An Outline of Forest Mensuration

with Special Reference to Australia

L. T. Carron

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For my parents and my family

Preface

Text books on forest mensuration are available for many countries such as the United States of America, West Germany, France and Italy. Many methods and techniques of forest mensuration used in Australia have been adapted from those of western Europe and North America, but they have been so modified to suit Australian conditions that undergraduates in forestry in this country need a text of reference to local practice and its background. No such text is available in Australia at present and this book attempts to fill the need, at least in part.

It is difficult to decide to what extent and depth the subject should be covered. Forest mensuration is an applied subject which includes aspects of pure and applied mathematics, statistical methods, land surveying, the use of aerial photographs, and data processing and computing. Authors have varied considerably in the extent to which they have included these aspects and the manner in which they have presented them. It has been assumed in this text that these various aspects will be treated separately but concurrently in an undergraduate course in forestry as their application is not limited to forest mensuration. To have given them adequate treatment even for the purposes of forest mensuration would have meant enlarging the present text to unreasonable size. Experience in lecturing on the subject over many years at the Australian Forestry School and the Department of Forestry of the Australian National University, and continual contact with professional practice, suggest that the scope and depth of this text are adequate for undergraduate study. It should be stressed that forest mensuration is a practical matter; this text is intended to serve as background to practical instruction in the forest, not to replace it. It has been assumed that the student would have access to a library so that extracts of literature have been given only when they served a particular purpose.

To the many colleagues and students, in Australia and elsewhere, who have contributed so much to this book I offer grateful acknowledgment. I am particularly indebted to Professor J. D. Ovinggton (Department of Forestry, Australian National University), Messrs T. E. Edwardson (Department of Forestry, Oxford University), N. B. Lewis and A. Keeves (Woods and Forests Department, South Australia), and P. R. Lawrence (Forests Commission of Tasmania), who made valuable suggestions for improving the text. They are, of course, in no way responsible for its shortcomings.

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L. T. C.

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1 Introduction

A forester is concerned with managing forests. Irrespective of the kind of forest and purpose of management - production, protection, or recreation - he needs quantitative information about what he is managing and how it changes with time. It is the function of forest mensuration to provide this.

Mensuration is that branch of mathematics which deals with the measurement of lengths of lines, areas of surfaces, and volumes of solids; forest mensuration is this kind of measurement for individual trees and forests. This is the most appropriate kind of mathematics because a forest might be regarded from the quantitative viewpoint as a number of solid bodies upright on a plane surface. If these solids were few in number, of simple, identical, and unchanging shape and size, and on a readily accessible plane surface, then the application of the appropriate principles of mensuration would be straightforward. Trees in forest formation, however, are usually numerous, of complex shape, differing from each other and continuously changing in size, and often in areas where access is difficult. To apply the principles of mensuration, the forester has to draw on other disciplines.

Since quantitative information is of little value unless related to area or space, he becomes involved with the definition of forest boundaries on land and plan by surveying and with the determination of area. Aerial photographs are very useful for mapping forests, interpreting qualitative information, and getting quantitative information by photogrammetry, so that the use of aerial photographs is also an essential part of forest mensuration. Statistical Methods are of particular importance. Since forests are extensive and individual trees are often large the forester must, for economic reasons, derive his quantitative information from a sample. He is also particularly concerned with determining relationships amongst

tree variables and stand variables in order to understand the behaviour of trees and to estimate a variable which is difficult or expensive to measure from another which is simple or cheap to measure. These are aspects of statistical methods. Many mensuration projects involve large amounts of data and so require modern methods of data processing and high speed computing.

Depending on whether the information is to meet a biological or business requirement, on the location, extent, and kind of forest, and on the money and labour available, so the most appropriate method of measurement and handling the data will differ and will draw variously from the mathematics of mensuration, the principles and techniques of surveying, the use of aerial photographs, the concepts and mathematics of statistical methods, and procedures of data processing and computing. To determine the most appropriate method, the forester must know what methods are available, how to apply them, and their relative advantages and limitations in various circumstances. The more familiar he is with them and with the techniques of applying them, the more effective will be his contribution toward the solution of a management problem.

The matter of error is of particular importance. If measurement is thought of as an exact determination of the size of some property in terms of a unit which relates to a standard, then the 'measurement' of forest mensuration is most often rather an estimate - an inexact determination. The difference between a true value and an inexact determination is an error. It is essential in any mensuration procedure to recognise the likely sources of error, to consider their effects, and to evaluate the kind and extent of error associated with an estimate.

In forest mensuration there are several kinds of error in the general sense. One kind of error is the mistake such as when a figure is read incorrectly from an instrument, called incorrectly, heard or recorded incorrectly, or a figure is wrongly transferred or interpreted from records. Such errors are caused by carelessness or casualness and can usually be avoided. Certain conditions, both in field and office, increase the likelihood of this kind of error, however, and should be anticipated in organisation. Mistakes may be made through ignorance of requirements or lack of appropriate training. This source of error is the responsibility of the supervisor. Incorrect arithmetic is a major source of mistakes but there is no excuse for slipshod calculations, whether due to ineptitude for

arithmetic or to the tedious nature of some calculations. Mistakes can be reduced to negligible proportions by care and checking, the most important preliminary check on any result being to test whether it seems sensible. Every effort should be made to design calculation procedures with built-in checks.

Another kind of error is accidental error. Small differences from the true value that occur unavoidably, despite every precaution, due to limitations of instruments, inconstant environmental conditions or lack of perfection in sight or touch, come in this category. Usually they are unimportant because they tend to vary in sign and size and thus to balance out. The danger is in wrongly ascribing to this category errors which are mistakes or are due to bias.

Bias implies a tendency to depart in a particular direction from the true value sought, for example an instrument with graduations of incorrect size or with an incorrect origin would give a biased reading. In sampling, 'an estimate is said to be biased if repetition of the procedures by which it was derived...would give results which, when averaged over an extended series of repetitions, differ from the true value of the quantity estimated' (Finney, 1947).

If the size of a particular variable of a heterogeneous population is estimated by sampling, the error that may be associated with the estimate, purely due to the sampling, is referred to as sampling error. Under certain conditions of sampling, the sampling error associated with the estimate of the arithmetic mean of the population is the standard error, the calculation of which involves the concept (though not the practice) that the sampling of the arithmetic mean is carried out a large number of times and these estimates of the mean vary amongst themselves. The term precision refers to this variation; 'by precision is meant ... the reproducibility of an estimate in repeated sampling conceiving an infinite repetition of the sampling procedure' (Finney, 1947). A precise measurement is one which repeats a value consistently. It is important to appreciate that a precise measurement may not give the true value - no matter how reproducible the value a bias in the procedure may prevent the estimate from ever being the true value. One can thus have estimates which are precise and unbiased, precise and biased, not precise and unbiased, and not precise and biased.

In some cases in forestry the material is so irregular or the environment such that an exact determination of size cannot be obtained. In these cases an estimate must be accepted. In some

cases estimates have to be accepted because of the limitations of time and money. In many cases an approximation will serve the purpose perfectly well. The important thing is to know when one is estimating rather than measuring, when one is making an estimate deliberately, when one is accepting an estimate because one has to, and in all cases what the kind and size of the error is likely to be. The record should not be made in such a way that a false standard of measurement is implied nor should one read into a record a standard which is not implied.

Forest mensuration is to a large extent the handling of figures and it demands systematic recording, clear notation, adequate labelling of information, and respect for the permanence of the record.

2 Units of Measurement of Major Forest Products

Trees and their products are measured in various units depending on country and locality, and on the particular dimension concerned. There is an enormous range of units throughout the world and various glossaries of these; Jennings (1965), for example, has compiled one for the log and timber trade of Great Britain. The units with which an Australian forester should be familiar are as follows.

Length. In countries using the English system of units, such as Australia, the units for measurement of length are the foot and the inch. For most purposes, such as length of log and height of tree, the value is rounded (usually down) to the nearest foot.

In countries using the metric system, the units are the metre and centimetre.

Girth, diameter and sectional area. In Australia, as in most countries using the English system of units, girth and diameter of trees or logs are measured in feet, inches, and decimals of an inch. The equivalent sectional area is expressed in square feet and decimals of a square foot.

In Great Britain, for most standing tree measurement, the units for girth or diameter are feet, inches, and fractions or decimals of an inch, the equivalent sectional area being expressed in square feet and decimals of a square foot. For logs, the circumference is measured but often expressed as quarter girth (a quarter of the circumference) in inches and fractions of an inch according to the Hoppus system (see ch. 3). The size of standing trees is also sometimes expressed by quarter girth in which case the equivalent sectional area may be expressed in quarter girth (Hoppus) square feet.

In countries using the metric system, girth and diameter are

expressed in metres and centimetres, and sectional area expressed in square metres and decimals or in square centimetres.

Tree volume. In Australia the volume of the standing tree is most commonly expressed in cubic feet and decimals of a cubic foot. Where the volume of the tree is assessed as that of the log which can be cut from it, and it is conventional to express the volume of a log in superficial feet or Hoppus superficial feet (see ch. 3), then the tree volume is so expressed. The superficial foot is represented by a solid one foot by one foot by one inch, there being 12 superficial feet to the cubic foot. There are 12 Hoppus superficial feet to the Hoppus cubic foot (see ch. 3).

In New Zealand, the general practice is to use the cubic foot.

In Great Britain, the Hoppus cubic foot and the cubic foot are used variously.

In the U.S.A., the cubic foot is now fairly common for research and management purposes. Where the volume of the tree is assessed on a log basis the unit used is usually the board foot which is the same as the superficial foot; but the tree contents may in this case be assessed as the volume of potential sawn timber by reference to a log rule (see ch. 3).

Where the metric system is used, tree volume is usually expressed in cubic metres and decimals.

To avoid confusion between the standard cubic foot and the Hoppus cubic foot, and between the standard superficial foot and the Hoppus superficial foot, particularly since people who are used to Hoppus measure are apt to omit the word 'Hoppus', the standard cubic and superficial foot are often qualified by the word 'true', thus 'true cubic foot' or 'cubic foot (true)' and 'true superficial foot' or 'superficial foot (true)'. The term superficial is commonly abbreviated to 'super'.

Log volume. Hanson and Wilson (1960) have outlined how methods and units of log measurement differ within Australia and Papua-New Guinea. The position may be summarised thus:

Qld, N.S.W., Vic. - Hoppus super foot.

A.C.T., S.A., Pap.-N.G. - super foot.

Tas. - Hoppus super foot for native broad-leaved species and conifers, super foot for plantation conifers.

W.A. - cubic foot (or load, equivalent to 50 cubic feet) for native

broad-leaved species, super foot for plantation conifers.

The transport industry in some States of Australia uses the ton as a unit for logs, being variously 50 cu ft for 'light' timbers (density about 45 lbs per cu ft) and 30 cu ft for 'heavy' timbers (density about 75 lbs per cu ft).

In New Zealand, the volume of logs is quoted variously in cubic feet or in board feet by the Forest Service and industry; the latter sometimes uses superficial feet.

In Great Britain, the common unit for round logs is the Hoppus cubic foot with subdivision in decimals or duodecimals.

In the U.S.A. the conventional unit is the board foot, the contents being assessed as potential sawn timber by reference to a log rule.

Where the metric system is used, log volume is usually quoted in cubic metres and decimals but special terms are given in some countries to a cubic metre equivalent.

Sawn timber (lumber). In Australia, the common unit is the superficial foot though quantities are usually referred to on a 100 superficial feet basis. The measure is sometimes referred to as 'super solid measure' to contrast with 'face measure' where the volume of dressed (planed) material is calculated on the dimensions before dressing. For sawn timber in standard sizes such as flooring, battens, weatherboards, and mouldings, the lineal foot is often used as the unit.

In New Zealand, the board foot is the common unit.

