias in the results from several plots.

11.10 Comments

Including any notes about the absence or death of missing trees, causes of damage, unauthorised interference in the plot, flowering or fruiting, etc.

12. Optional extra measurements

12.1 General

Many other tree-by-tree measurements may also be made in PSPs. In most cases the main aims of the PSP program may be achieved without them, but the program provides a unique opportunity for foresters and researchers to gather recurrent information from individually identified trees and their surroundings. The following extra items, and others, should be considered if an improvement is required in the growth models, by characterising competitive status and potential more precisely, or in the forecasts of saleable timber yields by relating total production to stem-timber yields.

12.2 Stem damage

A scale from 1 to 5 may be devised to suit local conditions as an indicator of possible effects on the chances of the tree's survival, on its growth rate or competitive effect and on its potential yield of usable timber. Where appropriate the score may be based on local log grading rules.

12.3 Stem form

Stem form, as an index of the quality and quantity of the saw-logs which may be obtained from a tree, is of great importance during logging and utilisation. It is therefore a factor which receives attention during timber inventories. However, it has rarely been included as a factor to be recorded in permanent plot studies, and even more rarely in analyses of data and studies of growth rate.

Stem form may not be closely correlated with increments (except at the extremes of bad form). However, current stem form is certainly
correlated with future timber yields in various categories and may be affeected by various silvicultural practices. It may be necessary to measure and monitor stem form, although probably not at every measurement, in studies which are concerned with forecasting timber yield in end-use or quality classes.

Stem form or quality scores may be developed locally, perhaps based on the local log grading rules. The following note and form-classes are from Shield (61):-

Quantitative stem 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 have been adopted in inventory practice in Papua-New Guinea and in the Jengka project (Malaya):

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>- a &quot;gun barrel&quot; log; straight in length and circular in section; no apparent defect; suitable for rotary peeling over the entire log length.</td>
</tr>
<tr>
<td>2</td>
<td>- a log suitable for rotary peeling over extracted lengths; entirely circular in section; otherwise class 1 but for straightness; no apparent defect;</td>
</tr>
<tr>
<td>3</td>
<td>- a good saw-log; reasonably straight and of reasonable section; no apparent defect;</td>
</tr>
<tr>
<td>4</td>
<td>- a marginal saw-log on the basis of straightness and section; no apparent defect;</td>
</tr>
<tr>
<td>5</td>
<td>- not apparently suited to sawing; possibly useful for reconstituted wood; no apparent defect;</td>
</tr>
<tr>
<td>6</td>
<td>- useless; defect apparent; recorded for eco-botanical purposes only.</td>
</tr>
</tbody>
</table>

12.4 Climber infestation

Infestation by climbers and lianes has a serious effect on current increment, tree form, survival and future timber yield. This is certainly a factor which should be monitored if the data are to be used for detailed growth and yield models.

A scoring system may be devised locally according to the characteristics of the forest and the types of climbers. The following classification has been used in Nigeria (62):

1 : Tree free from climbers
2 : Climbers on main stem only, crown free
3 : Climbers in crown, but terminal growth unaffected
4 : Whole crown smothered by climbers, and terminal growth lost.
12.5 Merchantable height

This is the height to the merchantable top above which a sawlog (defined in any way applicable to local conditions) cannot be produced. The merchantable top may be just below the first big branch, or at a fixed stem size such as 25 cm d, or just below some irregularities, crook, swelling, hole, etc. It must be carefully defined for each PSP program, and it may be measured in the same way, and at the same time, as the tree height and the height to crown base. The measurement of merchantable logs within the crown will usually be outside the scope of a PSP program, although it may be needed for inventories.

These values may be used for monitoring the progress of merchantable volumes, and predicting future merchantable yields. Clearly, the assessment of merchantable volume production is one of the main uses of PSP data. However, the criteria of merchantability change over time, and it is believed that the best results will be obtained by measuring more fundamental variables such as d, H, CB, damage etc. and then applying volume tables developed for particular purposes, rather than by applying a fixed concept such as merchantable size or height which may become outdated.

12.6 Upper stem diameter

The diameter at the crown base or at the merchantable height may serve the same purposes, related to merchantable stocking and future yields, as the measurements of merchantable heights and crown base. It is not necessary to measure them with the same precision as the breast height diameters, since the main aim is to monitor and predict plot yields rather than tree-by-tree growth.

The upper stem diameters may also be used for monitoring changes in form factors. Log volume tables and regression relations based on dbh used for monitoring standing volumes, for calculating sales and royalties and for volume increments (with program UPDATE) will not be accurate if the average form factors change after logging or treatment. Upper stem diameters, and hence form factors, may be monitored either as a regular operation on a small proportion of the residual stems and ingrowth in PSPs, or, perhaps more conveniently, as an intermittent separate operation once in several years on a higher proportion of the stems.

Upper stem diameters may be measured with a variety of diameter and basal area sticks and optical instruments such as Wheeler's pentaprism optical calliper, wedge prisms, the Zeiss teletop, the Spiegel teleselascpe and the Barr and Stroud dendrometer.

12.7 Stump heights and diameters

These data would also help in monitoring merchantable stocking and predicting yields, by means of the relation between d at stump height and d at breast height.

A regression may be calculated showing differences according to species, site, sizes and stump heights. The regression may be linear for the largest trees but non-linear for all sizes combined (32, p. 106).
12.8 Bark thickness

This measurement is important for biomass and timber volume studies. It can be used for processing the stand tables and predictions in terms of volumes under bark, thus further improving their use for monitoring the stand and predicting the merchantable yield. Bark thickness is not suitable for recurrent measurements in PSPs, partly because of the disturbance and possible damage caused, but a simultaneous assessment of bark thickness by species and sizes in the same forest will increase the value of the PSP program.

12.9 Tree volumes

PSP data are generally used for calculations of average diameter (or girth) increments per species, size class etc. and for basal area increments; production estimates and stand forecasts have been based on these calculations. However, in the end, volume production estimates are of greater importance. It is virtually impossible to monitor volume increments per tree with the same precision as diameter and b.a. increments, since accurate measurements of log lengths, tree heights and upper stem diameters in rainforest are difficult. It is not feasible, in a normal PSP program, to gather the data for calculating all individual tree volumes using e.g. Newton's formula

\[ v = (g_{\text{large}} + 4g_{\text{mid}} + g_{\text{small}}) \times \frac{L}{6} \]

or Hohenadl's method, dividing the stem into equal lengths

\[ v = 0.2L \left( \frac{\pi}{4} \left( d_0^2 \cdot 0.9 + d_0^2 \cdot 0.7 + d_0^2 \cdot 0.5 + d_0^2 \cdot 0.3 + d_0^2 \cdot 0.1 \right) \right) \]

where

- \( v \) = stem volume
- \( g \) = b.a. at large end, mid point or small end
- \( L \) = stem length
- \( d \) = stem diameter at appropriate proportional distance along stem.

Such precision is unnecessary for many purposes, including for example calculations of single tree volumes and plot volumes by categories of species and size for comparison between plots or treatments or for forecasts. For these purposes, individual tree volumes can be calculated from tariff or volume tables (using dbh and preferably also a measure of height or log length), or alternatively the total wood volume per tree (including branchwood) may be calculated from Dawkins' equation:

\[ v = gh^2 \]

where

- \( v \) = total above-ground wood volume, including branchwood down to c. 3 cm d
- \( g \) = basal area of main stem at breast height
- \( h \) = tree height

The basic data-processing program UPDATE can calculate tree volumes and volume increments in numerous categories by means of Dawkins' equation (18), and can be adapted to apply any regression equation equivalent to a local log volume table if appropriate data are available.
If better estimates of plot- and tree-volumes and increments are required, it is recommended that the following variables should be measured on standing trees as a regular PSP operation, and that volume equations should be calculated from these variables on felled trees:

- dbh
- d at a fixed height of e.g. 7-18 m or at just below the crown base CB
- h to the tip of tree or to CB

12.10 Crown diameter, CD

In order to define the index of crown size or growing space, the crown diameter may be measured from four radii or two diameters. With experience, the average diameter may be estimated quite quickly to the nearest metre if the 20 m and 10 m tapes have been laid out as recommended (Appendix 1.6).

Dawkins (18) pointed out the shortage of published methods of measuring crown diameter suitable for TRF. It is almost impossible to make quick and reliable measurements with instruments based on mirrors and prisms for vertical sighting because of the difficulty of distinguishing interlocking foliage and of obtaining a vertical line of sight to a crown margin. Dawkins used a simple "plumb stick", a straight stick of 1.5 m. His method is summarised here. Note that this is one of the most tedious of all items to be measured and is not recommended for normal PSP programs.

