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Permanent Sample Plot Techniques for Mixed Tropical Forest

by

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Cover illustration

Tropical rainforest, south-east Madagascar.
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Permanent Sample Plot Techniques for Mixed Tropical Forest

by

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SUMMARY

This manual provides a reference guide to permanent sample plot (PSP) techniques in mixed tropical forests. It is intended as an update to Synnott's *Manual of permanent plot procedures for tropical rainforests.** The manual considers the objectives of PSPs as that of providing data for growth and yield models which will be used to assist forest management. The PSPs are a means of measuring tree growth, mortality, and regeneration in relation to stand density. They may be laid down either as a network of sampling plots, passively sampling existing forest management practices; or as measurement plots within an experimental design. Both approaches are properly required for the optimum capture of data. There is no satisfactory method of calculating numbers of PSPs required, but approximate indications are that one plot per 1000 ha of forest, laid in a stratified random sample, will normally be adequate. Experimental designs should concentrate on the effects of extremes of stand density, from controlled logging or poisoning, and always include untreated and unlogged forest as a control to define maximum basal area and growth under maximal competition. Randomized block design is recommended as simple, robust and statistically rigorous. Replicates should be placed on different sites.

When considering plot shape and size, some compatibility is required with temporary plots used in forest inventory. Measures of basal area, competition and spatially-dependent ratio parameters will depend on plot size and shape, hence the need for some consistency. In general, a square PSP of 100 x 100 m, subdivided into 25 20 x 20 m quadrats, is recommended, but this may be varied where compatibility requirements so indicate. Compatibility can be achieved for various shapes and sizes by using a common sub-unit. For this purpose the 20 x 20 m quadrat is recommended as a basis for all permanent, temporary, and experimental plots. For plot location in the field, modern methods using global positioning satellites may greatly reduce survey time and cost, and ease the problem of relocating plots in future. Plots can be permanently demarcated by use of a combination of concrete or hardwood corner pillars, trenches to relocate boundaries, and use of tree numbers and positions to reconstruct the plot should corner markers be lost.

On plots, trees above 20 cm dbh should be permanently marked with paint or tags, uniquely numbered, and measured for diameter, crown position and crown form according to the Dawkins classification. Qualitative records of damage, disease or other features should be made via coded notes. A sub-sample of two trees on each plot should be measured for crown point height. Trees below 20 cm should be measured on a subplot, and if possible regeneration on an inner subplot or sample strip. All species should be measured, without consideration of economic utility. The manual covers site assessment briefly, including topographic indicators based on altitude, slope and aspect, soil sampling and classification methods, the use of vegetation associations as site indicators, and the use of quantitative stand parameters such as mean height and form height. Data recording forms are given, together with a description of database record structures compatible with the forms, and methods for data entry verification and the management of long-term data storage.

* Synnott, T.J. (1979) A manual of permanent plot procedures for tropical rainforests. *Tropical Forestry Papers, Commonwealth Forestry Institute, University of Oxford*. No. 14, 67 pp.

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LIST OF ABBREVIATIONS

ASCII	American Standard Code for Information Interchange
CFI	Continuous forest inventory
CSV	Comma separated values
CTFT	Centre Technique Forestier Tropical, Paris
CV	Coefficient of variation
EP	Experimental plot
FAO	Food and Agriculture Organization
GPS	Global positioning system
MTF	Mixed tropical forest
PAR	Photosynthetically active radiation
POM	Point of measurement
PSP	Permanent sample plot
PTM	Pan tropical mean
SPR	Sampling with partial replacement
SSO	Sampling on successive occasions
TSP	Temporary sample plot
URS	Unrestricted random sample
UTM	Universal transverse mercator

1 INTRODUCTION

This chapter defines the terms Permanent Sample Plot and Mixed Tropical Forest, discusses why PSPs are an important and integral part of the sustainable management and conservation of mixed forest, and explains the objectives of this manual and its usage as a reference work to assist in the design and implementation of permanent plot programmes.

1.1 Definitions

1.1.1 Permanent sample plots

1.1.1.1 This manual is concerned with the objectives, planning, design, establishment, measurement and data processing for permanent sample plots (PSPs) in mixed tropical forest.

1.1.1.2 PSPs are permanently demarcated areas of forest, typically of 1 ha each, which are periodically remeasured. They are maintained over at least five years, and often for very much longer. They provide estimates of changes in forest stocking and volume. This information is essential for the rational management of the forest.

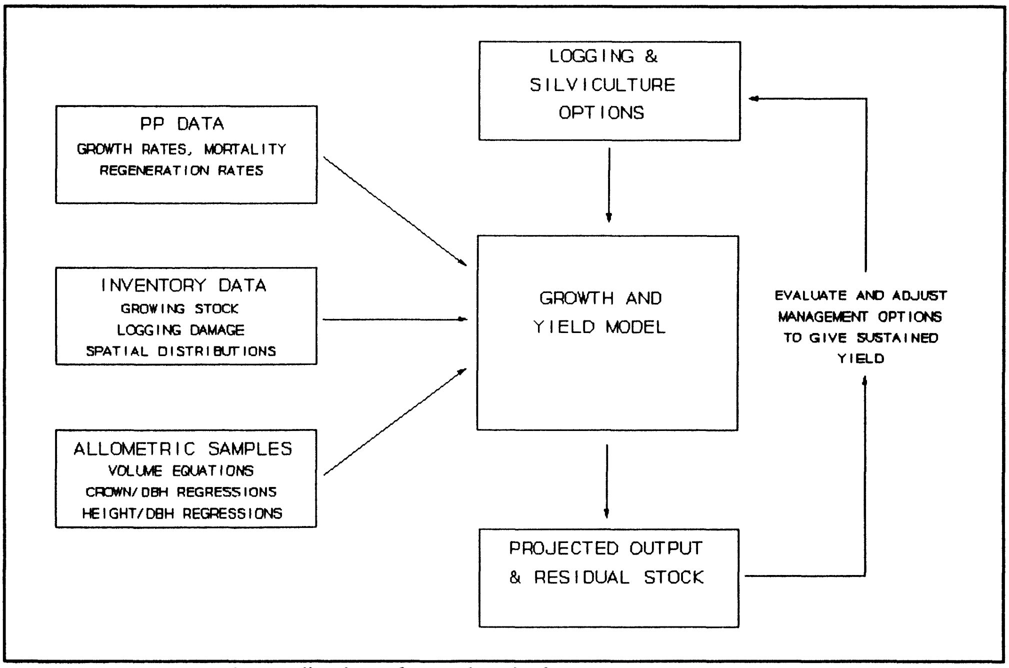

Figure 1-1 : The application of PSP data in forest management

1.1.1.3 When applied to forest management, data from PSPs need to be combined with other sources of information about the forest. These may include data from temporary sample plots (TSPs) laid down as part of forest inventory, data from long and short term experiments and ecological studies, and data from regression or allometric sampling, such as tree volume and biomass studies. These different types of data are combined into a *growth and yield model* that provides the means of determining the likely results of management practices on the forest (Figure 1-1).

1.1.1.4 PSPs have the unique role of providing data on changes in the forest over time. TSPs and allometric sampling are one-off sampling processes that do not include the time dimension directly. This special function of PSPs involves a number of distinct characteristics. Mensurational and sampling criteria applicable to TSPs, covered in such texts as Lanly (1981) and Loetsch & Haller (1973), are either inappropriate or only partially suitable for PSPs.

1.1.1.5 The denotation PSP in this manual generally refers to all types of permanent plot used for growth and yield studies. However, in discussion specifically of sampling designs and growth and yield experiments, it is useful to draw a distinction between permanent plots that are part of a sample and those that are part of an experiment. The latter are termed experimental plots (EPs) where the distinction is relevant. The term *permanent plot* includes both sample plots and experimental plots.

1.1.1.6 PSP procedures have been dealt with in a number of previous works, which the present manual seeks to update. Dawkins (1958) established many influential ideas in PSP design for mixed tropical forest that have been widely adopted. Synnott (1979a) reviewed the PSP practices of many tropical countries and produced a standardized field reference manual. The present book conforms to this earlier work, but incorporates recent technological developments in computers and instrumentation, and some revised sampling procedures based on the experience of analysis of older PSP data-sets.

1.1.2 Mixed tropical forest

1.1.2.1 This manual is specifically concerned with the establishment and remeasurement of PSPs in mixed tropical forest (MTF). Mixed forests are naturally regenerated, and thus comprise a mixture of age classes and species. In the tropical zone, they are generally characterized by a very large number of species compared with temperate and subtropical mixed forest. MTF occurs in a number of commonly recognized sub-types, including the true evergreen rainforests, seasonal semi-deciduous forests, drier forests on the margins of the forest zone, characterized by frequent fires and reduced species complexity, tropical montane forests at higher altitudes, and special types occurring in swampy or salinized soils (UNESCO, 1978; Whitmore, 1990).

1.1.2.2 PSPs established in plantations, in mixed temperate forests, and in mixed tropical forests involve distinctively different technical and operational problems. Plantations and temperate mixed forest are usually sampled by small circular PSPs, which are quite inappropriate for MTF. In plantations, the question of regeneration sampling, mortality and ingrowth does not arise, and the concepts of stand treatment and yield can be defined more simply. Adlard (1990) provides a reference manual of tropical plantation-oriented PSP techniques that complements this manual.

1.1.2.3 Mixed tropical forests have a number of special mensurational problems that affect inventory work generally, and also have additional repercussions for PSPs in particular. These include buttresses, stilt roots and woody stranglers that make measurement of both diameter and increment very difficult. For TSPs, optical instruments are used to measure diameter above buttress, but for PSPs these are insufficiently accurate and other means are necessary. Tree heights are very difficult to measure in closed MTF and cannot be directly used as a routine mensurational parameter. The forest is spatially heterogeneous, especially after logging, when different zones and types of destruction are superimposed on the natural pattern of chablis (tree fall gaps, Oldeman, 1978). This influences the size and shape of plots required compared with plantations, which are much more homogeneous in every respect.

1.2 Permanent plots, sustainable management, and conservation

1.2.1 Sustainable management of exploited MTF

1.2.1.1 Mixed tropical forests are often either being exploited for timber production, or are in the process of being converted to other economic land-uses, including shifting agriculture, tree crops such as cocoa, rubber and oil palm, or conversion to arable agriculture and grazing lands.

1.2.1.2 Under the economic pressures for human development, MTF can only be managed on a sustainable basis if two principles can be satisfied:

- It is possible to give an economic value to the forest, and to reflect that value in the cost of timber extracted from it.
- It is possible to regulate the felling of the forest in a way that will ensure its maintenance as a productive ecosystem.

1.2.1.3 Both these problems require a model of the forest's response to different kinds and intensities of logging, and to silvicultural or other treatments. Such a model can only be developed if extensive data on the forest are available, including permanent plot data, as shown in Figure 1-1.

1.2.1.4 Many of the problems of MTF exploitation can be traced to the management difficulties resulting from lack of adequate growth and yield data. Consequently, there is no consensus on either the economic value, or the means of management of such forest and by default, uncontrolled exploitation and conversion to other types of land use results.

1.2.1.5 *PSPs are therefore necessary for the sustainable management of mixed tropical forest.* Without them, there will always be a tendency to undervalue the forest in economic terms, resulting in conversion to other forms of land-use either by default or as a matter of policy. Attempts at sustainable management, without PSPs, will always be restricted by the basic ignorance of what aspects of exploitation, qualitatively and quantitatively, need to be regulated, and how these regulations can be translated into practical operational definitions (felling girths and cycles, permissible levels of damage, etc.).

1.2.2 Conservation of MTF

1.2.2.1 When MTF is located in conservation areas, and not subject to exploitation, there is still a need for PSPs, albeit at a lower intensity than in managed forest. PSPs in this case serve three functions:

- They provide very valuable control information relative to PSPs in exploited forest. Dawkins (1958) stressed the need for PSPs in conservation forest for this purpose.

- They monitor the dynamics of the unexploited forest, and assist in its management. It is a misconception to believe that conservation areas require no management. Most such reserves are fragments of previously much larger areas that are now subject to a variety of influences at the edges, including fire, gathering of non-timber products, and possibly encroachment by shifting cultivators. They are not always in a state of equilibrium, but require to be actively maintained (Whitmore, 1990).

- Where large animal populations exist in the forest, a long-term fluctuating dynamic equilibrium may exist between the forest and the animal population. This requires to be understood for the management of the wildlife population, and will require PSPs to examine the forest component of this ecosystem.

1.3 Manual objectives and usage

1.3.1 Objective: A technical reference for PSP field operations

1.3.1.1 The objective of this manual is to provide a technical reference for those responsible for the field operations connected with PSPs. It covers all aspects of the design and planning of PSPs, their demarcation and measurement, and the data recording and storage. It does not cover the analysis of PSP data to produce growth and yield models, which will be covered by a second manual in this series.

1.3.1.2 The manual is not a field guide or set of field instructions. Alternatives are presented and discussed for design criteria and field procedures. These need to be adapted for a local situations, to fit existing standards and practices where possible, and make use of available local technology, skills and infrastructure, before a field guide can be written. Rather, it is intended as source book from which a field guide of PSP procedures can be developed at a local or national level.

1.3.2 Usage of the manual

1.3.2.1 This manual is addressed to several levels of readership. These range from the senior forest administrator, concerned with the necessity of and justification for PSPs, to the technical forester in the field requiring specific instruction on measurement procedures. Different sections of the manual will concern these various readers to a greater or lesser extent:

- *Planners and senior managers* will have little interest in detailed measurement or demarcation procedures, but will be mainly concerned with sections 2-4 on design criteria. The remaining chapters will indicate equipment procurement requirements, depending on the particular choices of field procedures adopted.

- *Forestry research workers* will have a particular interest in section 4, on the execution of growth and yield experiments.

- *Senior forestry officers* responsible for planning and managing PSP programmes will find the whole book useful, but sections 2-4 particularly relevant.

- *Forestry officers* responsible for preparation of detailed field instructions will need to consider the whole book, but especially sections 5-9.

- *Technical foresters*, responsible for performing PSP demarcation and measurement in the field, will find sections 5-8 provide a useful rationale for procedures detailed in a set of field instructions.

2 COMPONENTS OF GROWTH AND YIELD IN MTF

This chapter explains what should be measured by PSPs in order to give information on stand growth and yield, and to provide the basis for the construction of a growth model. It defines the statistical population for PSP sampling and experimentation.

2.1 Definitions of yield and growth

2.1.1 Yield and total volume

2.1.1.1 The *yield* of a forest stand is the total utilizable production at the time of harvest (Knuchel, 1953). This includes the timber volume that it is technically and economically possible to remove (ie. the standing commercial volume), but is constrained by regulations for the retention of trees. In a uniform system of management, the yield will be equivalent to the standing volume. In a selection forest (which typically includes most managed MTF), only a portion of the standing commercial volume will constitute the yield.

2.1.1.2 The *potential yield* comprises the yield as defined above. *Actual yield* is based on the measurement of what is actually removed from the forest, and should be less than potential yield because of operational constraints in the forest, short term variations in demand for particular species, and rot and damage which make some felled or standing trees non-commercial at the time of logging.

2.1.1.3 It is relatively simple to define current yield. The commercial species and minimum economic sizes should be known, and the volume which falls into this category constitutes the yield. However, PSP programmes normally extend decades into the future, when species demand is likely to be broader, and possibly smaller sized and less well-formed pieces of timber may be accepted. Thus the definition of future yield is inherently uncertain.

2.1.1.4 For this reason, it is useful to define yield in terms of total standing volume per unit area (m^3/ha). This constitutes all the above ground woody matter down to the practical limits of measurement, which may be taken as 5 cm. Commercial yield can then be variously defined as subsets of total volume by considering size class and species distribution of stems.

2.1.2 Growth of stands and trees

2.1.2.1 The growth of a forest stand is the rate of accumulation of yield, normally expressed in terms of m^3/ha/yr. As with yield, there are qualitatively definable subsets of growth, to include size and species constraints.

2.1.2.2 The accumulated growth of a stand defines the yield at the time of harvest. This is the essential economic and technical quantity required by the forest planner and manager.

2.1.2.3 In plantations, with a single species and negligible ingrowth and mortality, it is correct to assume that the growth of the stand is the sum of the growth of the individual trees, just as the yield of the stand is the sum of the volumes of the standing trees.

2.1.2.4 *In mixed forest, tree growth and stand growth cannot be equated in the same way as for plantations.* This is a most important point. In the past, it has often been neglected, leading to over-emphasis on the measurement of tree increment, and omission of the analysis of regeneration, ingrowth and mortality.

2.1.2.5 In mixed forest, the growth of the stand over a period of years has three components:

- individual tree increment or growth,
- mortality, or the death of trees,
- ingrowth, or the appearance of new trees in measurable size classes from regeneration.

2.1.2.6 This can be expressed algebraically as:

$$I = I_s - M + R \qquad \text{-\{eqn.2-1\}}$$

where:

I	is the net increment or growth of the stand,
I_s	is the sum of the increments of the trees which survive over the period,
M	is the volume of the trees which have died during the period,
R	is the volume of ingrowth (regeneration) measured at the end of the period.

2.1.2.7 This leads to the important conclusion for PSP work that *accurate measurements of ingrowth and mortality are as important in natural forest sampling as measurements on tree increment.*

2.2 Sub-components and influences on growth

2.2.1 Tree volume growth and diameter increment

2.2.1.1 It is rare for volumes to be measured directly on standing timber. It cannot be routinely done to sufficient accuracy to allow assessments of volume growth with any reliability. The almost universal practice in stand mensuration is to determine volume indirectly via a tree volume equation.

2.2.1.2 In MTF such volume equations are usually defined to an adequate precision with reference to tree diameter alone, and take the general form:

$$v = f(d) \qquad \text{-\{eqn.2-2\}}$$

implying that volume (v) is some general function of diameter (d). The function used will depend on species, but it is usually possible to classify the numerous species in MTF into a small number of groups, each with a different volume equation.

2.2.1.3 Height may be included in the equation, but since its measurement is impracticable on all trees in MTF, a volume equation including height usually has to be reduced to one dependent solely on diameter by the process of establishing a height/diameter function. It is more precise, avoids bias, and is simpler to move directly to a volume equation based only on diameter.

2.2.1.4 Consequently, since volume growth of trees is a direct function of diameter increment, the latter is treated as the main subject of sampling. The volume growth of survivors (I_s) is inferred from the diameter increments of survivors; the volume loss due to mortality (M) is inferred from the diameters of the trees that die; and ingrowth volume (R) is calculated from the diameters of trees which grow above the minimum measurement diameter by the end of any given measurement period.

2.2.2 Competition

2.2.2.1 The growth rate and survival of trees is strongly influenced by available light, water and nutrients. For any given tree in the stand, its light regime is determined by the extent of overshadowing and crown density of neighbouring trees.

2.2.2.2 As the canopy becomes fully and efficiently occupied by foliage at all levels, a certain maximum production for the stand is achieved, which is a characteristic of the interaction between site and forest type, and determines the maximum yield of the stand. It is usually described in terms of the maximum basal area of the stand (m^2/ha), and is likely to be of the order of 45-55 m^2/ha for tropical mixed forest (Assmann, 1970; Alder, 1990).

2.2.2.3 At this level, net growth of the stand will be zero. However, locally there will be areas of active growth in gaps left by trees that have died recently. This growth will be balanced by current mortality.

2.2.2.4 The growth of individual trees is strongly influenced by local competition from overshadowing and adjoining trees. This can be measured in a variety of ways, of which the simplest is the Dawkins crown position code, discussed fully in section 6.6. More complex measures require a knowledge of tree positions relative to each other, and some information about crown diameter/tree diameter relationships. Adlard (1974) reviewed several methods of calculating inter-tree competition from tree position.

2.2.2.5 *Measures of competition on PSPs are essential.* There are four ways of obtaining suitable data:

- *By recording tree positions*, to allow possible calculation of tree polygons and competitive overlap zones.
- *By assessing the Dawkins crown position score.* This has proved to be an effective and simple measure of competition that can be recorded on both TSPs and PSPs.
- *By ensuring that all trees on the plot are measured.* Restriction of measurements to an economic subset of species or size classes results in inadequate information for the assessment of competition.
- *By placing some plots in undisturbed forest*, to estimate maximum basal area for the stand as a whole.

2.2.3 Mortality

2.2.3.1 Trees die continuously in the forest. The typical J-shaped diameter distribution (Figure 2-1) shows that only a small fraction of the sapling size class (0-10 cm) will survive to commercial dimensions. It is also clear from Figure 2-1 that small errors in estimation of mortality will result in large errors in predicting the number of surviving trees in the mature sizes, and hence the yield.

2.2.3.2 Mortality is assessed on PSPs by observing which trees have died. However, there are difficulties in this, as dead trees fall and decay rapidly, and may disappear completely between measurements. Various practical methods are described in section 6 to assist in this process, including especially the recording of tree positions and the use of coded notes to give prior information of factors tending to morbidity.

2.2.3.3 Natural mortality is strongly influenced by competition, especially deep shade, climbers, and age. In addition, following logging, mortality rises

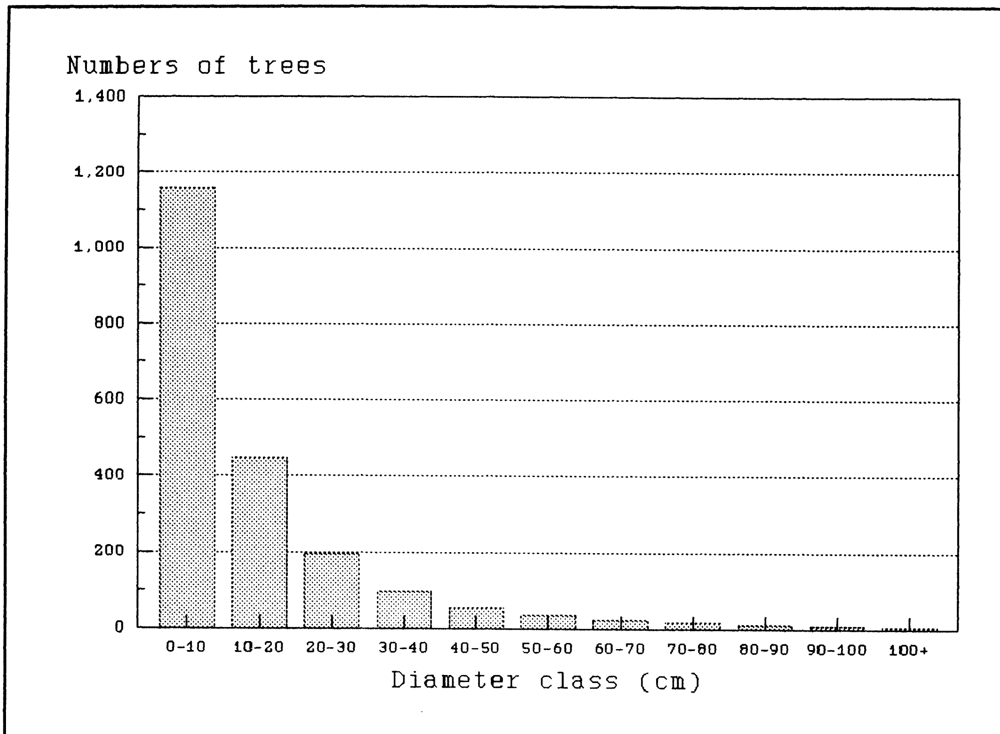

Figure 2-1 : Typical J-shaped curve of stem numbers

sharply on both damaged and undamaged trees (Tang, 1976), and may be as much as five times the undisturbed levels. The death of undamaged trees appears to result from the sudden change from deep shade to sunlight after a period of extended shade adaption (Oliver & Larson, 1990).

2.2.3.4 *It is therefore important to be able to relate mortality to the timing and intensity of logging*, and to indications of logging damage. This is discussed in section 3.6.2. Experimental designs can be used to study this problem directly and efficiently, as described in section 4.

2.2.4 Ingrowth and regeneration

2.2.4.1 Ingrowth is the process whereby trees 'appear' in the measured stand table, by growing into it from sizes below the measurement limit. It is thus closely related to regeneration, but is not synonymous. Regeneration is the process whereby new trees are added to the population by germination from seed (or perhaps by vegetative growth from roots, fallen stems, etc.).

2.2.4.2 The word regeneration, besides defining a process, can also be used to refer to the population of trees below the minimum size limit for measurement.

2.2.4.3 *A knowledge of regeneration and ingrowth is essential if long-term projections of yield are to be made.* Depending on species growth rates and competitive status, it is possible for some individuals in the stand to grow from seedlings to 70 cm in 30 years or so, and thus regeneration can significantly effect yield within the period of a single felling cycle.

2.2.4.4 As *the projected long-term yield has an immediate effect on the allowable cut* in normal methods of yield regulation, current regeneration can therefore have immediate implications for forest management. If there is inadequate regeneration over a period, an adjustment should be made to allowable cut to reflect the effects of a lower future yield.

2.2.4.5 The ingrowth rate will depend primarily on the pool of available regeneration, and available light, or competitive status. To model ingrowth rates thus requires some knowledge of the regeneration pool. For ubiquitous and common species, it can be assumed that adequate regeneration is always present, and ingrowth will therefore be a function primarily of local variations in stand density and the occurrence of small gaps, skid trails, etc. A knowledge of tree sizes and positions, and the timing and intensity of logging operations can allow these effects to be modelled.

2.2.4.6 For the less common species, which often include many of great economic importance, some knowledge of the size of the regeneration pool is essential. It cannot be assumed that adequate regeneration exists. This requires a study of the factors that influence and enhance the regeneration of these species, including the presence of mother trees and particular ecological conditions that favour seed germination and the survival and growth of seedlings. These studies can be achieved by sub-sampling within PSPs, as described in detail in section 7.

2.3 The measured population on PSPs

2.3.1 Definition of statistical population

2.3.1.1 In statistics, a population is an aggregate of units, where the units are clearly and explicitly defined (Lanly, 1981). For PSP programmes, it is important to be clear about the statistical population being sampled.

2.3.1.2 PSPs and growth and yield experiments are generally concerned with several levels or tiers of sampling, as detailed in sections 3 and 4, each of which defines a different statistical population. Without clarity in this matter, there is a danger that different sampling schemes and experiments may effectively sample and describe different and incompatible populations. This may be true even though, superficially, they may all be sampling trees and forests in a very similar way. Consequently, the results and relationships developed on these incompatible studies are very hard to generalize for the purposes of stand modelling and projection.

2.3.1.3 It is also important that PSPs and experiments for growth and yield studies, and TSPs for growing stock inventories sample compatible statistical populations. This can best be achieved by adhering to two principles:

- *PSPs should employ the broadest possible definition of the statistical population.* TSPs may then employ a narrower defintion that is a complete subset of the broader definition. For example, PSPs should sample and identify all species; related TSPs for forest inventory can then sample only economic species and identify only to trade groups if the purpose of the inventory is restricted to short-term commercial exploitation. Models developed from the PSPs will be compatible with this TSP database and can be used to project the future yield.

- *A standard area sampling unit should be defined for PSPs, TSPs and experiments.* Because, as discussed in detail in sections 3 and 4, there are different criteria of plot shape that are applicable in different situations, especially for TSPs, this area unit should be a sub-plot unit. A standard 20 x 20 m quadrat is suggested. This common quadrat unit can then allow data from a variety of different TSPs, PSPs and growth and yield experiments to be used and compared on a standard area basis.

2.3.2 Recommended statistical population units for PSPs

2.3.2.1 From the foregoing discussion, the following definitions are recommended for the statistical sampling populations for PSPs.

2.3.2.2 *The area unit for stand parameters should be a 20 x 20 m quadrat.* This can be aggregated to form different sizes and shapes of plots for different purposes, although typical PSPs will be 1-ha units composed of 25 such quadrats, as described in section 3.3.

2.3.2.3 *All trees and all species should be measured*, provided that (1) they are of tree form, not lianes, climbers, shrubs or herbs, and (2) the species normally reach a maximum size in excess of 20 cm diameter. This provides a population definition at the tree level from which sub-populations may be defined for narrower purposes, such as the short-term planning of commercial exploitation.

2.3.2.4 Where the PSPs are being used for research into the production of non-timber forest products or ecological or botanical studies, the above definition may be too narrow. However, such studies are outside the scope of this manual, and can be regarded in practical terms as a re-sampling or sub-sampling of PSPs established primarily for growth and yield studies.

2.3.2.5 At the quadrat level, as defined in 2.3.2.2, *all sizes should be sampled* down to 1.5 m high (effectively zero dbh), by a process of progressive sub-sampling on different qudrats within plots and sub-plots, as described in sections 3, 4 and 7. The predominant weight of sampling will be towards trees greater than 20 cm if the recommendations of section 3.4.3 are adopted, but some sampling will be carried out at all sizes.

3 THE USE OF PSPs FOR DYNAMIC FOREST SAMPLING

This chapter describes in detail how PSPs should be laid out according to a statistical sampling design. It defines sampling versus experimental plots, and discusses criteria for plot shape, size, numbers, internal subdivisions, and the timing of remeasurements

3.1 Introduction

3.1.1 The concept of dynamic sampling

3.1.1.1 Conventional forest inventory provides static data about the forest. PSPs give dynamic information about changes in the growing stock. The concept of coordinated dynamic and static sampling as a part of integrated forest management is discussed by Dawkins (1958).

3.1.1.2 Where the variables to be analysed do not include the time component in their physical dimension, then static sampling will suffice. In such cases, TSPs are generally more efficient than PSPs, with their associated cost of permanent demarcation. Such cases include the evaluation of standing stocks of volumes, tree numbers, basal area, biomass and non-timber forest products, and their classification by geographical or management units.

3.1.1.3 Static sampling also includes allometric or regression sampling, to determine relationships between basic units such as diameter and height, and secondary units such as crown diameter, volume, biomass, etc.

3.1.1.4 The procedures for static sampling in conventional forest inventories are well covered by texts on the subject, such as Lanly (1981) or Loetsch & Haller (1973).

3.1.1.5 Dynamic sampling with PSPs focuses primarily on measuring rates of change. These include diameter and volume increment, tree mortality rate and ingrowth rate. These factors will interact with static parameters, which must also be assessed on PSPs, preferably according to methods or standards that are consistent with their measurement in allometric and inventory studies.

3.1.2 Sampling versus experiments

3.1.2.1 It is useful to distinguish between plots that are part of a sample plot network, and those that form part of a formal experiment. PSPs for dynamic sampling differ from experimental plots (EPs) in that they are primarily concerned with the *detection of dynamic processes and their correlation with spatial variation*, which may include variations in forest type, soils, climate and human influences, including forest exploitation and cultivation.

3.1.2.2 On the basis of these correlations, expressed as suitable empirical mathematical models, inferences may be deduced about how the forest will respond in a more generalized way. In other words, sample plots can provide the data to build a growth and yield model.

3.1.2.3 However, sample plots by definition are constrained to existing conditions. On the other hand, experimental plots can be established to explore novel situations, particularly extreme treatments.

3.1.2.4 Sample plots, when used as the basis for determining the effects of logging or other human influences are often characterized by uncertainty as to the precise treatment to which they have been subjected. In properly devised experimental plots, on the other hand, the nature of the treatments is known with certainty.

3.1.2.5 There is an area of overlap between the sampling and experimental approaches to growth and yield model data acquisition. For example, a large scale field trial of some logging or management technique may be sampled by PSPs as part of its monitoring or evaluation. This involves aspects of both sampling and experimentation.

3.1.2.6 The difference between PSPs used for sampling and experimentation is therefore more one of degree than of kind. Where plots are being designed for sampling of a broad area of forest, then the design criteria in the present chapter are most appropriate. Where they are to be subject to controlled treatments, and may involve intensive measurement, then the section on experimental plots (Chapter 4) gives the most suitable design information.

3.2 Common sampling designs

3.2.1 Systematic designs

3.2.1.1 The simplest method of laying a network of PSPs is to use a systematic grid. A square or rectangular arrangement may be devised, with plots laid at each intersection. For example, if access lines are cut through the forest at a 2-km spacing, and plots are laid along each line at 2-km intervals, then a systematic layout of plots will be made with one PSP every 4 km^2 or 400 ha (Figure 3-1).

3.2.1.2 The advantages of this method are that it is simple to design and implement in the field, the sampling is objective, and the coverage is as uniform as possible.

3.2.1.3 The principal disadvantages are that it does not include any concept of stratification, systematic samples may be biased, and it is not possible to determine sampling error of variables precisely.