Round and hewn timber. Products such as poles, piles, girders and house blocks, are usually referred to in terms of lineal feet or running feet, price being adjusted according to diameter.

Hewn poles and girders are referred to similarly by lineal feet, or in terms of cubic feet. Railway sleepers (hewn or milled) are usually referred to on a piece or 100-piece basis, price being adjusted according to dimensions.

Stacked material. The common unit for stacked material in Australia, as in most countries using English units, is the cord representing 128 cu ft (8' x 4' x 4') of stack space, the solid wood content of this space varying according to such factors as the shape and size of the material and the way it is stacked. Some Australian pulp and paper companies use the cunit which represents 100 cu ft of wood with the stack space varying.

Where the metric system is used, stack volume is quoted in cubic metres of space but special terms are given to 1 cubic metre equivalent of space in some countries.

Processed material. The common unit for plywood, veneer, hardboard, softboard, and the like in Australia is the square foot, price being quoted usually on 100 square feet basis or per sheet in the case of standard sizes. In quoting statistics it is essential to refer to sheet thickness.

3 Logs

A log is a portion of the stem or of a branch of a tree prepared for commercial utilisation by felling, cross-cutting, and trimming. Its value is usually determined from its volume. Though the volume of such a solid could be derived by xylometric or hydrostatic methods, it is usually regarded as most practical to derive the volume of a log by equating it with a geometrical solid for which mathematical rules have been established to derive the volume - the simpler the solid, and the rules, the better.

The Shape of Logs

The solid which a log most closely resembles depends largely on the position of the log in the tree, the species, and the environment. In general the cross-section dimension of a stem decreases from ground upwards - it tapers; but there are differences in the ways in which stems taper and in the rates at which they taper. Stem shape and taper are discussed in some detail later. For the present it can be stated that considerable investigation has suggested that, for purposes of practical approximation, there are a limited number of simple solids which parts of trees resemble, of circular cross-section throughout, produced by the revolution around a vertical axis of a curve of the general formula $y^a = k.x^b$ where y = radius of section, x = distance from apex, the powers of y and x determine the way the solid tapers (the shape of the solid), and the value of k determines the rate of taper within the specified shape. These solids are the neiloid ($y^2 = kx^3$), the paraboloid of second degree ($y^2 = kx$), the cubic paraboloid ($y^3 = kx$) and the conoid ($y = kx$). For most

purposes, a log is regarded as a frustum of one or another of these solids.

The shape and rate of taper of the section of a stem closest to the ground, generally called the butt, is usually influenced by butt-swell in a way and to an extent that depends on the species and the environment. In the case of a tree with very little butt-swell, such as a young conifer in a dense plantation, little error may be involved in regarding the butt as a frustum of a second degree paraboloid. In most cases, however, this section is most likely to be neiloidal in shape. In the case of some rain-forest species and veteran eucalypts, the lowest section is very irregular due to flanges, fluting, or buttresses, but the tree is usually felled above these irregularities.

Most coniferous trees and young trees of some broad-leaved species have a single stem which is continuous from ground to tip. The part above butt-swell and for some distance into the living crown can usually be regarded as approximately paraboloidal in shape; the part from the tip downwards for a short distance into the crown usually has a conoid shape. Where the bole merges into crown by repeated branching, as in most broad-leaved and some coniferous species, the part above butt-swell is approximately paraboloidal up to the rather arbitrarily defined crown break. Beyond this is a series of conoid or paraboloid frusta. A log from anywhere within the main bole of any tree is thus usually regarded as a frustum of a paraboloid, usually a second degree paraboloid for convenience in measurement and calculation. A log from the very top of a tree might best be regarded as the frustum of a cone.

Tree branches tend to have a shape similar to that of the bole bearing them so that a log cut from a branch might be regarded as a frustum of a second degree paraboloid in most cases. Short pieces of branch material often approximate cylinders.

Formulae to Give True Solid Volume

Depending on the shape assumed for a log so its volume can be calculated using the appropriate formula. The formulae for the solids referred to previously are:

	Full	Frustum
Neiloid	$V = \frac{S}{4} . L$	$V = \frac{(S + 4s_{\frac{1}{2}} + s)}{6} . L$
Conoid	$V = \frac{S}{3} . L$	$V = \frac{(S + 4s_{\frac{1}{2}} + s)}{6} . L$
Paraboloid (second degree)	$V = \frac{S}{2} . L$ or $s_{\frac{1}{2}} . L$	$V = \frac{(S + 4s_{\frac{1}{2}} + s)}{6} . L$ or $= \frac{(S + s)}{2} . L$

where V = volume of log, L = length of log, S = sectional area at larger (basal) end of log, s = sectional area at smaller (top) end of log, and $s_{\frac{1}{2}}$ = sectional area midway between base and top of log.

The formula $V = \frac{(S + 4s_{\frac{1}{2}} + s)}{6} . L$ (usually called Newton's formula) recommends itself since it applies to a frustum of each shape. In practice, irrespective of where the log comes from in a tree and the kind of tree, a log is almost invariably regarded as a frustum of a second degree paraboloid and its volume calculated by one or other of the two formulae:

(a) $V = \frac{(S + s)}{2} . L$ (Smalian's formula)

(b) $V = s_{\frac{1}{2}} . L$ (Huber's formula)

For Smalian's formula, the average of the two end sectional areas should be used and not the sectional area equivalent to the mean of the two diameters. Very little error is involved in using the latter if the two diameters are nearly the same; the greater the difference between them, the greater the error, for example for diameters respectively 6 in and 12 in, the error is 10 per cent. The direction and extent of the error in volume using the Huber and Smalian formulae for logs of a shape other than paraboloidal has been investigated theoretically by Chaturvedi (1926) and many others. Theoretical arguments favour Huber's formula but it is often much easier to get to the ends rather than the middle of a log and the formula used in practice depends on the particular circumstances.

The representativeness of the position of measurement is important since it affects the extent of the error of estimate of volume. Logs are usually in some degree irregular in outline; if the actual position of measurement is, because of a local effect, unrepresentative of the shape assumed for the log then the volume estimate will be in error. More consideration should be given to this source of error in practice; it is doubtful if any other material of equivalent value is measured in as casual a fashion as are most logs.

For commercial purposes where logs of similar size are handled repeatedly, there are obvious advantages in having tables available from which volume can be read for various reference variables. A common table has length of log and centre girth or centre diameter as the reference variables. Another has top (small end) diameter as the reference variable because it dictates the sawing dimension in the mill, is safer to measure than centre diameter in log piles, is easier to measure than centre diameter of a log on the ground, and can be measured directly under bark. The compilation and use of tables of this kind in New Zealand are discussed by Duff (1959, 1960) and in Australia by Benson (1964).

Formulae to Give Approximations to True Solid Volume

At various times people have sought simple approximations to true sectional area which would give good approximations to true volume, called by several writers the 'escape from π'. Many formulae for these approximations are quoted in the literature, the commonest being the so-called fifth girth method, the formula for which is:

$V = \frac{(G)^2}{12} \cdot 2L$ where V = volume (super ft), G = centre girth (in) and L = length (ft).

$\frac{(G)^2}{(5)} \cdot 2$ substitutes for $\frac{G^2}{4\pi}$, the result being an over-estimate of only 0·5 per cent. There are a number of variations of this formula, such as $V = \frac{G^2 \cdot \frac{2L}{3}}{100}$, $V = \frac{D^2 \cdot \frac{2L}{3}}{10}$ where D = centre diameter (in).

Similar approximations were favoured by Burt (1888) whose tables are

still used for some purposes in the timber import trade of Great Britain. Such approximations are of little value unless the formulae are sufficiently simple for 'bush arithmetic', and few of them are.

Hoppus Measure: Quarter Girth Method

The formula for the quarter girth method as used in Great Britain is $V = \frac{\frac{(G)^2}{(4)}}{144} . L$ where V = volume (Hoppus cu ft), G = centre girth (in) and L = length of log (ft). The formula used in Australia, and referred to as Hoppus measure, is $V = \frac{\frac{(G)^2}{(4)}}{12} . L$ where V = volume (Hoppus super ft). E. Hoppus was a Surveyor to the Corporation of London Insurance. About 1730 he published a text 'Practical measuring made easy to the meanest capacity by a new set of tables' which was followed in 1736 by his 'Measurer' based on the formulae above. In those days 'the logs were lightly hewn where they lay felled in the forest. Their average cross-caliper measurements were used as a basis upon which to compute volume thus treating the logs as if they were actually square in section' (Laver, 1951). It became the practice in Great Britain to apply the formula to round logs. This practice seems to have become fairly well established in certain parts of Australia and is at present used extensively in the eastern States. Since in the Hoppus formula, $\frac{(G)^2}{(4)}$ substitutes for $\frac{G^2}{4\pi}$ in the formula for true solid volume, the volume derived is about 78 per cent of true volume. To convert true volume to equivalent Hoppus volume, true volume is multiplied by 0·78; to convert Hoppus volume to true volume, Hoppus volume is multiplied by 1·27. Just as there are 12 super ft in 1 cu ft so there are 12 Hoppus super ft in 1 Hoppus cu ft. There are 9·42 Hoppus super ft in 1 cu ft; 10 is often used as a convenient conversion factor. Tables for direct reading of volumes from log length and true girth have been compiled by many authors since Hoppus's time. One by D. Matheson is used in some States of Australia and has led to the terms Matheson volume and Matheson's scale. There has been considerable controversy on the advantages and disadvantages of the Hoppus system. On balance it would seem best to replace it with true volume but no practical steps have been taken to do

this. Care should be taken with the terminology: the term 'Hoppus foot' usually means a Hoppus super ft in Australia but a Hoppus cu ft in Great Britain, and the prefix Hoppus is often omitted by foresters in those States of Australia which use the measure, and this is liable to confuse others into thinking true volume is intended.

Estimates of Log Volume in Terms of Forecasted Product

The estimation of the volume of sawn timber likely to be produced from a log of given dimensions using log rules has a long history in North America, a log rule being 'a table which shows the estimated amount of lumber which can be sawn from logs of given length and diameter' (S. A. F., 1950) allowing for loss in conversion due to sawdust, edgings, defect, and so on. Graves (1914) discussed the subject comprehensively but modern North American texts should be consulted for the log rules in present use. There are no such log rules in Australia and because of their considerable limitations (which most North American texts stress) it would be difficult to sustain a case for their introduction to Australian practice.

Allowance for Defect

In Australia, as in most countries, logs are graded according to defects by the application of log grading rules, the principles and practices of which vary from State to State. They are discussed in textbooks on utilisation. In many cases, a direct deduction of volume is made to allow for pipe, a central portion which is hollow or not utilisable owing to the effects of ring shakes, fungi, or termites. Usually the volume of the pipe is computed assuming its cross-section is square, of a side equal to the diameter of the pipe as assessed by the measurer, because, though the defect area is usually circular in section, sawing removes it as a rectangular section.

Weight Measurement

If a log is to be converted into a product such as lumber where end use is related to volume, then quantity of log is most conveniently expressed as volume. For material such as firewood, it does not matter much from the viewpoint of end use whether quantity of log is expressed as volume or weight, though weight may be a more practical

measure if the pieces are small in size, irregular in shape, and of little value. If, however, the end product is strongly related to weight of log it may be much more suitable to express the log in terms of weight; and there may be very practical reasons for doing so if there are many logs. if they are reasonably similar in size and weight, if estimating the dimensions of each would slow up bulk handling, and if the basic value of the material is fairly low. This is generally the case for wood fibre products.