The assessor first examines the crown and forms a mental picture of a smoothed, average margin, excluding any excessive projections such as single branchlets. Four radii are selected at right angles along the NS and EW axes, or along the longest and shortest diameters, or arbitrarily. One man then holds the zero end of a tape measure beside the tree (adjusting the tape, if necessary, for the stem radius) or, in the case of leaning trees, vertically below the centre of the crown; another man holds the tape out horizontally along one radius to a point beyond the crown projection.

Figure 3. Plan view showing method for measuring crown radius, showing crown outline; smoothed, average outline; tape measure in position; position of assessor with plumb-stick.
The assessor then stands where he can see the outline of the smoothed crown margin, making sure that his line of sight is at right angles to the tape. By suspending a plumb-stick or plumb-line from the fingers at arm's length in the line of the vertical projection from the smoothed margin to the tape, the radius can be defined on the tape to the nearest m or 0.1 m. Great care is needed to keep the line of sight at right angles to the tape, to keep the plumb stick vertical and in line with the previously assessed smoothed crown margin (see Figure 3). This process is repeated for each radius, and the average diameter is derived from the four values. Dawkins found that he probably underestimated crown diameters by an average of c. 12% by this method; the accuracy of the results of different assessors will often be much less than this in a regular program, depending on the visibility of the crown margins and the care taken. It is enough to apply the method consistently, to achieve a value that bears a constant relationship to the true average crown diameter of all trees, avoiding excessive variability.

Greater accuracy may be achieved by a combination of aerial photographs and ground survey. Chaturvedi (13) increased the amount of calculation by measuring two diameters at right angles, treating a non-symmetrical crown as an ellipse and calculating the diameter of the circle of the same area as the ellipse.

A method involving still more fieldwork and calculations was used by Rushing (44) at El Verde. When trees were not approximately circular in horizontal projection, "several points on the periphery of the horizontal projection of the crown were located with a hand level modified for use as an optical plumb-bob ...... and plotted on the plane-table. The area of the irregular polygon thus formed is assumed to be the area of a circle and the diameter of this normalised circle is recorded."

These methods are for measuring the radii and diameters at any one time, as a measure of competitive status. They are not sufficiently precise for accurate measures of crown-size increments, a factor which is not included in regular PSP measurements.

12.11 Monitoring timber quality and technical defect:

Technical defects and decay affect an important and highly variable proportion of the standing volume; the usable round timber extracted from a stand may frequently be reduced to as little as 20% of the total standing volume in the appropriate sizes and species. Therefore a CFI which monitors only the total stocking will be of limited use for yield planning and management. In order to monitor and predict the production of usable timber, it is necessary to incorporate some information on reductions or losses from various forms of defect.

We have no experience of repeated assessments of a range of defect factors in PSPs in TRF, so it is not possible to make firm recommendations. Under different conditions of timber quality and markets and management requirements some or all of the following factors may be assessed either as a score (e.g. 1-5) or as an estimated percentage of the total stemwood which is rendered unusable by the defect, and often it will be necessary to record the height at which the defect occurs:
(a) sweep and crook
(b) fork
(c) lean
(d) scars from lightning, fire, falling trees, logging damage
(e) spiral grain
(f) dead branches and knots over various stem lengths or surfaces
(g) decay, with its various symptoms.

The future development of defects is notoriously difficult to predict and may bear little relation to the current status or appearance of defect and decay; further, it is impossible to know the significance of various types and intensities of defect for possible future utilisation. For short-term planning, a single inventory will provide the data on total and utilisable volumes without the need for the dynamic features of CFI. The long-term planning, it may be more appropriate to carry out occasional defect surveys in the PSPs plus extra survey lines or TSPs, in order to "correct" the results of PSPs.

Certain defects, such as severe decay and crown or stem damage probably affect survival and growth, and can be fitted into predictive models, and a simple scoring system for these features is therefore recommended; however, other technical defects like forks, dead knots and spiral grain may have no effect on survival and growth (within the sensitivity of PSP analyses) although they may have a great effect on the yield of certain products (although irrelevant for other products such as chipboard or pulp). It is not recommended that such technical defects should be measured in standard PSPs in most areas. While the PSP data may be used for estimating total stemwood stocking and production, the net production suitable for different end uses may be estimated separately later, perhaps by applying cull factors (32, p. 205).

13. Checking and remeasurement

13.1 Checking the first measurements

It is recommended that a partial or complete remeasurement of some of the plots should be carried out shortly after initial establishment, as a check on the accuracy of the surveying and linear measurements, as well as the tree data. The check will be more revealing if carried out by a different team of assessors without taking the first measurements into the forest.

In the office, the two sets of measurements should be compared, to assess the frequency and sizes of discrepancies. It will then be necessary to decide whether the errors can be tolerated or whether there are so many that a complete check and remeasurement is required.

13.2 Remeasurements

A complete remeasurement should be carried out at intervals of (1-2)(-3) years, depending on the reliability of the first measurements and the urgency with which production forecasts are required. After 3-5 remeasurements, the intervals may be extended to c. 5 years.

It is recommended that the remeasurement team should have a copy of the previous year's measurements or of the Updated List (sections 15, 23)
either in their base camp or in the plot each day. This will allow any discrepancies in size or identification to be checked, either on the spot or after comparing the old and new measurements in camp at the end of the day's work. It is believed that this procedure will greatly improve the reliability of the data; many discrepancies are revealed during data-processing by computer, but it is then too late to check the measurements or even to determine which of two measurements was in error. The availability of the earlier measurements may allow more opportunity for the subsequent measurements to be "fiddled", but in the hands of a conscientious team it also allows more accurate, and therefore more useful, data to be collected. Recommendations for some of the standard procedures to be carried out at each remeasurement are included in Appendix 1.

13.3 Checking instruments

   All instruments, especially compasses, tape measures and survey chains, should be checked and calibrated by surveyors at the start of a PSP program and at regular intervals (at least annually). The use of uncalibrated compasses can produce serious but unknown errors in spite of careful tree-by-tree measurements. Regular care and maintenance of all instruments is needed to ensure accurate results.

13.4 Dates of remeasurement

   The calendar dates of all measurements should be recorded on the same form as the data, and then converted to decimal dates for calculation of intervals by computer. Successive measurements should preferably be carried out at the same time of year, otherwise size-differences due to growth will not be distinguishable from those due to changes in temperature and moisture content or annual growth rhythms.

   Rates of tree growth vary greatly during the year in relation to wet and dry seasons, and discrepancies may arise if measurements are made at irregular intervals. It is usual for increments over periods of less than a year to be multiplied up to give a mean annual increment, which may be misleading if the measured period was wetter or drier than an average whole year. Preferably, all plot measurements related to growth should be taken during a dormant period, such as a regular dry season, and measurements related to numbers of seedlings and saplings should be taken at standard times in relation to periods of seedfall, drought and wet seasons.

   Decimal dates are shown in Appendix 7.

14. Recording data

   A field record form for the tree-by-tree assessments must be easy and unambiguous for use in the forest and suitable for photocopying and for interpretation by computing staff for card punching.

   In some departments, the data from the field records are first typed or copied by hand onto another set of standard forms which are then sent for data-processing. This system uses extra staff-time and money and paper, and it inevitably results in some copying errors, in spite of extra time and trouble spent in visual checking.
Some countries (Ghana, Nigeria, Uganda, etc.) have used ordinary duplicated paper forms of foolscap or A4 size for field records. Other countries such as Sarawak use Rite-in-the-Rain weatherproof cards c. 11 x 17 cm, which are easier to handle in the forest and better suited to wet and humid conditions but they are expensive and must be imported. The Hamburg-Reinbek team at San Carlos, Venezuela, also used small pages for recording their tree-by-tree data derived from 10 x 10 m quadrats within a much larger experimental area.

It is strongly recommended that regular plot measurements should be carried out on locally prepared field sheets of standard A4 duplicating paper, using a pencil for recording (all held inside a large plastic bag during wet weather). These forms can be printed with an 80 column layout, suitable for punching on to standard computer cards without transcription. Extra copies of the data should be obtained by photocopying with copies retained at more than one place.

Appendix 3 shows an example of a field record form which may be adapted according to the measurements being carried out, for tree-by-tree data in PSPs and Research Experiments, and for machine copying for data processing.

The TRF PSP Description Form (Appendix 2) may be used for remeasurements (omitting some of the unchanged information) for recording changes in the vegetation and information about logging or silvicultural treatments since previous assessment.

Data processing

This section refers to all the operations involved in converting the raw tree-measurement data into results which can be used for forest management and industrial planning. It is possible to extract some basic information by hand, such as composition by species and size classes; it is also possible to calculate times-of-passage between size-classes, and to make the corresponding stand-forecasts, with a calculating machine. However, it is not realistic to attempt even these basic calculations by hand for more than a few plots, and certainly not as a regular operation for a PSP program. In order to handle the large quantities of data obtained from a routine PSP program, and to extract all the required information from the data, it is essential to use a computer.