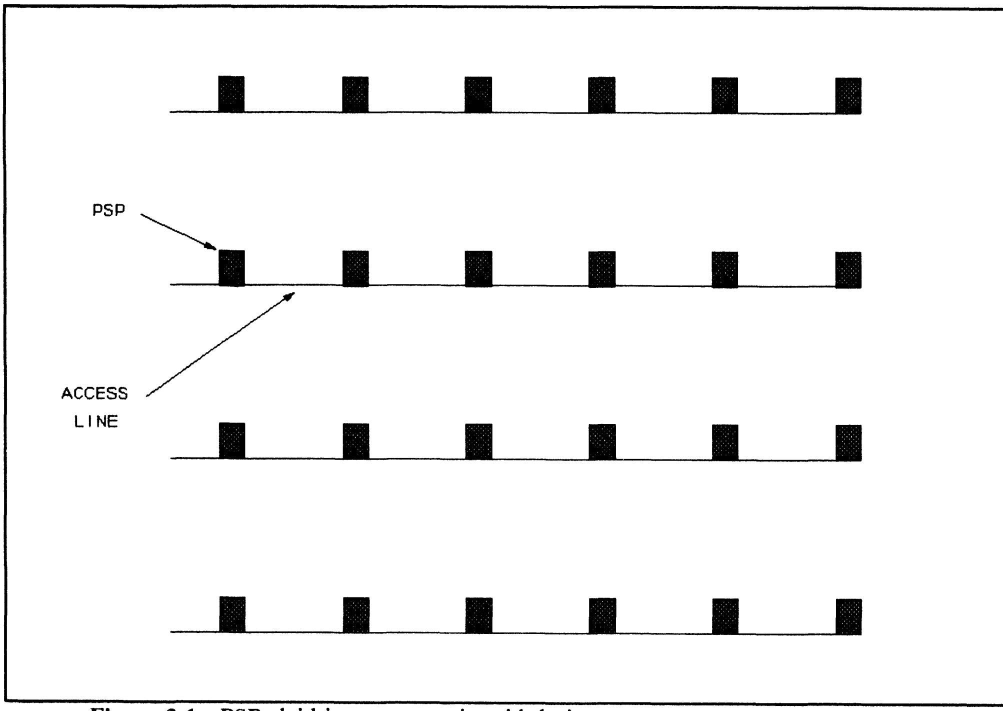

Figure 3-1 : PSPs laid in a systematic grid design

3.2.1.4 Stratification implies that the sampling intensity may be varied in different areas according to the degree of interest or importance assigned to that area. Thus it may be important to sample exploited areas more intensively, with only a small number of reference plots in unexploited forest or protection reserves.

3.2.1.5 *Systematic samples always involve the risk of bias.* If the interval between plots coincides with some periodic natural variation (or indeed if there is *any* uniform periodic natural variation), then the sample will be biased. This risk arises particularly in folded mountainous or undulating topography. The bias may be small in many practical situations; its magnitude will can be determined by comparison of the sample mean with the means of random sub-samples from the data set.

3.2.1.6 *The sampling error due to a systematic sample cannot be precisely calculated.* This problem is discussed in Loetsch & Haller (1973). It is generally concluded from theoretical and simulation studies that the sampling error of a systematic sample is smaller than that of an unrestricted random sample; and may be approximated by various *a postiori* methods of stratifying local groups of plots. Appropriate formulae are given in Lanly (1981).

3.2.2 Unrestricted random sampling

3.2.2.1 PSPs can be laid out according to the principles of an unrestricted random sample (URS), as shown in Figure 3-2. This method is rarely used without stratification, as it is inefficient for large areas, but within a stratum, plots are located as an URS.

3.2.2.2 The method involves deriving two coordinates as random numbers to locate each plot. Random number tables may be used, or the random number generator available in many calculators, or a small computer program. If the pair of coordinates so derived fall outside the required sampling area, then they are rejected and another pair derived.

3.2.2.3 After obtaining a list of suitable plot coordinates, they should be mapped and the shortest route determined to move from plot to plot. This is then converted into a set of field instructions in terms of bearings and distances to travel from plot to plot in the most efficient manner.

3.2.2.4 Although a purely unrestricted random sample is inefficient in that there may be gaps in the forest that are not sampled, and the sampling error will be higher than for a systematic design, the method avoids the possibility of bias, and has an exact theoretical sampling error.

3.2.2.5 When combined with careful stratification, a random sampling scheme will be more precise than a systematic sample (Dawkins, 1958).

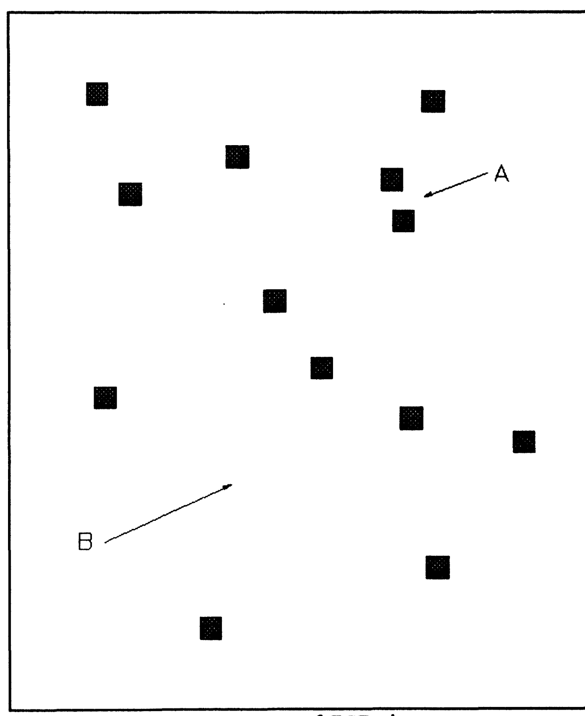

Figure 3-2 : Layout of PSPs in an unrestricted random sample. *(A) Densely sampled region. (B) Area where few plots occur.*

3.2.3 Stratified random sampling

3.2.3.1 In stratified sampling, the forest is divided into a number of zones or strata, that are as homogeneous as possible. Within these strata, plots are located at random as described in section 3.2.2.

3.2.3.2 The strata should be as small as possible, and should be arrived at by a hierarchical subdivision of spatial units. The major unit will normally be the broad forest type, corresponding to major climatic and edaphic zones. This may be subdivided by forest reserve or concession units, or by administrative regions, and further subdivided by felling coupes. If a felling coupe is transected by a known forest type boundary, then it is further subdivided.

3.2.3.3 It is required that the strata so defined are large enough that at least two plots can be placed in every stratum whilst not exceeding the sampling intensity goals of the PSP project. In other words, if the strata are too small, the resultant number of plots may be too great.

3.2.3.4 Where coupe size is very variable or exploitation history and control uncertain, then an effective system of stratification is that reported by Baidoe (1968) and adopted in the Ghana PSP programme at that time. Forest reserves (or equivalent administrative units such as concessions) are divided into blocks 4-km square (1600 ha) and two PSPs are placed in each block located at random, as shown in Figure 3-3.

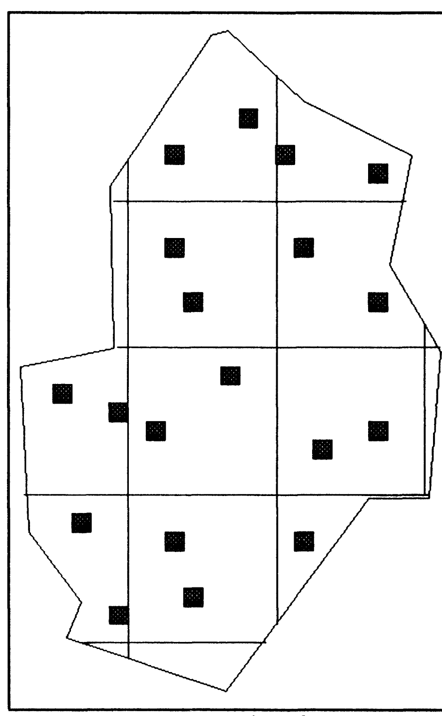

Figure 3-3 : Pairs of PSPs placed at random within artificial grid strata

3.2.4 Two-stage sampling designs

3.2.4.1 A stratified design requires that each stratum be sampled. In a 2-stage design, the primary sampling units are designated in a similar way to strata, as identifiable forest units, based on both silvicultural/ecological and administrative criteria. The blocks may be, for example, forest reserves, concessions, or watershed units. These primary units are termed blocks, rather than strata.

3.2.4.2 A sample is then made of the blocks. This should be made *objectively*, by for example, listing the blocks and then picking at random from the list. The selected blocks are then sub-sampled with PSPs placed as a random or systematic sample. It is possible, though usually unnecessarily complicated, to impose stratification within blocks, or between blocks, or both.

3.2.4.3 The formulae for deriving area means and standard errors from a two-stage sample are given in Lanly (1981) or Loetsch and Haller (1973).

3.2.4.4 The principal advantage of a two-stage design is that limited resources can be concentrated in given areas, and the logistic costs of a highly dispersed PSP program are reduced.

3.2.4.5 A two-stage design is inappropriate when the PSPs are being used as part of a formal system of forest management control and monitoring. In this case, PSPs should be placed in each management unit, and probably in each felling series or block within a unit.

3.2.4.6 It is possible to progress from an initial two-stage design to one involving complete coverage of the forest as resources permit. At the initial stage, sampling blocks are selected and subsampled with PSPs. As further resources become available and the number of PSPs can be increased, the intensity of the first-stage sampling is increased, more blocks are selected, and additional PSPs laid down. Eventually all blocks will be sampled with PSPs, and the two-stage design concept will no longer be necessary.

3.2.4.7 This correlates with the natural progression that may be expected with economic development from a lower intensity of research and management to a higher one. It is therefore possible to recommend that for an initial PSP programme, a two-stage design should be adopted.

3.2.5 Designs involving TSPs and PSPs: Sampling on successive occasions

3.2.5.1 Systems of forest inventory may incorporate PSPs to provide accurate retrospective estimates of net growth and yield on an area basis, with known confidence limits or sampling error.

3.2.5.2 Such methods are based on the theory of two-phase* sampling. One phase is the static forest inventory; another is the regression between static and dynamic parameters provided by the PSPs. The general theory for this type of sampling is that of *sampling on successive occasions* (SSO).

3.2.5.3 A variant of the technique of SSO is *sampling with partial replacement* (SPR). Ware & Cunia (1962) showed that in an SSO system, the most precise area estimates of growth resulted when 50% of the PSPs were replaced by a new set of PSPs after each remeasurement. The system in

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* *Two-phase* and *two-stage* sampling are distinct terms. The former involves the combination of regression estimates and sampling; the latter implies samples within samples.

which some PSPs are dropped from measurement, and a new set established, is known as sampling with partial replacement (SPR).

3.2.5.4 The phrase *continuous forest inventory* (CFI) is treated by some authorities as synonymous with SSO as applied to forest inventory (eg Loetsch & Haller, 1973). More commonly outside North America, CFI is used to cover any system of cyclically updating growing stock information, regardless of the particular statistical basis (Synnott, 1979a).

3.2.5.5 For the purposes of this manual, CFI is taken to include SSO and SPR, together with informal methods for using repeated or cyclic forest inventories for management purposes. However, CFI is not considered to include PSPs laid out only for the acquisition of growth and yield data, without any statistical basis as a forest inventory design. In particular, plots laid haphazardly for research purposes, and not part of a formal sample design, are not a form of CFI; nor are plots on which only a fraction of the growing stock is measured for the purpose of deriving tree increment statistics.

3.2.5.6 Where PSPs are part of a system of CFI, they must serve a dual function. They provide both dynamic and static data about the forest. Both components may be augmented by data from TSPs, and it is important that the design of the PSPs and TSPs, in terms of size and shape, should in such cases be compatible. This does not necessarily imply that they need be identical, but there should at least be a common subunit on both the TSPs and PSPs so that scale-dependent measurements such as competition indices (see section 6.6) can be presented on a common basis.

3.2.5.7 Detailed consideration of the design of CFI systems is outside the scope of this manual. They are generally associated with more intensive systems of forest management practised in plantations and uniform forests, rather than the extensive management of mixed tropical forest. CFI systems are intimately connected with problems of forest management control and monitoring, and with the scheduling and allocation of forest resources under conditions of large-scale industrial exploitation.

3.2.6 A practical recommendation

3.2.6.1 The combination of two-stage sampling with stratified pairs of PSPs provides a robust solution to the problem of sampling design for many situations.

3.2.6.2 As detailed in section 3.2.4, the total area to be sampled should be divided into forest units of the order of 10,000 to 50,000 ha. A suitable basis for formation of such blocks is by forest reserves, administrative districts, timber concessions, or watershed units. Coincidence of block boundaries with pre-existing mapped boundaries is desirable.

3.2.6.3 The blocks are listed, together with their areas. This is most conveniently done with a spreadsheet program such as Lotus 1-2-3. Table 3-1 gives an example. In a single stage sample, plots will be located in each block proportionately to area, using the formula N=a/A x P, where N is the number of plots in the block, a is the block area, A the area of all blocks (Σa), and P the total number of PSPs required.

Block no.	< Single-stage > Area	PSPs	<- Two-stage --> Area	PSPs
1	14241	4	14241	8
2	18440	5		
3	53507	14		
4	20330	5		
5	58473	15	58473	33
6	49350	13	49350	28
7	18120	5		
8	35990	9		
9	55658	15		
10	55059	15	55059	31
Total	379168	100	177123	100

Table 3-1 : Design of a sample by one- and two-stage methods

3.2.6.4 With the two-stage sample, the number of blocks to be sampled is determined from logistic constraints, but must be at least two if error estimates are required (ie the PSPs are to function as CFI plots). The blocks to be selected can be determined in the spreadsheet by the formula:

@IF(@RAND<AREA/$TOTAREA*$BLOCKS,AREA,0)

This formula uses the following symbolic names:

@IF	A function giving the first value after the comma if true, and the second value if false
@RAND	Generates a random number between 0 and 1
AREA	The block area in each corresponding row
$TOTAREA	The sum of the block areas (an absolute cell reference in the spreadsheet, hence preceded by $). This is 379,168 in Table 3-1.
$BLOCKS	The number of blocks required (four in the example in Table 3-1)

This produces the areas for randomly selected blocks in the fourth column of Table 3-1.

3.2.6.5 The fifth column is produced by application of the same formula as in paragraph 3.2.6.3, but using the sum of the areas of the selected blocks as A.

3.2.6.6 These calculations can also be done manually, using random number tables. In this case, each four-digit group of random numbers is preceded by a decimal to give a random number from 0 to 1 (as for the @RAND function).

3.2.6.7 Within the selected blocks, the required number of plots must be allocated, as either a systematic sample, an unrestricted random sample or a stratified random sample. A recommended procedure is to stratify by small rectangular units, and place two PSPs in each unit.

3.2.6.8 If possible, the stratification units should represent demarcated boundaries on the ground (such as compartment boundaries). Otherwise, a grid based on artificial units may be adopted. In the example above, for block 1 there are eight plots to be placed in 14,241 ha. This imples a grid cell of 14241 $\div$ (8/2), or approximately 3,600 ha. A grid of 6-km squares would give a suitable basis for sampling. This grid needs to exist only as a sampling concept, and does not need to be demarcated on the ground or accurately mapped.

3.2.6.9 Alternatively, if there were an existing system of compartmentation based on 130-ha units (½ sq.mile), then two PSPs would be placed in every group of 27 or 28 compartments. Ideally, the boundaries of real stratum units should be allocated to correspond to periodic or annual felling blocks.

3.2.6.10 Within the selected block, the PSPs are located by pairs of random coordinates. For example, if the 600 x 600 m grid is used, then the spreadsheet function @RAND*600 will give a random coordinate from 0 to 600 m. With random number tables, pairs of three-digit numbers can be taken, rejecting any above 600.

3.2.6.11 As a final step, the plot coordinates must be converted into bearings and distances for the survey party. If the survey is to start from a point with coordinates (x_1,y_1) and proceed to a plot at (x_2,y_2), then the distance will be given by $\sqrt{([x_2-x_1]^2+[y_2-y_1]^2)}$. The bearing, if x represents direction East, and y direction North, will be $\tan^{-1}([x_2-x_1]\div[y_2-y_1])$. This resulting angle must be corrected to fall in the appropriate quadrant of the compass.

3.3 Shape and size of plots

3.3.1 Principles governing plot shape

3.3.1.1 Sample plots may be point samples (based on trees counted in a relascope sweep), circular, rectangular, or combinations of these shapes in clusters. All these variants have been used in different situations for either TSPs or PSPs.

3.3.1.2 Point samples involve several difficulties when used as the basis for PSPs, and when used in mixed tropical high forest. The analysis and interpretation of mortality and ingrowth data in such plots involves theoretical difficulties in defining the area conversion factors applicable over time; whilst mixed tropical forest conditions make the sample selection very difficult. For this reason, *point samples as the basis for PSPs cannot be recommended under any circumstances and should be avoided.*

3.3.1.3 Circular plots are widely used in plantations, where their shape is advantageous in avoiding bias due to the regular arrangement of tree rows (Philip, 1983, p.216). In mixed forest, they have sometimes been used for inventory purposes, as TSPs, and have been adopted as PSPs in the Philippines (Canonizado, 1979, Revilla, 1981). In practice, circular plots are difficult to demarcate if larger than 0.1 ha (approximately 18 m. radius) except in very open woodland formations, and are therefore unsuitable for large plots. Other factors mitigate against the general adoption of small plots for PSPs, and hence *in general circular plots are unsuitable for PSPs in mixed tropical forest.*

3.3.1.4 Rectangular plots may be subdivided into those that are generally linear, with a length to width ratio (L/W) greater than 10, and those that approach a square shape, with L/W approaching or exactly 1.

3.3.1.5 Linear plots are widely used in forest inventory, and have some advantages in that situation in minimizing demarcation costs by combining the processes of plot demarcation and cutting of access lines. However, linear plots are very susceptible to error in area estimation, if the width is not exactly regulated, or if edge trees are not treated according to a carefully prescribed procedure. More importantly for PSPs, the edge of the plot is an anomolous zone for the calculation of competition indices. On a long linear plot, most of the trees will be subject to competition primarily from trees outside the plot and not included in the data. *Because of the difficulties of edge effect bias and competition index calculation, it is better to avoid using linear PSPs.*

3.3.1.6 Square plots, or those of broad rectangular shape (length/width < 2) are most suitable for PSP work in mixed tropical forests, and have been widely adopted. In dense forest, they are faster to demarcate than circular plots, and the square shape minimizes edge effects. *Square plots are generally recommended for PSP work in mixed tropical forest.*

3.3.2 Principles governing plot size

3.3.2.1 In general, with any sampling, precision of estimates increases with the number of sample points, irrespective of size. This is because the standard error of an estimate is equivalent to the standard deviation of the population divided by the square root of the number of samples. Hence standard error declines directly as the number of samples increases (Lanly, 1981, page 179).

3.3.2.2 Therefore, for a given sampling fraction, a smaller plot size will be more efficient. However, mixed tropical forest is notably heterogeneous at the local scale, so that variance increases as plot size decreases. Experience suggests that a plot size of 1 ha is a suitable compromise for sampling purposes (Lanly, *op. cit.*).

3.3.2.3 A square 100 x 100 m plot (1 ha) is, as noted by Synnott (1979a), convenient for subdivision into quadrats of 20 x 20 m or 10 x 10 m, and corresponds closely with older series PSPs established in imperial units of measure as 5 x 5 chains (2.5 acres or 1.01 ha.), giving directly comparable data series.

3.3.2.4 There are also cost constraints on the adoption of small plots. There is a fixed cost, or overhead, for any PSP regardless of size, for the survey of the access line. This cost is associated with unproductive time in terms of measurement, and should be minimized relative to time spent measuring trees. This is best achieved with fewer but larger plots.

3.3.3 Compatibility requirements in CFI

3.3.3.1 Where the PSPs are being established as part of a system of CFI which also involves TSPs, then *there should be compatibility of shape and size between the TSPs and PSPs.* Otherwise, projections and regressions involving per hectare units may be biased, particularly where competition indices (which are subject to edge effects) are involved.

3.3.3.2 This requires that there is some compromise between the optimum requirements for the static inventory (TSPs) and the dynamic phase (PSPs). For TSPs, a linear plot unit is preferable (length (L)/width (W) ≥ 10), whilst for the PSP L/W should be 1 (*ie.* a square plot).

3.3.3.3 A suitable compromise may be, in such cases, to adopt a broadly rectangular unit, with L/W ≈ 4, such as a plot 50 x 200 m. This shape is then used both for the TSPs and the PSPs in the CFI system.

3.3.3.4 Alternatively, area estimates such as basal area and volume/ha can be calculated and expressed via a common sub-unit on both the PSPs and TSPs. For this purpose, the 20 x 20 m quadrat is suitable. Linear plots 20 x 500 m or 40 x 250 m can be divided into such quadrats, just as the 100 m square PSP design can. The basic requirement is that in recording data on both the TSP and PSP, the quadrat identity is known. This will normally be the case for a PSP, but such quadrat information is often not recorded for inventory data.

3.3.3.5 It is often the case in practice that PSPs and TSPs are established without any formal linkage, and often by different organizations. PSPs are often regarded as a research activity, whilst forest inventory may be a component of forest management. In this case, plot size and shape are frequently incompatible. *It is desirable, in such cases, that every effort is made to adopt a common plot subunit (such as the 20 x 20 m quadrat).* This allows growth and yield projections to be made from this basic subunit without involving an unknown bias due to different bases for the calculation of competition indices on the PSPs and the TSPs.

3.3.4 Some examples of PSP shape and size

3.3.4.1 In Uganda, some 70-80 PSPs where established in Budongo and other forest reserves based on designs by Eggeling (Eggeling, 1947; Dawkins, 1958). These were 5 x 5 chain square plots, totalling 2.5 acres, or 1.012 ha. The same shape was adopted by Baidoe (1968) for an extensive series of plots laid in Ghana; in all, some 700 PSPs were laid down according to this design.

3.3.4.2 This 2.5-acre square plot was adopted in Sarawak in metric form for the assessment of some experimental trials (Korsgaard, 1982) as a 100 x 100 m plot. Other trials were assessed using a 50 x 50 m PSP. The basic quadrat on both types of plot was 10 x 10 m. In Sabah, Fox (1970) also reported the establishment of PSPs according to Dawkins (1958) recommendations, as 5 x 5 chain plots (1.01 ha) sub-divided into 1 chain (20.12 m) square quadrats.

3.3.4.3 Current PSPs being established in Ghana are also 100 x 100 m plots, laid down according to the recommendations of Synnott (1979a). These are closely compatible in size with the older series 2.5-acre plots, and differ mainly in the internal measurement protocols. Some 700 such plots will be laid down in a programme extending to 1993.

3.3.4.4 Some 298 PSPs were laid down in four states of Peninsular Malaysia between 1956 and 1965 according to a design described by Sandrasegaran (1965). The analysis of some data from these plots is reported by Tang (1976). The plots were of 1 acre (0.4047 ha.), linear in design, 10 chains long (201.2 m) by 1 chain wide (20.1 m).

3.3.4.5 In Karnataka state, India, Rai (1982) described the use of linear plots 20 m wide (probably originally 1 chain) that were established in 1939 and have been remeasured periodically since. The plots extend over distances of 380 to 1320 m. These plots are described as Tree Increment Plots, and the emphasis is on individual tree growth rates, rather than the measurement of changes in stand parameters, for which they are clearly not designed.

3.3.4.6 In the topical rainforests of Queensland, Volck (1968), reported on the use of linear plots prior to 1939, which was thereafter amended to the use of rectangular plots 0.5-acre plots.

3.3.4.7 Circular plots of 0.1 ha (17.8 m radius) were used in the Philippines, as reported by Canonizado (1979) and Revillea (1981). More than 3000 of these plots were laid down, but many were lost and not remeasured.

3.3.4.8 Kjellsen (1991) recommended the use of large circular plots of 30 m radius (0.2827 ha.) for work in the woodlands of northern Botswana. These PSPs are laid as part of a CFI system. One PSP is laid together with three TSPs in a square tract of 300 m. The design is suitable for open woodland, but would be difficult to apply in closed forest. It follows work by Geldenhuys (1990) in similar forest in Namibia.

3.3.5 Recommendations for plot shape and size

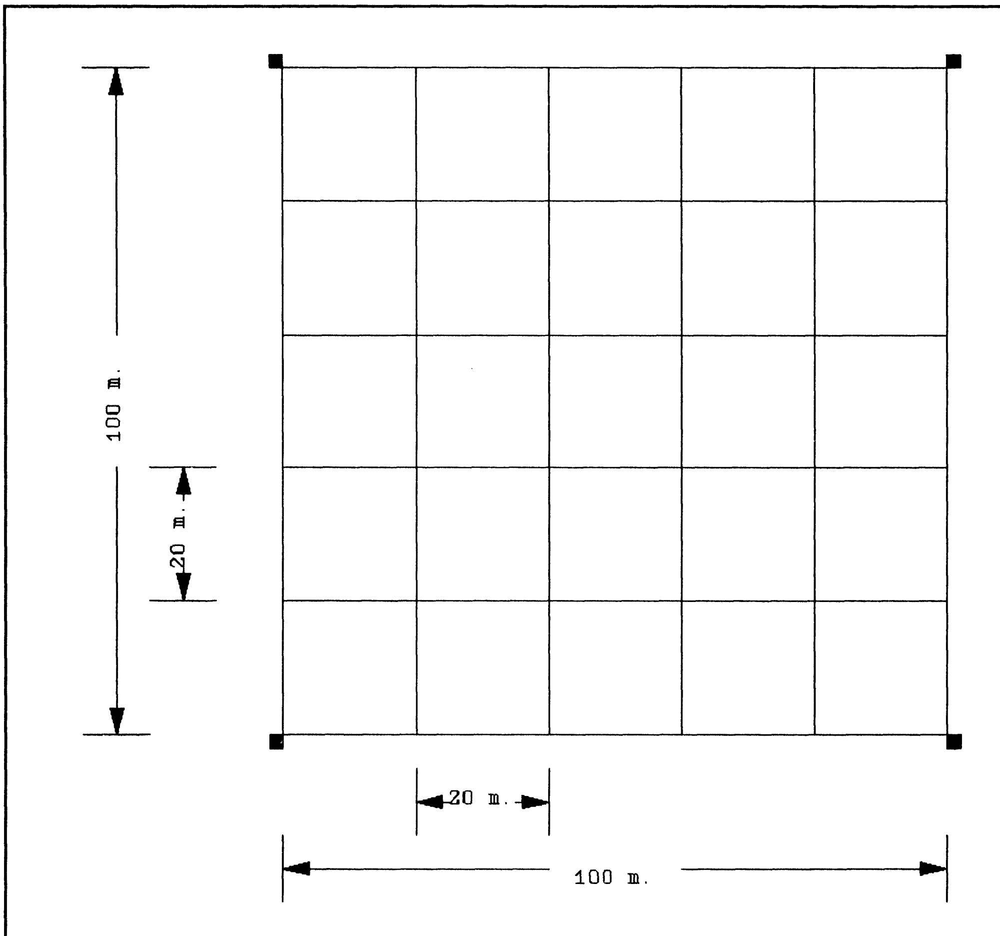

Figure 3-4 : Recommended standard 100 x 100 m plot

3.3.5.1 Synnott (1979a) recommended the use of a 100 x 100 m square plot (1 ha), subdivided into 25 quadrats, each of 20 x 20 m. This is probably the most practical unit to adopt in dense mixed tropical forest.

3.3.5.2 Where continuous forest inventory is planned, using both TSPs and PSPs, then a plot 40 m wide by 240 m long is suitable for inventory purposes, and can be subdivided into 20 x 20 m quadrats, which are compatible with the square PSP.

3.4 Plot subdivisions and tiers

3.4.1 Subdivisions as record units

3.4.1.1 Large plots require to be subdivided internally in order to organize and control the process of demarcating and measuring the plot. For the 1-ha square plot, 20 x 20 m quadrats provide a convenient working size. The maximum dimension in any direction of a record unit should not exceed visibility through the closed forest, which is typically 20-40 m.

3.4.2 Subdivisions as a basis for scale-dependent parameters

3.4.2.1 Measurement of stand parameters are generally somewhat scale-dependent. For example, if the number of trees per hectare is measured on a small plot (say 0.01 ha) it may vary between zero (if no trees are present) and a very large number, if one or two large trees are sampled. The same measure on a large plot will be much more uniform.

3.4.2.2 For example, in the West African MTF, *Ceiba pentandra* commonly occurs as a large tree with a diameter in excess of 200 cm. In such forest in Ghana, 1-ha inventory plots do not anywhere exceed 45 m^2/ha basal area (Alder, 1990). However, with small 0.04-ha plots, basal areas of 78.54 m^2/ha would occur if stocked by a single tree of 200 cm dbh. A measure of competition that is calculated relative to maximum basal area on a set of sample plots will have larger values if the larger plot size were used.

3.4.2.3 For this reason, there is a need to have a plot subdivision that can serve as a basic unit for the forest stand for growth modelling purposes. This should not be smaller than the area occupied by the crown of a single mature tree. For this purpose the 20 x 20 m quadrat is suitable, whereas a 10 x 10 m quadrat is probably too small. As has been noted previously, this basic subdivison should be retained also on inventory plots (TSPs) for compatibility of data.

3.4.3 Tiered plots and measurement size thresholds

3.4.3.1 Diameter distributions in selection-managed naturally regenerating forest normally follows a negative exponential distribution. Dawkins (1958), using data from various sources, calculated a pan-tropical stand table. This is shown in Table 3-2. The column headed *PTM N/ha* is the data from Dawkins' pantropical averages. These are converted into Q or De Liocourt ratios in the column *Q Obs* (see Philip, 1983, p.163), and from the regression of Q on diameter class (*Q Pred*), the numbers of trees that would be found in the smallest classes are estimated. From this are calculated the total number of trees to be measured on the plot above a given minimum diameter (*Cum N/ha*), and the time required in hours.

Class MidPt	PTM N/ha	Q Obs	Q Pred	Est N/ha	Min diam	Cum. N/ha	Hours reqd.
5				708	0	1157	105
15			2.80	253	10	448	41
25	101		2.57	98	20	195	18
35	42	2.40	2.34	42	30	97	9
45	20	2.10	2.11	20	40	55	5
55	11	1.82	1.87	11	50	35	
65	7	1.57	1.64	7	60	24	
75	5	1.40	1.41	5	70	18	
85	4	1.25	1.18	4	80	13	
95	2	2.00	0.95	4	90	9	
>100	5			5	100	5	

Table 3-2 : Cumulative numbers of trees expected on a 1-ha plot given different minimum size thresholds, from Dawkins (1958) pantropical stand table

3.4.3.2 This calculation gives an indication of how the work time on the plot may be expected to increase as the diameter threshold is reduced. With a 40-cm threshold, and a single party working for tree marking and measurement, time will be about five hours (five minutes per tree). This does not include demarcation of the access line or the plot and quadrat boundaries. Normally this time will be shortened by separating the marking and measurement processes, to about two hours.

3.4.3.3 *For each 10-cm reduction in size limit, working time approximately doubles.* These estimates are reasonable for woody stems, but should not be taken to include regeneration below 1 cm diameter, which may be much more numerous. Thus, even with two parties, measurement to a 10-cm threshold would take about three days (20 hours), whilst measurement of poles and saplings below this limit might take more than a week.

3.4.3.4 In order to keep total measurement time to a reasonable limit per plot, whilst still sampling the whole tree population, it is necessary to use a tiered plot, in which a subplot is specified for measurement to a lower threshold than the main plot.

3.4.3.5 *It is generally practical and desirable to specify 20 cm as the minimum diameter limit on the whole plot.* This allows two measurement teams to complete a plot in one day. This limit may be reduced in uniform forest, where the stocking of the smallest size classes is often lower than the pantropical average, or in undisturbed old forest, in which, similarly, the smallest sizes will tend to be less frequent.

3.4.3.6 For trees in the range 5-20 cm, an 0.2-ha subplot is suggested. This will require a working time of approximately one day for a special team that only marks and measures the small trees below 20 cm. They will normally not carry ladders, and can work more quickly than the large-tree measurers.

3.4.3.7 It is desirable, though often not practicable, to measure trees in the range 1.5 m high to 5 cm diameter, and also regeneration (trees below 1.5 m high). If it is possible to do this (*ie.* given adequate resources), then the trees below 5 cm can be measured on a central quadrat (1/25th of the whole plot), whilst regeneration can be measured on strips within this quadrat. The procedures are discussed in detail in section 7.

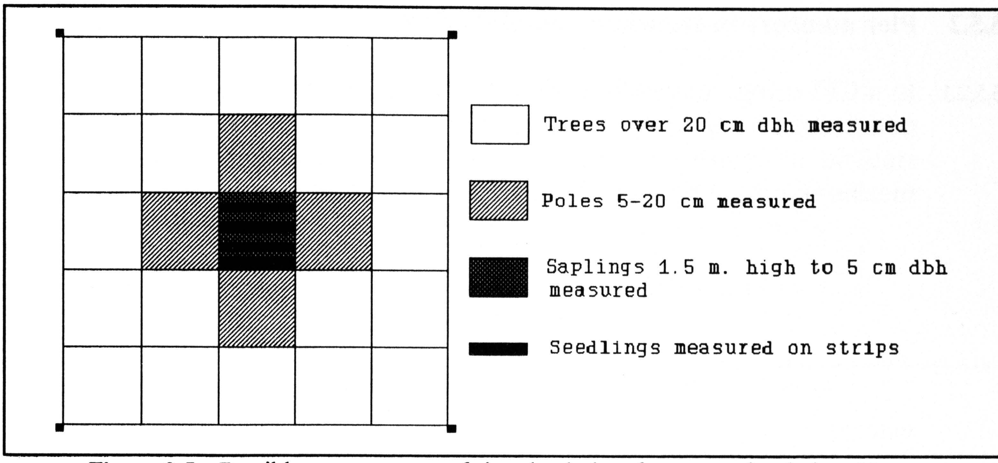

Figure 3-5 : Possible arrangement of tiered subplots for measuring below 20-cm and 5-cm thresholds on a 1-ha square plot.