Wood weight may be determined in several ways. Each log can be weighed individually on a scale situated somewhere along the production line from forest to factory and this is sometimes done. Since the material has usually to be loaded on to a vehicle for transport at some stage it can be weighed in bulk while on the vehicle; this is probably the commonest method. To find the weight of wood for a particular load from the total weight of the loaded vehicle, other weights are needed, for example the weight of the empty vehicle, of bark, and of foreign matter like mud and ice on the vehicle and the load. Average values of these are normally used to save determining them for each load. Another possibility is to develop tree-dimension and tree-weight relationships similar to tree-dimension and tree-volume relationships so that weight can be derived indirectly. Tree-weight tables of this kind have been compiled and are particularly useful for standing trees. Because it may be more convenient to use volume instead of weight in certain of the operations between forest and factory, volume-weight conversion factors may also be necessary.

Irrespective of how the weight is derived, if dry matter equivalent is required then conversion factors are needed according to the amount of water in the wood.

Considerable interest in measurement by weight instead of volume has been shown in certain parts of North America in recent years especially by the pulp and paper industry. Much of a conference on wood measurement held in Toronto (Canada) in 1966 was devoted to weight measurement and the proceedings (University of Toronto, 1967) outline the history of 'weight scaling' in North America, methods of compiling log- and tree-weight tables, and investigations into the determination of conversion factors needed to derive dry weight of wood matter from log volume, loaded vehicle weights and so on. Coulter (1959) has discussed the determination of such conversion factors for radiata pine in New Zealand and the effects on the factors of region, age, season, and variation in amount of vehicle equipment and in foreign matter.

In Australia, weight measurement of this kind has been carried out only on a limited experimental basis. Suggestions are being made for its introduction where conditions are suitable and it is likely that in the next decade much investigation will be carried out, on similar lines to that in North America, into its applicability to material from coniferous plantations.

Stacked Material

Two kinds of material are measured on a stack basis in Australia. One comprises small and fairly regular logs of similar diameter cut to a standard length. This material can be conveniently measured in stacks on ground or on truck as cords or cunits and converted by appropriate conversion factors to weight or volume. In the northern hemisphere, very large quantities of this material are used by pulp and paper mills and for industrial and domestic fuel and there is extensive literature on methods and techniques of measuring such stacks and estimating the solid wood content. Most pulpwood and cordwood for pulp and paper mills and case sawmills in Australia is measured in this way. The other kind comprises material of so low a value and so irregular in shape that measurement of individual pieces is uneconomic so that it is cut into standard lengths and measured on a stack basis - such as logs split into billets for pulpwood, stem and branch wood for industrial and domestic firewood. The amount and weight of this material varies more than the regular material referred to above and conversion factors from cords to weight or volume are likely to vary considerably depending on the irregularity of the material, the method of stacking, and so on. Measurement of such material from a poor quality eucalypt forest in the A. C. T. is discussed by Carron (1953).

4 Tree Girth, Diameter, and Sectional Area

In dealing with a population comprising a number of individuals of different size, it is often convenient for both quantitative and qualitative purposes to measure the same dimension on each individual. This measurement can be used to identify the individual and it also allows ready sorting of the individuals into groups of similar size. For standing trees, the most convenient dimension by general consent seems to be a stem cross-section taken somewhere within the reach of the average person from the ground. Ideally the measurement should be taken at a comparable place on each tree; since trees differ in height, the measurement should be made at the same relative position, for example at some percentage of total height. This involves first measuring tree height, which is not easy to do reliably, and furthermore a practicable position for measurement on a large tree may not be practicable on a small tree and vice versa. Because of these difficulties, standing trees are almost universally measured at a fixed height above ground level, this position being referred to as breast height.

In Australia, the fixed height is 4 ft 3 in, following the use of a height of 1·3 metres in Europe, ground level being defined as the ground at tree base if the ground is level and on the higher side if the ground is sloping. In many countries of the world such as the U.S.A., New Zealand, Burma, India, Malaya, and South Africa, the height adopted is 4 ft 6 in, ground level being defined as the ground at tree base if the ground is level and mid-way between highest and lowest level if the ground is sloping. In Australia, it is usually prescribed that where there is a mound of soil or litter around the base of the tree, the mound should be displaced if it is very loose otherwise its upper surface is taken as ground level; and that any material at breast height which is not an actual part of the tree such as moss and loose

or hanging bark, should be removed. Generally, if a tree forks between ground and breast height it is conventional to regard it as two stems: and if it forks above breast height to regard it as one stem. In some cases, for example in Tasmania (Lawrence, private communication), a forked tree is regarded as two stems if it is at all possible to measure them as such from the ground. The position of breast height is often estimated by eye or located roughly by reference to the operator's height. For most purposes it is more satisfactory to use a tape, a scale, or a marked stick to fix the position of breast height, even if one feels doubtful about being able to define ground level strictly. If a tree is to be measured periodically, it is essential that the position be identified permanently by some means such as a paint mark, scribe mark, or soft metal nail at breast height or at a prescribed distance from it. Otherwise determinations of increment at breast height over time may be confounded with differences due to measuring at a different position on each occasion, particularly as trees often tend to build up a mound at the base and as ground level rises so does the position of breast height.

The size of a tree at breast height can be measured and recorded as girth (circumference), diameter, radius, or sectional area. There is no particular convention about this except that radius is rarely used (though radial increment is a common expression) and trees are rarely recorded as individuals or tallied in classes according to their sectional areas. Girth or diameter is most commonly used, the choice depending more on local habit than on any particular advantage of one over the other, though most people can imagine size and change in size more easily in terms of diameter than of girth. Instruments for measuring girth are commonly graduated to read equivalent diameter as well; the reverse is rare. Very occasionally instruments to measure girth or diameter may be graduated to read sectional area also.

Measurement of Girth at Breast Height

Girth is usually measured in Australia with a tape or band, the kind varying with size of tree and purpose of measurement. For rough estimates or small stems, cloth tapes may be used but because of wear and the effects of weather they become unreliable and have a short life. For medium-sized trees up to about 12 ft in girth, steel tapes are commonly used, 3/16-3/8 in wide, 6-12 ft long, housed

in a steel or leather case with a return spring or winder mechanism. The steel is strong in tension but breaks easily if kinked.

Fibreglass tapes in metal, leather, or plastic cases are also fairly popular and in many circumstances are better than steel ones. For trees larger than about 12 ft in girth, steel, cloth-metallic (cloth with metal threads), or fibreglass tapes, usually 66 ft (one chain) or 100 ft in length, in leather or plastic cases are used. The shorter tapes are usually graduated in feet, inches, and tenths on one side and in π units on the other side to give equivalent diameter which has led to the name 'diameter tape'. It should always be kept in mind that it is girth that is measured by such a tape and any value of diameter obtained by a girth tape is only as reliable as the measurement of girth. For measuring trees over 2 ft in diameter, it is convenient to have a hook at the leading end of the tape which can be pushed into the tree to hold that end while the rest is taken around the tree by the operator.

Measurement of Diameter at Breast Height

Direct measurement of diameter at breast height (d.b.h.) is usually made by some form of caliper (calliper). The most common form of tree caliper comprises a scale, graduated in appropriate units, to one end of which an arm is fixed at right angles and on which another arm can slide and take up a right angle position when at rest. The scale and fixed arm are placed flush against the tree, the movable arm is then brought up against the tree, the intercept it makes with the graduated scale giving the tree diameter. The main requirements are that the whole instrument be durable but light in weight; the scale must be easy to read under field conditions (the kind and size of numbers may have important effects on errors in reading and calling); and the movable arm must move easily but come to rest at right angles to the scale when brought up against the tree, otherwise there is an error in tree diameter.

The earliest, simplest calipers were made of wood and are still used in many parts of the world. Their main fault is that the sliding arm is difficult to move or wears quickly and the provision of bushings to overcome this has not been very successful. The later metal types, usually of light alloy, are more successful, particularly those with devices to allow correct alignment of the arm if it gets out of adjustment. There is a wide variety of calipers some of which are discussed by Hummel (1951). One kind has both arms fixed, such as

the tree fork discussed by Essed (1957), and the Finnish type with one straight arm and one curved. For enumerations of stands of small trees with a limited range of sizes, a piece of plywood into which has been cut a series of gaps which decrease in width by steps from the outer edges inwards, is handy for enumerating trees in size classes. In another kind, the arms are bowshaped and pivoted on a pin with a scale suspended between them. There are various patterns which allow automatic register of size on a recording tape such as the Lignometer (FAO, 1958).

Diameter can be determined indirectly through the use of a geometrical principle as in the Biltmore stick which consists of a straight length of wood graduated in such a way that the diameter at any point on a standing tree may be read from the stick when it is held against the stem, tangential to the point, perpendicular to the vertical axis of the tree, with the observer's eye at the same horizontal level and a distance from the stick for which the stick is graduated. The stick is placed so that the zero end is in line of sight from one eye to one side of the tree; the graduation on the stick which is in line of sight with the other side of the tree gives the diameter. The geometrical principle involved, and the appropriate formulae for graduating the stick, are discussed in texts such as Chapman and Meyer (1949). The Biltmore stick is a simple and convenient instrument for placing medium sized trees in 2 in or 4 in diameter classes in inventory.

Sectional Area

By convention, sectional area at breast height is given the particular name basal area. It is normally derived indirectly by reference to prepared tables from a measurement of girth through the formula $\frac{g^2}{4\pi}$, or from a measurement of diameter through $\frac{\pi d^2}{4}$. In Australia, basal area is expressed in square feet and decimals. The formulae assume a circular section. A perfectly circular stem cross-section is rare; most stem sections are irregular in outline. If a tree section is assumed circular when it is not there is an error involved in the sectional area calculated from the formulae. For example, if a tree section is elliptical with a major axis of 22 and a minor axis of 20, then the errors involved in calculating the area of the section as a

circle by various ways are as shown in Table 4:1.

Table 4:1

Errors in calculation of tree sectional area

Method	Area	Error %
As an ellipse	345·6	0
As a circle on major diameter	380·1	+9·9
As a circle on minor diameter	314·2	-9·1
As a circle on mean of major and minor diameters	346·4	+0·2
As a circle on girth	346·7	+0·3

That is, calculating the cross-section as circular on the basis of the mean of the major and minor diameters involves least error but the error is only slightly less than that involved in calculating area from girth. Both errors are positive and relatively very small even for what is an eccentricity quite obvious to the eye. In fact, a truly elliptical section is as rare as a truly circular section. For practical convenience, the area of the section is almost invariably calculated as if the section were circular without regard for its actual shape either through girth measured by a tape or through diameter measured by a caliper. If there is obvious eccentricity the major and minor diameters may be measured with a caliper and the sectional area computed as a circle from the mean of the two diameters.

Comparison of Girth Tape and Caliper

If the cross-section of the stem is not circular, the sectional area will be overestimated from a measurement of girth by tape since, for a particular perimeter, the circle has a greater area than any other figure. The size and sign of the error due to one measurement by caliper will vary depending on where the caliper is placed. Measurement by tape is therefore likely to be precise for the same operator and among operators but measurement by caliper is not unless a mark is made on the tree against which the caliper bar should always be placed. If the section is elliptical, the caliper allows a better estimate of sectional area than the tape through the mean of the major and minor diameters, but, as shown in Table 4:1, the estimate is only slightly better and unless the actual major and minor diameters are measured the error may be larger than that from girth and may be positive or negative.

Provided a tape is correctly graduated there is no instrument error. If the sliding arm of a caliper is not strictly perpendicular to the scale when the reading is taken there will be an error which in practice is usually negative.

The main source of operator error results from not placing the instrument in a plane at right angles to the vertical axis of the tree. For an angle of displacement of A° from the correct position, in the case of a circular section of diameter D, a caliper measures a distance D sec A°; a tape measures the perimeter of an ellipse of major axis D sec A° and minor axis D.