Arrangements for processing all data should be made at an early stage of starting a PSP program; this includes negotiations to obtain a departmental computer or the use of another computer inside or outside the country, the adaptation of suitable computer programs to fit the data which will be collected and the capabilities of the computer, and arrangements for card-punching of raw data including discussions with the card-punchers to ensure that the format of the field-data is suitable for punching and for immediate input to the computer.

Many computer programs have been written for particular analyses of individual research plots or experiments in TRF, but there are few which are intended for handling PSP data on a regular basis and for extracting all the more important information required for management. UPDATE is the basic program, used at Oxford for more than 15 years, and
now in several other places, for combining all successive tree measurements into a single data-file for each plot, and for carrying out a wide variety of basic calculations; a suitable version of this program is recommended for all organizations working with repeatedly measured PSP or research plots in mixed forest with individually numbered trees. BASALAREAS is particularly useful for plots divided into quadrats or subplots, for calculating basal areas in various categories, for each separate measurement. GROPE is the stand-forecasting program still being developed.

UPDATE: This program was first developed in order to collate all the tree-by-tree measurements for successive years into an up-to-date list showing the tree number, species, and every measurement of size and status obtained for each tree. This list, the Updated List, is used as the basis for numerous calculations. For each date of measurement, stand-tables can be printed showing the numbers and basal areas (and the volumes if tree heights or volume tables are available) for each species or for any selected groups of species and each diameter (or girth) class. For each measurement interval (e.g. 1965-1970, 1970-1975), increment tables can be printed showing the ingrowth (recruitment), the mortality (losses), the numbers of stems, the average diameter (or girth) increment per tree, the average basal area increment per tree or per unit area (and if possible the average volume increment per tree or per unit area) for each species or group and each diameter (or girth) class, and for all species and/or size classes combined, in any chosen units of measurement.

As a check on the accuracy of field measurements, any discrepancies in species-identification on successive occasions are listed. An arbitrary limit for "unlikely" rates of growth or shrinkage may be set, and any trees exceeding these limits are listed for checking.

This program exists in many versions, in FORTRAN and ALGOL, including compact and slightly less versatile forms for small computers. Listings of the program in an appropriate language and size may be obtained from the Unit of Tropical Silviculture, C.F.I., Oxford.

BASALAREAS: this program operates on the plot data for one year at a time, and calculates the total standing basal areas per quadrat and per unit area in several categories which are defined by the species number-code. If the number-codes refer to single species, the program may be adapted to calculate basal areas in species groups (corresponding perhaps to end-uses, quality classes or ecological types); if the number codes refer to other categories, as in certain silviculture research plots (such as Poisoned, Desirable, Undesirable, Felled, etc.), the program will calculate basal areas in various combinations of these categories.

This program is useful for PSP analyses in which the quadrat basal areas may be used as a measure of the competition, or productive potential or useful growing stock per quadrat, for correlation with past and present increments and for input into growth and yield models. For silviculture research plots, these results are valuable as measures of the impacts of treatments (e.g. the b.a. poisoned, or the change in total b.a. before and after treatment) or of the responses to treatments (e.g. the relative changes in b.a. of unpoisoned desirables), which may then be studied further, by regression analyses, etc.
GROPE: This program produces forecasts of future stand tables, plot by plot and/or species by species. It is available as a research tool, and is still being developed, but it is not yet suitable for use at a management level (2)(cf. Occasional Paper No. 10). When fully developed, this program will make it possible to produce a reliable prediction of the composition of each PSP for any chosen future date; these results can be analysed like other inventory data to give an estimate of the stocking and composition of the forest as a whole.

16. Interpretation and use of PSP results

It has already been stressed that it is a waste of resources to establish PSPs unless the data are collected and analysed in appropriate detail. It is also to a large extent a waste unless the results are used for management planning, to guide the frequency and intensity of logging operations and silvicultural intervention and to plan the size and location of sawmills and other wood-using industries.

In many parts of the tropics, the current exploitation of rainforests is influenced by many economic and political factors without detailed consideration of future yields (or alternative sources of supply) in terms of quantity and quality. One of the reasons for this is the unreliability and lack of precision of existing forecasts of future yields from TRF areas, and the difficulties of obtaining precise estimates, particularly in contrast to the precision which is often confidently attached to yield-forecasts for new plantations. This manual, and all PSP programs, are designed to produce more reliable estimates of yields; the use of these estimates for planning rates and methods of logging should be one of the major duties of forest managers, but it cannot be treated in detail here.

TREATMENT EXPERIMENTS

17. Objectives of treatment experiments

This part of the manual deals with long-term or permanent plots established for studies of TRF silvicultural treatments. These include tests or demonstrations of treatments involving different intensities of logging, thinning, poisoning or refining by various methods and perhaps involving some enrichment or line planting.

Treatments which involve intensive line planting, in which interest is centred on the performance of the planted trees, can best be monitored and compared by methods based on plantation research (11). Experiments established to compare the production and performance in variously treated rainforest with that in other stands and crops established to replace the rainforest are not usually the concern of Forestry Departments; they involve different considerations of plot sizes and surrounds and much more detailed measurements of environmental factors including soils and hydrology, and they are not considered here. This subject comes within the scope of the UNESCO Man and Biosphere (MAB) Program, and many of the same techniques apply (9).

Experiments are often required for examining the non-timber production and processes in rainforest such as the seedling regeneration,
phenology, etc., which are of considerable interest to forest management. These experiments are also beyond the scope of this manual, and it is appropriate that research workers should devise their own procedures for such experiments, in the light of the recommended basic techniques and procedures described here and elsewhere (26, 37).

In the experiments considered here, the objectives will usually be to determine and compare the effects of various treatments on the growth rates of the trees, and the wood-production of the stand and the composition of the regeneration and of the future stand. All these factors can be assessed simultaneously in one experiment, often from the same data, and all may be required for evaluating the effects of the treatments on the future usable yields from the forest which is in the end the most important criterion. Current production and future yields are determined both by increments and by stocking, two factors which may be affected independently by treatments and which must therefore be evaluated.

The precise objectives of the research should be clearly stated. These objectives should include both

(a) a clear description of the information which is to be obtained from the experiment itself, in terms of the treatments to be applied, and the parameters of growth and production to be assessed and compared, and

(b) the objective of carrying out the experiment in terms of national priorities and management requirements.

Many of the inadequacies of earlier or existing treatment experiments stem from the acceptance of extremely limited, even simplistic, objectives, and of an equally limited assessment for evaluating and distinguishing between treatment effects. Regarding the treatments, it is necessary to consider and then to describe them in terms of their impacts/influences/changes/intensities on the pre-existing stand and, separately, in terms of the treatment-instructions for field application. For this purpose, some modest knowledge of at least the variability, structure and composition of the forest is required, and preferably of the range of responses and environmental consequences of various degrees of disturbance. Most important, the treatments should be consciously decided and selected according to the required physical impacts and not simply from a range of easily defined treatment-instructions. Sometimes, this may result in rather complex treatments, specifically designed to achieve particular impacts in the experimental area.

Regarding the assessments, the decision should first be taken about what aspects of the stand development are of prime interest, and the time scale of the experiment and of the local management aims. Interest may be focused on either tree increments or stand production, either from all trees or from selected sizes or species, or on all these aspects. It is necessary to define the requirements for assessments and comparisons in terms of measures of growth and production (e.g. b.a. in m² per ha; silver-volume in m³ from tariff tables) and, separately, in terms of the detailed field measurement and tree-by-tree data to be collected (e.g. dbh; h to crown base, etc.).
18. Location of experiment

Normally, silviculture experiments are designed to test and compare treatments which may be applied over large, variable rainforest areas and therefore must be tested on plots of reasonable size appropriate for realistic comparisons. In order to minimise site variation, the total area occupied by the different treatments and replications should be no larger than necessary and should normally occupy one defined experimental area. This means that the variability of the larger forest area cannot be compensated for by distributing a single experiment over a large forest area; if this is attempted there is great difficulty in distinguishing effects of treatments from the effects of site variation. In order to ensure that the results are applicable to the rest of the forest, and are representative of the effects which would be obtained by applying similar treatments elsewhere, the experimental areas should be chosen carefully to represent individual forest types or management areas. This decision may be made quite subjectively. Obviously, no one site can be absolutely typical of a large forest area, but if the site is reasonably representative then the carefully measured results of treatments may be quite typical of the results which would be achieved over the wider area of the forest.

The decision should also be influenced by the need to ensure that the experimental area is easily accessible and is safe from interference by any unauthorised logging or other disturbance.

It is probable that in future increasing use will be made of single-tree plots, for competition studies and treatment experiments. In this case, the location of the trees studied will be influenced by the need to obtain data from a wide variety of crop densities and tree sizes and the plots may be widely scattered. The methodology for such models is still in the early stages of development for TRF, although more advanced for plantation monocultures.