3.5 Sample size: plot numbers

3.5.1 Numbers of plots and precision in static inventory

3.5.1.1 The numbers of sample plots required to achieve a given level of precision in a forest inventory can be calculated from the equation:

$$N = \left(\frac{CV}{p}\right)^2 \qquad \{\text{eqn.3-1}\}$$

where N is the required number of plots, CV is the coefficient of variation of the variable of most concern (eg. commercial volume), and p is the acceptable limit of precision (eg 10%, p=0.10). This applies to an unrestricted random sample (Philip, 1983, p. 243).

3.5.1.2 In applying this formula, the coefficient of variation (CV) is first determined by a pilot study, using a small number of plots. From this, the number of plots required for the full inventory can be calculated. The plot size and shape must be unchanged between the pilot study and the full inventory, as this will influence the CV, which will be lower with larger or more linear plots.

3.5.1.3 However, *this method of determining sample size is not appropriate for estimating numbers of PSPs*, except in the unusual case of PSPs used as the sole basis for a system of CFI (*ie* without supplementary TSPs). PSPs are intended to provide parameters for an estimate of future yield. It is the accuracy of this forecast which is the critical factor in determining the numbers of plots required.

3.5.2 Plot numbers in recurrent sampling designs

3.5.2.1 In a CFI using both PSPs and TSPs, the optimum number of PSPs can be determined from the correlation coefficient between the volume (or other statistic of interest) at the first measurement and the volume at re-measurement. The formula given by Philip (1983, p. 270) is:

$$\frac{n_p}{N} = \frac{(1-r^2)}{r^2}\left[\sqrt{\frac{c_t}{c_p}} + \sqrt{(1-r^2)}\right] \qquad \{eqn.3\text{-}2\}$$

where:

r	is the correlation coefficient between 1st and 2nd measurement,
n_p	is the number of PSPs,
N	is the total number of plots (TSPs + PSPs)
c_t	is the cost of a TSP, and
c_p	is the cost of a PSP.

3.5.2.2 This formula can be used to give some idea of the numbers of PSPs appropriate for forest management forecasts using a growth and yield model. Projections for management and planning purposes are likely to be made over long periods (25-100 years), whereas actual plot data will frequently only extend over 5-15 years. Hence, direct use of the correlation coefficient over the actual period of observation is likely to be too optimistic.

3.5.2.3 An estimate can be made of the true correlation coefficient by constructing the simulation or growth model as a Monte Carlo model, including random components. From this, a set of PSPs are 'grown' over the projection period, and a correlation derived between the Monte Carlo projections and the original volumes (Shannon, 1975, Chapter 6). This is the appropriate statistic to apply to equation {eqn.3-2}.

3.5.2.4 Values from equation 3-2 are graphed in Figure 3-6 below. This shows the optimal proportion of PSPs with different correlation coefficients between projected volumes and initial volumes. Lines are plotted for TSP:PSP cost ratios from 1:1 to 1:6. In the typical range of PSP costs (1:3 to 1:6), the curve is not very sensitive to this factor.

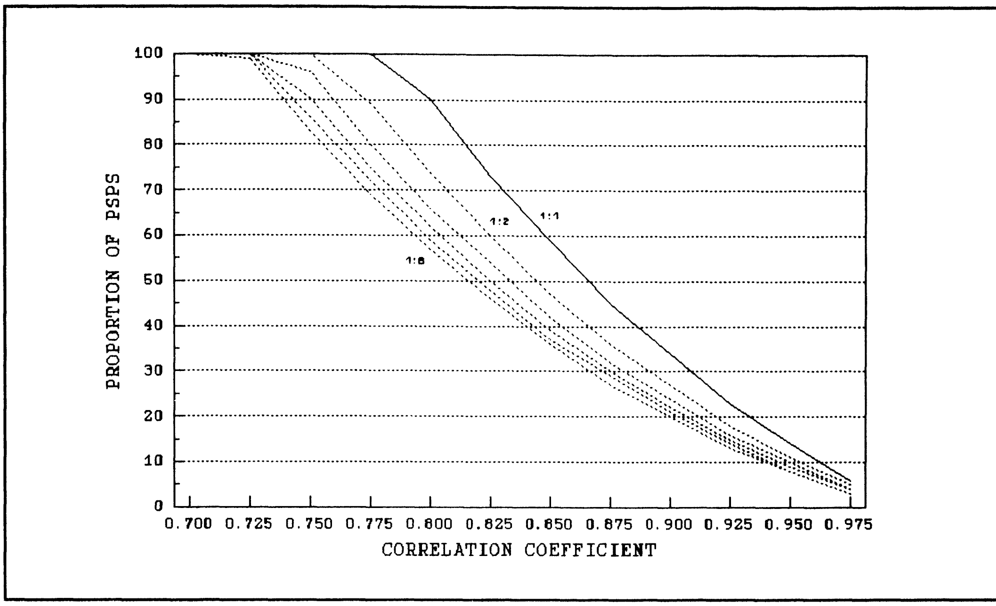

Figure 3-6 : Optimal proportions of PSPs with different model correlations

3.5.2.5 The graph shows that if the correlation of the future with present value is less than 0.8, then PSPs should be used for all plots. As the correlation increases, the proportion of PSPs may be reduced. An effective yield model should be able to achieve a correlation between starting conditions and projections of better than 0.90 ($R^2 \geq 0.81$), suggesting that in the typical cost range about 20% of plots should be PSPs.

3.5.2.6 Management level inventories typically operate with sampling intensities of the order of ½%. This suggests an appropriate density for PSPs of 0.1% of the area (20% of all sample plots), or a 1-ha plot in every 1,000 ha of forest. A 4-5 km square grid (1,600-2,500 1-ha squares) with two randomly placed plots per grid square achieves this approximate level within an efficient design.

3.5.3 A regression sampling approach to plot numbers

3.5.3.1 A growth and yield model may be, in a simple case, a simple regression model of yield on years since logging, logging intensity, and production class or site index (eg Canonizado, 1979). In this case, the numbers of plots required to achieve a given level of confidence for predictions can be determined from a preliminary set of regression statistics.

3.5.3.2 From multiple regression theory, equation 3-3 gives confidence limits for an estimate obtained from the regression (Draper & Smith, 1966, p.121):

$$SE_{\hat{Y}} = s\sqrt{\frac{1}{n} + X_0'CX_0} \qquad \text{\{eqn.3-3\}}$$

where SE_Y is the standard error of a predicted value Y, s is the regression standard deviation, n is the number of data points (sample plots), X_0 is a vector of independent variables, and C is the covariance matrix from the regression.

3.5.3.3 This is not of direct assistance in determining, *a priori*, how many PSPs should be established. Given, however, some PSP data, it may assist in indicating how many additional plots are required to achieve given levels of precision. The situation is complicated by the fact that the precision of the predictions depends very much on how the sample points are distributed. This is not obvious from equation 3-3, but for the simple case of a regression with 1 independent variable, equation 3-3 can be written as:

$$SE_Y = s\sqrt{\frac{1}{n}+\frac{(x_0-\bar{x})}{\Sigma(x_i-\bar{x})}} \qquad \text{\{eqn.3-4\}}$$

3.5.3.4 This shows that as a predicted point x_0 is further from the mean $\bar{x}$, so the standard error of the prediction will increase. It also shows that if the data points x_i are close to the mean, then the sampling error of predictions will also be larger. Thus the further the data points are from the mean values of the dependent variables, the more precise any resultant projections are likely to be (Draper & Smith, 1966, p.22).

3.5.3.5 From this may be concluded the fact that the distribution of PSPs over a range of values that are likely to be of predictive value in a model or regression is as important as the number of plots themselves. The PSPs should be distributed over the most extreme situations likely to be found, from stands of the highest to lowest stocking, from best to worst sites, from those immediately after logging to those completely unlogged. It is more important to target the extreme situations, than to place replicates of plots in the middle range of forest conditions.

3.5.3.6 The formulae for sampling error for regression predictions cannot be applied directly to more complex models that are commonly used in growth and yield studies. These usually involve combinations of single-tree and stand functions, together with some arbitrary and assumed components of indeterminate statistical precision. The only way to determine sample plot numbers for such models is via validation studies in which model outputs are compared with actual results from an independent data set. This process of itself implies the existence of a considerable body of data, and is not feasible at an early stage in a programme for the establishment of PSPs.

3.5.4 Pragmatic recommendations for plot numbers

3.5.4.1 Given the lack of any clear theoretical basis for determining at the outset numbers of PSPs required for growth and yield studies, it is necessary to arrive at recommendations on a pragmatic basis.

3.5.4.2 Synnott (1979a) recommended an initial sample plot programme of 50-100 PSPs. This provides a minimum basis for growth and yield work. However, a larger number of plots is required if all the diverse range of factors that contribute to and influence growth are to be properly explored. It is probably desirable to aim at an end objective of the order of 1,000 PSPs at a national level, well distributed over sites and forest types.

3.5.4.3 The total number of plots will also depend on the total forest area to be sampled. An intensity greater than one PSP in 100 ha exceeds what is necessary even for management inventory, whilst densities lower than one plot per 1,000 ha can only contribute directly to growing stock estimates if supplemented by other types of inventory (remote sensing, aerial photography, or TSPs).

3.5.4.4 Table 3-3 combines these three factors (a minimum of 50 plots, a maximum of 1,000 plots, and typically one plot per 1,000 ha) to give total plot numbers to be established in areas of managed tropical high forest. As the area totals are not additive, using the figures from table 3-3 on several project sites might involve an excessive number of plots at a national level.

Table 3-3 : Recommended numbers of PSPs

Forest or project area	Number of PSPs
< 50,000 ha	50
50,000 - 1,000,000 ha	1 PSP per 1,000 ha
> 1,000,000 ha	1,000

3.5.4.5 In pragmatic terms, a PSP programme aiming to establish and maintain 750 to 1,000 PSPs is feasible for many forestry organizations. A single well-motivated team can demarcate 150 plots per year; established and remeasured on a 5-7 year cycle, this totals to 750-1,050 plots.

3.5.4.6 In larger regions of tropical forest, this number of plots may not ultimately be sufficient. However, it will provide a basis for determining via statistical and simulation studies, what order of precision can be achieved and what the ultimate numbers of plots should be to satisfy given management and research objectives.

3.6 The timing of measurements

3.6.1 Interval of remeasurement and precision of estimates

3.6.1.1 Diameter, measured conventionally by diameter tape, cannot be recorded more precisely than to the nearest millimetre. The absolute error which occurs when different operators measure the same tree repeatedly can be determined by field trials, but is likely to be of the order of 1% of diameter (ie 1 mm on a 10-cm tree, or 1 cm on a 100-cm tree).

3.6.1.2 Diameter growth rates vary greatly, but are typically in the range 1-20 mm per year for a range of species in closed forest. Consequently, measure-

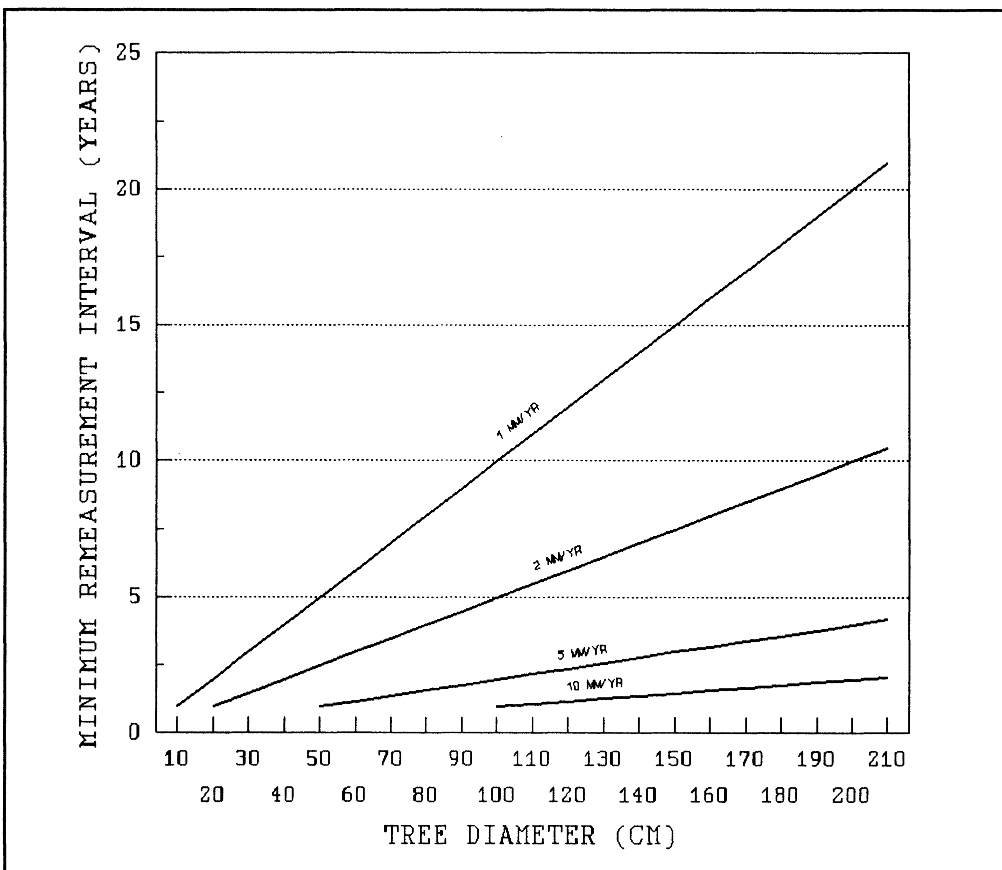

Figure 3-7 : Minimum remeasurement intervals for different tree sizes and growth rates, based on typical accuracy of diameter tape measurement

ments over an interval of one or two years on large trees will not give meaningful results for individual tree analysis, although large sample means may have some utility. Figure 3-7 shows how this 1% precision influences the minimum remeasurement interval for trees of different average growth rate and size. It is based on the premise that for a meaningful measurement of increment, it should be greater than instrument error (ie 1% of tree diameter) over a given period.

3.6.1.3 The figure indicates that a remeasurement interval of 5 years will be satisfactory for the majority of cases. Low increments, of the order of 1-2 mm per year, are usually associated with small understorey trees. Emergent or upper canopy species of larger dimensions will generally have increments above 5 mm, which can be determined with reasonable precision over a 5-year interval.

3.6.1.4 *It is therefore generally recommended that a standard remeasurement interval of 5 years should be adopted.* Shorter remeasurement intervals are likely to have too high a level of error in the increment estimates to give useful data.

3.6.1.5 Notwithstanding the above recommendation, *a shorter interval of two or three years for the first and second remeasurements may be desirable*, to develop and confirm field procedures and data processing methods for the remeasurement data, and to provide some preliminary results, albeit with a high error component.

3.6.1.6 The criteria affecting the precision of ingrowth and mortality are different and less critical than for diameter increment estimation. Ingrowth is estimated from current diameter relative to a fixed and absolute standard (usually 20 cm, although possibly 5 or 10 cm on tiered subplots). Consequently, the measurement error is about half that of diameter increment (which is a difference between two diameters, both with an error component). Useful ingrowth measurements may therefore be made over intervals of 2-3 years, as against 5 years for diameter increment.

3.6.1.7 Mortality also has an absolute quality. Trees are either dead or alive, and except for apparent death following fire, there is usually little room for doubt. As mortality is a process of great importance in stand dynamics, which may vary rapidly following logging or catastrophes (Tang, 1976), it may be desirable in special studies to assess mortality annually. This can be done more rapidly, and with fewer personnel, than a full plot enumeration.

3.6.1.8 For general sample plot work, the costs of relocating and re-entering the plot do not favour the use of different measurement intervals for different stand or tree parameters. In experimental plots, different measurement intervals may be a useful method of accelerating the acquisition of data, whilst annual assessement of mortality may be a necessary part of post-logging studies. This is considered in more detail in section 4.

3.6.2 Timing of remeasurements relative to forest operations

3.6.2.1 *It is preferable for PSPs to be established and measured immediately prior to logging*, and thereafter re-measured at 5-year intervals. A partial remeasurement should be made of the plot immediately after logging to replace corner posts or pillars, and to record the identification numbers of trees logged and significantly damaged.

3.6.2.2 This sequence of measurement gives more useful information than one using plots established after logging. It allows the intensity of logging to be determined objectively for the plot. Otherwise, logging intensity can only be inferred from stump diameters, and then only if measurement begins shortly after felling (as stumps of non-durable species will rot quickly and may be invisible after five years).

3.6.2.3 Similarly, if logging is conducted in forests that have established series of PSPs, then reporting mechanisms should exist or be established between the forest management authority and the organization responsible for the PSPs to ensure that the latter are notified of the timing of logging operations. Remeasurements should then be scheduled immediately before felling, with check assessments immediately after felling.

3.6.2.4 Similarly, remeasurements should be timed to coincide with silvicultural operations that may effect mortality and growth. It may be convenient to combine the assessment of plots with their silvicultural treatment.

4 GROWTH AND YIELD EXPERIMENTS

This chapter discusses why growth and yield experiments are needed to supplement conventional PSPs. It describes applicable statistical designs, and treatment specifications for various types of growth and yield experiment. It considers the multi-role nature of long-term experimental plots. Criteria, examples and recommendations for experimental plot shape and size, subdivisions, surrounds and numbers of replicates are given.

4.1 Introduction

4.1.1 The need for experiments

4.1.1.1 Many of the individual tree and stand relationships required to construct a growth and yield model can be determined from a suitable series of PSPs, laid down as a sample according to the principles discussed in section 3.

4.1.1.2 There are however cases where an experimental approach is advantageous. These include situations where:

- complex or expensive apparatus or measurements must be used,
- the time available for the investigation is strictly limited,
- treatments are required that are not performed in operational practice, and therefore cannot be covered by a sample,
- a rigorously defined hypothesis requires an experimental approach for evaluation.

4.1.1.3 If the methods of measurement rely on complex procedures or expensive instruments, such as girth bands, integrating photometers, detailed measurements of crown parameters or regeneration, then they will be very difficult and expensive to apply on a large number of PSPs in a sample, and must be restricted to a sub-sample or experimental site that can be closely monitored and managed.

4.1.1.4 Similarly, if growth and yield studies are constrained by the need to produce results within a short-term project (less than 5 years), then the use of an experimental site will reduce the time and costs involved in locating PSPs over a wide area, whilst still offering an objectively derived data set. An experimental site will eliminate much environmental variation from a sample, and will therefore allow key factors in a growth and yield model to be identified more precisely.

4.1.1.5 Probably the major justification for an experimental approach is that it allows treatments to be tested that are not performed in operational practice. This may involve novel types of logging method, the use of liberation thinnings, enrichment plantings, the retention of seed trees, or any other variant on standard silvicultural practice within a forest area.

4.1.1.6 If a hypothesis is rigorously defined with a statistical or mathematical formulation, then it may be determined that an experimental, rather than a sampling approach, is required to test it or define its coefficients. For example, if one wishes to prove that climber cutting reduces logging damage, then a statistical null hypothesis can be established (that climber cutting has no effect). A suitable experiment, perhaps with a split-plot design can test this efficiently and properly.

4.1.2 Hybrid situations: Experiments evaluated by sampling

4.1.2.1 As has been noted in section 3.1.2, some experiments may involve the conduct of treatments on a large scale, with their subsequent evaluation by sampling. This is likely to apply in cases involving evaluation or comparison of logging techniques, fire control, and other management practices which cannot be effectively applied on a small scale.

4.1.2.2 In these hybrid situations, the experimental design and allocation of treatments follows the principles decribed in this chapter. Within each treatment area, PSPs will be located using the criteria described in section 3.

4.2 Statistical design

4.2.1 The need for correct statistical design

4.2.1.1 Many experiments in mixed tropical forest have been conducted with unclear objectives and indefinite results (Synnott, 1979b). This situation arises from several factors including lack of replication, lack of control plots, variable and inconsistent plot sizes, treatments and measurement methods, variations in treatment over time, changes in the definition of the measured population, a failure to keep records of treatments, and a lack of any clearly defined hypothesis or model as the subject of the experiment.

4.2.1.2 The present volume provides a simplified approach to the design of growth and yield experiments in mixed tropical forests, by offering some common approaches to follow for establishing experiments that will lead to useful results.

4.2.1.3 However, if these standard designs are varied, it is essential to consult a statistican or have a sound knowledge of the principles of experimental design as described in text books such as Cochran & Cox (1957), Snedecor & Cochran (1967), or Maxwell & Delaney (1990).

4.2.1.4 If experiments are not properly designed it is often difficult to draw any conclusions from them. Consequently, the entire effort of the experiment, which may have been maintained over years or decades, will be to no purpose.

4.2.2 Split plot experiments

4.2.2.1 Split plot experiments are perhaps the simplest experimental design in concept, and are useful in examining whether a single type of treatment has any effect. They can answer the following questions:

- *Does the specified treatment produce any significant result ?*
- *What is the mean level of the effect produced by the treatment ?*

4.2.2.2 The split plot experiment may look like the example shown in Figure 4-1. A number of plots are laid down as an unrestricted random sample. Each is divided into half, and one half or the other selected at random for treatment. Within each plot, a smaller measurement plot is established (see section 4.4).

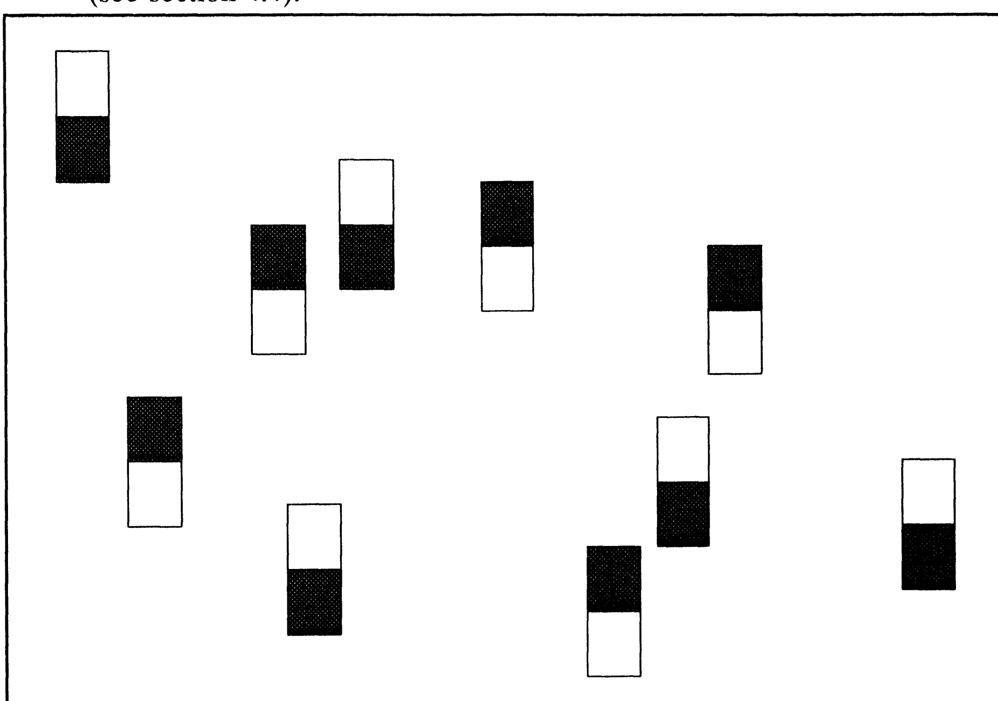

Figure 4-1 : A typical split plot experiment with 10 pairs of randomly located plots. One of each pair is randomly selected for treatment; the other is a control.

4.2.2.3 The split plot experiment is limited to a single type of treatment within one experiment. The example has been given in paragraph 4.1.1.6 of using such a design to see whether climber cutting prior to felling reduces logging damage.

4.2.2.4 Because of the long-term nature of growth and yield research, such a limited type of experiment is not much favoured. It is desirable to be able to combine multiple alternative treatments in a single experiment.

4.2.3 Randomized block experiments

4.2.3.1 Randomized block designs generally are the most appropriate layouts for growth and yield experiments in mixed tropical forest. Jeffers (1978) asks "*Have you considered the advantages of robustness and ease of analysis of a randomized block design ?*".

4.2.3.2 In a randomized block design, several different treatments can be accommodated. These may be graded treatments, such as different intensities of felling, or qualitatively different treatments. This type of experiment uses a number of blocks, each of which is one replicate of the experiment. Within each block, several treatment plots are established.

4.2.3.3 *The blocks should be located in such a way that the environmental variation between blocks is greater than the variation within blocks.* For example, each block may be located in different forest type, felling series, or site type.

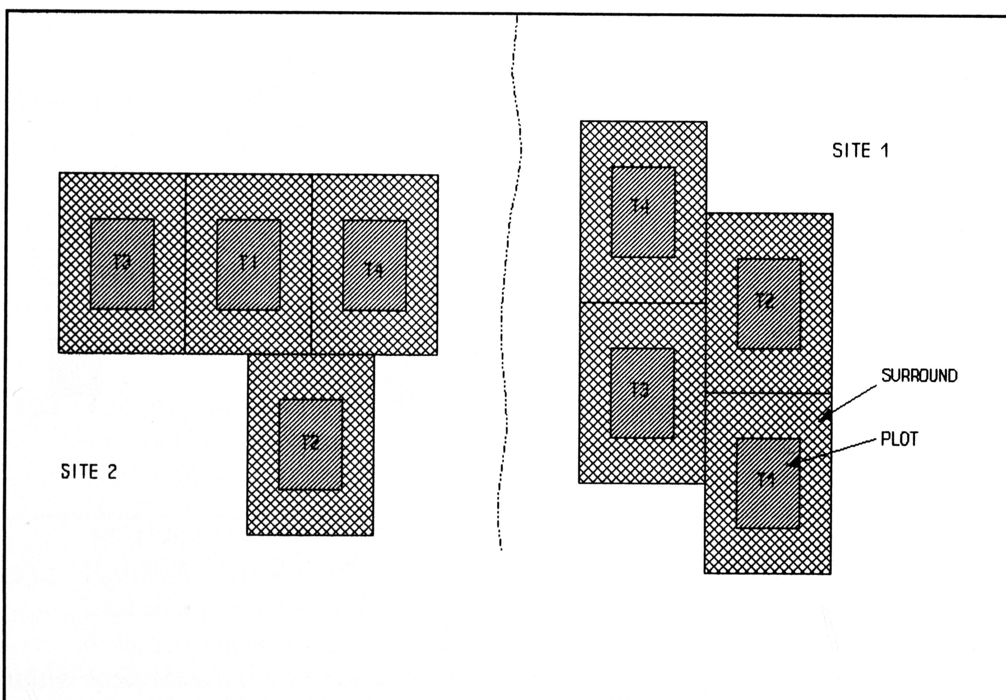

Figure 4-2 : An example of a randomized block design

4.2.3.4 Within each block, each treatment must be represented once and once only. One treatment in each block must be a control: a plot where no treatment is performed. The treatments are allocated to plots using random number tables, or a calculator, computer program or spreadsheet with a random number generator.

4.2.3.5 Figure 4-2 shows an example of a randomized block experiment with 4 treatments and 2 blocks, giving 8 experimental plots in all.

4.2.4 Factorial experiments

4.2.4.1 Physically, factorial experiments appear similar to randomized block designs. The treatments are organized into several blocks, each of which is a replicate. The blocks should be organized to maximize the natural variation between blocks, and minimize it within blocks.

4.2.4.2 However, the treatments are not regarded as simply qualitatively distinct, but as interacting sets of factors, each of which may have several levels. For example, there may be 2 intensities of liberation thinning (3 levels including the control, combined with 2 felling intensities (3 treatments including the control). The factorial design will then have 9 treatments altogether, comprising all combinations of thinning and felling.

4.2.4.3 This example indicates the complexity that rapidly arises with a full factorial experiment. The method is not particularly appropriate to mixed tropical forests as it leads to a number of unlikely combinations of treatments. Furthermore, the factorial design is directly geared to a specific type of analysis via a response surface and study of interactions that is not generally applicable to the MTF experimental situation.

4.2.5 Clinal or systematic experimental designs

4.2.5.1 Clinal experiments are designed to estimate parameters in a regression model. For example, the hypothesis may be established that yield is a function of the intensity of logging. By conducting logging at graduated intensities, this regression can be efficiently estimated. Because the hypothesis is a regression model, there is no requirement for the treatments to be assigned to plots at random, and they may be organized systematically.

4.2.5.2 In plantation work, this has led to a number of efficient designs, such as the Nelder fan (Nelder, 1962). There is a danger in this type of experiment that the regression trend may be confounded with site (Adlard, 1990), but against this may be set the advantages of minimizing space and cost for the experiment.

4.2.5.3 In mixed tropical forest, any treatment must be carried out on a large plot if it is to include a representative selection of species and size classes, and hence the advantages of a systematic design are minimal. Even where the basic hypotheses of the experiment are regression models or response surfaces (as should normally be the case), graduated levels of treatment can be organized adequately within a randomized block design. *The advantages of the randomized design outweigh those of the systematic design in the practical situation of mixed tropical forest.*

4.2.6 Key recommendations for statistical design of MTF experiments

4.2.6.1 *All treatments should be replicated*, that is repeated at least twice in different sites. For ease of analysis, the replicates should be orthogonal. That is, each treatment should be replicated the same number of times.

4.2.6.2 *One treatment must be a control plot*, where no treatment is done. If the experiment involves logging (either as a treatment or as a blanket operation on the whole experiment), then *an unlogged treatment must be specified*.

4.2.6.3 *Treatments should be assigned to plots at random,* using random number tables or an equivalent method.

4.2.6.4 *The experiment should be organized as a randomized block experiment*. This recommendation implies replication, orthogonality and randomization, but also includes the principle that each set of treatments are organized into a block that is as homogeneous as possible with respect to site, treatment history and forest type. The blocks themselves may be located remotely from each other in different sites, forest types, etc.

4.2.6.5 The foregoing recommendations are intended to provide a safe set of working rules for the non-statistician. There may be circumstances where more elaborate designs can be used and will economize on experimental resources. These recommendations are not intended to contradict the possibility of such designs under expert guidance.

4.3 Experimental objectives and treatment specifications

4.3.1 The definition of objectives

4.3.1.1 The objectives of an experiment need to be stated clearly at the outset and translated into specific questions that the experiment can be expected to answer (Jeffers, 1978). In general, two classes of experimental objective can be identified in growth and yield research:

(1) *Basic research into growth responses, species ecology, and stand dynamics.* Experiments in this group should be formulated to determine a specific mathematical model or precise logical hypothesis. The research is basic in the sense that it is not directly intended to prove operational silvicultural or logging techniques.

(2) *Field trials of silvicultural systems and logging techniques.* Experiments of this kind may have many contradictory effects on stand growth, and often contribute little to understanding of basic stand dynamics. They should be reserved strictly for testing systems defined from a sound theoretical basis, and should be based on a null hypothesis (that the specified treatments will have no net effect).

4.3.1.2 Unfortunately, there is a tendency to proceed to the field trial type of experiment before undertaking basic research. This is a special problem in mixed tropical forest, where the complexity of the system means that simple trials, undertaken without a sound examination of the theoretical basis, often give no conclusive result (Synnott, 1979b).

4.3.1.3 The objectives of experiments in the basic research category fall into the following groups:

(1) *The study of inter-tree competition.* Competition between trees strongly influences growth and mortality. The best practical methods of measuring it that can be applied on inventory plots and used to define or control silviculture have yet to be determined. The main competitive parameters within which stands should be managed are still a subject of controversy.

(2) *Logging damage and mortality.* Some experiments have been done in MTF into the effects of logging on mortality (eg. Tang, 1976). This work needs to be repeated in different forest types and with various harvesting methods and silvicultural systems. The mechanisms and quantitative dependencies of mortality need to be clarified, as well as the possibilities for controlling damage through different felling practices.

(3) *Encouragement or enhancement of regeneration.* Opening of the canopy, skid trails and the retention of seed trees will all tend to enhance natural regeneration. Basic studies of species phenology and seedling ecology are required for all valuable species. Enrichment planting may be feasible and effective with some species, especially pioneers in large gaps and landings (Hawthorne, 1990).

(4) *Manipulation of species composition.* Selective felling or killing of trees of various sizes can enrich the composition of required species and may lead to an economically more productive stand.