A girth tape is small, easy to use and to carry. The caliper is comparatively bulky and may over a long period be more tiring to use and carry than a tape. A tape can be carried up and used readily in any position on the standing tree. The caliper cannot be carried up a tree conveniently. One measurement by tape is usually faster than two by caliper; one measurement by caliper is usually faster than one by tape. It is often difficult to get the tape around felled trees and logs and, if one measurement is acceptable, the caliper may be much more practicable. The use of one instrument rather than the other probably reflects local habit more than objective test. The tape is much more common in Australia. One reason may be the inheritance of the Hoppus system of measuring volume. Another may be that, before coniferous plantations were established, measurement was confined to native species which were too large for calipers and use of the tape for them has persisted for all sizes. Calipers are used in some States for measuring end or centre diameters of logs from coniferous plantation thinnings. They are likely to be used more in the future in enumerations of coniferous plantations.

Measurement of Diameter at Other Positions on Standing Trees

Girth or diameter is often needed at various positions on a standing tree beyond convenient reach from ground level, for example to derive stem volume or an expression of tree taper. There are three main ways of getting it: direct measurement at the point by an operator; raising a tape or caliper to the point; or using an optical device, on the ground and at some distance from the tree, directed at the point of measurement.

Direct measurement is likely to be the most reliable. This is practicable for conifers in plantations in Australia. They can be

climbed with the aid of the branches, though a ladder is normally used for the lower section which is generally pruned or on which the branches are dead and unsafe for climbing. Alternatively, light metal ladders in 10 ft sections are strapped to the whole length up to the position of measurement; the branches usually have to be pruned along the path of the ladders. Climbing irons of the stirrup type, and climbing spikes, are not suitable for measurement work. Climbing devices such as the Baumvelo (Hummel, 1951) are suitable in special circumstances. Sectional ladders are probably the most suitable equipment for young broad-leaved trees. In Australia, direct measurement up the stem is rarely carried out on old, large trees of broad-leaved species except for a reference measurement in place of breast height in the case of trees with extensive butt-swell, flanges, or buttresses. For this the operator can scramble up the buttresses or erect a temporary scaffolding from litter or use a light ladder, but may still have difficulty in passing the tape around the stem.

The use of pole calipers or pole tapes is restricted to the height to which a pole can conveniently be held and the measuring device at its end can conveniently be seen or operated. The mechanics of these instruments limit their application to small trees and a height about 15 ft above ground level. Hummel (1951) discusses various types. They have not been used in Australia to any extent.

Many instruments of considerable variety have been designed on optical principles to determine stem diameters at heights above convenient reach. Hummel (1951) has an extensive discussion which is of particular historical value. Grosenbaugh (1963) has a modern discussion of instruments and theory. At one end of the range of cost and sophistication is the Barr and Stroud Dendrometer described by Jeffers (1955). At the other end of the range are simple instruments based on principles similar to that of the Biltmore stick such as discussed by Finlayson and Archer (1964) and Nousianen (1965). Within this range are a number of instruments such as the 'wide scale relaskop' described by Sutter (1965), the transit theodolite as outlined by Leary and Burns (1963), and the Pentaprism caliper (Wheeler, 1962) a test of which is described by Benson and Slinn (1964). In Australia the Barr and Stroud Dendrometer has been used in research and routine work such as described by van Schie (1967) and simple instruments based on principles similar to that of the Biltmore stick have been used to estimate diameters of large broad-leaved stems above buttresses.

The Representativeness of Positions for Girth or Diameter Measurement

The section at breast height is often unrepresentative due to the basal swelling of branches, callus growth resulting from wounds, or other factors. Usually in such a case the operator measures diameter (girth) at points equidistant above and below breast height outside the affected zone, and takes the mean of these two diameters (or better still the mean of the two sectional areas). This assumes that diameter (sectional area) above and below the affected zone changes with height in a regular way. Unless this is so, and frequently it is not, the mean of two such points may not be satisfactory and since the operator has in effect to pick subjectively two points which will give a satisfactory mean he might do as well or better by subjectively picking only one position of representative size. When breast height has to be permanently identified, the need for two positions to be marked and measured often provides an irritating source of error in practice - only one of the points is measured, only one has the mark renewed, mistakes are made in taking the mean, and so on. For these reasons, it is sometimes prescribed that the operator choose subjectively only the one point for measurement when breast height is unrepresentative. Tests show that the effects of bias are not likely to be serious.

It is difficult to decide whether this practice should be extended to measurement of positions elsewhere on the stem. The difference between the diameters under bark at 5 ft and 15 ft above ground level is commonly used in some parts of Australia as a measure of taper of Pinus radiata for reference as an independent variable in a tree volume table (see ch. 13). The chance location of these positions of measurement relative to branch swellings and general surface irregularity may give a quite unrepresentative expression of taper and so a biased value of tree volume. Again, positions nominated by the prescriptions of a method to derive tree volume (see ch. 8) may be similarly unrepresentative. The usual prescription in these cases is to take a mean of measurements equidistant above and below the nominated point. One point chosen subjectively may be more satisfactory in this case also. However, if too much subjectivity in selection of such points of measurement is introduced, the effects of bias may become important. How far the argument for one measurement over the mean of two measurements should be extended must be judged by common sense.

Ocular Estimate

It is difficult to justify ocular estimate of diameter or girth in any serious measurement project, it is far too much subject to error. Estimating upper diameters by eye to calculate volume is so liable to error that an inventory based on this method is only worthwhile carrying out if very rough estimates are acceptable. The forester should, however, be able to estimate stem diameter sufficiently well by eye to act as a rough check on measurement by instrument.

5 Tree Height

The total height of a tree is usually defined as the distance from ground level to the 'top' (highest point) of the tree - this assumes that the tree is straight and vertical. For most conifers the top of the tree can be easily nominated as the growing tip or resting bud and, because of the nature of the crown, an uninterrupted line of sight to it from the ground can usually be obtained. For broad-leaved trees with healthy conical crowns such as many young eucalypts, the top may also be readily nominated and sighted as the highest point of the crown. But for trees with umbrageous irregular crowns, such as most mature eucalypts, the top may be difficult to nominate, particularly if the upper part of the crown is dead, and it is frequently defined as that point where the crown is intersected by the imaginary upward projection of the bole. In Tasmania (Lawrence, private communication), the top is defined as the highest green leaf. Apart from the difficulty of nominating the top of such a tree, sighting it may also be difficult since the line of sight usually goes through the crown. For such trees, however, some measure of bole height is often of more interest than total height, for example from some defined stump height to a position on the upper bole fixed by an arbitrary diameter limit or by a quality limit set by branching or defect. Unfortunately, this position has usually to be judged by eye and differences in estimates of height may result from difference in definition of what is being measured.

Even if height can be unequivocally defined it is not easy to get consistently reliable measurements from the same operator or among operators and, since tree height is a variable of fundamental importance for quantitative descriptions of a tree and a stand, foresters have devised a considerable number of instruments and methods to measure the height of a standing tree. The ideal instrument should give precise and unbiased measurements, be easy

to carry and use in forest conditions, and be relatively inexpensive.

Height can be measured directly, or derived indirectly by instruments of two groups based respectively on geometrical principles and trigonometrical principles.

Direct Methods of Measurement

The most reliable way to measure the height of a standing tree is to take a tape to the top of the tree by climbing or by ladder and to measure the height directly with the tape. If the top section is inaccessible, a light, rigid, graduated pole may be carried or hauled up the tree and used to measure that section separately. For obvious practical and economic reasons direct measurement by climbing can only be carried out under special circumstances, and the most common method of measuring height directly is to use height rods or height sticks. Various types of single, folding, and telescopic height sticks have been invented to suit particular conditions of measurement. The chief requirements are lightness and rigidity, portability, ease, speed and safety of operation, and cheapness of construction. For short trees up to about 20 ft high a single graduated pole which folds into two sections, or a telescopic pole, is commonly used. For taller trees the rods are usually in sections about 5 ft long, of similar diameter, each fitting into the next by a ferrule, with perhaps one to three tapering sections at the top. The upper limit to the use of height rods of this type under best conditions seems to be about 100 ft but the average limit over a range of weather and tree conditions is probably between 60 and 80 ft. They are best used on trees with branches which will let the rods pass between them readily yet give them lateral support, such as plantation conifers in Australia. The most effective team for an extensive program of measurement using height rods is probably three men, one using the rods, the second looking after supply of rods to the first and recording results, and the third determining when top of rod and tree are coincident (for example from a vantage point in another tree), the three exchanging tasks frequently to avoid fatigue. The rods are usually made of wooden dowelling or hollow metal-alloy tubing. They sometimes come apart in the retrieving process so that wearing safety helmets to avoid head injury should be mandatory. Various carriers for the rods have been invented for easy portability; a carrier like a golf bag which can be slung over the shoulder is handy.

Indirect Methods of Measurement

Instruments Based on Geometrical Principles

These instruments depend on the properties of similar triangles, and their application requires either measurement of distance of the operator from the tree or measurement of the length of part of the stem. Many instruments have been devised but there are only a few principles involved.

The simplest principle is illustrated in the so-called staff or pole hypsometer which in practice need only be a straight stick, for example a piece of branch. The observer holds it parallel to the tree so that the length of the stick from its top to the point at which it is held is the same as the distance from the eye to where it is held, and in such a position that the top of the tree is sighted past the top of the stick and the bottom of the tree is sighted past the point at which the stick is held. The height of the tree is given by the distance from the eye of the observer to the base of the tree. For all practical purposes this distance is determined by pacing, since the nature of the method does not warrant measuring it by tape.

Another simple principle, in which a length on the stem is determined as equivalent to some predetermined fraction of the total height, is illustrated in what Hummel (1951) refers to as the hypsometer of Vorkampff-Laue. On a stick of a specific length a mark is made at a distance upwards from the bottom of the stick which is an arithmetically convenient fraction of the total length of the stick, for example at 1 in from the bottom of a 10 in stick. The observer holds the stick parallel to the tree at such a position relative to his eye and at such a distance from the tree that he can sight the top of the tree past the top of the stick and the bottom of the tree past the bottom of the stick. The intercept on the tree made by the bottom section of the stick is then measured or estimated and the height of the tree is given by multiplying the length of the intercept by the ratio of the length of the whole stick over the length of the bottom section of the stick, by 10 in this case. If the fraction is made $\frac{1}{12}$, tree height in feet is given by the length of the intercept in inches. These two hypsometers are useful for rough estimates.

Better estimates are given by instruments such as the Christen hypsometer and Weise hypsometer (Jerram, 1939), the Merritt

hypsometer (Husch, 1963) and the JAL hypsometer (FAO, 1954) but none of these have been used to any extent in Australia where instruments based on trigonometrical principles are favoured.

Instruments Based on Trigonometrical Principles

The basic principle of these instruments is simple and is illustrated in Figure 5:1.

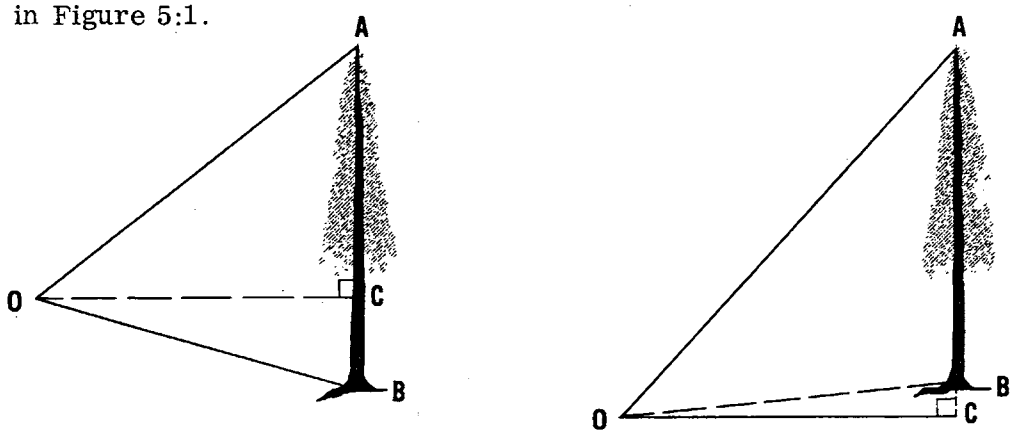


Fig. 5:1 Tree height measurement

(a) observer's eye above tree base (b) observer's eye below tree base

Sighting from O, the observer reads the angle AOC to the top of the tree and the angle BOC to the bottom of the tree. If O is above the base of the tree (as in Fig. 5:1(a)), he measures the horizontal distance OC, computes AC as OC tan AOC and BC as OC tan BOC, and adds AC to BC to get the height of the tree. If O is below the base of the tree (as in Fig. 5:1(b)) he measures the slope distance OB and derives the equivalent horizontal OC from it; he computes AC as OC tan AOC and BC as OC tan BOC, and subtracts BC from AC to get the height of the tree. The angles are read by some form of clinometer, an instrument for measuring angles in the vertical plane. There are two general cases.