19. Design, layout, replications

Recommendations here are based on the principle that experiments are laid out in plots, that assessments will be carried out as tree-by-tree measurements and that analyses will be based mainly on averages and totals per plot, for various categories of species and sizes. The data will be equally suitable for constructing stand models, particularly if several of the recommended variables are measured for all quadrats and large trees. It is important that the treatments applied and the whole experimental procedure should be easily comprehensible and demonstrable and should be obviously relevant to practical management options, so plot based experiments are recommended, incorporating sufficient measurements for the tree- and stand-models which may ultimately prove to be more revealing and more valuable.

Randomised block designs are recommended, particularly when the vegetation or soil types are known well enough to allow appropriate siting of the blocks, further reducing the within-block variation. This is particularly suitable when treatments are qualitatively different in their impacts as well as being quantitatively different in their intensities, as when selective treatments are applied to different species as well as to different sizes in each plot. Randomised replicated
designs allow the differences between treatments to be examined by analyses of variance. If various logging intensities are applied independently of treatments, the interaction between logging and treatment intensity can also be examined. Data for the state of the stand before logging or treatment can be used as covariates in analyses of growth rates and stocking after treatment; more than one covariate may be used, but this technique is usually easier to interpret if applied as a regression analysis.

The advantage of this design and the analysis of variance is that the treatments applied and the concept of statistically significant differences may be made obviously relevant to the forest manager. The disadvantage is that only large and obvious differences in response are likely to be "significant" while often real and perhaps important differences appear non-significant. Usually, analyses of variance and covariance have been unsatisfactory techniques for interpreting the effects of logging and treatment intensities. It may be more important to demonstrate correlations between treatments and responses; these may be indicated by testing for linear, quadratic or cubic components after an analysis of variance has indicated a significant difference due to treatments, and they may be more effectively demonstrated by regression analyses. The interpretation may involve examining a simple regression relationship (as was usually done during the research project (Occas. Paper 10), or multiple regressions, or comparing several separate regressions which may be linear, curved, or S or inverted-U shaped according to the factors examined. Methods for comparing and testing differences between regressions are found in many statistics text books.

Systematic clinal designs have not often been used in TRF but may be appropriate for examining a series of steadily increasing intensities of treatments. The advantage of this arrangement is that surrounds of treated, unmeasured forest would not be required around each measured plot, enormously reducing the total area required for the experiment, because each plot would have two neighbouring plots treated a little more and a little less intensively. Clinal designs are mostly used in uniform plantations with carefully controlled treatments and are less appropriate for diverse TRF in which the treatment intensities may not turn out as anticipated. There is also a risk of the clinal arrangement of treatments co-occurring with any clinal variation in the site or in logging intensity or damage, although this can be partly compensated for by arranging extra blocks aligned in different directions. In randomised designs, the site variation is accounted for by replication and by randomisation; in a systematic design, with no randomisation, extra replication may be needed but this may be easier to accommodate with a clinal design using less land.

An unreplicated design may be suitable for demonstration plots involving obvious differences, and also for experiments which will be analysed on the basis of individual trees and quadrats, and it may have advantages in minimising the forest area involved. At least two replicates are normally recommended so that an analysis of variance is possible, but regression analyses will usually be much more revealing in showing the relationship between treatment intensities and growth response; the value of a regression analysis will depend on the number of independent measurements (i.e. plot-averages, tree data or "points on the graph") and their range (from lightest to heaviest treatment, from minimum to maximum response), even if no treatments are replicated.
Finally, tree and stand models can be constructed from any tree-by-tree or plot-by-plot data and can be used for detecting and testing responses to treatments. The effect produced on individual trees by liberation by a silvicultural treatment is often little different from the effect produced by an appropriate logging system (except for the important factors of damage and environmental disturbance), in which case a model could be constructed by measuring trees in appropriate competitive situations without having to resort to elaborate and expensive trials. The techniques and programs needed for this approach are not yet sufficiently tested for it to be recommended as the principal method for examining treatment effects, but it appears so promising that plot-measurements should be collected in a way that will facilitate future modelling.

In conclusion the following priorities are recommended:

1) maximum detail in tree-by-tree and plot-by-plot measurements before and after interference so that
   (a) the initial state can be used as a covariate for analyses of variance of the final state or responses
   (b) the impact of all forms of interference and the growth rates and responses after interference can be quantified in many different ways, allowing many different variables to be examined by analyses of variance and regressions
   (c) each tree's performance and competitive status can be characterised in detail, for use in tree and stand models

2) maximum range of treatment intensities including untreated controls with the widest quantitative and qualitative differences between treatments, in preference to a larger number of intermediate treatments, to ensure that
   (a) the differences between responses to treatments are larger and more likely to be apparent in analyses of variance
   (b) the total range covered will be larger and more effective for regression analyses

   In spite of attempts to define differences between treatments, the variability of the forest (and of any uncontrolled logging) will ensure that treatment intensities approach a continuum anyway, so any lack of intermediate treatments is more apparent than real.

3) adequate replication (a minimum of two replicates) so that an analysis of variance, preferably with at least 10 degrees of freedom in the residual is possible.

   This allows
   (a) an analysis of variance, the most widely understood procedure
   (b) some insurance in case some of the plots in the experiment are accidentally destroyed
(c) some duplication at each level of treatment intensity, which helps, although it is not essential for, regression analyses

4) treatments which are potentially feasible and applicable; this may not be essential for the value of the results and conclusions, since appropriate and simple management schedules can be based on the responses to elaborately precise and unrealistically careful treatments, but it is essential in many cases to make the research program obviously relevant to management requirements as well as being statistically and scientifically satisfactory.

5) if various logging intensities are to be tested, with various silvicultural treatments superimposed on them a split-plot design is possible; two or more treatment plots, of up to the normal sizes, are located within each large logging plot. This allows

(a) the logging operation to be applied over realistically large areas, preferably much more than the measured, silviculturally treated plots,

(b) the interaction between logging effects and treatment effects to be examined, and, as in other experiments,

(c) the effects of logging and treatment to be assessed separately.

6) if local management experience makes it possible to narrow the choice of possible treatments down to only a few (e.g. three alternative grades of logging intensity), then these can be applied as field-scale trials, each covering 10-100 ha. This allows the collection of realistic data for costs and labour requirements, yields, logging and extraction damage etc., which are essential for economic appraisal and decision making. Measured samples may be distributed throughout the trial, in plots ranging from undemarcated circular plots of 10-15 m radius to square 1 ha plots. Detailed within-plot measurements, characterising the competition per tree or per ha, can compensate for the inevitable site variation within the experimental area.

20. Choice of treatments

20.1 Different types of treatment

The following forms of interference are widely carried out on a management scale in various countries, where the forest authorities are confident about their useful effects in promoting growth rates or survival. Some of these factors, and others of local importance, should be considered for silvicultural research:-

1) Logging intensities; involving limitation of logging to certain species or minimum size limits, or, if more precise control is possible, to certain basal areas or proportions of total b.a. removed or retained.

2) Refining (by poisoning, thinning or utilisation for fuel, poles, chips, pulp, etc.) involving different lists of species and sizes scheduled for removal or retention.

3) Climber cutting, either before logging to reduce logging damage and climber regeneration or during and after logging to cut large dominant
climbers or to liberate individual valuable young plants. A general climber cutting in the tangle of regeneration after logging is not recommended but selective cutting of large climbers which have penetrated the crowns of established trees is a cheap and promising treatment (practised at various times in Ghana, Malaysia, Uganda, etc.)

4) **Enrichment planting** at relatively low intensities, up to a few hundred per hectare, in groups, spots or widely spaced lines in a matrix of selectively logged and regenerating forest. If the planted trees are intended only to supplement the usable production from the developing forest, it is reasonable to compare the results with the effects of other methods of increasing TRF production, in the kinds of silvicultural experiment considered here; if the planted trees are intended to provide almost the whole future crop, then silviculture research should be carried out by methods suited to plantation research (weeding, spacing, thinning and species trials) while comparisons with TRF can be on the basis of PSPs.

5) **Tending and weeding** and other treatments which have their effect at ground level. These may include spot weeding around individual young plants or groups, and cutting undergrowth, shrubs, bamboos etc. to promote the survival and growth of newly established seedlings. Undergrowth cutting may not increase the growth rates of over-storey trees but in some circumstances, and with the right timing, it has an important effect on seedling establishment and growth (10).

20.2 **Logging intensities**

There is great variation in the amount of control which Forest Departments are able to exert on logging companies, in practice, irrespective of legal provisions, but in some cases minimum diameter limits and species can be controlled and in a few cases also the volume yield from a compartment or coupe.