(5) *Fire regime and other biotic and abiotic factors.* In particular forest types, periodic fires may occur and greatly influence regeneration and mortality (and hence growth). Fire may itself be influenced by stand density (Hawthorne, 1990). In other forests, cyclones, elephants, or other factors may similarly significantly influence forest devlopment and require special study and analysis.

4.3.1.4 *Objectives in basic research should hypothesise specific cause-and-effect relationships* in the above five categories. If possible, *these relationships should be defined as general mathematical models.* The experiment then becomes a matter of validating and estimating parameters for the mathematical model. If research is to be useful as a component of growth and yield study, then it must at some stage take a quantitative direction. Purely qualitative ecological and botanical research, whilst fundamental, is not of itself sufficient for improved forest management.

4.3.2 Tree competition studies

4.3.2.1 Experiments to study tree competition are based on the general hypotheses:

$$\text{growth rate} = f_1(\text{competition})$$
$$\text{mortality} = f_2(\text{competition})$$

In other words, that tree or stand growth rate is some mathematical function of tree or stand competition, other factors being equal; and similarly that the probability of tree survival (individual mortality), or net stand mortality is some function of tree or stand competition.

4.3.2.2 The experiments may also seek to examine alternative measures of competition, to determine which has the highest correlation with growth or mortality.

4.3.2.3 The following are some methods of measuring competition:

Stand basal area on a given sized plot
Basal area at a point with a given relascope factor
Dawkins crown classification (see section 6.4.1)
Relative diameter (Alder, 1979)
Competitive Influence Overlap Zone (Bella, 1971)
Tree crown polygons (Adlard, 1974)

4.3.2.4 Basal area is a simple measure, but not necessarily efficient (Synnott, 1979b). It is also often not recognized that basal area, as an index of competition, varies with the plot size on which it is measured, because its influence is relative to that of the subject tree and the maximum basal area possible.

4.3.2.5 Treatments to study competition must therefore be quantified in terms of the selected index of competition and applied to a plot or around subject trees on a plot (if the hypothesis is specified at the tree level) to give treatments of that level. This requires careful preliminary survey of the plot to convert the treatment specification for each plot into practical working instructions on precisely which trees are to be removed.

4.3.2.6 Application of the treatment by poisoning or girdling clearly causes less disruption and collateral damage, with consequent departures from the intended treatment. It is also generally less costly than treatment by logging.

4.3.2.7 Treatment specifications may be based on a single treatment or multiple treatments. With a single treatment, competitive status will change in the decade following treatment as tree crowns expand and advance growth develops into canopy gaps. Multiple treatments can be designed to maintain a low competitive staus over longer periods, to determine the upper limits of species growth potential.

4.3.3 Logging damage and mortality

4.3.3.1 Logging damage is very varied in its form and extent. On individual trees it may take the form of long swathes of bark stripped from the stem, crushed buttresses, trees pushed from vertical and with partial root damage on one side, and broken crown branches.

4.3.3.2 The method and intensity of logging will influence the degree and type of damage. Direct studies to correlate different logging methods with damage do not require PSPs and should be carried out on large areas. To follow up subsequent mortality, growth and regeneration requires PSPs that should be laid as a sample within the logging treatment plots.

4.3.3.3 The type of logging may be varied by:

- using different basic methods or equipment, such as bulldozer, rubber-tyred skidder, cable or high-lead logging, or elephant logging.
- controlling the orientation of felling and extraction. A herring-bone pattern of felling will tend to reduce bark abrasion as trees are skidded out.

4.3.3.4 The effects of a logging treatment will vary greatly according to the original stocking of the stand, and random factors such as the relative spacing of crop trees and of skid trails. Consequently, when treatments are specified in terms of operational parameters such as a minimum girth limit, clear differences between treatments may be obscured by the natural variation of the initial stand (Synnott, 1979b).

4.3.3.5 Logging experiments therefore need to be carefully planned to achieve expected results. Stock mapping of the treatment plots before and after treatment is essential. The stock map should be used to determine the effects of a treatment specification on the proportion of trees removed, and the residual basal area before the treatments are carried out.

4.3.3.6 Logging damage will tend to relate to the proportion of the stand removed, whilst growth of the residual stand will relate to the growing space that has been created for each remaining tree. Depending on whether the experiment is primarily a study of logging damage or of residual increment, it will be possible to determine whether the treatment specifications should be amended to give the expected and desired effect, by analysing the effects of treatment on the stock map before logging is performed.

4.3.3.7 Skid trails, landings, direction and position of fellings, and extraction roads should also be mapped on the treatment plots, as the pattern and area coverage of skid trails is an important characteristic of logging. It should be possible to relate logging parameters (type and intensity) to frequency distribution of degrees of forest disturbance (see example figure). This is important for modelling logging and subsequent stand development.

4.3.4 Encouragement and enhancement of regeneration

4.3.4.1 Treatments designed to encourage or enhance regeneration should relate to specific aspects of species phenology, seed dispersal, survival and dormancy, and seedling ecology in order to build up a complete picture of seedling population dynamics under different stand conditions.

4.3.4.2 Of particular relevance are the numbers of viable seeds that may be found in the soil at any given time, the factors that trigger seed development, and the survival and growth rates of seedlings under different degrees of shade.

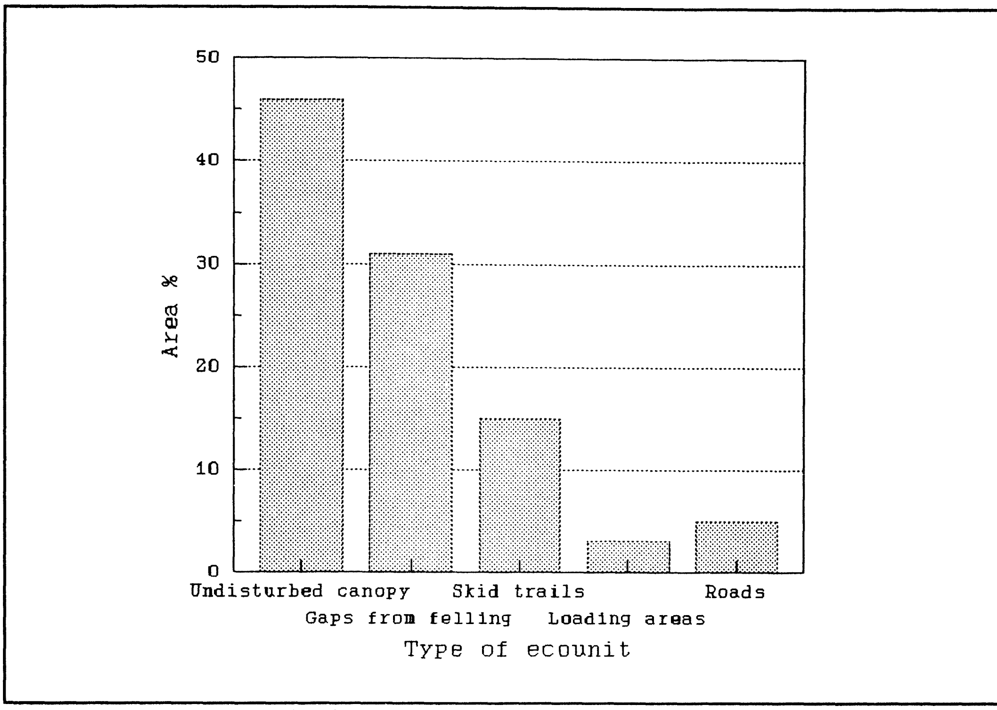

Figure 4-3 : Example of area histogram of logging effects

Studies of this kind are short-term in nature and do not require the use of PSPs.

4.3.4.3 On the other hand, experiments to induce natural regeneration require long-term plots. The treatments will involve opening the stand to various degrees and by various stages. The working hypotheses should relate regeneration to distance from and density of mother trees, the timing of flowering and the nature of eco-unit (Oldeman, 1978) where the seedlings develop. The latter may be characterized as skid trails, natural gaps, twilight zone, landings, etc. (Hawthorne, 1990).

4.3.4.4 The basic mathematical models that should be involved are:

- Flowering, as random function of mother tree size, time since last flowering, and trigger environmental variables, if known.
- Seed density, as a function of distance from the mother tree, prevailing winds, or possibly animal dispersal models.
- Seed survival, as a function of time since flowering and possibly site conditions.
- Germination, as a probability function of trigger factors such as soil temperature, exposure to light, fire, etc. Ideally this may be related to empirical units such as overstorey basal area, situation relative to skid trails or mineral soils, etc.
- Seedling growth and survival rate, as a function of light (PAR), overstorey basal area, etc.

4.3.5 Manipulation of species composition

4.3.5.1 Species composition can be manipulated to favour those of greater economic worth by killing or selectively logging less desirable species. This can be undertaken as a general operation, or as a liberation thinning, to selectively favour particular individual desirable trees.

4.3.5.2 If specified as a treatment, then like logging the effects may be complex and variable. For example, if a list of given species are to be poisoned (or otherwise removed) above a given size, then the effect will vary greatly from plot to plot according to the initial species distribution. In the case of liberation thinning, the effects will be similarly patchy and variable depending on the distribution and size of the subject trees and their competitors.

4.3.5.3 The underlying hypothesis of this type of experiment is that total yield will be unchanged or not significantly reduced by the treatment, but will be concentrated on a smaller number of more valuable stems. If undertaken as basic research (rather than a field trial of an operational technique), then extremes of treatment should be applied, including very heavy thinning.

4.3.5.4 The ultimate utility of any silvicultural method is based on its economic benefits versus its cost. It is therefore important to keep accurate costings, in terms of physical units (man-hours of labour, quantities of chemicals, lists of equipment) that can be interpreted at a much later date into currency units.

4.3.6 The influence of fire and other factors

4.3.6.1 Some abiotic factors, such as cyclones, are outside direct experimental control. Fire can be manipulated to some degree, but the type of rare, intense fires that are mainly of significance on the margins of humid tropical forest are difficult to bring within an experimental framework.

4.3.6.2 However, at the margins of the fire zone (ie forest types where fires regularly occur), experiments can be conducted into prescribed burning, logging practices as they may effect fire, or the use of fire breaks or other ameliorative practices. Like logging experiments, such studies require large areas and are probably best evaluated by sampling by PSPs within large treatment zones.

4.3.6.3 The basic hypotheses involving fire will relate the presence or absence of control measures, or the level or type of logging, to the frequency and or intensity of fire, or to some collateral effect such as the regeneration of fire-dependent species or mortality following fire damage.

4.3.7 Multi-purpose growth and yield experiments

4.3.7.1 The various classes of basic experiments enumerated in sections 4.3.2 to 4.3.6 are of a long-term nature and have quite similar methodologies. It is therefore natural to try and define a single class of experimental treatment that may serve multiple objectives via appropriate measurements and analysis.

4.3.7.2 This can be achieved by a graded logging or thinning experiment, covering a range of felling intensities. The treatment may be specifed either as removal of given percentages of the basal area, or the retention of fixed levels of basal area after logging. Experiments of this type have been established by CTFT in Ivory Coast (Ledoux, 1990; Bertault, 1986).

4.3.7.3 The principal objectives are to evaluate simultaneously:

- the effect of reduced competition on subsequent tree and stand growth;
- mortality following different intensities of logging, both for damaged and undamaged trees; and
- regeneration following canopy opening. With suitable plot designs after the methodology of Hawthorn (1990), this may discriminate between skid trails, landings, and the twilight zone.

4.3.7.4 In this type of experiment thinning and logging should not be combined as it unduly complicates the design, and makes it impossible to discriminate between effects directly from logging, and those arising from thinning. In principle, the two methods of opening the stand could be combined via a factorial approach, but the resulting experiment would be very large and complex.

4.3.7.5 The treatment levels suggested for inclusion in such experiments, specified as either residual basal area or percent basal area removed, are as follows:

Treatment No.	*Residual BA* m^2/ha	*BA removed %*
1	control	0
2	18	25
3	14	45
4	10	60
5	6	75

These treatments are approximately equivalent for a typical stand of about 24 m^2/ha basal area, but applied to a variable forest will have somewhat different effect. The constant percentage of basal area removed will imply a roughly similar degree of logging damage for a given treatment but variable residual stand. Conversely, the constant basal area treatment will involve variable intensities of logging but result in similar residual stands.

4.3.7.6 The treatments are applied to the plots after stock mapping and numbering each tree. The trees to be left should be spaced as homogeneously as possible. The trees should be retained in proportion to their natural occurrence, and not biased towards or away from economically valuable species. Other and separate experiments should be performed to investigate species enrichment or the regeneration ecology of rare but valuable species.

4.3.7.7 The largest trees should be marked first, to make up the required basal area of trees to be felled. The minimum diameter for inclusion in the basal area quota should be 20 cm. On the 6 m^2/ha treatment, this will leave a residue of trees that are growing with minimal competition.

4.3.7.8 The fellings should be performed as carefully as possible, and progress monitored during felling to add new trees to the quota of residuals if marked residuals are broken or very severely damaged. Moderate damage is acceptable and forms part of the experiment. In the case of the heavy felling treatments, the work can be performed more cleanly if felling is done from below (removing the smaller trees first), rather than relying on the commercial practice of allowing the largest trees to flatten the rest. Climber cutting prior to felling, and the carefully planned use of directional felling and extraction are necessary to minimize collateral damage.

4.3.7.9 These treatments will force the creation of a wide spectrum of stand conditions, but they are not intended to represent any operational practice. They are designed to provide data in the most efficient way for the development of growth models. From the model will flow recommendations for operational techniques which may then be the subject of field trials.

4.3.8 Field trials of logging techniques and silvicultural treatments

4.3.8.1 Field trials in the present context may be defined as experiments in which the treatments are intended to demonstrate operational conditions. In other words, *the treatments are specified as they would be for a general silvicultural or logging operation.* Logging operations are performed by ordinary crews, albeit with some special training or supervision for the purposes of the trial.

4.3.8.2 Such experiments are less efficient than the more basic controlled (non-operational) treatments in gathering data for growth and yield models because:

- The trial treatments will be quite variable in their application. Operational rules for felling, such as the use of a minimum felling girth, can have a very variable impact in different plots.

- They will tend to be moderate treatments, a more or less conservative adaption of existing practice.

Such trials do not usually explore extreme stand responses. In the context of growth and yield modelling, this is important, since it is under extreme conditions that models can be most efficiently tested and validated (see section 3.5.3).

4.3.8.3 Considered as experiments, field trials do serve a purpose in establishing confidence in, demonstrating the techniques of, and monitoring and evaluating the results of, proposed changes in management practice.

4.3.8.4 In growth and yield studies, the major value of field trials of this kind is that they represent a type of PSP whose treatment and history is known with some precision, which is often not the case for PSPs established in extensively managed forest.

4.4 Experimental plot size, shape and surrounds

4.4.1 Treatment and measurement plots

4.4.1.1 In an experiment, a distinction should be made beween the treatment plot, and the measurement plot. The treatment plot should be larger than the measurement plot, creating a *surround* or buffer zone, which is treated but not measured.

4.4.1.2 Within large treatment plots, several small PSPs may be established for measurement, either as a systematic or random sample. This is particularly appropriate with logging experiments and any kind of field trial.

4.4.1.3 In such cases, it may not be necessary to adopt a fully orthogonal randomized block design. The treatment plots may be regarded as strata, with randomly located plots within treatments. However, the proviso for a control treatment should remain.

4.4.2 Plot size

4.4.2.1 *Treatment plots should generally be larger than 10 ha and preferably of the order of 50 ha.* CTFT used 16-ha treatment plots in Ivory Coast (Ledoux, 1990). Korsgaard (1982) describing various FAO-supported experiments in Sarwak, reports treatment plot sizes ranging from 9 ha (RP068) to 50 ha (RP090) and 45 ha (RP102).

4.4.2.2 The measurement plots used in the CTFT experiments were 4 ha, whilst the FAO experiments generally used 1-ha assessment plots located at random within the treatments. Some examples are shown in Figure 4-4.

4.4.3 Plot shape

4.4.3.1 For the measurement plot, the square 1-ha plot (Figure 3-4) should be adopted, either as a unit in a random sample, or as a part of a larger measurement block (as in the CTFT example, Figure 4-4).

4.4.3.2 The treatment block shape should be square or broadly rectangular, but may be irregular to coincide with natural boundaries, compartments, roads or other convenient features. However, the higher the ratio of perimeter to area, the greater the area of the plot that will be unusable for measurement as part of the buffer zone. Consequently, very long and narrow plot shapes should be avoided.

4.4.4 Buffer zone and plot surrounds

4.4.4.1 The margins of a treatment plot are influenced by conditions from the untreated area outside the plot and should be avoided for assessment. The common practice in field experiments in forestry and agriculture is to make the treatment plot larger than the experimental plot, with a *surround* of treated area around the measurement plot.

4.4.4.2 Dawkins (1958) suggested that *the surround for a plot needed to be at least as great as the height to which the treatment was effective*. This would imply a minimum measurement plot surround of about 50-70 m for treatments of full canopy height (including logging and thinning). However, the lateral effects of many treatments extend well beyond that indicated by the full canopy height. Treatments involving natural regeneration, for example, need to consider seed dispersal distances and prevailing winds.

4.4.4.3 *It is recommended that a minimum surround of 100 m is adopted for all thinning and logging experiments.* This implies, with a central 1-ha measurement plot, a minimum treatment plot size of 9 ha. On large treatment tracts sampled randomly, the surround takes the form of a buffer zone inside, and adjacent to, the perimeter in which no measurement plots may be located.

4.4.5 Examples of experimental plot designs

4.4.5.1 Figure 4-4 shows examples of plot designs from four experiments, as follows:

(1) RP090, Sarawak (Korsgaard, 1982). The treatment plot is 1200 x 500 m (60 ha), including a 100-m surround. There are six measure-

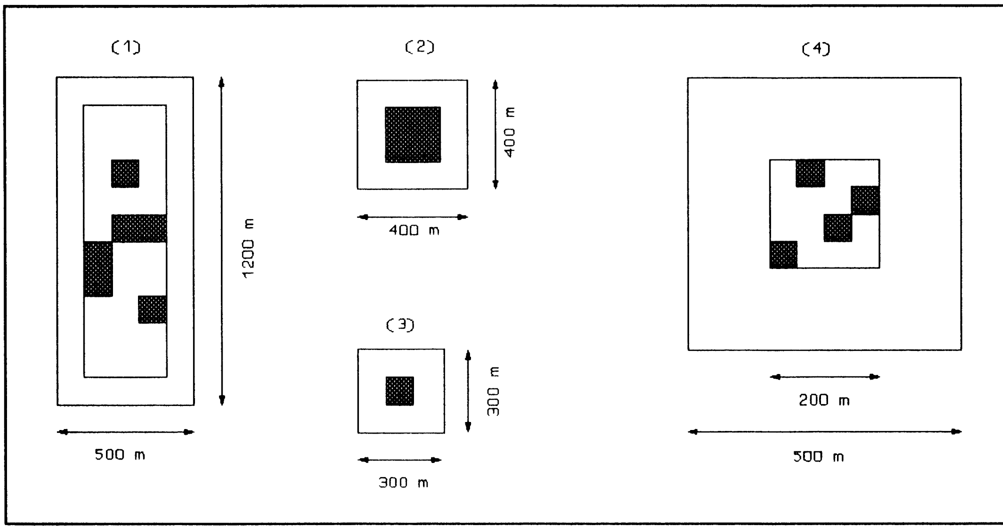

Figure 4-4 : Examples of arrangement of assessment and treatment plots *(See text for details).*

ment plots laid within the treatment block as a random sample. Each measurement plot is 100 x 100 m.

(2) CTFT experiments, Ivory Coast (Ledoux, 1990). The treatment plot is 16 ha (400 m x 400 m) with a measurement plot of 4 ha (200 x 200 m). The measurement plot is subdivided into four 1-ha sub-plots. The surround is 100 m.

(3) RP068, Sarawak (Korsgaard, 1982). A 1-ha measurement plot is centred within a 9-ha treatment plot. The surround is 100 m.

(4) RP106, Sarawak (Korsgaard, 1982). The measurement plot is 200 m square, with a surround approximately 150 m wide. The measurement plot is sampled by four randomly placed assessment plots, each of 0.25 ha (50 x 50 m). The total size of the treatment plot (including surround) is approximately 25 ha.

4.5 Experimental plot sub-divisions

4.5.1 Purpose of plot sub-division

4.5.1.1 Section 3.4 discusses sub-division for sample plots. There are three objectives in sub-dividing a plot:

(1) *To provide convenient record units.* It is much easier to control the measurement of trees on small record units of say 20 x 20 m than on a full plot of 1 ha or more. In particular, sub-divisions assist tree relocation, and measurement of tree position.

(2) *To facilitate the comparison of data from various sizes of plot.* If a standard record unit of 20 x 20 m is adopted on PSPs, experimental plots and TSPs, then scale-dependent measures such as basal area or tree position indices of competition can be exactly comparable (see section 3.4.2). Otherwise, there is always uncertainty as to whether data from the different sizes and shapes of plot are truly comparable.

(3) *To facilitate the measurement of small trees and plots.* As noted in section 3.4.3, measurement time approximately doubles with each 10-cm drop in minimum diameter threshold. This makes it prohibitively difficult to measure trees below 20 cm on a large plot of 1 ha. The use of plot sub-divisions allows a part of the plot to be sub-sampled more intensively.

4.5.2 Major plot sub-divisions

4.5.2.1 For experimental plots of several hectares, it is recommended that a 1-ha record unit is adopted, which can be treated in the database as if it were a 1-ha PSP. This allows close standardization of forms, data entry and analysis programs with those for PSPs.

4.5.2.2 Similarly, within these 1-ha plots, the 20 x 20 m quadrat should be adopted as the basic record unit, as discussed in section 3.4.

4.5.3 Regeneration sub-plots

4.5.3.1 On experimental plots, the assessment of regeneration and its permanent marking and measurement is often a necessary part of the experimental procedure. In sample plots, regeneration assessment can be conducted more or less systematically by laying regeneration strips in a standard position and orientation within the plot (see figure 3-5). In experimental plots, the regeneration sub-plots themselves must often constitute part of a designed sample.

4.5.3.2 For this reason, on experimental plots, regeneration plots must usually be regarded as part of a two-phase sampling process. That is, they constitute a sample that is independent of the main plots, and which may be related to them by regression.

4.5.3.3 The main criteria and methods for designing regeneration plots are described in section 7, as they involve a number of specialized methods which differ from those on the larger PSP.

5 PLOT DEMARCATION

This chapter details how PSPs should be located on the ground, and permanently demarcated with boundaries and pillars. It also covers the marking and numbering methods for trees, and the recording of tree locations.

5.1 Plot boundaries and access lines

5.1.1 Use of base maps

5.1.1.1 The plot locations will be determined initially on maps using random or systematic coordinates, as described in section 3.2. These must be translated into a location on the ground using base maps and field survey. This task will be relatively simple if there is an established permanent forest infrastructure of roads, compartment and coupe boundaries and survey beacons.

5.1.1.2 The plot locations must be described relative to the nearest fixed base point that can be accurately, reliably and permanently relocated on the ground, and whose absolute geographical coordinates are known with certainty. The plot locations are described as a bearing and distance from the base point.

5.1.1.3 Base maps may be inaccurate, especially if they have been prepared using second class plotting instruments, sketchmasters, etc. *Devising field instructions relative to inaccurate maps may make it impossible to relocate plots in the future*, after maps have been updated. It is therefore important that either:

(1) the accuracy of the maps are checked using GPS* equipment (see 5.1.2.4 below); or

(2) plot location instructions are tied to unambiguous and fixed topographic features, permanent roads, structures, triangulation points, or to absolute geographical coordinates by GPS fixes.

5.1.2 Survey instruments and methods

5.1.2.1 PSPs are normally located by compass traverse (chain and compass survey) from a fixed point. The instruments required for this purpose are:

- an accurate transit or compass suitable for taking bearings under poor light conditions. The Suunto forestry compass is often used.

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* GPS : Global Positioning Satellite

- a surveyor's chain or rope. Survey tapes may be used but will not withstand the rigours of continuous dragging on the ground. Modern chains are usually made of polyclad rope, and should be graduated in decimetres and metres. For access lines, 50-m lengths are usually most efficient, but on steep topography, 30-m lengths may be easier to use, to measure corrected lengths of 20 m.

Locally (usually cut in the forest) a compass staff and survey sticks and poles can be made up as required.

5.1.2.2 Slope corrections must be applied to all line surveys where the slope exceeds 5° (c.9%). This can be done be measuring the slope-corrected distance along the ground or by stepping the tape. The latter procedure is easier for short irregular sections of terrain such as gullies, river banks, etc. The former should be applied on long sections of steep slope.

5.1.2.3 If slope corrections are ignored, then on a 5-km access line with an average slope of 5°, the effect would be to underestimate true distance by about 20 m. On a 100 x 100 m PSP, the area would be underestimated by 0.0075 ha. These are small differences relative to other sources of survey error, and hence slope corrections can be neglected below 5° slope.

5.1.2.4 To establish an accurate base point for relocating the plot, GPS instruments are extremely useful. These comprise hand-held electronic units that can be used in forest clearings, in log landings, or under light forest canopies to obtain an absolute fix in geographical coordinates (degrees, minutes, seconds). Basic lower cost instruments (of the order of US$ 2,000-4,000) give absolute positional accuracy, horizontally and vertically, to ±50 m. This can be increased to ±5 m or better if the instruments are used in pairs in differential mode.

5.1.2.5 GPS technology is in the process of rapid evolution. It is likely that within a decade electronic instruments of this type may almost entirely displace conventional survey methods for plot location. They rely on the use of a system of satellites in continuous orbit around the earth that emit highly calibrated time and identification signals. Computer algorithms within the instruments decode signals from several satellites to calculate the positional fix. The algorithms themselves are complex and, together with the precision of the instrument's internal clock, determine the accuracy of a fix. Vanclay (1991) warns that experience in Australia shows that for some classes of instrument the UTM* transformations may need to be verified against ground control points. For further information see Bergstrom (1990).

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* UTM : Universal Transverse Mercator

5.1.3 The plot access line

5.1.3.1 Having determined a fixed base point from maps, ground features and possibly GPS instruments, an access line on an appropriate bearing should be cut to locate one corner of the plot. The access line should be as short as possible. If it exceeds 5 km relocating the plot is likely to be difficult and will depend on a very precise initial survey. Errors are likely to accumulate faster on terrain that is steep or transected by numerous rivers and streams.

5.1.3.2 Where several plots are located from one control point, it is desirable to minimize the number of access line segments and keep the total distance from the original control point to less than 5 km. If possible, a single straight base line should be cut, with the PSPs being connected to the base line by short offsets.

5.1.4 Adjustments to the plot location

5.1.4.1 On completion of the access line, it may be found that the plot falls largely within a river, swamp, farm, haulage road, log landing or other feature that makes the plot either very difficult to survey or largely deforested.

5.1.4.2 An approximate preliminary survey should also be undertaken along the proposed plot boundaries to ensure that no large buttressed trees intersect plot corners. These make the plot difficult to survey accurately.

5.1.4.3 If these conditions do arise, the plot should be moved back or forwards along the access line bearing in fixed multiples of 100 m to avoid the anomaly. It is then *essential to ensure that the adjusted plot location is recorded clearly* in the plot file and on the forest base maps.

5.1.4.4 However, where the PSPs form part of an inventory design for area estimates, the preceding procedure will cause some overestimation of forest growing stock. In such cases, it is preferable to consider one of two alternatives:

- Where randomly selected TSPs are adopted as PSPs, exchange the PSP with another TSP. Then treat the anomolous location as a TSP.

- Amend the forest map to show the anomaly, and then adjust the sampling so that the anomaly is avoided (Synnott, 1979a).

5.1.5 Outer boundaries of the plot

5.1.5.1 The outer boundaries of the plot are surveyed using the same instruments as for the access line. The right angles are formed by surveying along bearings at 90°, 180° and 270° from the original access line. Alternatively, it may be decided to orient the plot along the cardinal bearings (N, S, E, W) irrespective of the original access line bearing. The latter procedure may help to re-establish the plot at later measurements and is recommended by Synnott (1979a).

5.1.5.2 Assuming the plot is the recommended shape of a 100 x 100 m square, substantial stakes of durable hardwood species should be located at each corner and numbered. At 20-m intervals along the access line, smaller stakes should be located to mark quadrat boundaries. These form semi-permanent markers that may be supplemented by the methods described in section 5.1.8 for permanent demarcation.

5.1.5.3 During the process of demarcating the boundaries, trees inside the plot and above or close to the measurement limit should not be cut or cleared unless already dead. It is generally recommended that no trees above 5 cm diameter should be cleared or cut from the boundary lines.

5.1.5.4 Where large trees cross the boundaries, offsets must be constructed around the tree to establish an accurate alignment for the boundary, with stakes placed against the tree bole where it is intersected by the boundary line (Figure 5-1). Large trees at the corner of the plot create difficulties; it is best to relocate the plot slightly to avoid this situation, as noted above (5.1.4.2).

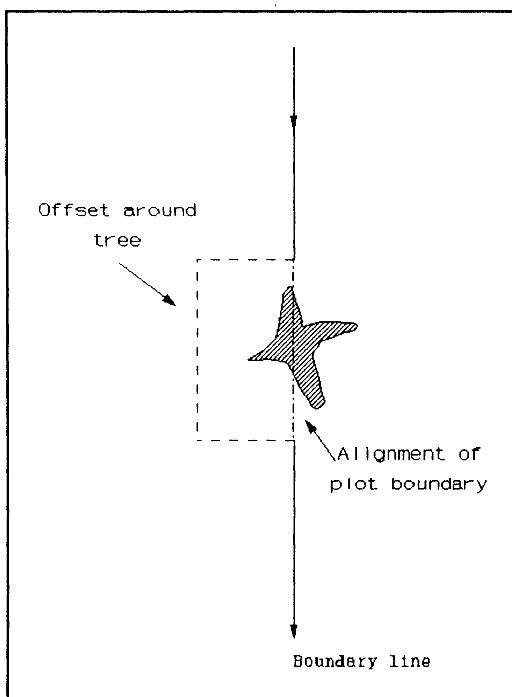

Figure 5-1 : Construction of offsets around large trees

5.1.6 Quadrat boundaries

5.1.6.1 Quadrat boundaries are cut across the plot from the end posts placed along the outer boundary. Care is needed when deciding if small trees should be cut, especially where the plot is tiered and an inner zone involves measuring trees 5-cm diameter or less. Where a quadrat boundary borders such an area, disturbance and machete work should be restricted to outside the boundary of the regeneration sub-plot.

5.1.7 Numbering of marker posts

5.1.7.1 Figure 5-2 shows how posts placed at plot corners and quadrat boundary intersections may be numbered. The south-west corner of the plot is numbered 00. Proceeding eastwards along the southern boundary, the stakes would be numbered 10, 20, etc., up to 50 at the SE corner. Similarly, northwards along the westerern boundary, posts are numbered 01, 02, etc., up to 05 at the NW corner. The NE corner is 55. The inner corners are numbered correspondingly.

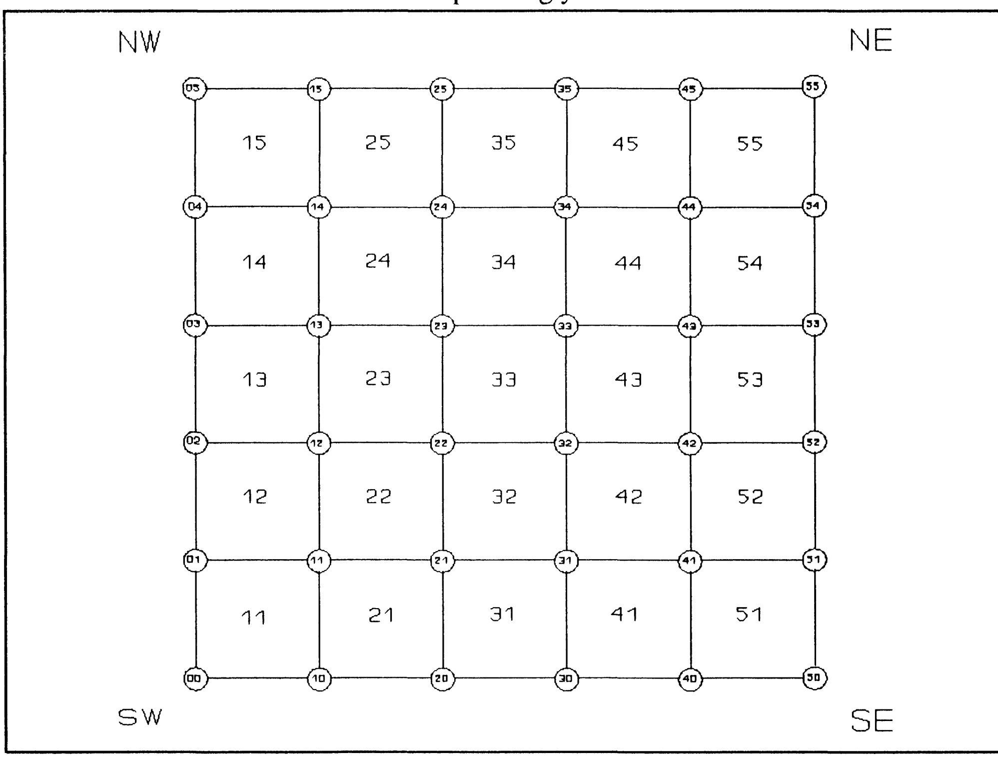

Figure 5-2 : Marking scheme for quadrat corner posts

5.1.7.2 Each quadrat number is thereby taken from the post at its NE corner. The SW-most quadrat is number 11, and that at the top NE corner 55. This scheme minimizes the amount of labelling that has to be put on the posts.