In one case, the observer stands from the tree a distance which is convenient for observation, measures that distance and the angles AOC and BOC, and derives the tree height as outlined previously. The angles can be read by any kind of clinometer. In particular cases a theodolite is used; for most practical purposes the simpler Abney level serves very well - an instrument commonly used in forest surveying and usually readily available. The Abney level provides a line of sight through a tube which carries an arc graduated to 90^{o}

each side of a zero, the arc supporting a movable index arm to which is attached a small spirit level. If the bubble of the level is brought to centre of run for any line of sight, the graduation on the arc indicated by the index gives the angle of inclination relative to horizontal. The instrument must be checked to ensure that the line of sight and the bubble tube axis are parallel; this collimation adjustment is described in textbooks on surveying. Disadvantages of the Abney level are that the bubble appears more and more distorted with increasing angle of elevation and becomes difficult to centre, and having to move the index arm to get the appropriate angle of inclination makes it difficult to keep the instrument steady. The field of view is also so restricted that mistakes are often made in sighting the top of the tree, particularly in conditions of poor visibility.

If the observer can so position himself above the level of the base of the tree that the angle of elevation to the top of the tree is 45^{o}, then AC = OC (ref. Fig 5:(a)) and he can determine the height of the tree by measuring the horizontal distance OC and adding to it the distance CB measured directly on the tree. The main disadvantage of this method is that in forest conditions the observer may not be able to see the top of the tree at an angle of observation of 45^{o}. Again, since it is advisable to measure tree height from two independent positions as a check on operator error, the observer must be able to see the top of the tree at an angle of 45^{o} at two different positions, preferably on quite different sides of the tree. This method is often referred to as the 'Abney 45^{o} method'. Various other clinometers utilising a different working principle are also used for measuring tree height, for example Benson (1961a) discusses the Suunto clinometer in which the angle of inclination of a line of sight is given by the appropriate rotation of a weighted cylindrical drum about its axis. Tables from which the values of AC and BC can be read for various values of OC or OB and the angles AOC and BOC are compiled for use with clinometers (for example, A. F. R. I., 1964).

In the other general case, the clinometer is graduated in terms of the tangents of successive angles of inclination so that for a specific distance from the tree the values of AC and BC can be read directly from the instrument or derived by simple arithmetic without recourse to tables. In the topographic Abney level the scale is graduated to allow readings of rise (elevation) or fall (depression) in feet per one chain horizontal distance. In the engineering Abney level the scale is graduated in percentages. The Haga altimeter has five scales on a

rotatable pentagonal rod - 15, 20, 25, 30 (for distances of 15, 20, 25 and 30 units) and per cent. The instrument is about the size and shape of a pistol; the inclination of the line of sight is indicated by a weighted pointer, the movement of which is controlled by a button release mechanism and trigger clamp. The Blume-Leiss height measurer is similar to the Haga in size and general principle except that the pointer is directed downwards from its pivot instead of upwards as in the Haga and the five scales, 15, 20, 30, 40 and per cent or degrees are in the form of five concentric bows. As an attachment for the Haga, and incorporated into the Blume-Leiss instrument, there is a 'range finder' whereby the observer can set himself at a specific distance from the tree by hanging on the lower part of the tree an appropriately graduated scale which he sights by the 'range finder'. These two instruments are in common use in Australia being in several ways superior to the Abney level. Whenever light conditions are poor or the top of the tree is likely to be confused with that of another, the external line of sight is superior to the internal, restricted field of view of the Abney; there is no bubble to centre by moving part of the instrument, and so the instrument gives a great flexibility for selection of distance in dense stands. Further, under suitable stand conditions and for vertical trees, by using the distance-measuring attachments, the observer can dispense with measuring distance to the tree. The moving parts of both instruments are subject to wear and they should be checked frequently. Various comparative studies of the instruments have been carried out, such as by Warren (1958).

The Leaning Tree

In the discussion so far it has been assumed that the tree to be measured is vertical. In fact many trees in plantations and native forest in Australia are not vertical, and the assumption that a tree is vertical when it is not is a major source of error in tree height measurement.

Errors will occur in indirect methods unless suitable precautions are taken. If the observer, standing in the plane of tree lean, measures with the lean towards him he will overestimate tree height; if he measures with the lean away from him, he will underestimate tree height. The extent of the error for various angles of lean of tree and angles of observation under these circumstances is shown in Table 5:1.

Table 5:1

Errors, as per cent of true height, for various angles of lean and angles of observation (Chaturvedi 1926)

Angle of lean	Angle of observation to top of tree					
	60°		45°		30°	
	Towards	Away	Towards	Away	Towards	Away
5°	+15	-15	+ 8	- 9	+ 5	- 5
10°	+29	-32	+16	-19	+ 8	-12
15°	+41	-48	+22	-29	+11	-19
20°	+53	-65	+28	-40	+13	-26

The table shows that the smaller the angle of observation, the less the error in measuring the leaning tree as if it were vertical, that for a particular angle of observation, the greater the lean the greater the error, and that for any angle of lean and angle of observation, the negative error (in terms of true height) which occurs when the tree leans away from the observer is greater than the positive error incurred when the tree leans towards the observer, as can be seen from Fig. 5:2 and the following explanation.

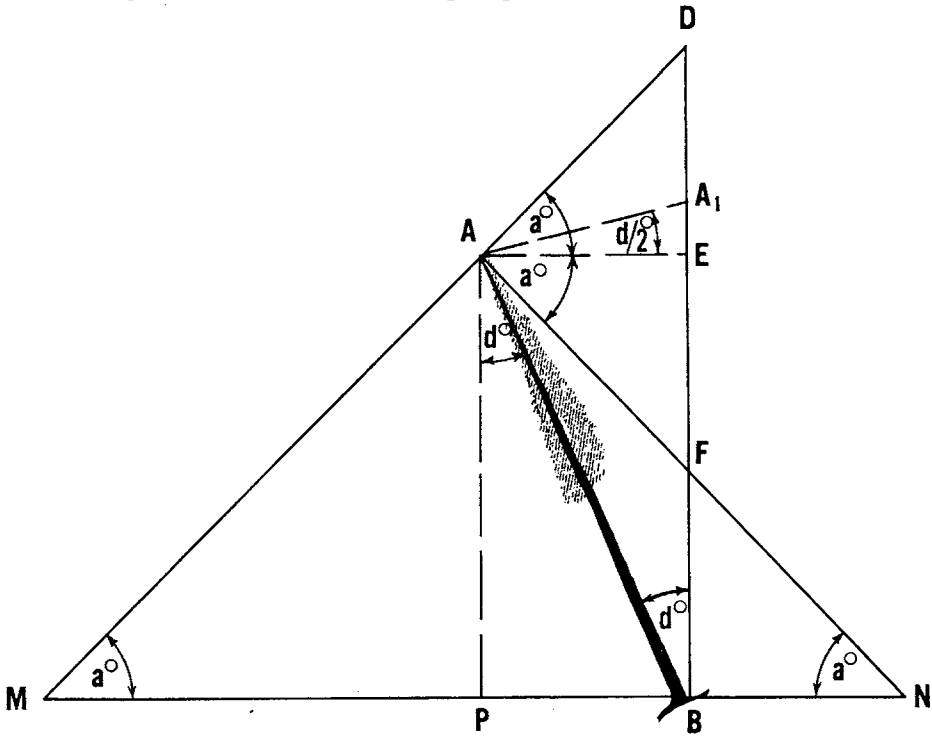


Fig. 5:2 Leaning tree

Assume AB is a leaning tree and P is the plumb position on the ground of the tip A, AP being the 'vertical component'. Let the angle of lean from the vertical be d^o. Let the angle of observation from both M and N be a^o, that is the same on both sides of the tree. Assume for convenience that the operator's eye is at ground level; in practice, MPN would be above ground level. Then the height measured from M with the tree leaning towards the observer is $BD = BE + ED = BE + AE \tan a^o$. The height measured from N with the tree leaning away from the observer is $BF = BE - EF = BE - AE \tan a^o$. BA' is made equal to BA (BAA' then being an isosceles triangle). The true height is then $BA = BA_1 = BE + EA_1 = BE + AE \tan d^o/2$ (since it can be shown that the angle $EAA_1 = d^o/2$).

The error in BD (lean towards) = BD − BA_1
$= (BE + AE \tan a^o) - (BE + AE \tan d^o/2)$
$= AE (\tan a^o - \tan d^o/2)$

The error in BF (lean away) = BF − BA_1
$= (BE - AE \tan a^o) - (BE + AE \tan d^o/2)$
$= - AE (\tan a^o + \tan d^o/2)$

The conventional recommendation is to measure the leaning tree at right angles to the plane of lean. If the observer moves from the base of the tree at right angles to the plane of lean of the tree (at right angles to a line joining the base of the tree and the plumb point of the top) and measures the angles of inclination to the top and bottom of the tree, the correct tree height can be obtained. From any other position an error of varying amount will result.

If the observer moves from the plumb point of the top, at right angles to the plane of the lean, until he sees the top at an angle of 45^o, the height of the tree will be given by the distance from him to the base of the tree (in fact, since the angle is read from eye level, the distance will be from the operator's eye to eye level on the tree plus the distance on the tree from eye level to ground). If two measurements are taken from independent positions as a check on operator error, one must be taken on each side of the tree, along the line at right angles to the plane of lean through the plumb point of the top, at an angle of 45^o from the top. It may or may not be possible to see the tree top from this position.

Fig. 5:2 shows that if the same angle of observation (not the same distance) is used on each side in the plane of lean of the tree the mean of the two observations is the 'vertical component' (the distance from the top of the tree to its plumb position on the ground). The observations

respectively with the lean toward and away from the observer are BE + AE tan a^{o} and BE - AE tan a^{o}, the mean being BE which equals PA (defined as the vertical component). The vertical component is for most practical purposes a close approximation to the true height of the tree; for an 8^{o} lean, it is 99 per cent of true height, for an 11^{o} lean 98 per cent, and even 95 per cent for an 18^{o} lean which is a severe lean indeed. True height can then be derived from the vertical component by measuring from the base of the tree to the plumb point of the top and calculating the true height trigonometrically or by reference to prepared tables such as those of Falconer (1931). The disadvantages of the method are that the measurements on each side of the tree differ from each other and provide no check on observer error in one or both; that the top must be visible from positions along the plane of lean which subtend the same angle of inclination to the top; and that the instrument used must be such as can be set at the same angle of observation for both sides.

For all the methods discussed above the top of the tree must be plumbed to the ground so as to establish the plane of lean. This being done, it is then more convenient to measure the vertical component directly by any sort of instrument and from any position. The distance from plumb point to tree base can be measured and true height can be derived if required. There is a check on operator error because measurements of the vertical component from any position should be the same; and there is complete flexibility in position of observation. The top must be plumbed in from at least two directions at about right angles. A convenient way is for one observer to sight the top behind a plumb-bob string held at arm's length in front of his eye and to direct another observer into that line, then repeat the process from another direction at something like right angles, the intersection of the two lines giving the plumb point.