Clearly the logging intensity affects the yield of timber, the profit to the logger and the revenue to the Government, but it also greatly influences the development of the logged stand and hence the future cutting cycles and yields; this is because the logging intensity influences the tree-by-tree growth rates and also the stocking and composition in the residual stand, i.e. the numbers and sizes of trees, and their increments, available to provide, or compete with, a future crop. It is therefore silviculturally essential to determine what effects different girth limits and logging intensities have on current production and future yields.

To some extent, this information can be obtained by measuring the logging intensity plot by plot after the event, without attempting to control it in advance; and then by correlating various measures of logging intensity with various measures of growth and production. This is because uncontrolled selective logging varies enormously in intensity from one hectare to another, and a wide range of intensities can be obtained from any logging area, suitable for regression analyses; however, there may be a deficiency of very lightly or very heavily logged plots.

In an experiment, it would often be very valuable to include treatments in which the logging intensity is controlled, even if this means
using extra labour to assist a commercial logging gang. The following treatments may be appropriate:-

1) Felling (and, if possible, removal) of the maximum possible intensity, involving all trees whose form is suitable for sawmilling, of the maximum number of species, down to a small size (20-30 cm d)

2) One or two moderate logging intensities, removing larger trees of the most valuable species plus at least some of the other trees which are known to be usable for timber even if not so readily saleable down to a moderate size, around 40-60 cm d. These may be equivalent to normal logging operations.

3) A light logging, removing the biggest and best trees; this would be considered a normal logging in some countries and a wasteful creaming operation in others.

4) If possible, one or more unlogged areas.

Logging treatments involve different intensities of extraction and allied operations, and so they need larger areas for realistic implementation than silvicultural treatments. Plots of at least 5-10 ha would be appropriate for each logged plot even if the area measured and monitored in detail may be much less. In order to keep the experimental area within reasonable limits, it would be best to apply each logging treatment to a larger block onto which other silvicultural treatments are superimposed (split plot design). However, larger treatment plots will be required for collection of reliable data on costs, labour and logging damage, as explained above.

Where possible, these treatments may be modified to include cutting the less valued species down to a smaller diameter than the more valued species, so as to give the more valued species an advantage both in increased growth rates after liberation and in increased regeneration resulting from a relatively larger seed supply.

In some regions, extensive silvicultural operations may not be feasible, either administratively or economically, and may not even be justifiable. In these cases, the forest service may have no means of modifying the forest other than through the provisions of the concession licence, by controlling logging intensities. Treatment experiments may then concentrate entirely on testing the effects of different logging intensities, preferably under fully realistic conditions with the co-operation of logging and extraction teams. Factors examined should includes costs, yields and damage at the time of logging, as well as subsequent production.

20.3 Refining

Many silvicultural treatments consist of removing or killing the trees which have not been extracted for timber and which are not expected to be saleable for timber at any time in the future. While markets for timber species, fuel, hardwood pulp, etc. gradually expand into new regions, the number of trees which have no present or future market is gradually decreasing. However, there will almost always be trees of certain categories of species, sizes, forms or defects which cannot be sold; in addition to these, there are other categories which can be sold
only at a low price.

In many cases, it is important to determine the responses of the residual (perhaps previously logged) stand to the removal of these categories, particularly in relation to the costs of the treatments. The treatments may be worthwhile only in terms of the increased growth rates resulting from reduced competition (an effect which could also be achieved by an appropriate utilisation intensity) but it is even more likely to be justified if the less desired species and categories are easily replaced by natural regeneration of more valued species.

Suggested treatments to be applied include girdling or poisoning of unwanted trees (of carefully defined categories), usually combined with climber-cutting, down to minimum sizes of e.g.

1) 10 cm d
2) 20 cm d
3) 30 cm d
4) No treatment

If valued trees are expected to regenerate naturally, no individuals of the most highly prized species should usually be poisoned for silvicultural purposes even when they are highly defective and not potentially usable, because of their continuing importance as a source of seed. This argument applies to silvicultural operations on a large scale, but need not necessarily apply in a research plot which is concerned with the results of treatments on production increment rather than on seedling regeneration.

A "no treatment" treatment should be included, even if it is expected that some form of treatment will in practice be applied, since it is a valuable measure of the effect of the other treatments.

20.4 Climber cutting

The effects of climber cutting on the growth rates of established residual trees, on the survival and growth of established regeneration and on the establishment of seedlings can be assessed in relatively simple experiments, although this has seldom been done. Smaller plots, and modified Diagnostic Sampling surveys may be appropriate for assessing the effects of climber cutting on seedlings, saplings and poles.

20.5 Enrichment planting

Planted trees can be measured and monitored in the same way as natural regeneration. However, the factors which affect the success or failure of planted trees in TRF introduce a new range of problems and it would normally be appropriate to test and develop methods of planting and tending independently.

20.6 Tending and weeding

These treatments are usually aimed at influencing survival and growth near ground level or in the understorey, and the plot sizes and surrounds used for logging and refining treatments are not the most appropriate for them. It is possible to superimpose these treatments in
smaller plots within the logging and refining plots; however it would probably be very difficult to detect the effect of this added source of variation. It would usually be more appropriate to establish a separate experiment with smaller plots treated with various weeding and tending regimes.

21. **Plot sizes and surrounds**

The area subjected to controlled logging or treatment in an experiment will usually be larger that the area monitored or measured in detail, partly because the logging or treatment requires a larger area for effective application than the area required for measurements, and because the measured area must be surrounded by a similarly treated area to eliminate edge-effects when neighbouring plots are treated differently.

The optimum plot size depends upon the nature and the size of the differences which are to be examined and analysed, and the required level of confidence; these cannot be known until after the plots have been measured, so any decision must be a compromise.

Dawkins (17, p. 48) has stressed the importance of having plot areas large enough to "absorb gross variations in stocking due to gaps". The total basal area of the plot, before any logging or interference, may be required not only for covariance analyses but also as an indicator of the site quality and potential; the plot must then be large enough to ensure that the basal area stocking is realistic for that locality and not distorted by being too small in relation to the distribution of large trees and gaps.

As stated in Section 3, the larger the plots the fewer are needed to achieve the same sampling error, but the total measured area will also be larger. Dawkins (17, p. 118) has discussed the plot sizes and surrounds for silviculture experiments, and the general principle that the surround should be at least as wide as the height to which treatments are effective. He suggested that assessed plots of 100 m square (1 ha) with similarly treated surrounds amounting to treated plots of 180-200 m square (3.24-4 ha) were needed for long term experiments involving the full height of the forest (i.e. if the treatment directly affects the forest canopy or if the forest is likely to react to the treatment throughout its profile, sooner or later). The treated area may, however, be much larger if the logging or treatment requires it.

Not many TRF silviculture treatment experiments have been analysed in sufficient detail to suggest conclusions about the most appropriate width of surround. However Philip (43) analysed the data from a large trial in Uganda established in 1960 with surrounds of only 20 m around each assessed plot and he concluded (p. 22) that the width was inadequate.

If the treatments directly affect and induce responses in only the understorey of the forest, the plots and the surrounds can be smaller. Dawkins suggested plots of 20 x 20 m for treatments which affect only the herb and shrub layers.

It is recommended that the fully measured plots in silvicultural treatment experiments should be 1 ha, within a plot of similarly treated forest extending in all directions not less than 40 m beyond the boundaries
of the measured plot, or more if appropriate for the method of treatment.

22. Establishment and measurement of plots

22.1 Demarcation and measurement

The recommendations for permanent demarcation, plot description, tree marking and location and tree measurements in PSPs apply equally to treatment experiments. The Instructions for Establishing PSPs (Appendix 1) also apply, except for the paragraphs on Siting on Map and Location in the forest.

22.2 Measurements before treatments

In order to calculate the intensities of logging or treatment applied in each plot, and to define the initial state of the forest, it is essential to measure the quantities (numbers, sizes) of all trees removed or killed by logging or treatments.

Ideally the treatment experiment should be fully laid out and measured before any interference is applied, with all trees above 20 cm d or perhaps 10 cm d individually marked, numbered and measured in each plot. Better still, the trees should be measured 2-3 times over 1-5 years in order to obtain a measure of pre-treatment growth rates and mortality. In this way the impacts of all interference can be measured in terms of pre- and post-logging/treatment stockings and the responses to treatment can be calculated directly by comparing growth rates (measured in various ways) before and after interference; an analysis of treatment-effects simply by a comparison of effects in different plots treated in different ways is inevitably rather less reliable. If not even the pre-logging stocking can be measured, then it will be impossible to quantify the total amount of interference caused in any plot, but the trees will nevertheless be reacting to differences in logging intensities as well as in treatment intensities.