5.1.7.3 However, other numbering schemes are in common use and may be adopted if preferred. Synnott (1979a) recommends marking the actual distances from the SW corner of the plot. Korsgaard (1982) gives the plot numbering scheme for PSPs on the FAO experiments in Sarawak, in which quadrats are numbered consecutively, as shown in Figure 5-3.

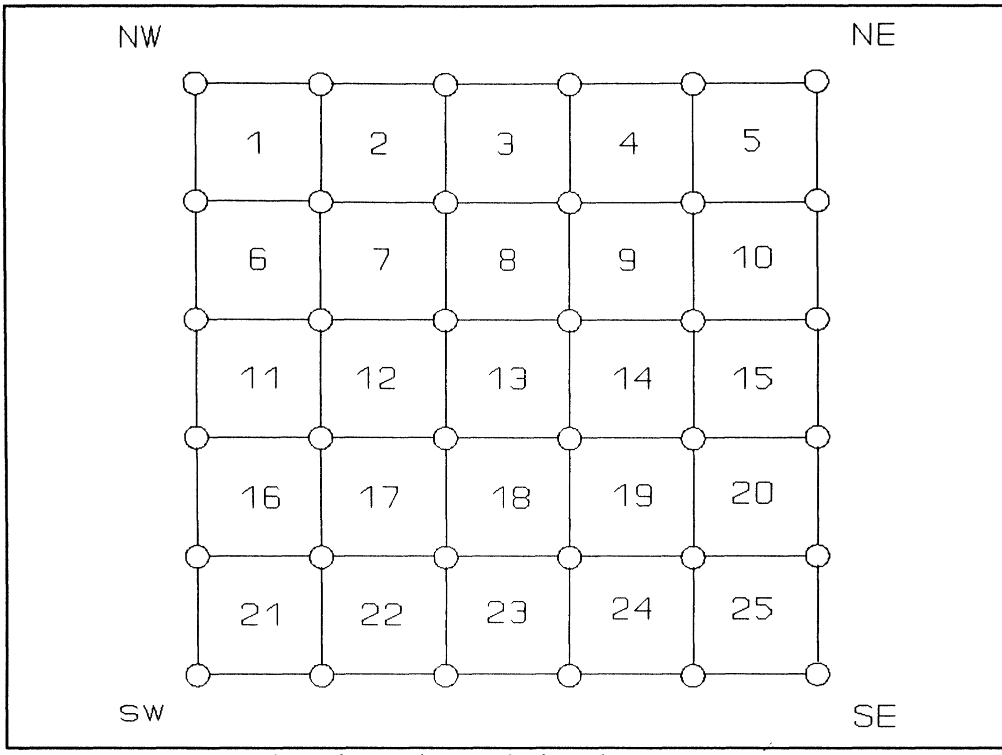

Figure 5-3 : An alternative quadrat numbering scheme

5.1.7.4 Whatever method is adopted, it should be simple, invariant (not changed from time to time or place to place), practical in the field and clearly related to the sample plot record forms and the method of measuring tree positions.

5.1.8 Permanent demarcation of plot corners

5.1.8.1 The corners of the PSP need to be permanently marked so that after an interval of 5 years or more, they may be precisely and unambiguously relocated. The basic method involves marking the corners of the plot with concrete beacons or durable wooden posts. These beacons or posts can be placed in cairns of heaped soil. However, in such a position the post can be readily pushed over by logging equipment. It is usually better to bury the beacon, so that only a small part protrudes, but to indicate its approximate position through the use of trenches.

5.1.8.2 The use of trenches is recommended by Synnott (1979a). These are dug along the boundary lines, ending 1 m from each corner, as shown in Figure 5-4. The trenches should be 30 cm deep, 30 cm wide, and 1.5 m along the quadrat or boundary line. Although such trenches will tend to erode and fill in over a 5-year period, and may be eradicated by logging equipment, in heavier clay soils they are likely to remain clearly visible.

5.1.8.3 Concrete beacons, marked with the PSP number and the corner position (SW,NW,NE,SE) can be placed, largely buried, at each corner. This method is used in Ghana for current PSPs. The beacon is placed with only about 5 cm above the soil, so that it will be buried rather than dragged by the passage of any logging equipment. The central metal rod, apart from strengthening the pillar against cracking, allows it to be relocated by metal detector in future. In practice, the beacons are relocatable without special equipment if the approximate position of the plot corner is known, even when partially buried, and provide a precise and durable marker. The main disadvantage of this method is that in some areas, cement, sand and aggregate may be difficult to obtain, and the beacons are heavy to transport if walking distances to the plot are great and labour is limited.

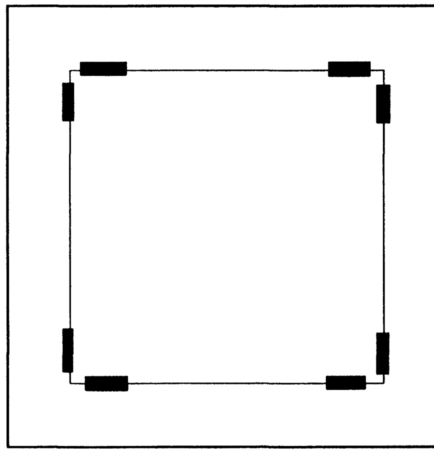

Figure 5-4 : Location of trenches to assist in marking plot corners

5.1.8.4 Durable hardwood posts, with a metal identification plate attached, are also frequently used as permanent markers. These can be readily made in the field, but are also more difficult to relocate if disturbed, knocked over or pushed into the ground as they are not readily distinguishable from the mass of other woody material on the forest floor.

5.1.8.5 If the corner beacons or posts are lost, it should be possible to relocate the corner position from the coordinates of numbered trees on the plot, provided that tree positions were recorded when the plot was established.

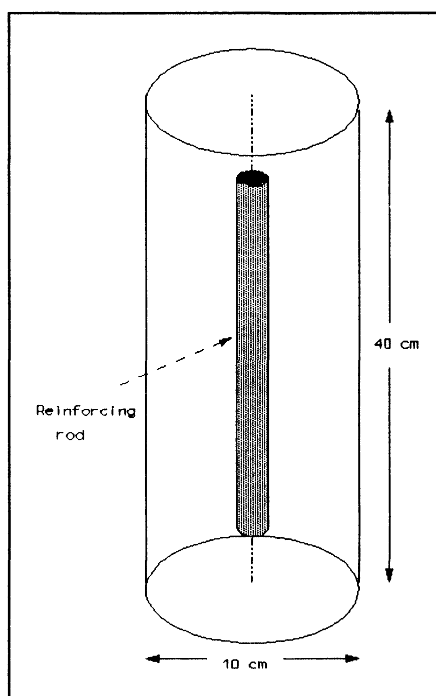

Figure 5-5 : Design of concrete corner beacons used in Ghana

5.2 Tree numbering and marking

5.2.1 Tree numbering

5.2.1.1 Trees should be numbered sequentially on the plot so that each tree bears a unique number. If pre-numbered tags are used, then sequential numbers are not necessary, provided that they are unique.

5.2.1.2 There are several methods of marking numbers on trees:

- Writeable tags nailed to trees.
- Pre-numbered tags nailed to the tree.
- Tree numbers scribed into the bark.
- Numbers painted on the tree.

5.2.1.3 In addition to writeable tags (soft alloy tags that can be written on with a ball-point pen or stylus), labelling machines can be used with alloy tape. However, these expensive machines are readily damaged by continuous exposure to moisture and soil particles and are not generally recommended for field use. The principal advantage of such labels, as with pre-numbered tags, is that they cannot easily be falsified. However, in the context of PSPs, this problem should not normally arise. *Note that plastic tags deteriorate rapidly under tropical conditions and should not be used. Metal alloy tags should always be used.*

5.2.1.4 Methods that involve nails must give careful consideration to the type and placement of the nail. Some trials should be done to select the most suitable nails. Forestry equipment suppliers are usually able to offer special corrosion-resistant alloy nails for this purpose. These have spiral shanks to make extraction difficult (reducing theft) and are sufficiently stiff to penetrate most hardwoods, yet are easily sheared by saws. Steel nails corrode quickly, and require renewal at each 5-year re-measurement. Hardened galvanized or alloy masonry nails are suitable for very hard timbers and are corrosion resistant, but will certainly cause saw damage if embedded in the wood. Alloy nails designed for softwoods are generally unsuitable for tropical hardwoods.

5.2.1.5 If nails are used, they should be placed a fixed distance above or below the point of measurement (30 cm above is recommended). If placed close to the POM, callus formation around the nail would distort diameter measurement. Nails of 5 cm length should be used, inserted about 3 cm into the bark, with 2 cm free. This allows for growth, and should avoid the head of the nail and the label becoming covered by callus over a 5 year period.

5.2.1.6 Scribing tree numbers in the bark is cheap, simple and reasonably permanent. However, callus will form around the numbers, and fungi may enter at the point of damage. Some trees may produce copious exudates from the wound that make the numbers unreadable. It is suggested as a method to be used only as a last resort if suitable nails or paint are unavailable. The numbers should be scribed well below the point of measurement.

5.2.1.7 Painting numbers is an effective and widely-used method. It is slower than using tags, and may be impossible under wet season conditions. Oil-based paints may cause callus formation in some species (Vanclay, 1991). If paint is used, then it should be a conspicuous, light colour (eg white). An exterior grade emulsion paint (water based) should be suitably durable and have a minimal effect on cambial activity. The number should be at least 30 cm above or below the point of measurement.

5.2.1.8 Trees below 10 cm, which may be permanently marked on subplots, should be tagged with a loose wire loop tied around the tree and allowed to rest at ground level. These loops should be renewed if they become tight, and replaced with paint or nailed tags (according to current practice) as the tree becomes larger. Copper wire (electrical earth wire) is suitable; steel wire will corrode and should not be used.

5.2.1.9 The numbers given to trees should never be re-used if the tree subsequently dies or is logged. Such duplicate numbers are a source of considerable confusion to the data analyst. Ingrowth trees that achieve the minimum measurement diameter should be given a new unique number that has not previously been used by any tree on the plot.

5.2.1.10 *As a general recommendation, either painted numbers or numbered metal tags may be used.* Both methods have minor disadvantages which may determine the choice in particular situations. Painted numbers in the longer term offer easier plot remeasurement and maintenance than tags, and cause less interior damage to the wood (nails inevitably become embedded). However, painted numbers are difficult to use on small trees (below 10 cm), for which writeable or pre-embossed tags on wire loops are necessary. They are also difficult to apply when working under wet season conditions.

5.2.2 Marking the point of measurement

5.2.2.1 Section 6.1.1 discusses how the point of measurement is defined. It should be marked on the tree by a continuous painted band, located so that the top of the band marks the point of measurement (ie. position of the measuring tape).

5.2.2.2 At the first measurement of the tree, the procedure to be adopted is as follows:

- Mark the point of measurement with a crayon.
- Place the tape around the tree and record its diameter.

- Make additional crayon marks to record the exact position of the tape on the stem.
- After completing measurement and removing the tape, paint a circular band around the tree whose top edge is coincides exactly with the crayon marks.

This procedure ensures that the diameter tape does not come into contact with wet paint.

5.2.2.3 If calipers are used, rather than a diameter or girth tape, then a spot should be placed on both sides of the tree where the caliper arms make contact. The centre of the spot should be the exact point of contact. This will normally be done in two directions mutually at right angles.

5.2.3 Visibility of tree markings and plots

5.2.3.1 There are arguments for and against highly visible PSPs in the forest. On one hand, such plots may be subject to atypical treatment, being generally avoided by loggers and managers, who may think that they are part of some esoteric research scheme. On the other hand, visibility is a great aid to relocation of the plot boundaries and the surviving trees, and considerably speeds up remeasurement.

5.2.3.2 On balance, Synnott (1979a) concludes that visibility is more of an asset than a liability. Even the somewhat atypical treatment of such plots can be advantageous. It implies that loggers will consult with forest officers before entering the plots, thus ensuring the possibility of careful recording of logging, and of assessments of the plot immediately before and after felling to check damaged trees and renew corner pillars, etc.

5.2.3.3 Visible PSPs alone do not constitute an adequate monitoring device for unauthorized farming or tree felling, or for general evaluation of felling damage characteristics; there are other methods that are more appropriate for this. Remote sensing can efficiently detect and map any farming or extensive felling within the forest, whilst suitable temporary or experimental plots can be used to study logging characteristics.

5.2.3.4 If inconspicuous plots are deemed to be essential, then the following techniques should be employed:

- Marking of trees with metal tags (not painted numbers).
- Omission of painted bands at the point of measurement. This significantly reduces the accuracy of increment estimates.
- Plot corners marked with nearly buried concrete pillers. Alternatively, durable hardwood blocks with a numbered metal plate nailed across the top can be used. Trenches to mark the corner beacons should not be dug.

Such plots may be difficult to relocate, and a significant number could be lost. Remeasurement times will be slower than for conspicuously marked plots.

5.3 Mapping tree locations and plot characteristics

5.3.1 Uses of the tree and plot map

5.3.1.1 A map of the tree positions on the plot allows various types of competition index to be calculated. Without a plot map, only position-independent competition indices such as quadrat basal area can be used.

5.3.1.2 A plot map is also useful in relocating and remeasuring the plot. By showing the numbered trees, with their approximate sizes and species, the work of re-measurement is considerably aided. It is especially helpful when some tags or tree numbers have faded or been lost, and where logging or tree falls have substantially changed the appearance of the plot.

5.3.2 Approximate methods of tree mapping

5.3.2.1 Older procedures for PSP measurement usually rely on producing a sketch map on a standard form. To assist this, each 20 x 20 m quadrat is quartered by tape to form 10 x 10 m sub-quadrats. Within each corresponding sub-quadrat on the sketch map the approximate tree positions are marked, together with tree numbers and possibly a mnemonic species code.

5.3.2.2 This method is approximate and useful only as a guide in remeasuring the plot. Positions are unreliable as there is a tendency for location and orientation to be confused as the trees are mapped. The method is not recommended for current use.

5.3.3 Measurement of tree coordinates

5.3.3.1 Direct measurement of tree coordinates is the simplest and most effective method of recording tree position. Coordinates are recorded relative to the SW corner of each quadrat. The method requires the use of two 20-m surveyor's tapes. One tape is laid from the western-most boundary of the quadrat beside the tree, and the distance in metres and decimetres read to the tree centre. Another tape is laid from the southern-most boundary, and similarly read. The two coordinates are recorded on the plot record form (Figure 9.1).

5.3.3.2 When the data is processed, a plotter can be used to draw the plot map from this tree position information, with different sized circles representing diameter, and tree number and species mnemonic shown on the plot. The method is accurate and simple.

5.3.3.3 An alternative method, suitable for circular plots, is to measure the compass bearing and distance of the tree from the plot centre. This method is complicated if applied in square plots and is not recommended in such cases.

5.4 Determination of species

5.4.1 Preliminary identification

5.4.1.1 A preliminary determination of tree species should be made at the time of initial demarcation and measurement. Often this may only be possible as a vernacular or trade name that may refer to a group of botanical species of similar appearance. This preliminary identification should be coded with a note (see coded notes, section 6.5.3) when there is any uncertainty as to the precise botanical identification.

5.4.2 Authoritative determination

5.4.2.1 It is ultimately necessary that every measured tree on the PSP is identified as fully as possible. This will usually involve the much slower process of gathering botanical material from trees of unknown or uncertain species, and must be conducted after the initial establishment and demarcation of the PSPs. It implies that a botanist and herbarium must be available to the PSP programme at all times.

5.4.2.2 By the time remeasurement of the PSP is due (3-5 years), this process of confirmatory species identification should be completed. Provided that the tree number has not been lost, there should be no need for re-identification of species at second and subsequent measurements.

5.4.2.3 PSPs, especially on experimental sites, can therefore serve as training areas for foresters in tree identification, once the initial demarcation and confirmatory botanical work has been completed.

5.5 Re-demarcation and plot maintenance

5.5.1 Annual maintenance

5.5.1.1 It is desirable that access lines and plot boundaries are cleared annually and kept open. This greatly facilitates access to the plot, and ensures that it is not lost. During annual maintenance, beacons or marker posts should be cleared of vegetation and soil, and replaced if necessary.

5.5.1.2 Annual maintenance ensures that any logging in the plot is noted promptly. An assessment should then be made immediately post-logging to record the numbers of removed trees, and to record damage on the residual stand. The position of gaps caused by felling, skid trails, roads, and landings should be sketched on a plot map form.

5.5.1.3 Similarly, where fire, cyclone damage or other periodic events have occurred, details should be reported and an assessment made of dead and damaged trees.

5.5.2 Operations at re-assessment

5.5.2.1 The full re-assessment of the plot will normally be made at 5 year intervals, or at shorter periods in some special cases. At this re-assessment, the recurrent measurements described in section 6 are made on trees, and the following maintenance procedures carried out:

- Plot boundaries are renewed, boundary pillars and trenches are replaced and cleared of vegetation or soil, as necessary.
- Tree markings are renewed. Painted numbers are repainted, as far as possible, on top of the old numbers.
- Where nails and tags have been used, nails that are being grown over are removed (if possible) and replaced by new nails with 2 cm left protruding to allow for additional growth.
- If there are any trees that cannot be found, their expected locations must be carefully checked for signs of a stump or felled bole. A suitable coded note is entered.
- Trees that bear no markings are carefully compared with a list of missing trees to find correspondences of location, size and species. If there are none, the unmarked trees are recorded as ingrowth.

5.5.2.2 Ingrowth trees must be given new unique numbers and marked for point of measurement and tree number. Their positions are recorded. Care is required to ensure that trees that have lost their markings are not confused with ingrowth. This is relatively simple if tree coordinates have been measured accurately and mapped.

5.5.3 Searching for lost plots

5.5.3.1 PSPs are occasionally lost, especially when there is no routine of annual maintenance. Logging can severely disturb the forest, completely obliterating access lines, corner beacons and the like. Only a few marked trees may remain. If the option of inconspicuous marking has been adopted (5.2.3.4), these may be very difficult to see.

5.5.3.2 Plots may also be lost because of inadequate initial survey, inaccurate base maps, or control points that are not invariable (such as curves in rivers, stream junctions, minor forest roads). Sometimes survey beacons are moved or destroyed by local populations as a result of land disputes or similar matters. All these problems can be avoided by using GPS systems to fix the absolute longitude and latitude of control points close to or on the plot.

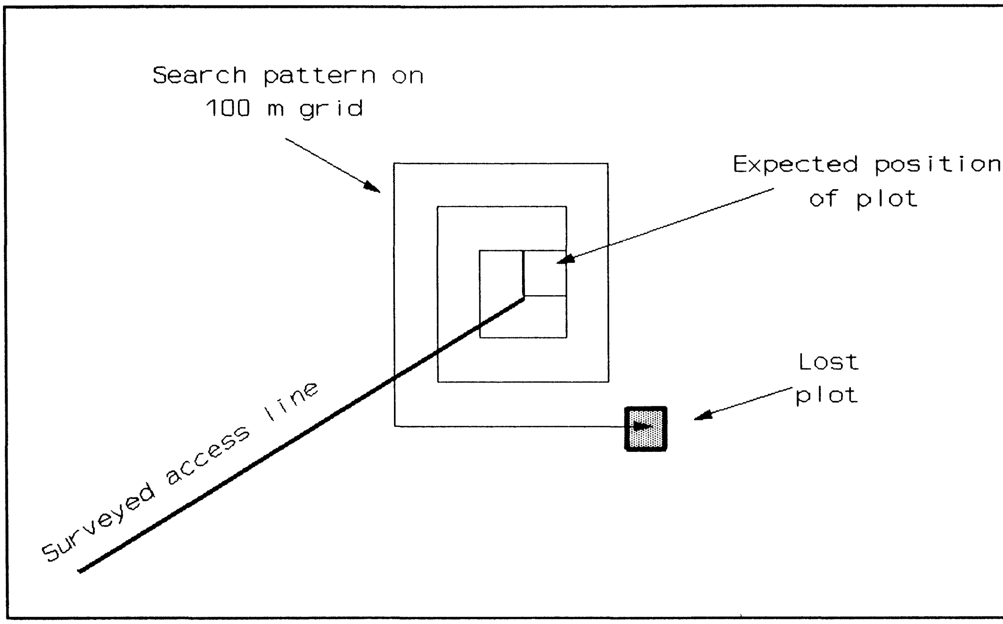

Figure 5-6 : Search pattern to find lost plots

5.5.3.3 When a plot is lost, an access line must be laid to the best estimated position, and then a search made in the outward spiral pattern shown in Figure 5-6. The spiral is surveyed approximately, and increased by 100 m on each leg, with a 100-m spacing between spirals. Searchers should be spaced at intervals of about 10 m inside and outside the search path and up to 50 m from it, to look for any marked tree.

5.5.3.4 Once a marked tree has been found, the plot must be relocated and its boundaries re-constructed. This can only be done completely successfully if tree coordinates were originally recorded. If the original boundaries cannot be precisely re-established, then data on ingrowth and mortality will be unreliable.

6 TREE MEASUREMENTS ON PSPs

This chapter specifies the methods for measuring diameter, height, crown diameter and crown classes, and for recording qualitative information relating to mortality and tree vigour, by a system of coded notes.

6.1 Reference diameter

6.1.1 Point of measurement

6.1.1.1 The reference diameter of the tree is the diameter of the stem or main bole measured at a point 1.3 m above ground level (breast height), or at a specified distance above the point of convergence of the buttress or other anomaly preventing measurement at breast height.

6.1.1.2 Standards must be defined and adhered to for the method and procedures of reference diameter measurement. Apparently minor variations in method can lead to large errors in the estimation of increment. The standards recommended here are widely, although not universally, adopted and can serve as a basis where existing practices are not adequately or rigorously defined.

6.1.1.3 For trees without buttresses, the measurement height is 1.3 m above ground. This is measured from the uphill side of the tree on a slope, or on the inside of the lean for a leaning tree (Figure 6-1). Trees that fork below the point of measurement are treated as two trees; those that fork at the point of measurement are measured as two trees at a point above the fork. Measurement below the fork, as is commonly defined for inventory work (see Cailliez, 1980, section 211.1) is unsuitable on PSPs as buttresses will grow into the point of measurement (POM) which will then have to be moved above the fork, creating confusion.

6.1.1.4 For trees with deformations or excrescences at 1.3 m, the measurement should be made at the first sound point on the stem above the abnormality. A tree condition code should be recorded indicating the presence of such an abnormality (see Table 6.1).

6.1.1.5 For buttressed and stilt rooted trees, a POM is selected approximately 1 m above the convergence of the buttress. Ladders will frequently be required to reach this point, which may be up to 5 m above ground. The distance above buttress selected will vary with standards adopted in different countries and is often specified as, for example, 30 cm for inventory work. However, on PSPs a distance of 1 m (or more) above buttress is preferable so that the POM may be stable for a decade or more and does not require to be continually moved.

6.1.1.6 For trees with highly fluted stems, or buttresses that converge very gradually, a POM must be selected arbitrarily above the major deformation of the stem.

6.1.1.7 The POM thus determined is permanently marked on the tree (see section 5.2.2 for procedures). At subsequent re-measurements, the same point is used, regardless of whether the ground level has changed in the interim period.

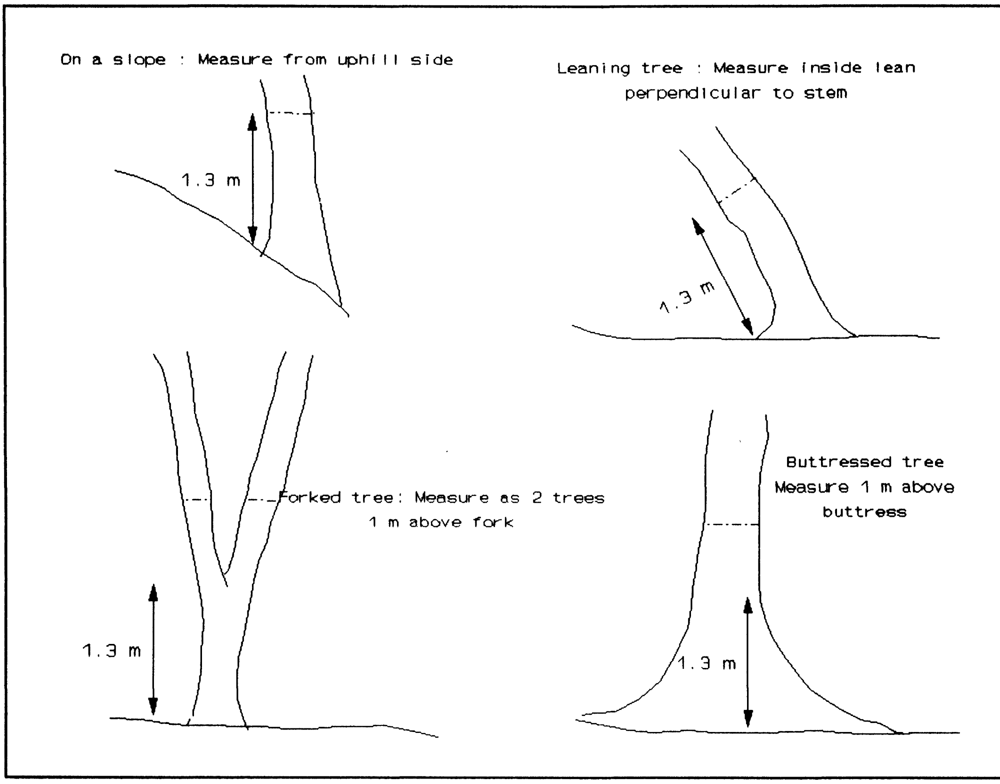

Figure 6-1 : Common standards for measuring diameter on leaning and abnormal trees.

6.1.1.8 When the tree is marked with a painted band at the POM then measurement should be made exactly along the top line of the band. The ιape should be adjusted to lie along this line.

6.1.1.9 When the point of measurement is indicated by a nail, measurement is made at a fixed distance above or below the nail. A common standard is to place a nail 30 cm above the POM. This method is less accurate than a painted band as the exact alignment of the tape may vary between successive readings, giving differences of several millimetres on large trees.

6.1.2 Use of diameter tapes

6.1.2.1 The preferred instrument for measuring diameter is a diameter tape, marked in millimetres and centimetres. Steel, reinforced cloth or fibreglass tapes are all acceptable. *Lower quality cloth tapes may stretch when wet and should not be used.* Cloth and fibreglass tapes may frequently be accidentally cut by machete under normal working conditions. Steel tapes, which should be of the plastic coated type to avoid rust and cuts to the hand in use, are expensive and subject to breakage when kinked. A hook at the end of the tape reduces the number of people required to measure large trees.

6.1.2.2 When making the measurement, loose bark, small climbers or epiphytes should be lifted above the tape or removed if possible. Woody climbers adhering to the stem make accurate measurement impossible. A tree condition code indicating their presence should be entered on the data recording form (see section 6.6).

6.1.3 Moving the point of measurement

6.1.3.1 As the buttresses or stilt roots develop in tropical trees, they will eventually reach the POM originally adopted. In this case, the POM must be moved. The procedure is illustrated in Figure 6-2.

6.1.3.2 A new POM is established 1.5 metres above the first. Diameter at both the old and new POMs are recorded. The booking form (see figures 9-1, 9-2) must allow a column for a second reference diameter, which is termed the *alternate diameter.*

6.1.3.3 At the subsequent re-measurement of the plot (3-5 years later), the old POM is discontinued and not measured. Only the new POM is measured. A coded note is made that the old POM has been discontinued. The alternate diameter from the previous measurement has now become the new reference diameter.

6.1.3.4 A practice that has been adopted on some older PSPs is to move the POM without establishing a bridging measurement (*ie.* one measurement when both old and new POMs are measured). This results in the loss of a continuous series of increment data and significantly degrades the utility of the results. *This practice should be avoided.* It is especially confusing when no note is recorded in the computer database that the POM has been moved. In this case, the tree appears to shrink substantially without any apparent reason.

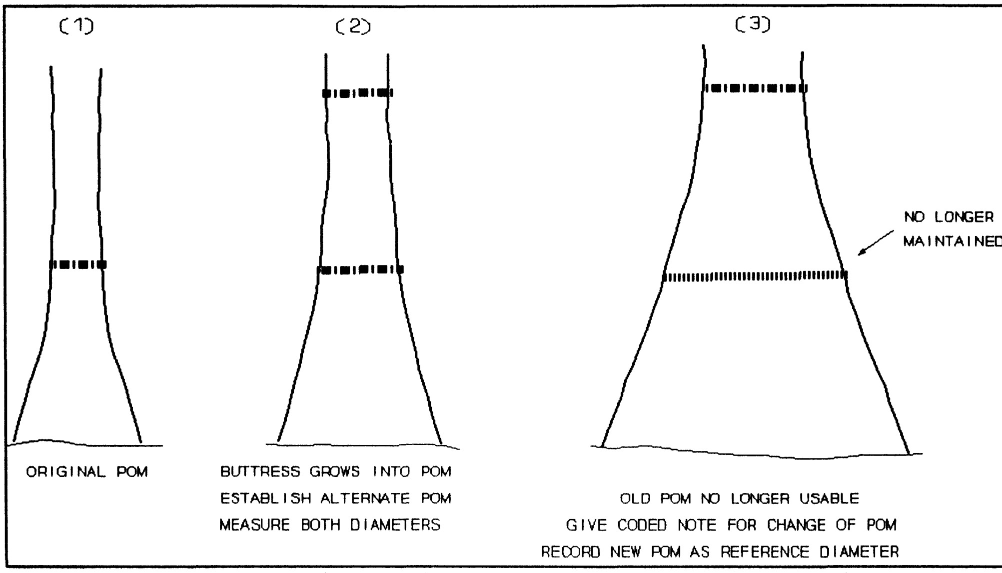

Figure 6-2 : Method of moving diameter measurement point to allow for buttress growth

6.1.4 Type of measurement scales

6.1.4.1 Mixtures of different types of measurement scale can confuse operators in the forest and lead to data recording errors. It is better to avoid tapes printed with dual scales, such as metric on one side, and imperial on the other; or diameter equivalent units on one side and linear measure on the other. A tape printed with a single scale is clearer and easier to use. However, most commercially available tapes use both linear and diameter scales; operators must be thoroughly trained to avoid confusion and the data recorder (booker) aware of unreasonable sounding dimensions for a tree.

6.1.5 Method of rounding

6.1.5.1 When reading a tape, a consistent method must be adopted for rounding. Three common standards are in use:

- Rounding up or down to the nearest graduated unit. If the scale reading appears to be exactly halfway between graduations, then it should be rounded up. This is a common practice in the reading of scientific instruments and is probably the most widely used standard.

- Reading to the last complete graduation. This standard is common in forest inventory work, and is associated with the practice of tallying trees by centimetre or wider classes. It is however not appropriate when reading a scale with small graduations (eg. mm), and should preferably be avoided in PSP work unless already adopted as a standard.

- Estimation of the fractional reading. This may be possible with millimetric diameter tape, where the actual scale marks are 3.14 mm (π mm) apart. In this case readings will be recorded to 0.01 cm or 0.1 mm. This is a reasonable procedure but does not add accuracy compared with the rounding method as the inherent variability in placing the tape will be more than 1 mm. The added precision of reading is therefore spurious and creates unnecessary activity in data entry and storage.

6.1.5.2 *The recommended procedure (unless a prior standard is in use) is to round up or down to the nearest millimetre.* However, it must be emphasized that any existing standard must be respected and consistently adhered to.

6.1.6 Girth tapes

6.1.6.1 Some institutions may use girth tapes rather than diameter tapes. Girth tapes are simple linear surveyor's tapes, and may be easier to procure locally than diameter tapes. It is an older practice, which is tending to drop out of use, and should be avoided unless already established as a standard.

6.1.6.2 Many older series of PSPs began by being measured for girth and later converted to diameter. This change is sometimes inadequately documented, causing confusion for the data analyst. The situation is especially confusing when there are undocumented changes from girth measure in inches to diameter measure in centimetres, as the units are of similar magnitude. For example, a tree of 20 inches girth has a diameter of 16.2 cm.

6.1.7 Calipers

6.1.7.1 Calipers may be used as an alternative to diameter tapes. For small trees they are faster, but they are impracticable for large trees. Diameter measured by caliper and by tape are not directly comparable, as calipers always tend to give a smaller average reading than a tape (see Cailliez, 1980, section 211.22).