Errors

There is always a likelihood of observer error in height measurement - wrong reading or recording, wrong setting out of distance or angles, measuring the wrong top in a dense stand, measuring a side branch instead of the top, difference of opinion amongst observers in nominating the top of a tree with an umbrageous crown. Personal error is best checked by two independent measurements, either by the same operator from different positions

or by two operators from different positions. The measurement of distance from observer to tree must be done to the centre of the tree, not to the side of the tree facing the operator. A sighting angle of about 45° (less rather than more) has theoretical and practical advantages. Instruments are obvious sources of error and should be checked before use to ensure they are in adjustment. A major source of error is measuring a leaning tree as if it were vertical. Whatever method of measuring the height of a leaning tree is used it is essential to determine the plane of the lean to avoid errors, and the only satisfactory way to do this is by plumbing in the top with an aid such as a plumb-bob; the eye cannot determine the plane of lean without some objective aid.

Ocular Estimate

For management purposes, heights of trees in coniferous plantations are usually determined by instrument, but estimates of tree heights are often determined ocularly in native forests because conditions of topography and undergrowth would make the use of an instrument difficult. In fact, the more difficult it is to use an instrument the more likely are ocular estimates subject to bias. If a tree height is required for any but a casual purpose it is worth the trouble and expense to determine it by instrument.

6 Form and Taper

There are good reasons for wanting to know the shape (form) of a tree stem. In Chapter 3 it was pointed out that the most practical way of determining the volume of a solid such as a stem is to equate it with a geometrical solid and determine its volume from the formula for deriving the volume of that solid. We need to know the shape of the stem so as to decide what geometrical solid to equate it with. Also, if we can determine why a stem develops to a particular shape we might be able, for example by breeding, to increase the volume of utilisable wood - cylindrical stems, for example, would be less wasteful of wood in sawing than tapering stems. Consequently, the kind and the rate of stem taper have always been of particular interest to foresters.

Observation shows that there is a large variety of stem shapes - the bulbous bole of an Australian kurrajong, the conoid appearance of an open-grown redwood, the large buttresses of some rain-forest trees, the slow regular taper of a plantation-grown conifer. Nevertheless, tree stems can be classified into two broad groups. In one group, apical dominance is strong, at least to a fairly mature age, so that the stem is continuous and undivided from ground to tip and the branches extend laterally over the whole or the upper part of the stem, depending on factors such as the growth habits of the species and the environment. In the other group, apical dominance is weak at least after an early age and the stem is not continuous from ground to the tip of the tree but merges into a crown either gradually or abruptly, the crown being in general of an umbrageous shape on top of the stem. The terms conifer and broad-leaved are conventionally used to identify these two groups. These terms are unsatisfactory as the characteristic of the first group is not typical of all conifers under all conditions and is typical of some broad-leaved trees under certain

conditions; and the characteristic of the second group is not typical of all broad-leaved species under all conditions and is typical of some conifers under certain conditions. However, no other suitable terms are in general use; 'excurrent' and 'deliquescent' for the two groups as suggested by Baker (1950) have not been widely accepted. The conventional terms conifer and broad-leaved will therefore be used here with their limitations implied.

For both groups, the stem at any particular time appears as a solid generated by the revolution of a tapering radial profile around a vertical axis. In the case of the first group, the profile has at least two main points of inflection - one in the butt region and one somewhere in or close to the crown. In the case of the other group, if we regard the stem as stopping at some arbitrary point and crown beginning there, there is perhaps only one main point of inflection - in the butt region. There are, however, many minor points of inflection and the profile of any stem is relatively complex; even within a group of trees of the same species, d.b.h., and height growing close together there may well be differences between diameters at similar positions along the stems. It is possible there are never two stems with identical profiles. It is difficult to specify the whole profile of a single stem and even more difficult to specify a profile to represent all stems.

Foresters have, however, attempted to specify stem profiles in two broad ways. One is by investigating growth processes and deducing what shape a stem might take as a result of them. The other is by determining stem shape from empirical evidence and rationalising this as a result of growth processes.

Growth Processes and Tree Shape

Even under continuously favourable environmental conditions, a tree rarely grows continuously but rather in an episodic way. The stem of a tree is a solid of material which has accumulated as a series of layers but a layer may or may not be of the same thickness along the vertical axis of the stem nor around the stem at any particular height. For certain species in a certain environment, the development of the layers is correlated with season and the layers are more or less readily identifiable - the well-known annual rings, each differentiated into early and late wood. For other species under other environmental conditions, the layers may be identifiable as separate layers but are not correlated with time. For other species and other

conditions again, there may be no differentiation into layers at all and it is difficult to appreciate that growth has not been continuous in time at all points on the tree.

The manner in which the material is accumulated depends on the individual - its species and genetical make-up; its age; on the present and past conditions of its environment - the soil, meteorological, and stand conditions; and on the length of time it has spent in those various environmental conditions. An enormous number and range of investigations over a long period have shown this. 'Growth of a tree is a complex phenomenon compounded of responses of its primary apical meristems and its secondary cambial meristems to both intrinsic and extrinsic forces which are not uniform either in time or space' (Forward and Nolan, 1961). Larson (1963) has an excellent summary of the variables affecting stem form, a discussion of the characteristics of open-grown and stand-grown trees, the effects of inheritance, site, thinning and pruning, and so on. The variations in tree form and factors with which these variations appear to be correlated are also discussed in many texts on tree growth such as those of Kramer and Kozlowski (1960) and Kozlowski (1963). To explain the variations in the way trees accumulate woody material with time, various stem form theories have been proposed. The better known of these theories were proposed during the period 1880-1920.

The original propositions of the nutritional theory by Hartig, and later developments by other workers, and the hypothesis of Jaccard's water conduction theory are summarised by Larson (1963). Though variations in the distribution of increment on the stem are presumed to be explained by these theories, neither leads to assumptions of specific shape of the whole or the main stem.

The mechanistic theory, on the other hand, does propose a stem shape. Associated most prominently with Metzger, it assumes 'the principle of wood formation in the stem is governed by the requirement of the tree for mechanical strength' (Busgen et al., 1929) and is often referred to as 'Metzger's beam theory'. In a series of papers, Metzger suggested that the main stem should be primarily a vertical structural member able to withstand horizontal wind forces on the crown and stem and the vertical forces comprising the weight of the stem and the weight of water, snow, and ice on the crown; and should be made of minimum material consistent with the idea that the maximum proportion of the food supply is directed to crown and reproductive organ development. That is, it should be a beam of uniform resistance,

having the highest possible bending strength in all parts with the smallest expenditure of material. This implied, according to Metzger, that the main stem should be of the shape of a third degree paraboloid and he demonstrated that many tree stems, particularly conifers and to a lesser extent broad-leaved species, conformed with this principle by the linear relation of the cubes of diameters with the respective heights from ground level at which they were measured, over most of the bole (excluding a section near the top and a section near the ground under the influence of butt-swell). Since this theory proposes to account for the internal and external forces acting on a stem, the resulting stresses in the stem, and the way the stem develops, many investigations have been planned to prove or disprove these aspects of the theory. Some of these are summarised by Larson (1963).

Recently, the role of growth regulators (growth substances) has been studied intensively in relation to the initiation and control of cambial activity and the development of cambial products, comprehensively summarised by Romberger (1963). Larson (1962) outlined how gradients of auxin translocation originating in the crown might regulate the distribution of radial growth on the stem. Whilst this hormonal theory provides a physiological explanation of how a tree grows and why trees differ in the way they taper, it does not specify the particular shapes which trees might have under varying circumstances.

The quality of the wood is just as important as the quantity of the layer of wood at any position in the tree and is correlated fairly closely, from the viewpoint of density and thus strength, with the proportion of late wood in the growth rings. Many observations have been made of the patterns of variation of early and late wood but none is readily related to stem form.

Larson (1963) summarised the position of these theories thus:

> the nutritional theory is convincing in many respects but research has shown that nutritional gradients cannot possibly provide the required regulatory control. The water conduction and mechanistic theories, being functional in nature, cannot in themselves provide an adequate physiological explanation for the observed facts. From the standpoint of strength requirements and support function, the mechanistic theory provides a realistic interpretation that has survived experimental study reasonably well. This is particularly true when the variations in latewood percentage and wood density are considered in conjunction with stem taper. The hormonal

theory, envisioning spatial and temporal variations in auxin gradients throughout the stem, provides the most promising approach to the stem form problem. In terms of this theory, auxins exert the regulatory control governing the distribution of radial growth on the stem and thereby provide a physiological basis for the nutritional as well as the functional theories of stem form.

Heger (1965) found differences in the 'form' of early and late wood layers in Douglas fir which he felt could not be explained by the mechanistic, nutritional, conductive, or hormonal theories of stem formation and proposed that 'radial growth may proceed at varying rates for unequal periods of time within different parts of the cambium cylinder depending largely on the levels of subcortical temperatures'.

Various workers have studied the stresses and strains in tree stems as they grow; Jacobs (1965) and Boyd (1950a, b, c) have been prominent in work on Australian species. From this work, however, no suggestions have been made as to the shapes tree stems might take in developing and accommodating to these stresses and strains.

Stem Profiles

At the same time as stem form theories were being proposed to explain how a tree grows and the cause of variations in tree shape, various workers were investigating the empirical evidence of tree shape. About the turn of the century in western Europe attempts, by Jonson in particular, to describe the profiles of conifers by formulae derived as the best fit to diameters at various heights on the stem stimulated a large amount of work of this kind in many parts of the world. Description of a tree profile by formula is conventionally called a stem profile equation. For some time prior to this, thinking in Europe about tree volume was particularly concerned with finding correlations between form factor and some index which could be measured conveniently on a stem, form factor being a factor by which the product of the height and some cross-sectional area of the stem has to be multiplied to give a particular expression of volume of the stem. Depending on the species of the tree, its genetic background and environment, on the expression of height used and where the cross-section is measured, and on the expression of volume required, so the kind and quantitative value of a form factor varies. It may or may not infer by its value something about the form (shape) of a stem. Such a correlation was found between form factor and form quotient,

generally defined now as the ratio of the diameters respectively at half the height above breast height and at breast height, the ratio being conventionally expressed as a decimal, for example ·70. Conventionally, classes of form quotient values known as form classes were established for classifying trees in frequency distributions, for example form class 70 (trees with form quotients from ·675 to ·725).

From numerous measurements of diameter at percentile heights (that is at tenth heights above breast height) of certain west European conifers, Jonson (1910-12) proposed that the profile of such trees from breast height upwards could be described by the formula

$$\frac{D_L}{D} = C \log \frac{(c + L - 2{\cdot}5)}{c}$$

where D_L = the diameter at percentile distance L from the tip, D = diameter at breast height and C and c are constants varying with form class. This formula was a modification of one which Höjer had proposed some years previously. From this equation, Jonson compiled tables giving tree diameters at percentile heights, as a percentage of diameter at breast height, for various form classes. The profile of a stem being defined according to its form quotient, so the form factor of the stem was automatically defined. This led readily to derivation of stem volume as the product of basal area, height, and form factor. Because of the obvious practical difficulty in measuring diameter at half tree height above breast height, Jonson looked for an index with which form quotient might be correlated. Arguing from Metzger's beam theory that the centre of gravity of the crown should be such an index, he established a correlation between the relative position of this form point on the tree and the form quotient so that form quotient could be determined for a tree from an estimate of the relative position of the centre of gravity of the crown. From the nature of the expression of the stem profile, trees of the same total height and diameter at breast height but of different form quotient are regarded as being of different shape.