Demarcation and one or more measurements before logging will be possible if the location and timing of logging operations is known or can be controlled. If not, the measurements of all trees standing, felled and knocked down can be carried out after logging. This will usually be adequate but is subject to inevitable inaccuracies if stump sizes instead of breast height sizes are measured on felled trees and if some smaller stumps are missed or buried under debris or totally destroyed by felling and extraction operations.

Usually, an inventory of the stump sizes of all the larger felled and killed trees after logging will be adequate for characterising the intensity of logging and the pre-logging stocking of the forest.

22.3 Application of treatments

If it is possible to gain access to the experimental area and to demarcate the plots before logging, then climber-cutting treatments may be applied first, preferably 1-3 years in advance.

Usually, silvicultural treatments such as refining are applied after logging; with increasing intensity of logging, and decreasing control by
silviculturists over logging activities, there is now little interest in pre-logging refining or canopy-opening operations. Operations carried out on a large scale are much easier and cheaper immediately after logging, when roads are open and access through the forest is relatively easy, than if delayed by several years.

In certain cases the effects on the composition and growth of the regeneration may be preferable if the first silvicultural treatments are delayed by 5-10 years. If the original design is suitable, treatments applied several years after logging may be superimposed on an experiment involving treated and untreated plots established immediately after logging. This would have the added advantage that the growth of trees could be monitored before and after the application of the delayed treatment. Alternatively the delayed treatments could be established in an area logged but not treated several years earlier, but it would then be difficult to quantify the logging intensities plot by plot.

Any refining operations should also be quantified by recording the numbers and sizes of all trees cut or poisoned, dead or recovering.

22.4 Measurements after treatments

All the recommendations for recurrent measurements, methods, timing and data-recording in PSP are applicable with appropriate modification to research plots (cf. Appendix 1). The tree-by-tree assessment of logging damage, and a description or measurement of the area affected by roads or tracks in each quadrat and plot, are relatively more important in research plots.

23. Data processing and analysis

The recommendations made for PSP (Section 15) apply to research experiments also. It is particularly important to consult a statistician or biometrician for advice about the design and analysis of the experiment before laying it out to ensure that the objectives of the experiment will be adequately covered; as with PSPs, arrangements for data collection, card punching and computer processing should be agreed during the preparation of the experiment and not left until after data have been collected.

The standard data-processing computer programs used for PSPs (Section 15) are also appropriate for experiments:

UPDATE: many of the calculated variables, such as the stockings and basal areas of various sizes and species and their increments in different plots may be used as measures of the impact of, and response to, treatments.

BASALAREAS: this program is particularly effective for characterising the impact of treatments; in a single run with appropriate data it can print the total b.a. before interference, after logging, and after treatment, with the residual b.a. sorted into quality classes. The response to treatment may be characterised by comparing the standing b.a. in each quality class on successive dates in each treatment. This program prints the results for each quadrat in turn, so that the impacts and responses may be correlated quadrat-by-quadrat for all plots.
GROPE: It is hoped that, eventually, the development of program GROPE will lead to much more sensitive and comprehensive comparisons of treatment effects (Occasional Paper No. 10, section 1.82).

These programs can provide the basic calculations for each treatment plot to allow analyses and comparisons of differences between the treatment impacts and responses; at this point data-analysis takes over from data processing. Most computers are equipped with standard packages of programs for routine analyses, and it will often be easiest to adapt one of these for the particular requirements of TRF data. Two programs have been written at Oxford specifically for the requirements of data from permanent plots in forests:

ANOVAR and various derivatives: for analyses of variance and covariance of any measures of plot stocking and average increments, and calculation of linear, quadratic and cubic components.

CSPSP: for linear regression analyses and for printing scatter diagrams and regression lines (extremely helpful for interpreting correlations).

24. Interpretation of treatment experiments

The project report (Occas. Pap. 10) deals with the interpretation of treatment effects at some length. In this section, two points are to be stressed: the use of existing experiments for deciding on future cutting or treatment regimes, and the choice of experimental treatments which will help to decide on future treatments on a management scale.

In the report it was explained that the impact of, and response to, treatments may be characterised in many ways, independently of the original treatment definitions. No matter what the original objectives of the treatments (e.g. to increase the regeneration of mahoganies) or the original treatment specifications, if appropriate data are available it will be possible to identify which responses correspond most closely to the management objectives. If a stand-model is used, the net effects of different levels of increment, stocking and competition will be integrated, showing which treatment plots result in the highest future yield, or sustained annual yield, in the required categories of species and size. Even if comparisons are based only on regression analyses of the results of UPDATE and BASALAREAS, it is possible to decide, partly subjectively, which results (in terms of increases in average increments, volume production and improvements in species composition) satisfy management requirements. These results may then be correlated (on the scatter diagram or regression line, for example) with a certain level or threshold interference.

A simple analysis of variance, comparing the different treatment numbers, may suggest that there is little correlation between increments and treatment intensity, whereas forecasts based on stand models or a full plot-by-plot regression analysis may demonstrate a good correlation between, for example, average increments of valuable trees and the proportion of the initial b.a. removed (cf. Occas. Pap. 10). An examination
of several regression correlations and scatter diagrams will show what levels of interference are generally associated with (and may therefore be expected to produce) the required levels of response. This indicates the level of interference (such as the proportional b.a. reduction, or the residual b.a.) required to satisfy management objectives; by examining the stand-stable representative of the forest (derived from PSPs or an inventory), it is possible to devise a simple set of instructions, such as a standard set of minimum diameters for logging or for refining after logging, which will produce the required level of basal area reduction, on average, over the forest as a whole. These minimum diameters (or whatever criterion is chosen) may then be incorporated, with some flexibility, into concession licences or silvicultural instructions. In this way, realistic treatments may be derived from experiments which originally involved quite a different set of treatments.

For the same reasons, the treatments chosen for a new silvicultural experiment do not need to be simple, easily defined operations suitable for large scale implementation. It has already been shown that a simple set of instructions, applied to a variable forest, inevitably results in highly variable impacts, which may not be acceptable in a controlled experiment. It may be sometimes necessary to specify treatments as, for example, reductions of b.a. by 20%, 40%, 60% and 80%, or by 5, 10, 15, 20 m²/ha; this will require careful assessment of standing b.a. plot by plot, and calculation of the appropriate numbers and sizes of each tree to be removed. This will be more laborious, but should produce better results, and will still allow quite simple treatment guidelines to be derived.

25. Resource requirements

Labour and administration

The time and labour required for demarcating, measuring and remeasuring rainforest plots varies enormously according to the density of the forest, the numbers of trees (or minimum sizes) to be measured, the number of items to be measured on each tree, the accessibility of each plot and the irregularity of the terrain.

Under favourable conditions of terrain and weather, with fairly short access lines and travelling time, using experienced workers, and with assessment of only simple items (DBH, CP, CF and a few others) a single 1 ha plot may be established and measured by a 5 man crew in 3-4 days, including cutting the access line, demarcating plot and subplot boundaries, painting rings at p.o.m. and recording data for trees of say 15 cm dbh and over. In Uganda (5) it has been found that initial plot establishment and measurement require the following men for 2 days (or 3 days for a distant plot or in bad weather):

1 Forest Ranger with technical training
1 Forest Guard, an experienced supervisor
3 painters and tree spotters
2 other men on line cutting and trenching

If the access line is long, more labour is needed for trenching. Any complications or more detailed measurements will add to the time.
For remeasurements, dealing with simple items on already-numbered trees of 15 cm dbh and over, an experienced gang may be able to handle 2 ha per day, including repainting of rings where necessary, under favourable conditions. However, remeasurements often take 1 day after a short period, and 2 days after a longer period (2-5 years) per ha.

Clearly, the labour and supervision of a large treatment experiment or PSP program may be very large. Like other inventory and stock-taking operations, the expense should be small compared to the value of the forest and the revenue from sawmilling, but it is justified only if the results are made available, and are used, for management.

Permanent plots of all kinds produce great quantities of raw data. Arrangements must be made at the start for the efficient collection, storage and processing of these data. The appropriate administrative and clerical back-up must be provided or the fieldwork will be wasted effort. Arrangements for data-processing on a computer, as a regular ongoing operation, must be made before the data are collected and data processing should start as soon as the first measurements are made.
Appendix 1. Instructions for establishing, measuring and remeasuring PSP.

1.1 Siting on map

EITHER lay out 2 plots per block, on a stratified random system:

(1) Within each chosen stratum of vegetation, site or management type, demarcate on a management map blocks of c. 300-400 ha of productive forest, not counting any mapped areas of vegetation types which can be excluded from the calculations of forest area and yield, such as savanna and swamp. The blocks may be square and do not need to take any account of permanent compartment boundaries, annual coupes or natural features such as streams unless these also form the basis for stratification.

(2) For each block in turn, apply a transparent overlay grid marked with lines or dots in square-spacing, at the same scale as the map, such that each square or dot on the grid corresponds to 1 ha on the map; alternatively, draw vertical and horizontal axes on the map (north-south, east-west) at intervals equivalent to 100m, forming a grid such that each square corresponds to 1 ha.