6.1.7.2 The largest tree that may normally be measured by caliper is about 125 cm. Commercial calipers are not readily available for larger trees. An aluminium caliper of this size costs about US$150, as against a synthetic fabric tape that may cost about US$35 and is able to measure up to 3 m diameter.

6.1.8 Marking the alignment of measurement when using calipers

6.1.8.1 For increment estimation, the alignment of the caliper must be precisely repeated on each occasion. This requires that the position measured is marked on the tree. Synnott (1979a) recommends that a spot is painted or sprayed at the point of contact of each caliper arm. This should be done in two directions mutually at right angles. The caliper should be positioned so that the point of contact is in the centre of the spot.

6.1.9 Recommendations regarding calipers

6.1.9.1 The use of calipers for trees larger than 10 cm diameter is not generally recommended. There are many sources of error and they are expensive and unwieldy instruments. Nonetheless, some forest services have a tradition of caliper use and prefer to adopt them. In this case, the precautions noted above must be observed if accurate increment estimates are to be obtained.

6.1.9.2 Calipers used for increment estimation should always be graduated in centimetres and millimetres and read to the nearest millimetre. Calipers marked only in centimetre classes should not be used for PSP work.

6.1.9.3 If calipers are adopted, then *their use should never be mixed with diameter tapes.* The resulting measurements are not comparable and will not yield reliable increment estimates.

6.1.10 Optical methods: relascopes and pentaprism calipers

6.1.10.1 Optical methods of diameter measurement are less accurate than direct measurement by tape or caliper, and are generally unsuitable for determining increment as the difference between successive measurements.

6.1.10.2 However, optical methods have a role where very large buttressed trees occur in the forest, in determining the diameter of the tree at a reference height in order to estimate its competitive influence on the plot. Such large trees may be very difficult to measure directly.

6.1.10.3 For example, *Ceiba pentandra* in West Africa normally attains diameters in excess of 2 m, with buttresses ascending 10 m before convergence. Direct measurement of such trees is impracticable and optical measurements must be adopted.

6.1.10.4 The most useful instrument for optical diameter measurement above buttress of large trees is the Spiegel Wide-Scale Relascope. This can measure reliably to an accuracy of ±5 cm on a tree of 2 m diameter.

6.1.10.5 Since the relascope is employed to measure trees whose buttresses are too high to be reached directly, it is not possible to mark the point of measurement. A recommended procedure is to place a tag at approximately breast height in the stem in the direction of measurement, marked with the distance from the tree at which it was taken, and the angle reading in % to the point of measurement. At the same time, the booking form should record the actual height of the point of measurement (ie % x distance).

6.1.10.6 When measuring diameters with a relascope, the operator should stand as close to the tree as possible, to obtain a reading with as many bands as possible. This improves accuracy. However, proximity to the tree should be limited to a point where the % slope scale reading is less than 100% (as accuracy also decreases with excessively oblique angles of view).

6.1.10.7 The Wheeler Pentaprism is another optical instrument for diameter measurement. However, this is not recommended for general diameter measurement on PSPs. It does not allow sufficiently accurate diameter measurements for increment estimation, nor does it permit measurement of very large trees. It has been used for measuring diameters of competing trees where these are not permanently demarcated, and is useful for this purpose in that the measurements can be made from the position of the subject tree.

6.2 Direct increment measurement

6.2.1 Role of direct increment measurement

6.2.1.1 Diameter increment on PSPs is normally estimated by taking the difference between diameters on successive occasions. This is subject to a number of sources of error and will not normally give a useful result with a measurement period of less than three years except with the fastest growing specimens.

6.2.1.2 When increment data are required over a shorter period of observation, then direct measurement of increment by girth band or various types of dendrometer or dendrograph may be used. These are precise instruments that can show daily or even hourly fluctuations in increment, as affected by changes in water stress as well as by growth.

6.2.1.3 Although individually inexpensive, these types of dendrometer nonetheless must be limited in application to at most a few hundred trees because of their cumulative cost. Apart from the initial expense, they require frequent supervision to avoid animal damage or human interference; their use is generally limited to experimental or research plots.

6.2.1.4 Short periods of measurement also will be affected by variations in seasonal and annual growth associated with climate. If such short-term observations are averaged to estimate growth over longer periods, the results may be biased.

6.2.2 Vernier girth bands

6.2.2.1 The vernier girth band is a simple and inexpensive instrument that can be made locally for less than US$1. It has been used in some MTF increment studies (eg Mariaux, 1969, 1970). The instrument was originally described by Hall (1944), and its local manufacture further elaborated by Liming (1957).

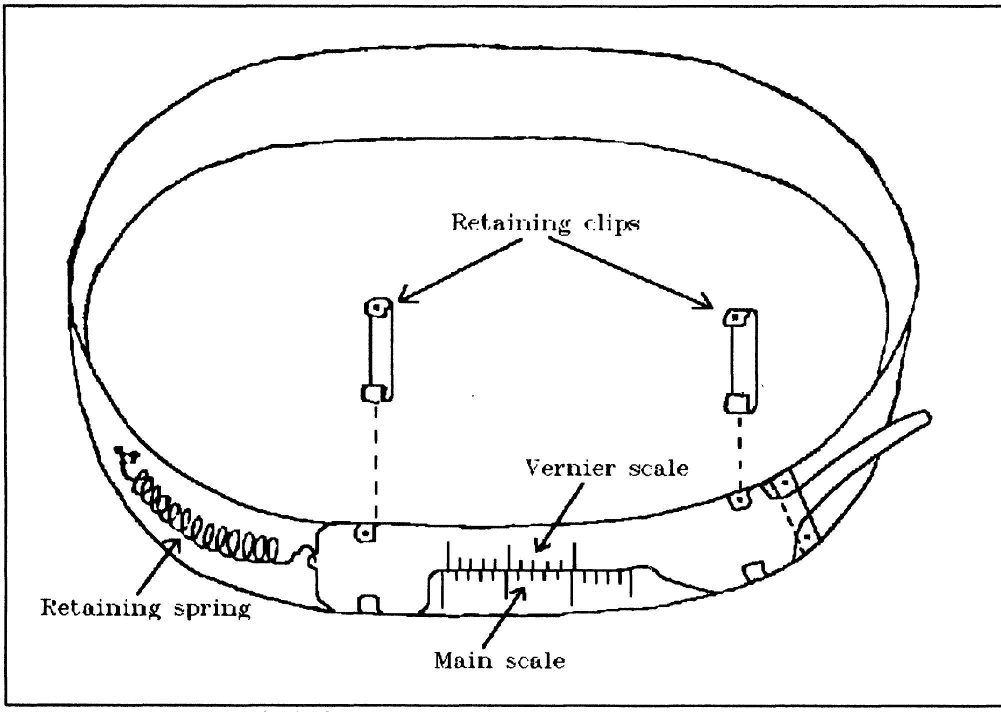

Figure 6-3 : Method of construction of a vernier girth band

6.2.2.2 The band is made from banding material of steel or aluminium. Black painted packing case banding is usually most convenient. On one end of the band graduations are scribed using a template graduated in π mm, extending over the equivalent of 15 cm (allowing for about 5 years use with typical increments). At the other end, a vernier scale is marked. This contains 10 graduations at intervals of 0.9 π mm. The tape is cut to length before marking the scales, so that the first vernier reading falls at the beginning of the main scale.

6.2.2.3 The scale is fixed in position using a spring for elasticity. This can be made from spring steel wire wound on a lathe, or ordinary spring curtain-wire may be used. Short pieces of steel band are cut and bent over to hold the girth band in place.

6.2.2.4 The scale marks are scribed accurately using a steel template which is made up in a workshop. Alternatively, a hand die-press can be used for aluminium tape. Steel tape is too hard for this to be effective.

6.2.2.5 The vernier scale allows readings to an accuracy of 0.1 mm of diameter increment. Readings are made relative to the first position of the band, which will be some small positive value above the zero point on the scale if the band is correctly fixed.

6.2.2.6 Once the bands are in place, reading them is a rapid process and can be repeated at short intervals for physiological or ecological studies. Girth bands do not give an absolute measure of diameter, and at first placement, the diameter at the band's location should be recorded using a conventional tape.

6.2.2.7 Girth bands of this type are however not practicable for trees of less than about 7 cm diameter because there is insufficient room on small bands for the spring and scale assemblies.

6.2.3 Other types of increment dendrometer

6.2.3.1 Other instruments have been developed for recording cambial activity with high precision over short periods, including ones that produce a graphic record of the growth process (dendrographs). Breitsprecher & Hughes (1975) give a short review and an introduction to the literature. Most of these more elaborate instruments are unsuitable for PSP work and are restricted in use to special experimental situations.

6.3 Height measurements

6.3.1 Types of height measurement

6.3.1.1 Three components of tree height are normally significant. These are total height, crown point height, and buttress height. Crown length can be derived as the difference between total height and crown point height. Figure 6-4 shows the components of tree height.

6.3.1.2 Total height is measured vertically from ground level at the centre of the stem to the highest point of the crown. This may not be possible to estimate precisely even under conditions of clear visibility if the ground is sloping and the crown is asymmetric or the tree is leaning. The flattened nature of most crowns of mature trees makes the lateral and vertical position of the highest point uncertain, even when clearly visible. This can introduce a large measurement error when measuring with a clinometer or hypsometer (Cailliez, 1980).

6.3.1.3 Crown point height must be carefully defined for consistency. It is usually taken as the height to the first major live branch, excluding small

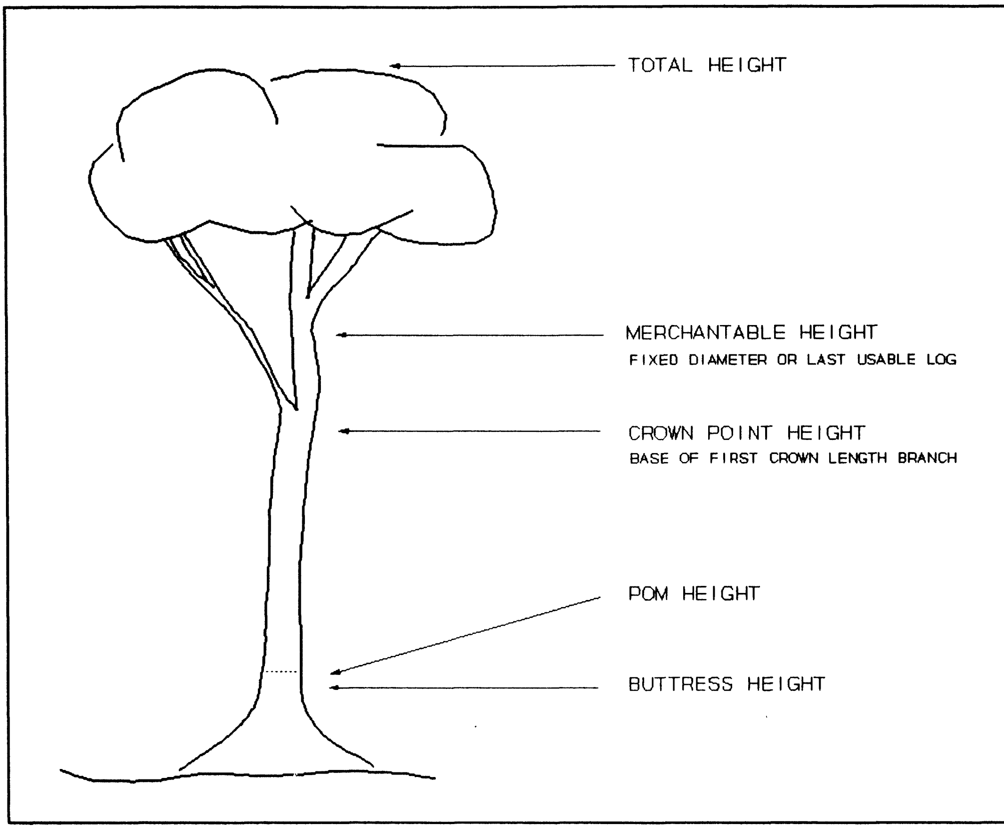

Figure 6-4 : Types of height measurement

epicormic shoots (Synnott, 1979a). Merchantable height is a similar but less precisely definable quantity, as merchantable stem may exist above the first major branch as a continuation of the main bole. Merchantable height can be rigorously defined to a minimum diameter, but this requires upper stem measurements with a relascope. Crown point height is very highly correlated with merchantable height in angiosperm trees (but not necessarily for conifers) and is more easily and precisely definable under field conditions.

6.3.1.4 Buttress height is the height to the convergence of the buttress. As discussed in section 6.1.1, this cannot be unambiguously defined when the shape of the buttress or the bole itself is fluted. As the POM is defined as being above the convergence of the buttress, it is sufficient to record the height of POM, rather than trying to measure a second, rather indefinite point a short distance below.

6.3.2 Clinometers and hypsometers

6.3.2.1 The most common instruments for height measurement in forestry are the hypsometer and clinometer. Both instruments are based on the same trigonometric principle, ie. reading the angle between the horizontal and the line of sight to the height of interest. However, a clinometer is graduated in slope % and degrees; a hypsometer reads height directly for fixed distances from the tree.

6.3.2.2 Mensuration textbooks and handbooks such as Cailliez (1980) or Philip (1983) describe the principles of height measurement with these instruments.

6.3.2.3 Height measurement to a point of interest on the tree is always calculated as the difference between height recorded to the point of interest (almost invariably a positive reading), and height from the observer's eye level to the base of the tree (which may be either negative, when the observer is above the tree base, or positive, when he stands below it on a slope). In form 9-1, it is assumed that this difference is computed in the field by mental arithmetic. This is normally accomplished easily by a trained operator. When several height measurements are made on the same tree (such as buttress, crown point and total height), it will be preferable to record also the height measurement from eye level to the tree base. The form should allow for this base height to be either negative or positive. In most cases it will be negative, as the base will be below the observer's eye level but it may be positive on slopes, when the observer is standing below the tree.

6.3.2.4 When using a clinometer, horizontal distance from the tree is used to calculate height. However, a computer form may use distance measured along the slope from the observer to the tree base, since the measurement to the tree base provides the information required to calculate horizontal distance from distance along the slope. The procedure needs to be unambiguously specified in the field instructions and allowed for on the data recording form.

6.3.2.5 With a hypsometer, the scale is selected that corresponds to the distance from the tree. This distance should be corrected for slope if the latter is greater than 9% (5°). Then, reading the appropriate scale, heights are read directly to the base of the tree, POM, crown point, and total height.

6.3.2.6 The advantage of a hypsometer, compared with a clinometer, is that it gives a direct reading of height. No calculation is required beyond adding the height measurement to the base of the tree. The disadvantage is that under tropical conditions, visibility through the foliage to the crown point and top of the tree is very restricted, and it may be time consuming or impossible to select a distance from the tree that exactly corresponds to one of the hypsometer scales.

6.3.2.7 In general, it is recommended that height readings are made with the % scale of a clinometer and recorded as such, without field calculation.

6.3.3 Telescopic height sticks

6.3.3.1 Telescopic height sticks can be used to measure tree heights up to 15 m with a high degree of accuracy. The instrumental error is in the order of ± 1 decimetre, although ambiguities regarding tree shape may result in errors greater than this. Measurements with height sticks are therefore of sufficient precision to allow estimation of height increment for small trees. Clinometer measurements have higher levels of error (typically ± 1 m for trees of about 15 m) and are much less suitable for such studies.

6.3.3.2 This is of particular interest when studying the development of poles and saplings in gaps or clearings and is discussed further in section 7.3.3 in relation to regeneration studies. For trees over 20 cm dbh, use of height sticks is generally impracticable for total and crown point height, as the trees will exceed 15 m height.

6.3.4 Optical rangefinders

6.3.4.1 Optical rangefinders use parallel mirrors or prisms that are adjusted to bring two images into coincidence. Accuracy decreases rapidly with increasing distance from the instrument to the object. They can be used for obtaining estimates of total height by sighting vertically up through the foliage and estimating the highest point of the tree. This may be considerably easier and more accurate with the flattened crowns of large tropical trees than using a clinometer. They are less useful for crown point height, which can be more easily and unambiguously sighted from a lateral position with a clinometer.

6.3.4.2 Rangefinders fall into two groups with regard to accuracy and price. Lower cost instruments are of the order of $70-100 and will give a precision of around ±1 m at 40-50 m. More precise instruments are available at around $900 with a precision of ±25 cm at this distance (*eg.* the Leitz 8026-16 optical rangefinder).

6.3.5 Selection of trees for height measurement

6.3.5.1 Total height measurement on standing trees in closed forest is so difficult that it cannot be prescribed as a routine measurement. Total heights may be measured outside PSPs in areas of felling operations (where large gaps enable good visibility). From this data regressions can be derived for use with PSPs, to estimate total height from crown point height. This is discussed further in section 6.8.

6.3.5.2 Crown point height is usually easy to measure in closed forest, but on a local scale it is highly correlated with diameter for a given species. As it is time consuming to measure height, it is more efficient to measure a subsample of trees on the plot for crown point height and construct regressions of crown point height on diameter.

6.3.5.3 The size of this subsample can be determined on a work study basis so that the height measurement process does not significantly slow down the total plot measurement. Measurement of the two largest diameter trees (excluding those that are broken or malformed) on each 20 x 20 m quadrat achieves this end and gives a substantial sample for determining average canopy heights on the plot, its quadrat by quadrat variation, and a pool of data for species diameter/crown point height regressions. This amounts to measurement of the 50 largest trees per hectare.

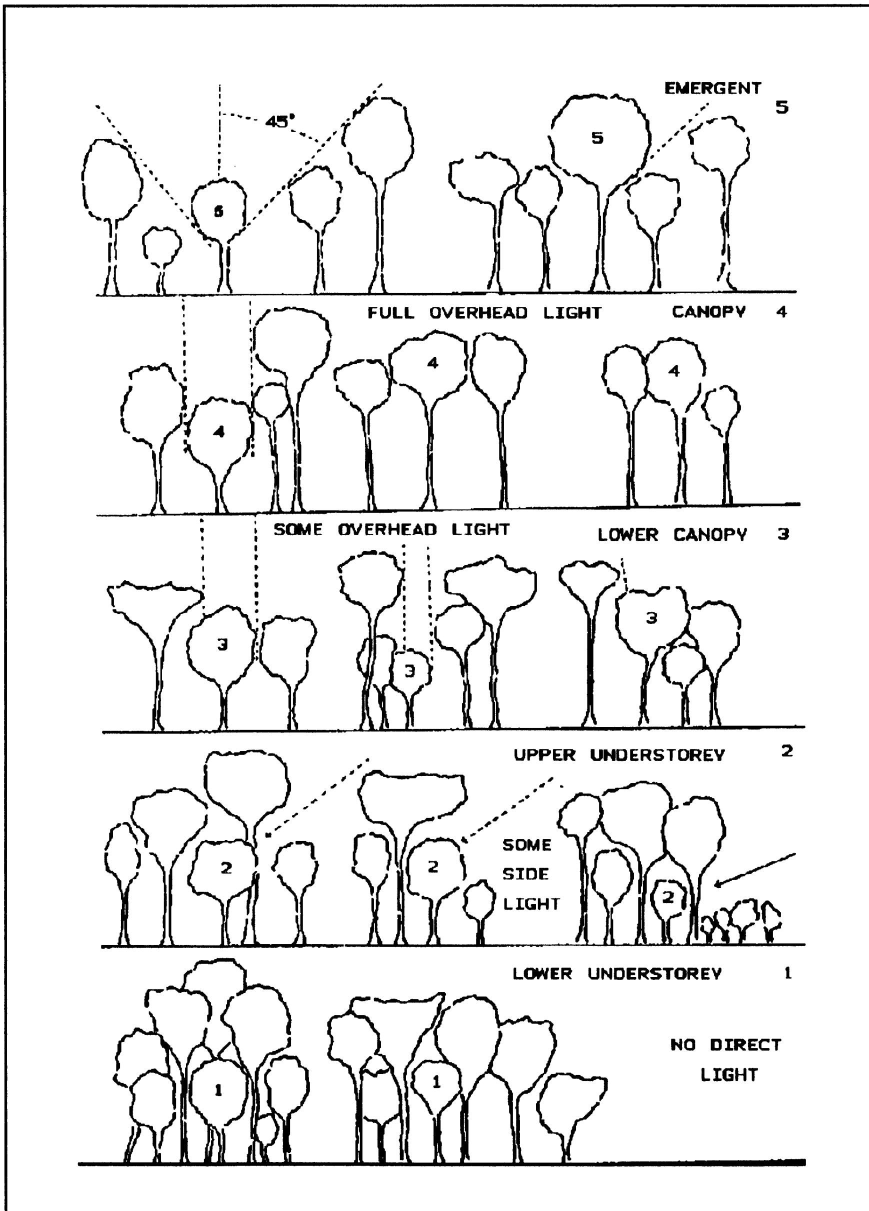

Figure 6-5 : Dawkins crown position classification (after Synnott, 1979a)

6.4 Crown diameter, position and form

6.4.1 The Dawkins classification of crown position

6.4.1.1 A simple subjective system of crown classification developed by Dawkins (1958) has been adopted for PSP work in Ghana, Uganda, Sarawak and elsewhere. It can be readily applied to all trees measured for diameter, and has been shown in analysis to be more consistently related to increment than tree diameter (Alder, 1990).

Crowns are classified on the following scale (see Figure 6-5):

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

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

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

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

1 **No direct light:** Crown plan entirely shaded vertically and laterally.

6.4.1.2 Although the classification is subjective, it appears to give reliable and consistent results (Wyatt-Smith & Vincent, 1962), and correlates well with increment (Alder, 1991). As a simple and rapid procedure, it is recommended that crown position be assessed for every tree on the plot.

6.4.2 Dawkins crown form classification

6.4.2.1 Dawkins (1958) developed a classification for the shape of the crown that is indicative both of its photosynthetic capacity and the general vigour of the tree, and may be correlated both with increment and subsequent mortality.

6.4.2.2 The following crown form scores are defined (Figure 6-6):

5 **Perfect:** The best size and development generally seen, wide, circular in plan, symmetrical.

4 **Good:** Very nearly ideal, silviculturally satisfactory, but with some slight defect of symmetry or some dead branch tips.

3 **Tolerable:** Just silviculturally satsfactory, distinctly asymmetrical or thin, but apparently capable of improvement if given more room.

2 **Poor:** Distinctly unsatisfactory, with extensive dieback, strong asymmetry and few branches, but probably capable of surviving.

1 **Very poor:** Definitely degenerating or suppressed, or badly damaged, and probably incapable of increasing its growth rate or responding to liberation.

0 **Dead**

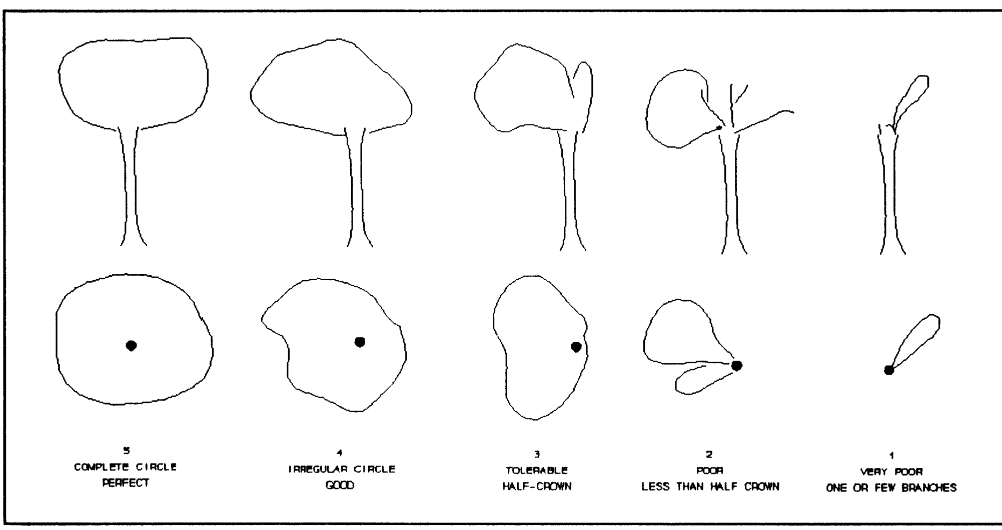

Figure 6-6 : Crown form scores according to Dawkins classification

6.4.2.3 Published data on the correlation of this score with increment is not evident, but low crown scores provide a useful indication of moribund trees. Like crown position, it is an item that can be rapidly assessed, and is therefore recommended for recording on all measured trees.

6.4.3 Crown diameter

6.4.3.1 Measurement of crown diameter in tropical mixed forest is often difficult. In closed forest three people are required. One stands some distance from the tree with a clear view of the edge of the crown tangentially to a given radius. A second holds a tape at the base of the tree, whilst a third moves out until he is sighted by the first operator as being aligned with the edge of the crown. He then measures the radius. This procedure is repeated along four axes mutually at right angles.

6.4.3.2 The four measures of radius can be summed and divided by two in the forest to give mean crown diameter. Alternatively, the four raw measurements may be recorded. The latter may be useful, as the variance in crown radius is an indicator of asymmetry, and should correlate with and substantiate the Dawkins crown form classification.

6.4.3.3 Tubes, prisms and other devices for making vertical sightings of the edge of the crown do not greatly assist the procedure described in paragraph 6.4.3.1. In tropical forest, the density of foliage and low light levels make such instruments difficult to use. It is more rapid and effective to use three people as described.

6.4.3.4 Measurement of crown diameter is a slow procedure. There is a close correlation between crown diameter and tree diameter, and it is usually more effective to undertake a programme of subsampling to determine the crown diameter/tree diameter ratios for species under conditions of varying stand density. As with height, it may normally be sufficient to measure the crown diameters of two sample trees per quadrat, and use this information to build the allometric relationship.

6.5 Coded notes and tree condition indicators

6.5.1 Definition and applicability

6.5.1.1 It is a common practice when assessing PSPs to make informal notes about broken or lost trees, logging or storm damage, flowering, and so on. These notes are in principle very useful, but they cannot be processed in this informal way by computer. It is necessary that a rigid system of codes be adopted that can be analysed so that, for example, mortality can be associated with causal factors, or that trees exhibiting some abnormality can be clearly identified and treated appropriately in the statistical analysis.

6.5.1.2 Various systems of coding can be devised, but they should all have the following common characteristics:

(1) *Flexibility and extensibility.* The method of coding should allow field workers to devise and report back new codes for unforeseen but obviously significant factors. The coding system should therefore be open-ended in the number of classes allowed.

(2) *Careful definition.* Each code should be carefully and clearly defined in an instruction sheet to field workers, with appropriate training and explanation in its application. If new codes are devised, these should be similarly documented.

(3) *Mnemonic character.* Mnemonic letter codes are preferable to purely numeric codes. Besides being easier to remember in the field, such codes will be less easily applied in error, and preserve the essentially qualitative aspect of the note.

6.5.2 Single-letter mortality codes

6.5.2.1 Synnott (1979a) gives examples of single letter codes that can be used to identify various causes of death. These codes can be entered as letters or numbers, and are listed below:

1	T	Logged or felled for timber
2	F	Felled for use as a non-timber product
3	K	Killed by falling tree or branch
4	P	Killed by silvicultural operation(eg poisoning, thinning)
5	E	Killed during road building or log extraction
6	C	Broken by climbers or lianes
7	L	Killed by physical agent such as windblow, lightening, landslide
8	M	Killed by visible mammal damage
9	D	Killed by insect and/or fungal disease
10	S	Apparently killed by shade or competition
11	W	Killed by waterlogging
12	U	Dead or disappeared from unknown cause

6.5.2.2 These codes indicate causes of mortality. However, they are difficult to use in practice as they are applied *after* the tree has died. Under normal humid tropical forest conditions, decay is rapid, and except for cases where records are kept (thinnings, logging extraction), it will be often very difficult to assign a cause of death.

6.5.3 Extended two-letter codes

6.5.3.1 Table 6.1 provides an extended set of two letter codes. These are directed at factors that may *predispose* the tree to mortality or reduced increment, such as logging damage, leaning trees, crown damage, fire damage, etc. They also include indicators of mensurational difficulties that may influence the accuracy of increment estimates: fluted bole, optical measurement, change of point of measurement (DC).

6.5.3.2 This list is not exhaustive and should be added to as appropriate. For example, if silvicultural operations are being undertaken, then PT (poisoned tree) or GT (girdled tree) could be added. Notes on tree markings may be desirable (eg MF: marked for felling). If animal damage is a factor, appropriate codes should be devised (ED: elephant damage; BD: buffalo damage, etc.).

6.5.3.3 These codes are intended to be used in combination and are not mutually exclusive. The suggested data entry forms (see Figure 9-1) allow for up to six codes to be combined.

6.5.3.4 The use of these codes is important and should be adopted as suggested or appropriately modified. The codes can help to screen doubtful data, assign probable causes for mortality and disappearance of trees, and partition components of the stand that may have lower increment.

6.6 Indicators of competition

6.6.1 Implied measures of competition

6.6.1.1 Competition strongly influences increment and mortality. However, measures of competition can be devised that depend on tree position and size relative to neighbours, on stand basal area, or on the tree diameter relative to quadrat mean diameter (Adlard, 1974; Alder, 1979).

6.6.1.2 These measures are implied by and computed from other plot measurements, especially tree positions, quadrat subdivisions, and tree size relative to other trees on the plot. For these implied measures to be calculable for a PSP, *it is essential that all large trees on the plot are measured for diameter.*

6.6.1.3 For this reason it is recommended that, even when a tree is too large to measure reliably for increment estimation, it should be measured by optical methods (see section 6.1.10) so that its competitive influence may be estimated. Similarly, large non-commerical species or those of poor form should be recorded.

Table 1 : List of recommended Tree Condition Codes

BS **Broken stump:** Only a broken stump has been found at the tree's coordinates.

BT **Broken top:** The crown has completely broken off.

CD **Crown damage:** Major branches have been broken in the crown.

CI **Climber infestation:** The crown of the tree has been invaded by climbers, which are seriously competing with the trees own foliage. This code should not be applied if the climber foliage is generally below the main tree crown, and therefore not offering serious competition.

DB **Dead bark:** Bark has been lost over part of the stem, exposing wood underneath.

DC **Diameter change:** The reference diameter is now part of the buttress and can no longer be measured. The alternate diameter is adopted instead (see Section 6.1.3).

DF **Defoliation:** The tree has lost all or some of its foliage, leaving apparently dead branches. This should not be confused with foliage loss associated with broken branches (CD), but may arise from insect attack, bats, foliage eating mammals, drought, after fire, etc.

DT **Dead tree:** The tree is apparently dead, but remains standing.

DU **Diameter unreliable**: The diameter measurement is unreliable because of large climbers, splits, damage or wounds at the point of measurement.

EX **Excrescenses:** Lumps of callus or wood bulge from the stem, sometimes bearing epicormic branches. Commonly caused by insect or fungal attack.

FB **Fluted bole:** The bole has substantial concave sections up its length and cannot be properly measured.

FD **Fire damage**: The tree shows evidence of charring of the bark or wood.

FU **Fungi:** Fruiting bodies of fungi are growing from the stem or surface roots.

FW **Flowering:** This is noted if the tree is in flower, or has recently flowered and is bearing or dropping fruit.

IN **Ingrowth**: This code is used only at remeasurement (not initial demarcation). The tree has appeared above the measurement limit and is being marked and measured for the first time.

LD **Logging damage:** The tree has suffered damage obviously attributable to logging.

LS **Logged stump:** A sawn stump, indicating logging, is found at the tree's coordinates.

LT **Leaning tree:** The tree has been pushed or has fallen from its normal position and is some degrees from the vertical.

NT **No tree:** The tree is missing. There are no indications of the tree at the required coordinate.

OD **Optical diameter measurement:** Used when the trees diameter has been measured by relascope or dendrometer, rather than by tape.

RB **Rotten buttress:** The butt or buttress is rotten and partially hollowed.

RT **Rotten timber:** Evidence of rot entering the tree from visible rotten pockets left by broken branches.

ST **Strangled tree:** The tree has been invaded and its crown dominated by stranglers. Normal diameter measurement will be impossible if this code is present.

TF **Tree fallen:** The tree has completely fallen.

US **Unknown or uncertain species** identification: The species code entered (if any) is provisional or approximate.

6.6.2 Competing basal area

6.6.2.1 Dawkins (1958) recommended a system for measuring competing basal area of neighbouring trees based on the relascope principle. Trees whose girth in inches exceeded their distance from a subject tree in feet were to be counted. The basal area factor applicable is 7.7, giving a competing basal area in square feet per acre.

6.6.2.2 This method was applied over some 20 years of observations on PSPs in Ghana (Baidoe, 1968). The results from this data do not suggest that this measure of competition has any strong correlation with increment (Alder, 1991).

6.6.2.3 Basal area as an index of competition can also be measured by summation of the tree basal areas on the quadrat of the subject tree, or if tree positions are measured, it can be calculated for different radii of circles or for various theoretical basal area factors.