Following Jonson's work, Wright (1927) carried out a detailed study of taper curves (stem profiles) of certain conifers in Canada. In the United States, Behre (1927) proposed an equation to describe the stem profiles of several North American conifers which, in terms of the symbols used in Jonson's equation above, is $\frac{D_L}{D} = \frac{L}{c + CL}$ the constants C and c having, of course, different arithmetic values

from those in Jonson's equation. The diameters at percentile heights for various form classes are reasonably similar to those of Jonson for the most part. These and other formulae proposed by workers in Europe were subjected to considerable investigation with confirmation or denial of the satisfactory nature of stem profile equation depending on the species studied and its environment, and subjective opinions of what was 'satisfactory'. One major problem was that the formulae only applied above butt-swell and if butt-swell were present above breast height application of the formulae was difficult.

In Australia, Gray (1943, 1944, 1956, 1966) hypothesised 'that within the usual limits of accuracy of tree measurement, the central length of the bole under-bark approximates as closely to a solid body generated by a second degree parabola as to any other geometrical body even though variation of form quotient may be considerable'. He suggested that this shape may have different taper (more strictly, different rates of taper) according to factors such as the size and shape of the crown, the forces of wind on the crown and the weight of crown and stem. These factors would also influence the extent and shape of top and butt sections which are superimposed on the main bole. Gray based his hypothesis on empirical evidence from measurement of a large number of trees over a wide range of species. He subsequently attempted to show that the hypothesis was consistent with the physiological and structural requirements of trees. The practical implications of the hypothesis are discussed in Chapter 8.

Many workers such as Petrini (1921) have emphasised that the profile is of a compound nature and can only be described adequately by separate expressions for the top section, the main bole, and the butt-swell region.

The Main Propositions of Tree Shape Compared

If the under-bark diameter of a mature forest-grown conifer, undivided from ground to tip, is measured at very close intervals along the stem, these values plotted on rectangular co-ordinate paper against the heights of the measurements from ground level, and these points are joined, almost invariably they form an irregular line which, however, if smoothed out, appears as a compound curve with two main points of inflection - one in the crown region and one near the ground.

Some people consider three separate curves are involved - one for

most of the stem bearing live branches; one for the main stem, particularly the part without live branches; and one for the butt-swell region; and that the sections of the stem described by these separate curves vary with species, size, age, stand structure, environment, and individual vigour so that there is no reason to expect that even two trees of the same species and the same d.b.h.o.b. and height growing alongside each other would have the same kind and extent of these curves.

Proponents of the stem profile equation would say that the taper curve could be described along its whole length by one general equation, shapes indicated by the curve differing only as the ratio of the diameter at breast height and half-height above breast height differs for different stems, the shapes of stems being the same irrespective of overall size if their ratios are the same.

Those following the proposals of Metzger or Gray would say that all trees have a main stem of common shape - cubical paraboloid according to Metzger, second degree paraboloid according to Gray - with different rates of taper (strictly, different rates of change of taper) according to species, size, age, environment, and so on; and with varying butt-swell and top.

Tree Shape in Australian Forests

The effects of butt-swell and bark thickness make it difficult to determine under-bark form quotient consistently but if the influence of butt-swell can be removed the range of under-bark form quotient for plantation conifers in Australia is about 0·60 to 0·80. Over this range of form quotient, Jonson's equation gives a reasonable fit for varying lengths of main stem depending on a number of factors - stand density, site quality, the extent of pruning. Stems with a form quotient about 0·80 also give a reasonable fit to Metzger's cubical paraboloid since the form quotient of a cubical paraboloid is about 0·80. Stems with a form quotient about 0·70 give a reasonable fit to Gray's second degree paraboloid since the form quotient for a second degree paraboloid is about 0·70. It so happens that a large percentage of the stems of plantation conifers in Australia have a 'basic' form quotient (that is, form quotient measured so that butt-swell does not influence it) of about 0·70 so that Gray has found considerable evidence for the 'generality' of his hypothesis. Under certain stand conditions which influence the number, size, and disposition of the branches (which

similarly affect the fit of Jonson's equation), some trees show an evident point of inflection in their profiles within the live crown. If this inflection is slight, one taper line may serve as a reasonable approximation for the whole of the main stem; sometimes two separate taper lines may be preferable; sometimes the section of the main stem within the live crown cannot be fitted at all satisfactorily with a linear taper line and for such trees only a profile of a compound curvilinear nature would be really satisfactory. Data from the Queensland Department of Forestry (Henry, private communication) suggest that hoop pine in plantations approximates as closely to a second degree paraboloid as to anything else; but for a fairly large sample of plantation slash pine, the Jonson equation provided a very good fit over most of the stem over a 10-16 in range of d.b.h.o.b. and a 60-70 range of form quotient.

Gray has suggested that the stems of broad-leaved species up to crown break are truncated second degree paraboloids with butt-swell variously superimposed. As for conifers, this seems to hold for most native broad-leaved species much of the time but not for a species all the time. It holds well for young second-growth eucalypts. For older eucalypts, a large proportion of the stem is usually influenced by butt-swell.

7 Bark and Crown

BARK

The radial thickness of the sheath of bark on a tree decreases from ground to tip, usually in a fairly regular way though not necessarily with the same rate of taper as the stem. Bark thickness varies amongst species and also within a species according to age, size, and environment. Even in an even-aged stand of one species, bark thickness may vary amongst individuals of the same d.b.h.o.b. and height. On an individual tree, bark thickness may vary around the stem at a particular height above ground. Nevertheless, correlations can usually be established between expressions of bark thickness and tree or stand variables. From these relationships estimates of the quantity of bark as a useful or waste product can be made, and estimates of under-bark dimensions obtained from over-bark dimensions. Under-bark dimensions can also be determined by direct measurement on felled trees by measuring at the ends of logs or removing rings of bark, and on standing trees through measurement of bark thickness. The terms diameter over-bark (d.o.b.) and under-bark (d.u.b.) are the ones commonly used in Australia. In some other countries, the terms diameter outside bark (d.o.b.) and inside bark (d.i.b.) are conventional.

Since tree volume is expressed on an under-bark basis almost everywhere in Australia, the matter of bark thickness is very important.

Measurement of Bark Thickness

On felled trees or logs, bark thickness is sometimes measured on a chip. If so, care should be taken that no bark is lost, or that the bark is not compressed, in cutting the chip. For standing trees, and as an alternative to measuring a chip in the case of felled trees, bark

thickness is measured by some form of bark gauge. The most common type is the Swedish bark gauge, essentially a semi-circular gouge-chisel with a wooden or metal handle. By pressure on the handle, the chisel end is forced through the bark, the depth of penetration of the chisel being determined on a suitably graduated scale, while the gauge is in the tree, by the upper end of a sleeve the bottom end of which has a flange which is pressed against the outside of the tree. There are simpler home-made types which take various forms depending on the inspiration of the maker. Lewis (1953) describes two designs which have been used in South Australia. A very simple type can be made by driving a graduated nail through a block of wood which serves as a handle. Usually with the simple types, the level of the bark on the gauge is marked by thumb-nail while the gauge is withdrawn and the graduation read.

Any such bark gauge depends for its function on the assumption that the bark will be penetrated, and that the sapwood will not be penetrated, by the gauge; or that the bark is more easily penetrated than the wood and the operator can detect when the point of the gauge reaches the junction between the two. Unfortunately, these assumptions are not always tenable, many tree barks being considerably harder than the sapwood. Even when the bark is softer than the wood, no practicable way has yet been found of judging when the gauge has just passed through the bark and is about to penetrate the wood. After considerable experience, particularly with one species, operators develop a 'feeling' in using a bark gauge and their measurements can be relied on. The effect of error in bark thickness measurements is not always appreciated: an error of 0·1 in in the radial bark thickness of a 10 in d.o.b. log results in an error of nearly 5 per cent in the under-bark volume; an error of 0·2 in results in a volume error of about 9 per cent.

Various modifications to the Swedish bark gauge have been suggested to improve reliability without much success, but no alternative way of measuring bark thickness, such as removing cores of bark for direct measurement of bark thickness, have proved as generally satisfactory as by the bark gauge. Any of the simple types seem satisfactory in smooth bark up to about 0·5 in; beyond that thickness the Swedish gauge is usually more satisfactory. When measuring the thickness of rough and deeply fissured bark, it is important to keep in mind the purpose of the measurement and how the over-bark measurement was taken, for example whether by caliper or tape.

Because of the likely variation of bark thickness around a tree, several estimates of it should be made - two at right angles (on the long and short axes if the tree section is eccentric) or four on a cross. Care should be taken with a bark gauge while climbing a standing tree; in good order, a bark gauge is a sharp gouge chisel and a guard should be placed on the sharp end to avoid possible injury to the operator.

The relationships between over-bark and under-bark dimensions on a stem are:
radius under-bark = radius over-bark - radial bark thickness
(r.u.b. = r.o.b. - b.t.);
diameter under-bark = diameter over-bark - radial bark thickness x 2
(d.u.b. = d.o.b. - 2b.t.);
girth under-bark = girth over-bark - radial bark thickness x 2π
(g.u.b. = g.o.b. - 2π b.t.).

Bark Relationships

The relationship between bark thickness at breast height and diameter over bark at breast height is of practical interest. In establishing this relationship for a species, the relative contribution of locality, age, tree height and site to variation in bark thickness at breast height should be investigated. Studies of radiata pine in Australia suggest that differences occur due to locality. For example, values in South Australia are considerably less than in the A.C.T. Some investigations have shown that, within localities, variation is related to both tree height and d.b.h.o.b.; other investigations have suggested that a simple relationship between bark thickness and over-bark diameter was sufficiently precise for all ages and sites. This is sometimes linear. For data of 2,800 trees of Pinus radiata in Kowen Forest, A.C.T., with a d.b.h.o.b. range of 4 in to 18 in, the relationship was curvilinear but very flat with values as shown in Table 7:1.

Table 7:1
Bark thickness at breast height P. radiata, A.C.T.
(after Carron and Jacobs, 1964)

d.b.h.o.b.(in)	2b.t.(in)	d.b.h.o.b.(in)	2b.t.(in)	d.b.h.o.b.(in)	2b.t.(in)
5·0	0·65	10·0	1·58	15·0	2·20
6·0	0·88	11·0	1·73	16·0	2·33
7·0	1·08	12·0	1·85	17·0	2·42
8·0	1·25	13·0	1·98	18·0	2·52
9·0	1·43	14·0	2·10		

For some species under certain conditions, bark thickness bears approximately the same ratio to over-bark diameter at any position on the tree. For other species or different conditions this is not the case.

The volume of a log of a broad-leaved species or a native conifer is generally derived in Australia by reference to the centre girth. This is sometimes measured over the bark and a generalised allowance for bark thickness subtracted to give under-bark centre girth. Alternatively, a ring of bark is removed at the point of measurement and the under-bark girth measured directly. The time spent in removing the ring of bark is disproportionate to the time spent in falling, topping, and butting under modern conditions and there is an increasing tendency to measure over-bark girth and use corrections for bark thickness. When the relative bark thickness is the same everywhere on the tree the simple relationship d.u.b. = k d.o.b. will suffice, otherwise factors such as the position of the log in the tree and the log length have to be introduced into the relationship as further independent variables.

For some species under certain conditions, bark volume is also the same relative to stem volume, over a wide range of tree size, for example for radiata pine in the A.C.T. the under-bark volume of stems or logs can for most purposes be regarded as 85 per cent of the over-bark volume. For more reliable estimates, corrections need to be based on factors such as locality, size, and site. When bark is a minor product there is considerable advantage in compiling a bark volume table. Usually the same methods are used as for tree volume table compilation (see ch. 13). A bark volume table for radiata pine, Uriarra Forest, A.C.T., is shown as Table 7:2. For trees with furrowed bark, the volume of bark computed from conventional measurements of bark thickness by bark gauge will include the air space of the furrows.