(3) From a table of random numbers (e.g. Appendix 6) select two numbers as co-ordinates of the first plot and mark the position of that plot on the map, (e.g. with a pin through the overlay).

(4) Use successive pairs of numbers for selecting two plot positions in each block.

(5) If two plots fall in adjacent positions, or are separated by only one vacant plot position, one position is discarded and another pair of random numbers is drawn for another plot position. The same applies if any part of a plot position on the map lies in a mapped unproductive vegetation type.

OR lay out the plots systematically on the map, having first chosen a suitable sampling intensity or number of samples.

(6) Allocate a number to each plot in a series for each forest or reserve. Any plots in pairs should have adjacent numbers in the series. Each plot then has a unique reference in its forest name and plot number and its pair is immediately identifiable (e.g. Kafinzu plot 5 with plot 6).

(7) On the map, measure the bearings and distances of a suitable access line to one plot corner from a convenient starting point, for each plot separately. The line should be straight unless it is necessary to avoid obstructions like rivers or cliffs. Each starting point must be easily retrievable in future, using the map and the recorded information. Where it lies on a roadside or forestry boundary, its distance from some permanent, mapped landmark such as a survey pillar, a Ministry of Works milepost, a permanent building or a bend or fork in a road or river should be measured and recorded. The starting point should normally be beside an easy access route such as a road or permanent track, a river used for navigation, or a permanently maintained boundary line.

(8) Mark the position of each plot, its number and its access line on all management maps and preferably also on aerial photographs backed up by ground photos.
1.2 Location in the forest

(1) Using the map, find the starting point in the forest, mark it permanently with a mound of earth, a post or pillar, a notice and/or a suitable live plant.

(2) Using the bearings and distances measured on the map, survey and cut an access line to the nearest corner of the plot. Enough shrubs and small trees should be cut to make a reasonably clear path, allowing easy access on foot, without excessive disturbance.

(3) If it is found, owing perhaps to errors in the map, that any part of the plot lies in mapped unproductive vegetation, or within 100m of the nearest edge of a previously selected plot, or within 20m of a road or railway, or overlapping the boundary of the forest or reserve or a large river, then its position can be moved back along the access line sufficiently to avoid the overlap and to allow 20m along roads for any subsequent clearing or widening.

1.3 Plot demarcation

(1) Demarcate the perimeter of the plot: Using calibrated tapes and compass, survey each side 100m long preferably on true north-south and east-west bearings, irrespective of the direction of the access line, taking care to correct for slopes. If possible, check the plot diagonals which should be $100 \times \sqrt{2} = 141.42$ m.

(2) Slope correction: either measure horizontal distances by "stepping" the tape in short, measured, horizontal lengths which add up to the required length of boundary or measure the angle of slope along the boundary, e.g. with a hypsometer, relascope or Suunto clinometer, and multiply the required horizontal distance, e.g. 100 m, by a cosine correction factor (Appendix 8) to determine the length along the slope; this calculated length is then measured along, or parallel to, the ground.

(3) Along each side, cut enough undergrowth to form a narrow footpath and clear lines of sight for at least 20 m.

(4) At each plot corner, excavate a "broken L" trench, with each arm 1.5 x 0.3 x 0.3 m, piling the excavated earth into a mound over the exact corner spot.

(5) Mark the mound at the end of the access line with a plastic post, concrete survey pillar or durable wooden post, marked with the PSP number, or with an easily recognisable understorey plant such as Dracaena or Agave. Concrete survey pillars can be prefabricated with numbers but they are inconveniently heavy. Aluminium sheets of c. 5 x 20 cm can be marked with number-punches and wrapped around and nailed to the wooden posts. Stainless steel dymotape labels are recommended.

(6) Demarcate the internal divisions: Mark the plot perimeter at 20m intervals; survey internal lines across the plot from each mark to the corresponding mark on the far side of the plot. A high standard of accuracy is required, with regular checks to ensure that each line lies 20m from the next parallel division throughout its length.
(7) Clear the undergrowth along the line of each division as for the plot perimeter.

(8) At 20m intervals along the plot perimeter, where the internal dividing lines meet the plot boundary, set up durable wooden posts or excavate a "broken T" trench with two arms of 1.5 x 0.3 x 0.3m, and excavate L-trenches at the four corners of the central division containing the four central quadrats. Soil from the trenches may be piled into a caern to mark the junction. If these corners are flagged with coloured plastic strips on poles, it is easy to check the alignment of quadrats and diagonals, even in rough country with logging debris.

(9) Excavate direction trenches of 1.5 x 0.3 x 0.3m at the beginning and end of the access line, at intervals of 20m along the line and at any corners.

(10) At each assessment, mark the boundaries of each 10 x 10m quadrat with tape measures. The boundaries may be semipermanently marked with conspicuous plastic string tied to shrubs along each boundary, or with plastic flagging tied to stakes. It is also helpful to make a temporary subdivision of each quadrat with tape measures across the central axes at 5m, to help in accurately determining the co-ordinates of each tree.

(11) In the plot records, number each quadrat according to its 10m xy co-ordinates, measured along the x & y axes of the plot, with the origin at the SW corner (if the plot is oriented exactly NS, EW) or at the southernmost corner (irrespective of where the access line meets the plot).
1.4 Plot description

Complete the standard Description Form, including local observations about the state of the plot (a quick examination of the soil and notes on conspicuous human or wildlife activity, windblow or diseases) and local information about the history of the surrounding area (details of logging and silviculture).

1.5 Tree marking

(1) Make a label for each tree each with a number which is unique for its quadrat. Stainless steel dymotape labels are recommended (the plastic and aluminium labels often deteriorate).

(2) Use a rustproof (e.g. aluminium or heavily galvanised) nail to fix each label exactly 20cm above the p.o.m., leave 2-3cm of the nail outside the bark to allow for tree growth, and do not penetrate the wood too deeply. (Note: the p.o.m. will usually be at 1.3m above ground level or above the base of the tree on the uphill side. On trees with buttresses, deformities or forks at the usual p.o.m., a p.o.m. should be selected at standardised heights above. Such abnormal heights must be recorded on the field-data sheets. cf. section 10.4).

(3) If the tree is too small to take a nail (<3-5cm d), attach the label loosely to the stem at a convenient height, using enough nylon string to allow for growth between measurements.

(4) Use a stiff brush to remove loose bark, moss, epiphytes etc. in a ring c. 10cm wide around the stem near the line of the p.o.m.; do not cut any climbers or vines if there is room for a tape measure between them and the tree, but tightly adpressed vines should be cut away.

(5) Hold an old tape measure or a piece of canvas webbing round the tree with its lower edge along the exact line of the p.o.m., making sure that it is at the correct height and exactly at right angles to the axis of the tree.

(6) Paint a line 2-3cm wide around the whole stem, using the lower edge of the tape or webbing as a guide, marking all parts of the stem which are in contact with the guide.

1.6 Tree location and mapping

(1) Use A4 millimetre graph paper, divided into 100 squares of 2 x 2cm each square representing one quadrat of 10 x 10m on the ground; at this scale, 1mm represents 50cm. Or: use 3 sheets of A4 graph paper, marked into 4 x 4cm squares, each representing a quadrat of 10 x 10m; at this scale 1mm represents 25cm; sheet 1 may contain quadrats 00-39, sheet 2 quadrats 40-79, and sheet 3 quadrats 80-99.

(2) Lay out four calibrated 20m tape measures along the permanently demarcated sides of each subplot in turn, and two more to join the midpoints of each side to demarcate each 10 x 10m quadrat. Layout two 10m tapes in each quadrant in turn to demarcate four quarters of exactly 5 x 5m. Ensure that each tape has its zero in exactly the correct position, and is aligned so that the readings increase with increasing distance.
from the origin of the x and y axes. An attempt should be made to lay out all these tapes, both to make reading easy and to compensate for the sections of the lines where tapes cannot be aligned correctly because of large trees on the lines.

(3) If only an approximate sketch map is required, and particularly if relatively few trees are to be mapped, the map-maker can estimate the position of each tree by eye, making use of the tapes in position. It may not be necessary to demarcate the four 5 x 5m subdivisions if all trees are easily visible from the 10 x 10m quadrat boundaries. Mark the position of each measured tree with a point on the map, as precisely as possible, with each tree number beside it.

(4) If more accurate information is required, use the larger scale plot map (3 sheets of graph paper per plot) and, if required, record the co-ordinates separately. Assess each 5 x 5m area in turn, with one reading the tape along the x axis, another along the y axis, each person calling the co-ordinates in turn for the trees which are closest to the tape which he is reading, and then moving to the tape on the opposite side for trees closer to that side. The data-recorder will record the co-ordinates for each tree in the appropriate columns on the data sheet, while another assessor completes the map.