6.6.2.4 Basal area as an index of competition has a number of attractive features. It should be appreciated however that it is a scale-dependent measure. In other words, basal area measured on a quadrat of 20 x 20 m is not equivalent, as an index of competition, to that measured on a 1-ha plot or that derived from a relascope sweep with a given factor (such as the Dawkins system described in paragraph 6.6.2.1).

6.6.2.5 Therefore, if basal area is used as an index of competiion, the method of measurement adopted should be compatible between the PSPs and the TSPs used in forest inventory that may form the database to which any yield model is applied. In other words, the same method of measuring basal area should be adopted on both types of plot. If basal area is derived for a large area, such as a whole plot, then the plot shapes should be compatible. The use of a standardized quadrat on both PSPs and inventory plots (TSPs) is recommended for this reason.

6.6.3 Counts of competing trees and climbers

6.6.3.1 Trees whose crowns are crowding or overtopping the subject tree can be counted, with this score being used as an index of competition. This basic method can be elaborated by identifying the competing trees by number, so that a weighted scale of competing tree basal area relative to subject tree basal area can be computed as an index of competition.

6.6.3.2 However, such counts and further measurements are time consuming in the field, and the same competition data are implicit in the tree positions, tree diameters, and crown diameter/tree diameter regressions that are also measured on the plots. It is more efficient to compute a competition index than to attempt to measure it by counts of competitors. In general direct counts of competitors are not recommended as a procedure.

6.6.3.3 Climbers are, however, a different matter as their size and influence cannot be directly imputed from other plot data, and some method of assessing their influence should be included.

6.6.3.4 Climbers significantly competing with the crown can be counted, as in the procedure described by Baidoe (1968). As a simple count, this is a crude system that can be expected to discriminate between trees essentially free of climbers and those infested. There is a need for the method to be refined into degrees or classes of climber competition.

6.6.3.5 The following scoring is proposed as a guide. It can be modified as appropriate in the light of local experience:

Climber score	*Description*
0	No climbers present that significantly affect crown.
1	Climbers with foliage present in crown but below the level of the trees own foliage.
2	Climber foliage in upper part of crown and starting to compete for light with the host tree.
3	Climber foliage tending to dominate the host tree foliage, although the latter is still present and receiving direct light.
4	Climber foliage completely dominanting the crown; foliage of the host tree mainly suppressed.
5	Host tree foliage absent or not visible. Tree completely strangled by climber.

7 REGENERATION ASSESSMENT AND MEASUREMENT

This chapter covers methods for recording regeneration sub-plots on PSPs, with methods for measuring seedling locations and dimensions, and tagging and marking methods for seedlings.

7.1 Application and definition of regeneration sampling

7.1.1 General definition of regeneration sampling

7.1.1.1 Regeneration sampling can be taken to include the enumeration and measurement of all trees, saplings and seedlings below the minimum diameter limit that is adopted for a PSP programme. That minimum limit, which will commonly be 20 cm as recommended in section 3.4.3, is applied to the whole of a PSP.

7.1.1.2 Below the 20-cm limit, the small tree population becomes very numerous. In addition, the number of species increases radically; many of the species occurring in this size class never attain larger dimensions and are irrelevant to forest management for timber, although they may be important as non-timber products.

7.1.1.3 Owing to the broad definition of regeneration (ie. all trees below the normal minimum measurement limit (20 cm)) further sub-classes must be defined for practical sampling.

7.1.2 Applicability

7.1.2.1 Regeneration sampling is essential to the proper management of the forest. In inventories it is used for obtaining a complete table of the size class distribution of the growing stock. On PSPs and experiments it is needed for studying the dynamics of the smallest trees.

7.1.2.2 Because of the high work load involved in permanently tagging and marking small trees, it may not be possible to undertake regeneration sampling on all PSPs. Table 3-2 gives some idea of the additional work involved. With the type of sub-sampling suggested in Figure 3-5, plot assessment and demarcation time will be approximately double that for simply demarcating a main plot down to 20 cm diameter.

7.1.2.3 It is suggested that regeneration sampling is carried out on a systematic sub-sample of PSPs whose proportion is determined by the resources available. For example, one PSP in five could be selected for regeneration sampling. For experimental plots it is likely that regeneration sampling will be required more frequently, as many treatments will directly or indirectly influence regeneration.

7.1.3 Definitions: Poles, saplings and seedlings

7.1.3.1 Synnott (1979a) defines the following terminology and usages for PSP work:

Seedlings	:	0-150 cm high
Saplings	:	from 150 cm high to 5 cm diameter
Poles	:	5-20 cm diameter

7.1.3.2 Trees below 5 cm diameter must generally be measured using calipers, and cannot be nailed or painted with numbers. Their measurement therefore forms a distinctively different technical problem to that of the poles, which can be generally be measured and marked in exactly the same way as larger trees.

7.2 Establishment of sub-sampling units

7.2.1 Location and size of sub-plots

7.2.1.1 As shown in Figure 3-5, three tiers of nested subplots are recommended on most PSPs and experimental plots. Nesting implies that the sub-plots being measured to the smaller limits are wholly contained within the plots measured to the higher limits. Thus, the sub-plots being measured down to 1.5 m high are contained within the subplot measured down to 5 cm diameter, which in turn is within the main plot measured down to 20 cm.

7.2.1.2 On a standard 1-ha plot, five quadrats will be measured down to a minimum diameter of 5 cm. The central quadrat of the plot has all saplings measured and tagged. Within that quadrat strips 1 m wide are located, within which all seedlings of tree species are marked and tagged. From the pantropical stand table in Table 3-2, the following are the areas and numbers of trees likely to be measured and marked:

Number of quadrats	*Minimum diameter for measurement*	*Area of sub-sample (ha)*	*Approximate number of stems measured*
25	20	1	100-200
5	5	0.2	75-150
1	>1.5 m high	0.04	20-40
0.2	any tree seedling	0.008	40-80

7.2.1.3 The 1-m wide seedling strips are located within the sapling quadrat. Their position should be systematic (at distances of 4, 8,12 and 16 m from the southern boundary of the quadrat). However, if a large tree intersects the strip, it should be moved so that a clear line is obtained. The positions of the other strips can be adjusted so that if possible the space between strips is always 2 m or more.

7.2.1.4 On experimental, as opposed to sampling, plots different criteria may determine the arrangement and size of the sapling and seedling sub-plots.

The experimental plot may be mapped according to disturbance patterns, and then regeneration plots laid systematically or randomly within these mapped strata.

7.2.2 Marking and tagging methods

7.2.2.1 Poles from 5 to 20 cm diameter can be marked and tagged by the same methods as those applied to larger trees. Below 5 cm, neither nails nor painted numbers are practicable. Saplings and seedlings should have an alloy tag tied to them with copper wire (see section 5.2.1). This should be tied loosely and allowed to rest on the ground.

7.2.2.2 The point of measurement on trees above 1.5 m high (saplings) should be marked with paint. Trees in this size range are too small to measure efficently with a tape, and should be measured by calipers, as described in section 6.1.7.

7.2.2.3 Small seedlings (below 1.5 m high) should be tagged similarly to the saplings, with loosely tied labels, resting at ground level.

7.2.3 Demarcation precautions

7.2.3.1 The demarcation of the subplots for poles, saplings and seedlings must be carried out more carefully than for the main plot. Although quadrat and subplot boundaries must be clearly marked, care must be taken not to cut any trees which represent part of the measured population, or are likely to grow into it during the next 10-year period. This implies that:

- On pole subplots, boundaries should be brushed only for non-tree vegetation.
- On sapling and seedling subplots, boundaries should not be brushed or cut at all.

7.2.3.2 During measurement of the subplots, care must be taken by the workers not to trample or break seedlings and saplings. Some damage is inevitable, but every effort should be made to minimize it.

7.2.3.3 The seedling subplots are arranged as 1-m wide strips, so that all measurements can be made from the edge of the stip, without walking on it. During plot measurement, plastic flagging should be used to mark the sensitive areas in two zones. One colour should be placed around the perimeter of the sapling quadrat; a second colour should be used to demarcate the edges of the seedling strips. This flagging should be removed once work on the plot is completed, but may be left in place for some weeks if follow up work is being done by a botanical team (see section 5.4).

7.2.3.4 The end points of the centre-line of the seedling strips, and the corners of the sapling quadrat, should be permanently demarcated with durable hardwood posts 40-60 cm long and buried with only 5 cm showing. A plate of soft galvanized sheet can be nailed on top of these posts to help relocate and preserve them. These markers are desirable because of the small size of the sample, and the fact that the exact re-delineation of the perimeters is necessary to avoid relatively large errors in ingrowth and mortality estimates. This is particularly desirable for the regeneration strips, whose linear shape makes them prone to errors at their perimeters.

7.3 Measurements on small trees and seedlings

7.3.1 Location, survival and ingrowth

7.3.1.1 As with larger trees, locations should be measured to assist in identifying trees at remeasurement, and to allow various methods of estimating competitive effects to be tested. The method of measuring locations for poles and saplings is the same as for larger trees, as described in section 5.3.3.

7.3.1.2 For seedlings, the measurement of locations within strips is somewhat faster. A tape is laid along the centre line of the strip. This should be laid from the western edge of the quadrat (which reads as zero) to the eastern edge. The position of the seedling along the tape gives its E coordinate directly. The distance from the centre line should be measured by a measuring stick, to the nearest decimetre. This distance (O) is added or subtracted from the N coordinate of the centre line. Figure 7-1 illustrates this process. With a suitable data recording format, the centre line coordinate is recorded once, and only the offsets need to be entered on the form, with a direction north or south of the centre line.

7.3.1.3 Seedlings and saplings that die between measurements will usually disappear without trace, and the tag will be buried in the soil. An important purpose of regeneration studies is to assess survival rates of small trees under different degrees of competition. It is, therefore, important to try and locate every seedling tagged at the preceding measurement. The tree coordinate information should assist this process. Stems that cannot be located should be marked with the coded note NT (No Tree), and are presumed dead.

7.3.1.4 New stems may arise directly as regeneration from seed between measurements or, for the poles and saplings, as ingrowth from the unmeasured sizes. In either case, such new stems are marked, mapped and tagged at remeasurement, and given the coded note IN (ingrowth). In the case of the seedling class, ingrowth is something of a misnomer, but the note should still be used to clearly identify new stems and assist in error checking of the data.

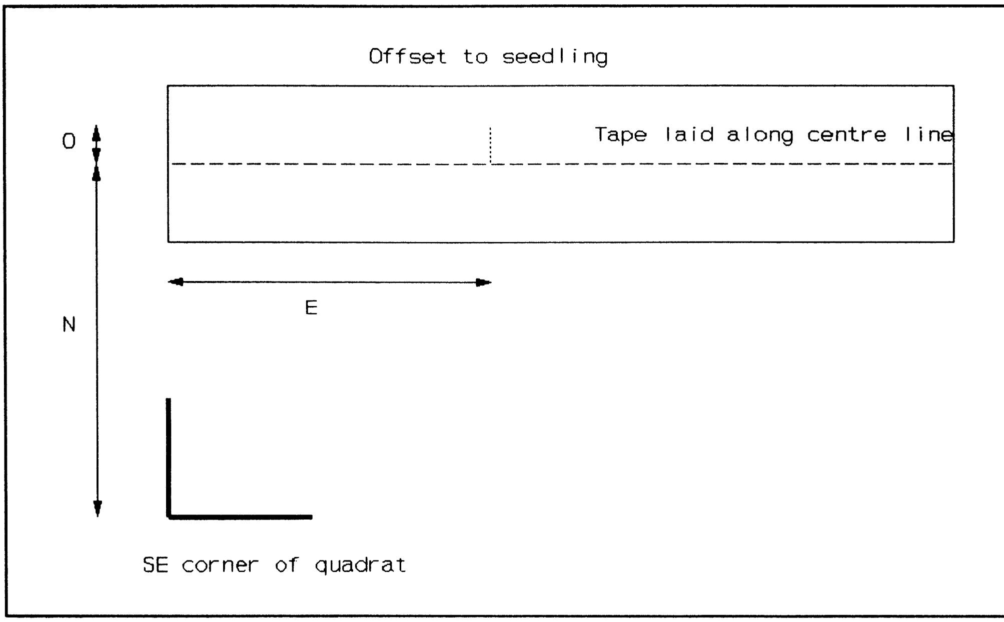

Figure 7-1 : Method of coordinate measurement on seedling strips

7.3.2 Diameter

7.3.2.1 Diameter is measured on poles (trees above 5 cm dbh) in the same way as for larger trees, preferably using diameter tape (see section 6.1).

7.3.2.2 For saplings, diameter should be measured using calipers, as tapes become inaccurate on small stem dimensions. The orientation and point of measurement should be marked with spots of paint, but for trees below 2-3 cm these will inevitably merge into a single mark, so that the original orientation cannot be assured at remeasurement.

7.3.2.3 For seedlings below 150 cm height, diameter need not be measured. However, for some research studies it may be useful. In this case, diameter can be measured immediately above the root collar using calipers.

7.3.3 Height

7.3.3.1 For seedlings and saplings, height can be measured accurately using telescopic height poles, and should be recorded to the nearest centimetre. For poles, this procedure becomes too time consuming, and is only necessary on some research plots to study the general relationships between diameter and height growth under conditions of competition.

7.3.3.2 Heights of trees greater than 15 m cannot be efficiently measured by telescopic height stick. Such trees may be measured by hypsometer if required.

7.3.3.3 The height of seedlings and saplings should be measured to the highest point of the tree without straightening it. A seedling or sapling will often be bent over at the tip. It should be measured as shown in the illustration.

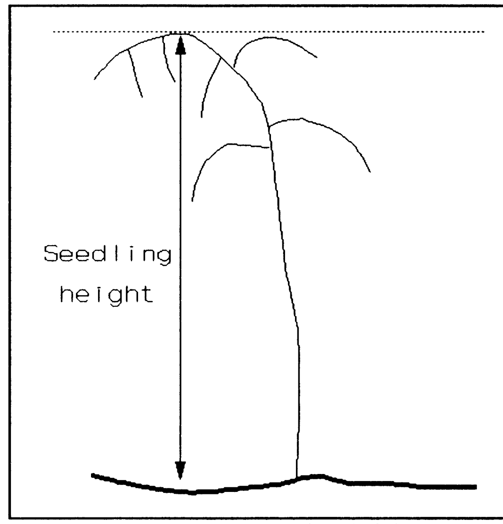

Figure 7-2 : Measuring heights of saplings and seedlings

7.3.4 Other observations

7.3.4.1 The Dawkins crown position classification (section 6.4.1) should be applied to all poles, saplings and seedlings. For the saplings and seedlings, the general situation of the quadrat will affect the whole classification. If the quadrat carries large trees, almost all the saplings and seedlings will be in crown classes 1 and 2. If, on the other hand, the quadrat is in a skid trail or gap, then the larger poles and saplings will be in classes 4 and 5. Seedlings growing in direct sunlight in skid trails or gaps should be classified as 5.

7.3.4.2 Coded notes should be applied to regeneration as for larger trees.

7.3.4.3 Measures of photosynthetically active radiation (PAR) can be applied to regeneration to determine available light within the plots. This method may be appropriate for experimental plots. Integrating lightmeters can be used for this purpose. An alternative, more convenient, method is to use a camera with a very short focal length 'fish-eye' lens. For example, a lens of 21 mm for a standard 35 mm camera. The camera is placed horizontally on its back at ground level, or at a standard height above ground using a tripod, and a photograph taken using high contrast black and white film. On development, it is printed on lithographic or high contrast paper, and then scanned by computer. The ratio of sky (white) to foliage and woody material (black) can be determined by a pixel count by the computer. This should correlate with available light in the understorey. If a scanner is not available, a dot grid can be used to count systematically the exposed and clear areas of the photograph (Turner, 1988).

8 SITE ASSESSMENT

This chapter describes basic methods of site assessment for PSPs, including topographic and soils-related indicators, the use of indicator species and vegetation associations, and quantitative methods based on crop height and diameter.

8.1 Principles of site assessment

8.1.1 Objectives

8.1.1.1 As with plantations, the growth rates and yield of mixed species forests can vary greatly with site. An efficient growth forecasting system must, therefore, include a method of forest site classification.

8.1.1.2 For a method of site classification to be useful, it must not only be applicable on PSPs, subject to more or less intensive and long-term study, but it should also be applicable on forest inventory TSPs. This allows the database on the forest growing stock to be classified by site type. Such a method must be simple and rapid in the field, yet have a with good predictive capability.

8.1.1.3 Unlike plantations, where site index based on height is a well established technique, there is no consensus as to a single method applicable to mixed tropical forest. PSPs should, therefore, be assessed by a number of the methods described in this chapter, to determine at the analytical stage which shows the best correlation with predicted yield.

8.1.2 Classification of methods

8.1.2.1 The general methods of site assessment that may be applied in mixed tropical forest include:

- *Visually assessed indicators*, including the presence of swampy soils, signs of fire, indications of farming, presence of logging tracks or human structure. These type of indicators are intended to assess disturbance of various types and degrees, thus showing that the forest development has been modified in some way.
- *Topographic and climatic indicators.* These include both indications assessed on the ground, such as slope, aspect, and slope position, and information derived from maps and records, such as monthly and annual temperature and rainfall regime.
- *Soil type.* Soil type may be a good indicator of site in particular localities. However, soil survey may not be practical as a basis for classifying TSPs, and hence even if effective with PSP data, soils-based indicators may be of little general value.

- *Vegetation types and indicator species.* The occurrence of species is a sensitive reflection of environmental conditions, and hence potential productivity.
- *Mensurational site indices.* These are quantitative site indices that can be derived from the routine tree measurements on the PSPs, especially diameter and height.

8.1.3 Area basis of application

8.1.3.1 Site assessment needs to be based on and related to standard units of area. For this purpose, *it is proposed that assessment is normally conducted quadrat by quadrat*. It is difficult to define the meaning of many indicators on a 1-ha area, as soils, topography, slopes, etc., may change markedly over short distances.

8.1.3.2 Furthermore, site indicators (as with competition indices) must ultimately be related to TSP inventory data when making forest growth projections for management purposes. TSPs are often linear units, which may average out site variation even more than a 1-ha square PSP. This effect can be avoided by basing site classification on quadrat level units on both TSPs and PSPs.

8.2 Descriptive indicators of site

8.2.1 Method of use

8.2.1.1 Descriptive indicators are coded notes, analogous to those applied at the tree level, described in section 6.5.3. They relate mainly to types of disturbance, rather than intrinsic factors of site productivity, but are very important in classifying quadrat level data at the time of analysis.

8.2.1.2 They are determined from a visual assessment of the quadrat, and are recorded, quadrat by quadrat, on the data coding forms. As with the coded tree notes, several indicators may be applied at once.

8.2.2 List of suggested indicators

8.2.2.1 The following table lists suggested indicators:

CC	**Climber cutting** has or is being carried out on the quadrat.
CT	**Climber tangle**. Large masses of climbers have formed on top of pole sized regrowth.
FI	**Fire.** Indications of recent forest fire.
GA	**Gap**. The quadrat intersects a natural gap formed by tree fall.
GU	**Gully or embankment**. A dry gully (as opposed to stream) or embankment intersects the plot (see section 8.3.1).
HF	**Human (forest dwelling) community.** Indications of an indigenous human habitations on the quadrat.

LA	**Log landing**. A log landing or loading bay intersects the quadrat.
LO	**Logging.** Signs of recent logging on the quadrat.
LR	**Logging road**. A logging road or part of the cleared margin for one intersects the quadrat.
PF	**Plantation forestry**. Part of the quadrat intersects a forest plantation.
RK	**Rock outcrop**. Rock outcrops intersect part of the quadrat.
RS	**River, stream or lake**. A river or stream intersects the quadrat.
SC	**Shifting cultivation**. Part of the quadrat has recently been felled and cultivated.
SK	**Skid trail**. A skid trail passes through the quadrat.
SV	**Silviculture.** Trees on the quadrat have been killed by girdling or poisoning as part of a refining or liberation thinning operation.
SW	**Swamp**. Indications of extensive and continuous waterlogging of the soil, including presence of stilt-rooted or swamp species, dark black soils, standing water. Standing water may be absent in the dry season.
TC	**Tree crops** (rubber, cocoa, oil palm etc.) are growing on the quadrat.
UP	**Underplanting**. Underplanting, line planting or enrichment planting has been done on the quadrat.

8.3 Topographic and climatic site indicators

8.3.1 Slope position

8.3.1.1 Slope position should be scored according to the codes shown in Figure 8-1. On flat or level ground, the slope position should be given as zero. The slope position is taken for the central point of each quadrat. However, if the quadrat is dissected by a gully or embankment, this should be noted with a GU code, and the general slope position of the quadrat considered apart from the local features within it.

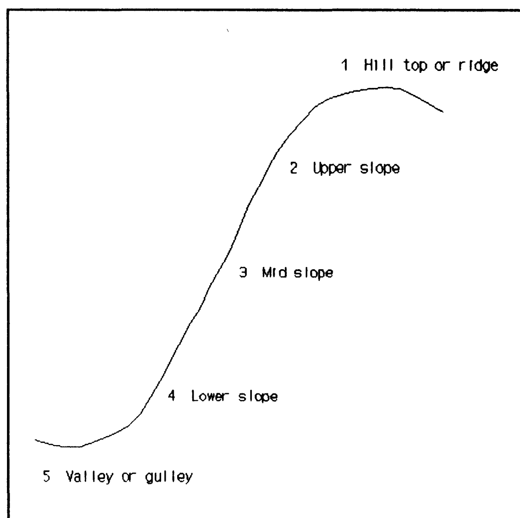

Figure 8-1 : Slope position codes

8.3.2 Aspect and slope

8.3.2.1 It is unlikely, in the intertropical zone, that either aspect or slope will correlate with site productivity. Very steep slopes may be less productive owing to soil erosion. Recording slope and aspect on each quadrat however takes little time relative to other plot measurements, and may be done if required. It is not necessary if the plot is being surveyed by level (section 8.3.4).

8.3.2.2 Slope is recorded in the steepest direction, using a clinometer graduated in degrees or percent. The use of the percent scale is more normal.

Aspect is the bearing along which the slope is recorded, *facing down the slope*.

8.3.3 Altitude

8.3.3.1 The altitude of the plot may be measured from maps, or recorded in the field using a barometric altimeter or GPS instrument. Altitude in mountains or hilly terrain directly affects mean air temperature, and hence plant growth, and should be recorded whenever possible.

8.3.3.2 Barometric altimeters are simple to use and reliable if properly calibrated at a point of known height. GPS instruments also give absolute altitude to ±50 m, but require clearings in which to operate, and therefore may be difficult to use on the PSP.

8.3.4 Survey of microtopography

8.3.4.1 On experimental sites, it may be desirable to survey the plot using a level. This should be done along the quadrat boundary lines. The resulting survey data can be used to produce a contour map of the plot, which may be overlaid on the tree map.

8.3.4.2 Such intensive surveys are of no direct value, as they cannot be replicated on TSPs, but may help in understanding species preferences and associations, and can be useful in the context of ecosystem research. They are normally associated with soil surveys.

8.3.5 Local climatic data

8.3.5.1 Climatic data from weather stations in the general vicinity of the plot are very useful as a basis for site classification. Monthly rainfall and mean maximum and minimum temperatures can be used to compute various climatic indices that may be related to productivity.

8.3.5.2 Climatic data is principally useful in conjunction with species association studies. Species associations are usually a more sensitive and easily determined indicator of long-term climate than data from sparsely scattered weather stations. By correlating the components of species association analysis with climatic data, it is possible to determine which combinations of species have preferences for different climates (Hall & Swaine, 1976).

8.4 Soil survey

8.4.1 Survey methods and tools

8.4.1.1 Soil surveys are a separate topic, outside the scope of this manual. A useful reference is Clarke & Beckett (1985). However, soils on PSPs can be examined, chemically analysed, and classified within an existing scheme of classification for a region.

8.4.1.2 It is not generally practicable on a PSP to dig soil pits, both because of the time and labour involved, and the disturbance and danger that the pit may cause on the plot. For this reason augurs should be used.

8.4.1.3 Augur holes can be bored near the centre of each quadrat. A separate field form will be completed for each quadrat. The survey work will require an experienced soils technician, as matters such as the field determination of soil texture, colour and pH require experience and training.

8.4.1.4 Apart from the soil augur, the principal equipment required is a Munsell colour chart with tropical supplement, a pH test kit, and possibly plastic bags for collecting samples for analysis. A container of water will be required to assist in texture determination and to clean the hands between samples.

8.4.2 Field description of the soil

8.4.2.1 Each augur full of soil material should be examined and described for texture, colour, the presence of stones and aggregates. Soil structure is largely obliterated by the use of an augur (as opposed to soil pit) and may not be determinable. Assessment of pH in the field may be useful, and it can also be done at different levels in the bore hole.

8.4.3 Sampling for laboratory analysis

8.4.3.1 Determination of soil nutrients requires laboratory analysis. A field laboratory can be set up for temporary use as the equipment involved is not very complex, comprising mainly glassware, heating and shaking equipment that can be powered by a portable generator, and analytical instruments such as colorimeters for organic carbon (C), nitrogen (N), phosphorus (P), and potassium (K) determination. For determination of trace elements and organic compounds, a gas chromatograph is required. Field-portable types are available.

8.4.3.2 In most cases however, samples will be sent to a specialist laboratory for analysis. Therefore, it is important that:

- Samples are taken and packed in accordance with specialist advice, preferably from the laboratory doing the analysis.
- The sample bags are labelled with indelible waterproof marker. Each bag should be labelled with a serial number comprisng PSP number, quadrat number and approximate sample depth in centimetres.

8.5 Vegetation associations and indicator species

8.5.1 Vegetation associations

8.5.1.1 Vegetation analysis using numerical techniques is widely established. For PSPs no special observations are necessary provided that species on the plot are correctly identified. It is often the rarer and more obscure species that are most useful as a basis for classification, which emphasizes the importance of correct and rigorous species identification.

8.5.1.2 Hall & Swaine (1976) provide an example of the use of the technique for forest type classification in Ghana. Pielou (1977) and Grieg-Smith (1964) are useful textbooks. Hill (1973) details the method of *reciprocal averaging*, which is an efficient and straightforward ordination method for presence/absence data.

8.5.2 Indicator species

8.5.2.1 Some species occurring in the understorey as shrubs or herbs, ferns, palms or climbers may be useful indicators of special site conditions, including waterlogging, fire and past disturbance. The presence of cultivated trees may similarly indicate farming at some earlier time.

8.5.2.2 Data on these species will not be collected as part of the routine plot measurement of trees. Specialized procedures need to be devised with the assistance of a botanist to define:

- *A list of significant species*. This will generally include light-demanding weeds indicating canopy opening, species that germinate following fire, and swamp species.
- *A method of quantification*. Simple presence/absence indications on a quadrat-by-quadrat basis is probably sufficient, but percentage coverage of the quadrat may be estimated for plants such as *Eupatorium spp.* or members of the *Marantaceae*.

8.6 Mensurational site indices

8.6.1 Dominant height of economic species

8.6.1.1 In stands managed under a uniform system of silviculture, the height of the dominant trees can be used as a site index in a method analogous to the techniques employed on plantations. On PSPs, this requires that the height of a selected number of the largest trees per hectare is measured. In plantation work dominant height is based on the mean height of the 100 largest diameter trees per hectare.

8.6.1.2 There is no standard definition of dominant height for mixed forest. Measuring total height, except immediately after exploitation, is difficult and inaccurate for the reasons cited in section 6.3. Consequently, it is unrealistic to propose that 100 trees/ha should be measured in this way.

8.6.1.3 An alternative suggestion, given in section 6.3.5, is to measure the crown point height of the two largest trees on each quadrat (assuming the plots comprise 25 20 x 20 m quadrats). These data should be supported by separate allometric studies between crown point and total height, based on measurements taken in exploited areas where it is possible to sight a hypsometer to the top of the crown. This approach to total height determination was taken by Vanclay (1989), in the context of a site form index (see 8.6.2 below).

8.6.1.4 These data may be used either to build a dominant height site index function, using years since logging rather than stand age as in plantation techniques (Alder, 1980), or a site form related function (Vanclay & Henry, 1988; Vanclay, 1989).

8.6.2 Site form

8.6.2.1 Site form is a concept described by Vanclay & Henry (1988). It is analogous to a conventional site index based on dominant height, but uses the relationship with diameter, rather than age, to build the set of site index curves (see Alder, 1980, p.41). A closely related concept is that of a site indicator based on mean height within a given diameter class (Canonizado, 1979).

8.6.2.2 As discussed in the previous section, for PSP work it is sufficient to measure the crown point height of the two largest trees on each quadrat, or 50 trees/ha, provided that a separate and reliable allometric regression is made between crown point height and total height.

8.6.3 Basal area

8.6.3.1 On undisturbed stands maximum basal area is both an important indicator of site, and a necessary parameter for growth model development. Better sites may be expected to carry higher basal areas (Assmann, 1970).

8.6.3.2 However, logging will remove variable amounts of basal area, some of which may be recorded, and some of which may be lost because of logging damage and post-logging mortality. Hence basal area is unlikely to be useful as a site indicator in managed stands.

8.6.3.3 Recording of basal area is implicit in the diameter measurements taken on the PSPs; no special measurements are required for the use of basal area as a site indicator.

9 DATA RECORDING AND PROCESSING

This chapter gives general procedures for recording data on PSPs, and presents examples of forms suitable for field use. It describes methods of data entry and validation, and record structures for use with database programs, consistent with the field forms given. Requirements for the long-term management of PSP databases are discussed.

9.1 Methods of field data recording

9.1.1 Paper forms

9.1.1.1 The use of preprinted forms on which measurements and other observations are written in the field provides the simplest, most robust and cheapest method of recording tree and plot measurements.

9.1.1.2 The forms used should be written in pencil. Pen tends to smear and spread under humid conditions. Pencil entries can be corrected if necessary, although erased portions of text tend to be illegible. A clipboard should be used to hold the forms while entries are made.

9.1.1.3 Because forms are cheap they can be distributed among a number of working parties on the plot. The booker who fills the recording form should work closely with the measurement crews. A common source of error arises when one booker serves two or more measurement crews, and attributes measurements that are called out to the wrong tree.

9.1.1.4 The principal disadvantage of paper forms is that they require an additional process in the office, that of computer data entry, which in some countries may be excessively expensive due to high labour costs.

9.1.2 Use of computer terminals in the field

9.1.2.1 Field-portable computers are readily available, and range from units that run the MS-DOS IBM PC compatible operating system (*eg* Husky Hunter), to calculator type units with small displays and their own programming language (*eg* Psion Organizer). Systems vary greatly in their degree of shock and water resistance.

9.1.2.2 A typical unit will allow data to be entered onto a screen form, edited if errors have been made, and stored on a semi-durable memory pack or diskette for down loading onto a desktop computer in the office or a portable computer at a base camp. Data can be transmitted direct from the field camp to the office for processing using a modem with radio or telephone link.

9.1.2.3 The principal disadvantage of field computers is their high unit cost. Depending on the specification and durability, they may range from $400

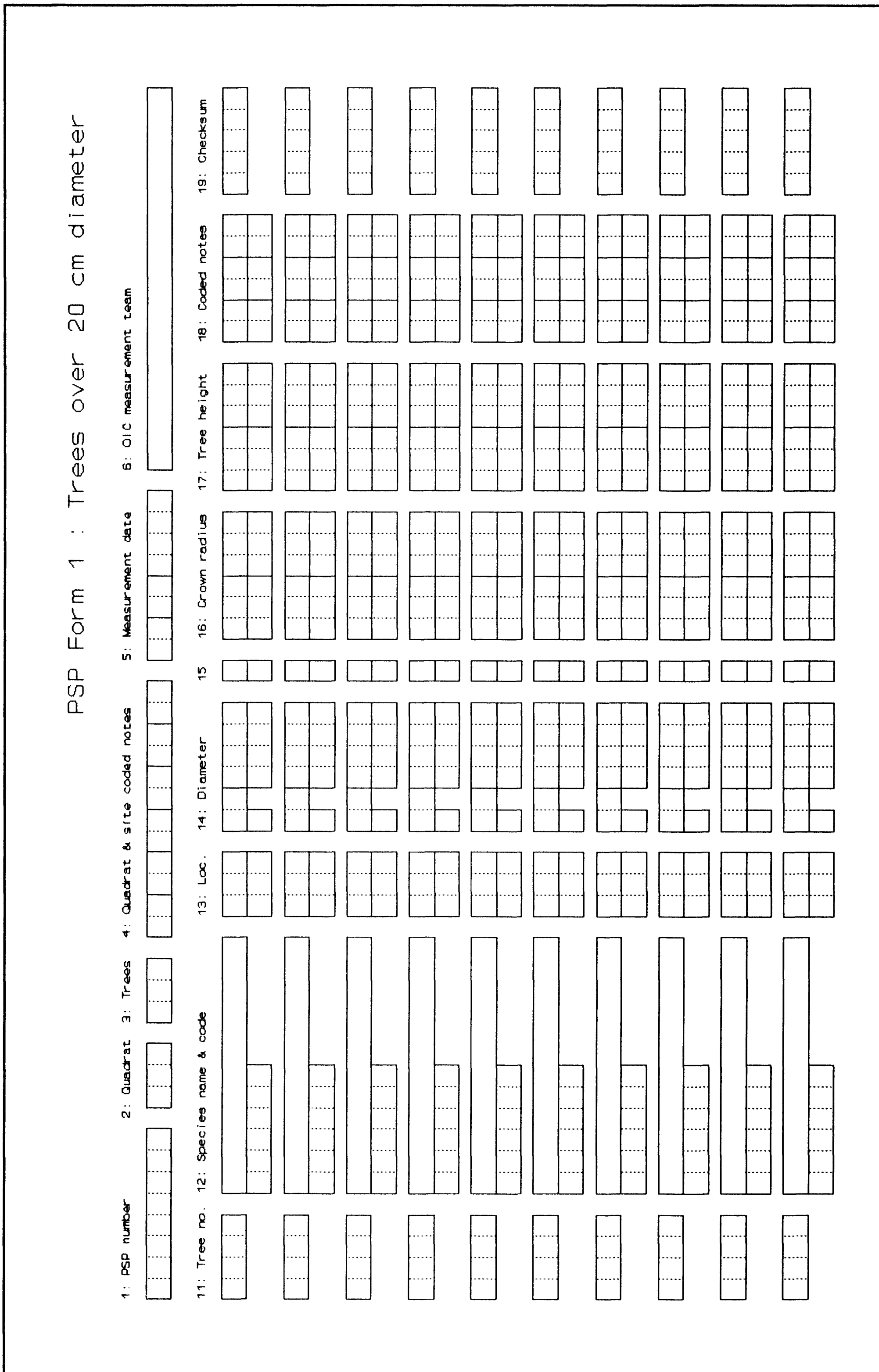

Figure 9-1 : Form to record large-tree data (over 20 cm dbh) on PSPs

upwards. This implies that it is only practicable to use one unit per plot. This will considerably slow down the measurement of the plot as compared with the use of several bookers with paper forms. The units also require spares, technical backup and programming skills to set them up ready for use.

9.1.2.4 The major advantage of field computers is that they eliminate the data entry process in the office, and can thereby considerably reduce costs in countries where it is too expensive to employ staff solely for data entry.

9.2 Data recording forms

9.2.1 Example form for recording trees over 20 cm dbh

9.2.1.1 Figure 9-1 shows a recording form suitable for measurements on trees over 20 cm. This form is designed to cater for all the recommended measurements described in section 6.

9.2.1.2 The form is divided into a *quadrat record*, at the top of the form, and multiple *tree records*. Each record is divided into a number of *fields* or individual data items. The fields are sub-divided into character boxes by dotted lines. Fields that are shown without character boxes are not used for computer entry. The fields are numbered for ease of reference in the tables below.

9.2.1.3 In normal use one sheet is completed per quadrat, although for heavily stocked quadrats more than one page may be required. The quadrat record is completed as shown in Table 9-1.

Table 9-1 : Description of the quadrat record of PSP Form 1

Field no.	*Field name*	*Description*
1	PSP number	Unique number for the PSP
2	Quadrat	Quadrat number
3	Trees	The number of trees entered on the form. This should not include any trees entered on Form 2 (trees below 20 cm).
4	Quadrat & site notes	This allows for up to 6 coded notes of 2 letters each, as discussed in section 8.2.
5	Measurement date	This can be entered according to local convention as day/month/year or month/day/year. The form allows 4 digits for the year, to avoid confusion with the change of century (1900s to 2000s).
6	OIC measurment party	The name of the person responsible for filling the form is entered here, to allow later queries to be referred back if required. This entry is not stored in the computer.

9.2.1.4 Below the quadrat record are 10 sets of tree records. Each tree record occupies two lines on the form. Some of the measurements will not be taken on every tree. Height and crown radius measurements will normally be made on a sub-sample comprising the two largest trees on each quadrat (see sections 6.3.5, and 6.4.3). The tree records are completed as shown in Table 9-2.

Table 9-2 : Description of the tree records of PSP Form 1

Field no.	*Field name*	*Description*
11	Tree no.	Tree number, which should be unique for the plot.
12	Species name	The common name of the species is written in the upper box in the field. The species code is looked up and entered in the lower box later on, in the camp or on completion of the quadrat.
13	Loc.	The tree location coordinates. The upper box contains the X (east) coordinate and the lower box the Y (north) coordinate, both in *decimetres*.
14	Diameter	The diameter box comprises 4 fields, as shown in figure 9-2. The normal reference diameter is entered in *millimetres*. If measured other than at 1.3 m, the height of the point of measurement (POM) is entered in *decimetres* as shown. If a second, alternate diameter is required because of buttress development (see section 6.1.3), then this is entered below the established reference diameter measurement. If the measurement is made other than with standard diameter tape, then the type of instrument is coded with a letter in the box (R for Relascope, C for Calipers).
15	Crown class	The Dawkins crown position is entered in the upper box (1-5), and the crown form in the lower box (0-5). See section 6.4.
16	Crown radius	Four crown radii should be measured mutually at right angles, in *decimetres*, and entered in the 4 boxes provided in any order.
17	Tree height	The tree height measurements are entered directly as instrument readings to avoid field calculation. Figure 9-2 shows how the boxes are organized. The top left height field is the distance from the tree in *decimetres*. Below this is entered the height to the base of the tree (usually with a preceding minus sign) in %. The upper right box is the crown point height, and the lower right box is the total height. Both are recorded as % readings.
18	Coded notes	Up to 6 coded notes, of 2 letters each, can be entered in the boxes provided. Section 6.5.3 gives appropriate codes.
19	Checksum	This figure is completed at the base camp or in the office, as discussed in section 9.4.2 below.

9.2.2 Example form for recording small trees and regeneration

9.2.2.1 For small trees, crown measurements, diameter above buttress and clinometer height measurements are not usually required, and a simplified form is possible, that allows one tree record per line. An example of a suitable form is shown in Figure 9-3.

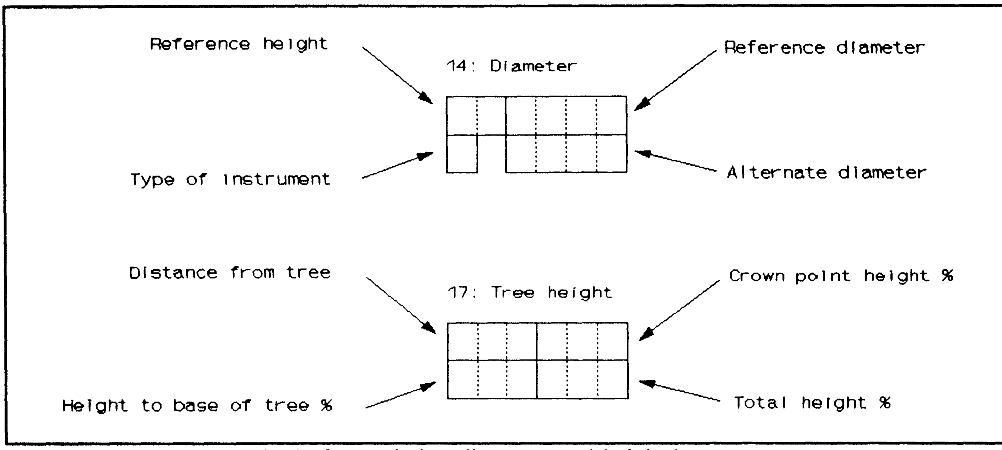

Figure 9-2 : Method of completing diameter and height boxes on Form 1

9.2.2.2 Form 2 differs from Form 1 in the specifications for some data fields. For the quadrat record, field #4 is given as the *strip position* instead of the quadrat and site codes. This field is used to record the position of regeneration strips. It is not used when Form 2 is applied to a whole quadrat for poles or saplings, and is then left blank.

9.2.2.3 For regeneration strips the orientation of the strip is entered in the first box, and its distance from the origin (SW corner) is given in the second box in *decimetres*. The orientation will be N (or Y), if the strip runs parallel to the southern or X boundary of the quadrat, and E (or X) if the strip runs parallel to the western or Y boundary of the quadrat. It is assumed that the strip is 1-m wide, as specified in section 7. The distance is taken to the centre line of the strip from the quadrat origin. The X-Y notation can be used instead of E-N if the plot has not been aligned with the cardinal points of the compass.

9.2.2.4 For poles and saplings recorded on the whole quadrat, the location fields (#13) are entered conventionally. The first coordinate is the E or X distance, in decimetres; the second coordinate is the N or Y distance.

9.2.2.5 For strips, one coordinate is measured relative to the centre line of the strip. For strips laid E-W, parallel to the S or X boundary, this will be the second field. If strips are laid the other way (parallel to the N-S boundary), then the first field is measured relative to the centre line. For relative measurements, a + should be entered for measurements on the side of the centre line tape away from the quadrat origin, and a - entered for offsets towards the origin.

9.2.2.6 Diameter can normally be measured at breast height (1.3 m) on saplings and poles, but it is not recorded on seedlings, so only a single box is provided (field #14). This is diameter in *millimetres*. The diameter field will normally be left blank for seedlings.

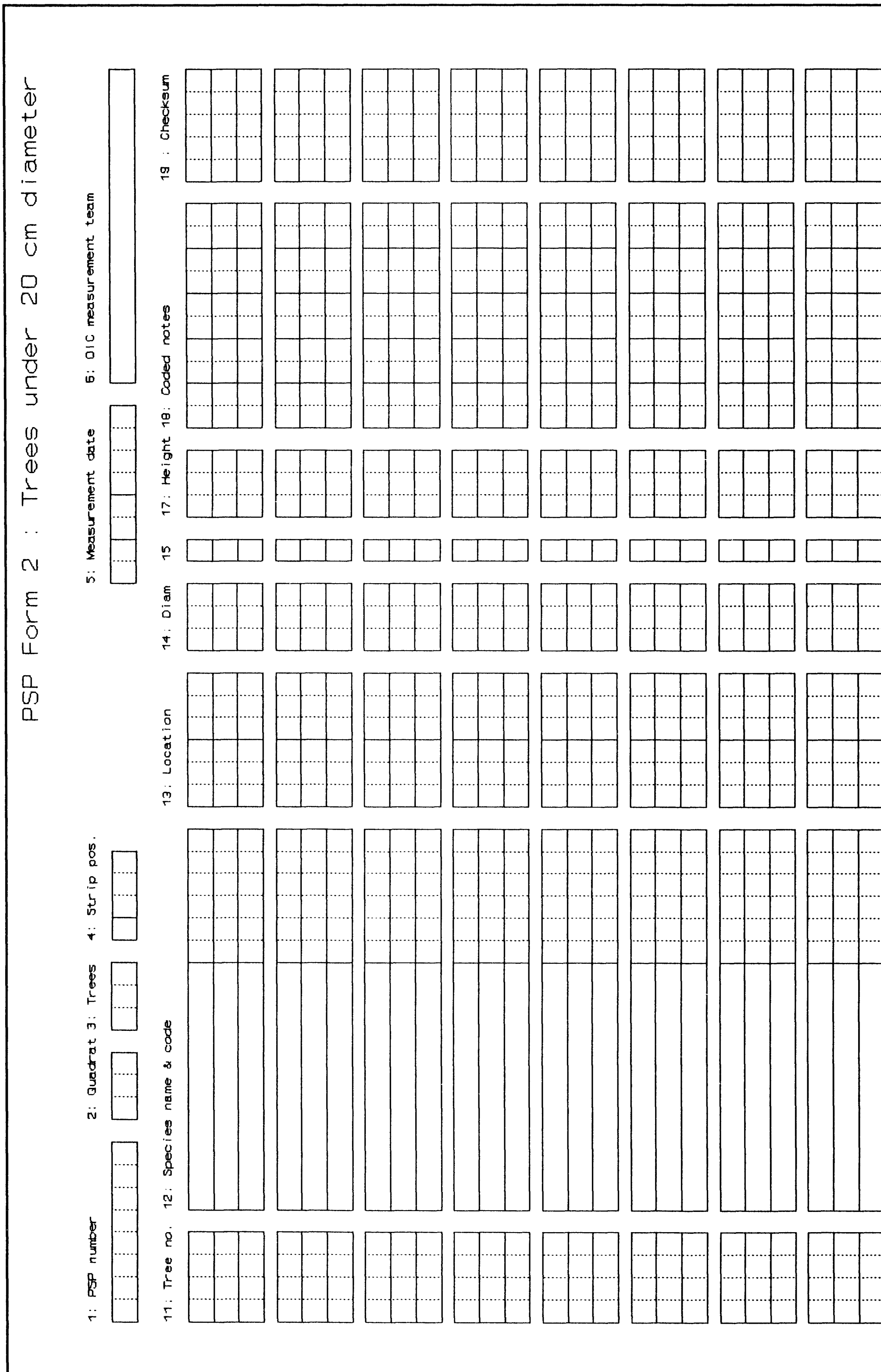

Figure 9-3 : Form for recording data from poles, saplings and seedlings

9.2.2.7 Crown position may be recorded, but crown form is not meaningful on small trees. Hence only a single box is provided for field #15, for crown position.

9.2.2.8 Similarly, height measurements are made in a simpler way on small trees, using height sticks to give a direct reading. For seedlings, every tree will be recorded for height, which should be entered on the form to the nearest *decimetre*. For poles and saplings, height measurements will be made on a sub-sample only, to establish local height-diameter regressions. These measurements will be made with telescopic height sticks, and again entered to the nearest *decimetre*.

9.2.2.9 The coded notes are entered in the same way as on Form 1, as is the checksum (see section 9.4.2).

9.3 Computer data entry

9.3.1 Computer programs for data entry

9.3.1.1 The PSP data must be keyed into a computer to facilitate their analysis and long-term storage. There are three basic types of computer program available for this purpose: key-to-disk data entry programs, text editors and word processing programs, and database packages.

9.3.1.2 *Key to disk programs* are found in most mainframe environments (large multi-terminal computer systems). The software generally provides the facility for entering data, carrying out range checks on certain data items, and data verification. They are perfectly suited to the task of entering PSP data. Most offer screen format facilities that allow the data entry screen to correspond to the field form to a high degree.

9.3.1.3 *Text editors and word processing programs* available on desktop computers are suitable for data entry, but cannot provide any online error checking or data validation. Word processing packages such as *Word, Word Perfect* or *Wordstar* all have means of storing text files in ASCII or non-document mode, so that only the visible characters in the file are saved on disk, and processing programs are not confused by invisible word processing codes in the file. Text editors such as QEDIT or the primitive DOS utility EDLIN do not use such hidden codes, and can be used efficiently for data entry.

9.3.1.4 *Database packages* such as *dBASE, Paradox, DataEase, SuperBase* and *R:Base*, can all function both as flexible key-to-disk systems, and as facilities for data manipulation. The dBASE language has become something of a *de facto* standard and is available in several dialects, including *Foxbase* and *Clipper*, both of which are substantially faster than the original.

9.3.1.5 On the other hand, *spreadsheet programs* such as *Lotus 1-2-3* are not suitable for entry of PSP data. The computer memory cannot hold the extensive data involved, and the only way to use such programs is to create one file per plot. This becomes excessively cumbersome and impracticable if the data need to be manipulated.

9.3.1.6 There is no single criterion that determines the best method of data entry, and hence the choice of software to be used. All approaches will require some programming skill. Database packages are essentially high level computer languages, and do not provide an instant solution for the inexperienced.

9.3.1.7 The following factors may help to determine the choice:

- In a mainframe or multiuser environment, consult the systems analyst for the computer regarding the use of a standard key-to-disk system.
- With desk top computers, if any database package is in current use and there are personnel experienced in that package, use it to create the necessary data entry system.
- If there are experienced programmers available in languages such as Basic or Pascal, consider the use of text editor-based data entry.

9.3.2 File formats for text editor data entry

9.3.2.1 When data is input with a text editor or word processor, it may be stored in one of two general formats on the computer disk:

(1) *As a word processor file.* These are often unintelligible to software other than the package used to create them. Such files may be used temporarily during data entry and editing, but cannot be read by error checking or processing programs directly. They must first be converted to ASCII format.

(2) *As an ASCII file.* These files use the standard ASCII coding notation for characters, and can be read by processing programs and database packages if the records and fields are suitably delimited.

9.3.2.2 Word processor files can be read and stored in ASCII format by all major WP packages. ASCII files are normally created by system text and program editors such as EDLIN, QEDIT, or the MS-DOS 5 EDIT command.

9.3.2.3 When inputting data by text editor (or word processor) it is necessary to define the separators for fields and records, and the method of marking the start and end of plots and quadrats. The fields are normally separated by either one or more spaces, or by commas, whilst the records are separated by the newline/carriage return key (marked *Enter* on most keyboards).

9.3.2.4 Files in which the fields are separated by commas are known as Comma Separated Value (CSV) files and can be conveniently read in BASIC, dBASE, and many other languages. The comma separator is not very convenient when programming in PASCAL, C or some other languages, which may work more easily with space separators between the data.

9.3.2.5 Programming languages such as FORTRAN or COBOL generally prefer a different type of data presentation, in which each field occupies particular character positions on the line. Thus tree number might occupy characters 1-4, species characters 5-10, etc. DBASE can also read this type of file. However, files of this type are tedious to create with normal text editors, requiring that all data be properly and exactly placed on the line. Key-to-disk systems normally create this type of file.

9.3.2.6 However, all programming languages have the flexibility to cope with any logically consistent data format. They only differ in the degree of effort and expertise required of the programmer to write the necessary instructions.

9.3.2.7 For this reason, and because CSV files are more time consuming to type and difficult on the eye to read (because of the extraneous commas), *the following standards are suggested*:

- The first quadrat record of the plot should have the characters $$ at the beginning of the line.
- The quadrat records for Form 1 should start with $ (other than for the first quadrat of the plot, which should start with $$).
- The quadrat records for Form 2 should start with @.
- The tree records for each form should start directly with the tree number, and should follow the related quadrat record in the file.
- No quadrat record should be typed for continuation sheets of tree data.
- Each field should be separated by one or more spaces.
- Blank fields should be typed as zero (0).
- Each record should end with the *Enter* key (Carriage return/newline).
- On Form 1, the field on the second line should be typed after the field on the first line. Thus the example shown in Figure 9-4 would be typed as:

  124 KHAIVO 53 27 32 1094 5 4 62 58 52 65 400 -11 125 84 [] 2196

- Coded notes should be enclosed in square brackets, which should be empty if there are none, as shown.

- After the last tree record of the plot, the characters ## should be typed on an otherwise empty line to signify the end of the plot data.

9.3.3 File formats for a database system

9.3.3.1 For a database package or system, separate record structures must be specified for the quadrat record and the tree records. These should be made identical for Forms 1 and 2, with a supplementary field (FORMTYP) to distinguish the two.

9.3.3.2 Table 9-3 illustrates a structure for the quadrat record. Note that it includes space for both field #4 on form 1 and on form 2. On Form 1, this field is SITECODE, whereas on Form 2, it is RSDIR and RSPOS. The Fields of type C are character information, whilst those of type N are numeric. In some database languages, such as Paradox, there is no length required to be specified for numeric fields.

Table 9-3 : Database structure for quadrat records

Field name	*Type*	*Length*	*Description*
PSPNO	C	8	PSP number
QUADNO	C	3	Quadrat number
FORMTYP	C	1	Type of form (1 or 2)
NOTREES	N	3	No. of trees on the form and attached continuation sheets
SITECODE	C	12	Coded site assessment notes
RSDIR	C	1	Regeneration strip direction
RSPOS	N	3	Position of centre line of regeneration strip
MDAY	N	2	Measurement day
MMONTH	N	2	Measurement month
MYEAR	N	4	Measurement year

9.3.3.3 Table 9-4 illustrates the tree record structure. Some fields will always be blank on Form 2 entries, whilst others such as the location fields, may be interpreted differently on regeneration strips. The first three fields (PSPNO, QUADNO and FORMTYP) form a key that links the tree record with the appropriate quadrat record. They will normally not be typed in, but will be filled automatically by the system.

Table 9-4 : Database structure for tree records

Field name	*Type*	*Length*	*Description*
PSPNO	C	8	PSP number
QUADNO	C	3	Quadrat number
FORMTYP	C	1	Type of form (1 or 2)
TREENO	C	4	Unique tree identification no.
SPPCODE	C	6	Species code
LOCE	N	3	East (or X) coordinate of tree
LOCN	N	3	North (or Y) coordinate of tree
POMHT	N	2	Point of measurement height
TOMI	C	1	Type of measurement instrument
RDIAM	N	4	Reference diameter
ADIAM	N	4	Alternate diameter
DCP	N	1	Dawkins crown position
DCF	N	1	Dawkins crown form
CR1	N	3	Crown radius 1
CR2	N	3	Crown radius 2
CR3	N	3	Crown radius 3
CR4	N	3	Crown radius 4
HDIST	N	3	Distance from tree for height measurement
HBASE	N	3	Height to base of tree
HCP	N	3	Height to crown point
HTOT	N	3	Total height
NOTES	C	12	Coded notes
CHECKSUM	N	5	Checksum

9.4 Error checking and editing of data

9.4.1 Online and batch error checking

9.4.1.1 It is inevitable that as data is entered in the computer some mistakes will be made. These may originate from mis-measurement of trees, mixing up measurements for the wrong trees, illegible handwriting, writing in the wrong fields on the form, or mis-reading a form or hitting the wrong keys during data entry. These arise arise equally whether direct data entry is used in the field, or whether it is done in the office from field forms.

9.4.1.2 There are two basic approaches to checking data. They may be used separately or in combination. These are *online data validation*, and *batch error checking.*

9.4.1.3 *Online data validation* is done whilst the data are being keyed in. Each field is checked for logical consistency, and checks are made on the whole record when the user tries to go to the start of the next record. If these checks detect an error a message comes up immediately on the screen, and the operator has to make a correction before the data are added to that already stored on disk.

9.4.1.4 *Batch error checking* allows data to be entered into a file. At a later date, the entire file is processed by a program that scans it line by line, and checks for errors. These are printed out as an error list. From the error list, the data file is edited to make corrections, and then run through the error checking program again until a clean file is obtained.

9.4.1.5 Online validation is only possible when data entry is directly controlled by a programming language or database package with programming facilities. It is not possible for data entry by text editor. Some types of error check are slow and difficult to implement online, and may be better handled by a batch program.

9.4.1.6 Batch error checking can release keyboards and monitors from unproductive usage: Time spent researching errors whilst the keyboard is not being used. Error checks that require lookup references to a large database, such as species occurrences, or a previous assessment of the plot may be slow if done online, and can be impossible with field portable equipment. These checks are better done by batch programs.

9.4.1.7 *The optimum usage is to combine both methods.* Online checks should be basic, and should cover checksum errors (see section 9.4.2), field data type, and simple logical checks. Such checks help to alert operators when they are becoming fatigued. More extensive and thorough checks should be done by batch programs.

9.4.2 The checksum test of data integrity

9.4.2.1 Checksums in various forms are widely used in data processing, and form the basis of automatic error correction methods for data communications. The basic principle is that the data in the fields of a record are totalled across the record as they are entered, and compared with the checksum in the final field. If they agree, the data are valid; if they differ, then there is an error in the record, which must be corrected before it is accepted.

9.4.2.2 On PSP Forms 1 and 2, only numeric data are used to total the checksum; alphabetic data are ignored. For example, data may be recorded as shown in Figure 9-4, giving checksums for the two records shown of 2196 and 1157 respectively. Note that the minus sign is also ignored, in the height to crown base or, as may be the case, in regeneration strip location measure ments. If the species coding system is numeric, then the species code should be included in the checksum.

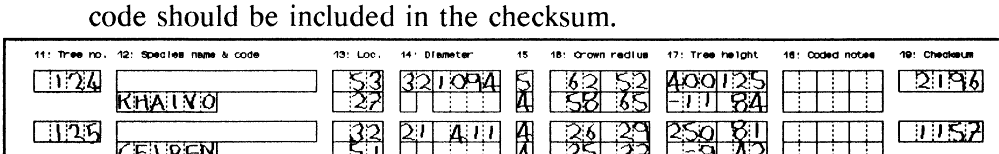

Figure 9-4 : Calculation of the checksum field

9.4.2.3 In the first line of the example in Figure 9-4, the checksum is computed from 124+53+27+32+1094+5+4+62+52+58+65+400+125+11+84 which totals to 2196, as shown.

9.4.2.4 An alternative method of calculating checksum is to add up only the single digits in the record. That is, 1+2+4+5+3 etc. This can be done by mental arithmetic at the base camp, without requiring a calculator. However, this type of checksum gives the same result if two digits are transposed (eg 17 for 71) and is therefore less thorough as a check on the data (Vanclay, 1991).

9.4.2.5 The normal procedure in computing checksums is to leave the checksum field blank. It is filled in in the office by clerical staff, using calculators.

9.4.2.6 The checksum method is a very reliable and simple method of verifying data entry. It is much faster than conventional verification, and more thorough than logical and range checks alone. *It is strongly recommended as a standard procedure for data entry.*

9.4.3 Data verification

9.4.3.1 *Verification* is a method of error checking developed originally in the days of punched card machines, and available as an option with mainframe key-to-disk software. It requires that all data be keyed in twice. At first entry, the data are stored in a file. When the data are re-entered, they are checked, record by record, against the file already stored. If there is any disagreement, the operator is alerted by a beep and some suitable message.

9.4.3.2 Verification is very thorough, but results in a doubling of data entry time. Unlike the checksum method, it is equally efficient with numeric and non-numeric data (checksums can normally only be used for numbers).

9.4.3.3 An alternative batch method of verification can be carried out using *file compare utilities* available in MS-DOS, Unix, and as part of many wordprocessing packages. The data are typed in twice, using a text editor, into two separate files. These are then compared with the FC program, which will highlight differences between the files. These can be examined for errors.

9.4.3.4 In general, the checksum method is better than data verification for PSP data. It can be carried out with a simple calculator, and does not tie up a terminal to the same extent as verification. It is less tedious for keypuch operators, as the staff can be rotated between data entry and checksum calculation, giving some variety of work and posture, as compared with continuous data entry. The checksum method is not, however, suited for data with a high alphabetic content.

9.4.4 Logical consistency checks

9.4.4.1 The checksum and verification methods can be used without any knowledge of the significance of the structure of the data being processed. However, fields in the data will be subject to various logical constraints, which can be tested either as the data are entered or in batch mode by an error checking program. The logical tests that are appropriate with PSP data are as follows:

- *Range tests on fields:* Each field will have a characteristic range of values that will be either numeric, alphabetic, or alphanumeric. Most database packages and key-to-disk systems allow online checks of range and permitted character type as part of the screen format.
- *Value lookup from lists:* Species codes and coded notes should exist in a stored list. The computer looks up the entered value in the approriate list and checks that it exists. This is a powerful technique that can be easily programmed in database packages, and is part of the screen format facility in some relational database packages.
- *Logical inter-relation between fields:* The values in some fields will have a logical connection with those in other fields. These can be tested for consistency. For example, the alternate diameter should be smaller than the reference diameter. The height measurements should be smallest for the basal measurement, intermediate for the crown point and greatest for the total height. The crown radius measurements should be either all present or all absent.
- *Logical connections between successive measurements:* The second and subsequent measurements on a tree or plot can be compared for consistency. In general, the species code should be the same, diameters and heights should increase with time, and trees that are missing or that appear in a subsequent measurement should be noted. These kinds of checks are most efficiently carried out by a batch program rather than online during data entry.

9.4.4.2 Logical consistency checking of the data should always be done, even when checksums or verification are used. Logical checks detect errors at a higher level, which may have been written on the forms and correctly keyed in or calculated into the checksum. It is most convenient to use a batch program for these checks, although simple range tests may also be built into screen formats with most database packages.

9.5 Archival and long-term storage

9.5.1 Planning for long-term data storage

9.5.1.1 PSPs can be expected to be maintained over two decades or more. Over this time changes in computing standards and equipment will inevitably occur. Some forethought should be given to this, to plan the best long-term method of storing the PSP data.

9.5.1.2 Over the past two decades, data entry and storage has moved through three different common standards:

- In the late 1960s and early 1970s punched cards were used for data entry, with long-term data storage on 800 or 1600 bpi magnetic tape to computer industry standards.
- In the late 1970s and early 1980s key-to-disk systems replaced punched cards. IBM 3270 (8-inch) diskettes became a common standard, with continued use of 1600 bpi tape and the emergence of the 6250 bpi tape standard.
- From mid 1980 onwards, desk top computers have almost completely supplanted mainframes in forestry research and data processing. The IBM standard has moved through various stages of data storage, from the 360K 5 ¼-inch diskette, to the 1.44 MB diskette. There are several largely incompatible standards for data archival on tape cartridges.

9.5.1.3 Over the next decade optical disk technology is likely to become pre-eminent. Such disks are especially suited to remote sensing data because of their vast storage capacity (typically over 500 MB), and hence optical disk drives are becoming increasingly common in forestry institutions.

9.5.1.4 However, at the present time the preferred choice for long-term storage media is the 1.44 MB 3 ½-inch diskette. This is the most common current standard for desk top machines, and compatibility with it is likely to be maintained over the next 10 years.

9.5.1.5 Other storage media may be in use in particular installations. It is recommended that copies of all PSP databases (and other forestry databases requiring long-term storage) are made on 1.44 MB diskettes, using the following principles:

- *Files should not be split over more than one diskette.* Multi-volume files created by BACKUP, PCBACKUP or other utilities should be avoided. A suitable standard is to group PSP data by districts or forest reserves so that each diskette represents data from one district.

- *Successive assessments of the same PSPs should be written on different diskettes.* This is better than adding assessments in a merged format, as the diskettes will be full when initially written, and cannot be extended to accommodate the new data.
- *The data should be stored in ASCII* rather than the internal format of any particular database. Fixed length, non-delimited fields should be used with the file format discusssed in section 9.2. This gives maximum compression (within an ASCII context) whilst maintaining a robust data structure that can be recovered in the event of minor media failures.
- *At least two copies of the data should be archived in different buildings*, stored in an area secure from extremes of heat, humidity and insect attack. A fireproof data safe or a conventional safe is a suitable storage unit.

9.5.2 Standards and documentation

9.5.2.1 It is important that clear and explicit records are kept of the archived data. These records should cover the following:

- *A description of the archive file formats.* These should define the media standard (eg 1.44 MB MS-DOS 4.01 compatible 3½-inch diskette), and the record structure of the files themselves (as for the example shown in section 9.2).
- *An index of the diskette serial numbers* with the PSPs and assessment dates stored on them should be maintained on a file. The PSP numbers should also be written on the diskette labels.

9.5.3 Upgrading and replacing computer equipment

9.5.3.1 Inevitably computer systems will be replaced by new equipment from time to time. When this is done, the new equipment must be able to read and write to the archive standard. If a new and clearly defined standard exists, then the archive must be converted in its entirety.

9.5.3.2 It is important to avoid a situation developing where reading and writing to and from the archive depends on a single possibly increasingly obsolete mechanism. This could happen, for example, if a particular non-standard data cartridge were used for the archive. As time passes, that system would no longer be suported by the manufacturer (who could even go out of business). If the single data cartridge reader broke down, it would be impossible to access the archived data.

9.5.3.3 For this reason, no archive standard should be adopted that cannot be supported by multiple read-write devices at the installation concerned. Any system, no matter how logically efficient (such as 9-track tape, WORM disk, Bernoulli drive, removable hard disk, etc.) will be fragile if dependent on a single expensive mechanism. Low cost and replication are important for the archive storage device, and should outweigh considerations of maximum storage capacity or data compression.

9.5.4 Backing up working files

9.5.4.1 During the process of data entry the PSP data will normally be stored partly in memory and partly on hard disk. If the system fails whilst data entry is in progress, the portion of data stored only in memory will be lost. For some database packages this can include portions of indexing data that may well corrupt the whole data file on disk and make it unreadable.

9.5.4.2 It is therefore important during work on a file that three kinds of backup are made regularly.

- *Data should be forced from memory to disk by closing the file and re-opening it.* Most word processors provide a facility to do a *save* operation of this kind with one or two keystrokes. Database packages can be programmed to achieve a similar effect. This should be done at intervals of not more than 30 minutes whilst entering data, and more frequently if power supplies are erratic.

- *The hard disk file should be duplicated when memory is flushed.* This is normally done automatically during the cycle of closing and re-opening the file by copying the original file to a second version (the .BAK file in most MS-DOS applications).

- *The hard disk file should be copied onto a diskette at the end of each day's work.* This is an essential precaution, which if neglected will sooner or later result in a disasterous loss of data when the hard disk fails or the working file is corrupted. Such failures can result from many causes, including mains voltage transients (spikes) which can send the disk controller into an anomolous state and make it re-format the disk or overwrite critical disk control tracks; faulty programs, which can have the same effect; computer viruses, deliberately designed to subtly corrupt the disk; and technical failure of the disk.

9.5.4.3 Once the working data file has been completely error checked, it should be transferred to the archive in ASCII format.

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