1.7 Remeasurements

The remeasuring operation should include the following tasks:

Clear the access line and all subplot boundaries to keep them open as narrow footpaths, with only the minimum essential cutting.

Repair all trenches, mounds and other markers around the plot, along the access line and at the starting point.

Revise the tree position map, marking all recent deaths and all new recruits which have reached the measurement-size.

Check all tree-number labels and replace any that are lost or damaged, using the tree position map and the last measurements to avoid errors.

Use a claw hammer to pull out, by a small amount, the nails holding the tree numbers in order to prevent occlusion, especially in young forest and fast growing trees.

Repaint all rings at p.o.m. and painted numbers where necessary, using the same methods and care as initially. If buttresses develop at the p.o.m., it should be moved up above the buttresses to the next standard height (e.g. 3, 5 or 7m). The size measurements and the heights of p.o.m. must be recorded for both new and old p.o.m. for at least one measurement and preferably for 1 or 2 subsequent measurements. This will allow increments to be computed by hand for both p.o.m., and with care it will be possible to estimate the earlier increments at the new p.o.m.
Appendix 2. TRF PSP DESCRIPTION FORM FOR INITIAL SURVEY AND SITE DESCRIPTION.

Forest:
Plot established by:
checked by:

CPT./COUPE:
Plot No:

Plot location map reference:
Start of access line, map reference:
Start of access line, description:

Directions or survey data along access line:

Locality map
Plot chart showing access line

Scale 1: 09 99 00 90
N

SITE: Altitude:
Slope:
Topographical position:

SOIL: Type:
Texture:
Colour:
Rooting Depth:

CLIMATE: Mean Annual Rainfall:
Mean Annual Temp:
Nearest met. station:

VEGETATION HISTORY: Original forest type:
Dates of harvesting and names of loggers:
Volumes of main species removed from coupe:
Dates and descriptions of silvicultural treatments:
Present vegetation type:
Trees:
Shrubs and climbers:
Regeneration of trees:
Ground flora:
Other site factors:
Appendix 3. Data card for field recording in TRF PSP.
(Example for one 10 x 10 m quadrat)

Forest:
Assessors:
Date:
Quadrat No. from co-ordinates of
S.W. corner of quadrat:

<table>
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<tr>
<th>Tree No.</th>
<th>Sp</th>
<th>d</th>
<th>h</th>
<th>CB</th>
<th>CD</th>
<th>CP</th>
<th>CF</th>
<th>Imp</th>
<th>Death</th>
<th>Co-ords. X Y</th>
<th>Comments p.o.m. etc.</th>
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### Appendix 4. Conversion factors

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<th>Unit</th>
<th>Conversion Factor</th>
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<tr>
<td>ins</td>
<td>2.540 = cms</td>
<td>miles²</td>
<td>259.05 = ha</td>
</tr>
<tr>
<td>ft</td>
<td>.3048 = m</td>
<td>circ²</td>
<td>.07958 = sect. area</td>
</tr>
<tr>
<td>yds</td>
<td>.9144 = m</td>
<td>ins. circ²</td>
<td>.0005526 = sect. area</td>
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<tr>
<td>chns</td>
<td>20.12 = m</td>
<td>ins. circ²</td>
<td>.0000513 = sect. area</td>
</tr>
<tr>
<td>miles</td>
<td>1.609 = km</td>
<td>m</td>
<td>1.6214 x 1.3377 = furlongs</td>
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<tr>
<td>oz</td>
<td>28.35 = gm</td>
<td>inches per furlong</td>
<td>22.615 = miles</td>
</tr>
<tr>
<td>lbs</td>
<td>.4536 = kg</td>
<td>f²/ft²</td>
<td>1.296 = m²/ft²</td>
</tr>
<tr>
<td>tons</td>
<td>1016 = kg</td>
<td>f²/q.g./ac</td>
<td>.2922 = m²/q.g.</td>
</tr>
<tr>
<td>long tons (2240 lb)</td>
<td>.9072 = tonnes</td>
<td>oz/yd²</td>
<td>33.91 = gms/m²</td>
</tr>
<tr>
<td>short tons (2000 lb)</td>
<td>1.1023 = tonnes</td>
<td>gm²/day</td>
<td>36500 = tonnes/ha/yr</td>
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<tr>
<td>galls</td>
<td>4.546 = litres</td>
<td>lbs/ac</td>
<td>1.119 = kg/ha</td>
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<tr>
<td>circ</td>
<td>.3183 = diam</td>
<td>tons/ac</td>
<td>2.506 = tonnes/ha</td>
</tr>
<tr>
<td>ins. circ</td>
<td>8085 = cm. diam.</td>
<td>gall/yd²</td>
<td>5.437 = litres/yd²</td>
</tr>
<tr>
<td>ft. circ</td>
<td>9.702 = cm. diam.</td>
<td>gall/ac</td>
<td>11.23 = litres/ac</td>
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<td>ins²</td>
<td>6.452 = cm²</td>
<td>miles/U.K. gall</td>
<td>.3560 = km/litre</td>
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<td>.09290 = m²</td>
<td>ins³</td>
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<td>ft³</td>
<td>.02832 = m³</td>
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<td>H. ft.</td>
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<td>chns²</td>
<td>.04047 = ha</td>
<td>H. ft</td>
<td>.03605 = m³</td>
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<td>acres</td>
<td>.4047 = ha</td>
<td>ft³/ac</td>
<td>.06997 = m³/ac</td>
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<tr>
<td>miles</td>
<td>2.5905 = km²</td>
<td>H.ft/ac.</td>
<td>.08905 = m³/ac</td>
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<tr>
<td>pop. per sq. mile</td>
<td>.3861 = pop. per sq. km</td>
<td>H. super ft/ac</td>
<td>.007421 = m³/ac</td>
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<tr>
<td>lbs/ft³</td>
<td>.01605 = sp. gr.</td>
<td>62.29 = sp. gr.</td>
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Appendix 5. A selection of symbols for forest mensuration

Note. Lower case symbols refer to individual tree values; upper case symbols refer to crop values per unit area.

**Principal symbols**

- **c**: circumference, girth
- **d**: diameter
- **g**: basal-area
- **G**: Basal-area total per unit area, e.g.: \( m^2/\text{ha} \)
- **h**: total height of a tree
- **i**: increment, of a single tree in one year
- **k**: form-quotient of diameter at half-height divided by \( d \)
- **n**: number, usually of stems in some sample
- **N**: total number of stems per unit area
- **p**: increment percent
- **t**: age, usually in years from planting
- **v**: volume of stemwood over-bark in a single tree
- **f**: form factor, for total stemwood over-bark i.e. generally \( f = v/gh \)
- **V**: total volume per unit area, e.g.: \( m^3/\text{ha} \)

All the above may be qualified by subscripts or other modifications, of which the more useful recommendations are:-

**Qualified symbols**

- **\( \bar{d} \)**: arithmetic mean diameter of a stand, i.e. \( (d)/n \)
- **\( dg \)**: diameter of the tree of mean basal-area
- **\( \bar{g} \)**: basal-area of the tree of mean basal-area in a stand, i.e. \( G/n \)
- **\( \bar{h} \)**: arithmetic mean height of a stand, i.e. \( (h)/n \)
- **\( h_g \)**: height of the tree of mean basal-area
- **\( h_{\text{hd}} \)**: height of the tree of arithmetic mean diameter
- **\( h_{\text{dom}} \)**: "top-height", mean height of the one hundred thickest trees per hectare
- **\( i_d \)**: increment in diameter of a single tree in one year
- **\( \bar{v}_7 \)**: volume of stem-wood (of a single tree) exceeding 7 cm diameter over-bark i.e. volume to a 7 cm diameter top
- **\( v_b \)**: total above-ground volume of a tree, all branchwood included

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Appendix 6. Random numbers for plot co-ordinates.

These random numbers may be used for selecting the position of PSPs, following the system of stratified random sampling, two per block, described in section in Part 2, section 6, and Appendix 1.

Two numbers (one for each co-ordinate) are required for each plot, and two pairs of numbers are used to locate the two plots in each block of forest.

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Reproduced from Forest Dept. Standing Orders, Uganda (5).
### Appendix 7. Decimal dates for computer programmes

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Appendix 8.

Correction factors for measuring horizontal distances for plot boundaries and diagonals on sloping ground. The required horizontal distance (e.g. 100m for a plot boundary) must be multiplied by 1/cos A or sec A (where A is the slope angle) to obtain the equivalent distance which must then be measured along, or parallel to, the sloping ground. Thus, a 100m plot boundary aligned down a 20° slope should be measured as 106.42 m along the ground.

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45 Sabah Manual of Silviculture (1972) Sabah Forest Record No. 8, 80 p.