CROWN

The diameters of the crowns of trees in a stand are frequently correlated with the diameters of the stems at breast height. The relationship is commonly a simple ratio and so is usually called crown ratio. In many cases it is not a simple ratio and may even be curvilinear. The relationship has been used for a long time for various silvicultural purposes. Jacobs (1955) discusses its use in the

Table 7:2
Bark volume (cu ft) to 4 in d.u.b.; P. radiata. Uriarra Forest, A.C.T., 170 sample trees

d.b.h.o.b. (in)	Total height (ft)				
	40	50	60	70	80
6	0·52	0·63	0·72	0·82	
7	0·70	0·84	0·90	1·15	
8	0·90	1·10	1·30	1·50	
9	1·13	1·37	1·68	1·95	
10	1·38	1·70	2·05	2·42	2·70
11		2·00	2·50	2·95	3·30
12		2·40	3·00	3·50	4·00
13			3·50	4·10	4·70
14				4·80	5·50
15					6·40

silviculture of the native eucalypt forest; Dawkins (1963) discusses its behaviour in some tropical forests. The relationship is also valuable in mensuration on aerial photographs since stem diameter can be derived indirectly from crown diameter measured on the photographs; and crown diameter can be used as an independent variable in aerial tree volume tables as discussed by Spurr (1960).

To establish the relationship actual crown diameter has to be measured. For some trees this can be done by climbing the tree and extending a calibrated pole horizontally. In most cases the trees or crowns are too large for this to be done and crown diameter is measured by projecting points of the crown perimeter on to the ground in some way and measuring on the ground the distance between those projections. Usually the mean is taken of two diameters at right angles. Various methods are used or have been suggested to project the edge of the crown to the ground. For some purposes, visual subjective judgment may be sufficient. Commonly, one operator aligning a plumb-bob string on to the edge of the crown directs an assistant on to the projected point. Various optical devices for directing the assistant to a position vertically below the crown edge or for an operator to so position himself are discussed by Nash (1948), Sarvas (1956), and Walters and Soos (1962).

The sectional area of the crown of an individual tree can be calculated from its diameter as if the crown were circular. If the crown is irregular and a more exact estimate of its sectional area is required, the outline of the crown can be drawn on plan by plumbing the crown edge to the ground at an appropriate number of positions,

plotting these points on plan by rectangular co-ordinates, joining the points and calculating the enclosed area by planimeter or dot grid. Mapping the outlines of crowns on a plan in this way is one method of determining crown closure, the ratio of the area of the vertical projections of crowns to the equivalent area of ground occupied by the stand. This is a measure of stand density which is of particular interest in silviculture and also a useful index for stratifying stands on aerial photographs. Except in special cases, actual mapping of crown projections is usually too laborious and various devices which give a measure of crown closure at sampling points have been suggested such as the 'moose horn' (Robinson, 1947; Garrison, 1949). The term crown closure better describes the sectional area of the canopy than the term crown density which is sometimes used for this but better implies the total bulk of the crowns which affects quality, direction, intensity and duration of light and so can be measured by a light meter.

Crown length is usually determined from appropriate heights measured with some height measuring instrument. The ratio of length of crown to total length of tree is sometimes referred to as crown per cent.

Crown surface and crown volume are sometimes computed for special purposes. A shape appropriate to the growth habits of the particular species is assumed, for example conoid, paraboloid, or hemispherical, and dimensions obtained for calculation of surface and volume by appropriate formulae. Dale (1962) gives approximations for easy calculation of crown surface area.

Crown weight is important in as assessment of total production and the weight of slash left after fellings. Brown (1963) illustrates a relationship between tree crown weight and tree d.b.h.o.b., site quality and stand density, for stands of red pine in the U.S.A. Wile (1964) illustrates a relationship of crown diameter, length, and weight with tree d.b.h.o.b. for red spruce and balsam fir in Canada. There is very little information of this sort for either the native forest or plantations in Australia.

8 Stem Volume

If a forest is managed for wood production, the volume of wood in the forest is a particularly important criterion of management and the estimation of that volume is an important aspect of measurement. Whatever the method of estimation used, it is based directly or indirectly on estimates of the stem volume of individual trees. The reliable estimation of individual stem volume is therefore one of the most important mensuration requirements.

The Definition of Stem Volume

Very few stems exactly represent simple, ideal, geometric solids and most have irregular surfaces due to the episodic growth pattern of the stem and swellings at the base of branches. This irregularity being natural to the tree as a result of its growth habits, we might think of the volume of a stem in biological terms; that is as the volume of a stem whose branches have been trimmed off at their junction with the stem, excluding any irregularities that are not part of the natural growth habit of the stem such as those due to the effects of insect and fungal attack and fire. This is an objective definition of volume. It has, however, obvious disadvantages. If our interest is in utilisation, the biological volume of the stem may be quite unreal. Further, we would expect stems with common values of d.b.h.o.b., height, and taper to have the same volume and this expectation should not be upset by irregularities unique to individual trees. From these viewpoints it is logical to exclude the normal irregularities of episodic growth and branch junctions in determining stem volume - but to what extent? For a tree with a smooth stem such as Eucalyptus grandis, potentially utilisable volume and biological volume are the same. For a tree with large branches in close whorls such as Pinus radiata, biological volume

may have some reality for a pulpwood operation but not for sawn timber production, and perhaps it is more realistic in such a case to define volume by the minumum diameters in internodal areas. There are many grades of irregularity between these two cases. Obviously any volume other than biological volume involves some subjective judgment and the volume of a stem can no longer be rigidly defined; though this is not to say that biological volume can be readily measured.

The volume of a stem is defined largely by the method used to determine it and so comparison of methods by reference to some standard volume is difficult. A particular method might best be judged according to how well it meets the objectives. Before applying a method one must decide what volume one wants.

Factors Affecting Methods of Direct Estimation of Stem Volume

If in a method of estimating volume a stem or a part of it is assumed to approximate a certain solid, the reliability of the estimate of volume will depend on the validity of that assumption for the particular case and how closely the dimensions which are determined conform to those appropriate to deriving volume for that solid.

The type of tree may influence the choice of method. For a conifer, volume can be estimated for the whole stem or for any part between certain arbitrary limits. For a broad-leaved species, an upper limit is imposed by crown break. A method applicable to the one may not be applicable to the other.

Whether a tree is felled or standing is of particular importance. A tree on the ground is readily accessible for measurement and there is hardly any limit to the number of measurements that could be taken. However, practicability and economics set limits to measurement of a standing tree.

Requirements of the Ideal Method

The method of estimating stem volume should suit the purpose for which the information is required. It should be simple and practicable, particularly if it is to be applied to standing trees, and it should be economical in time and money, particularly if a large number of trees is involved. The method should give a result which is unbiased, and which is precise for the same operator and among operators. The method should be such as to permit mistakes to be readily detected if

they occur. No method will meet all these requirements perfectly and some compromise has to be accepted.

Stem volume Derived by Volume of Sections

If a stem is considered to consist of a number of sections, its volume can be derived as the sum of the volumes of those sections. It has previously been pointed out that in practice the volume of a log cut from the main stem is calculated almost invariably by either the Huber or Smalian formula as if it were a frustum of a second degree paraboloid. Following this, the volumes of the sections comprising the stem are usually calculated by either the Huber or Smalian formula.

Sectional Method

This is a very old method (Chaturvedi, 1926) which goes by various names. It is commonly known as the sectional method in Australia. The stem is considered to consist of sections of some constant convenient length, girth (diameter) is measured at the centre of each section, and volume is calculated by Huber's formula. In Australia, the length used is 10 ft because this is convenient in laying out the positions for measurement of girth, and the volume of a section is quickly calculated in cubic feet by merely shifting the decimal point of the sectional area in square feet one place to the right. The method can be applied to conifers or broad-leaved trees, felled or standing, for total volume, or volume to any particular limit, over-bark or under-bark. It can be applied to trees with multiple stems. The sections may start at ground level or at an arbitrary stump height. For conifers, if total volume is the main requirement, the last section to the tip is usually regarded as a cone. If the volume required is to some arbitrary limit such as 4 in d.u.b., the last section, normally less than 10 ft in length and often called 'the odd log', is measured at its mid-point and its volume calculated as the product of the mid-sectional area and the length. The method is illustrated in Fig. 8:1 on a pro forma found to be convenient for recording the measurements and calculating volume. There are many variations of this pro forma.

The method is simple and practicable for standing trees as well as felled trees. To the extent that each section is equivalent to a second degree paraboloid frustum and that the nominated point of measurement is representative of it, the method gives an unbiased estimate. The

Fig. 8:1

Individual tree volume, sectional method

Location:	Mt Stromlo, A.C.T.	D.b.h.o.b.	11.4 in	Meas. by:	Black
Species:	P. radiata	Tot. ht:	68 ft	Recorded by:	White
Identity:	32	Ht to 4 in:	57 ft	Date:	4/5/67

Main stem to odd log

Ht above ground	Over-bark		2BT	Under-bark	
	Diam.	Sec. area		Diam.	Sec. area
5 ft	10·6	·613	1·2	9·4	·482
15 ft	9·4	·482	0·6	8·8	·422
25 ft	9·0	·442	0·5	8·5	·394
35 ft	7·6	·315	0·4	7·2	·283
45 ft	6·0	·196	0·3	5·7	·177
Sum					1·758
Vol.					17·58

Odd Log

Diam. meas. at	Length	Over-bark		2BT	Under-bark	
		Diam.	Sec. A		Diam.	Sec. A
53 ft 6 in	7 ft	4·4	·106	0·3	4·1	·092
					Vol.	0·64

Merch. vol. u.b. = 17·58 + 0·64
= 18·22 cu ft

ABOVE ODD LOG

Length (L) = 11 ft

Volume = $\frac{\cdot 087}{3}$ x 11 ft = ·32

Total vol. u.b. = 17·58 + 0·64 + ·32
= 18·54 cu ft

bottom section of most trees is affected by butt-swell and the assumption that the stem there is a frustum of a paraboloid may lead to a biased estimate. This bias may be reduced by taking shorter sections in that region, for example two 5 ft sections instead of one 10 ft section, since the shorter the sections the less the overall error in assuming neiloidal sections are paraboloidal. The positions of measurement are fixed and any observer should measure at those points on every occasion; to this extent the method is precise for the same operator or amongst operators. The precision amongst operators may be reduced, but usually only slightly, when positions of measurement are considered unrepresentative and operators use different techniques to overcome this, for example by measuring at one position elsewhere or taking the average of measurements at positions equidistant above and below.

Since there is no visual check on the measurements, as there is in graphical methods discussed later, the recorder must be alert to pick up mistakes made in measuring, and to avoid mistakes in reading section area values from tables, in recording them and summing them. He should see that measurements of girth and bark thickness up the stem follow a sensible trend. This method is used in several States of Australia for felled and standing plantation conifers. Usually merchantable volume is derived, that is volume under-bark to a top d.u.b. limit of 3 in or 4 in with or without allowance for stump. For a few trees, the calculations are carried out manually. If many trees are involved the method is easily programmed for calculation by computer.

Percentile Method

This is also an old method which goes by several names but is commonly known as the percentile method in Australia. By its nature it is restricted to whole stems undivided from ground to tip and is usually associated with the compilation of stem profile equations for such trees. The stem is considered in two parts:

(a) The part below breast height which is regarded either as a truncated paraboloid, in which case the volume is derived as the product of a sectional area 2 ft $1\frac{1}{2}$ in from ground and a length of 4 ft 3 in, or as a cylinder, in which case the volume is derived as the product of sectional area at 4 ft 3 in from ground and a length of 4 ft 3 in.

(b) The part above breast height to the tip which is regarded as 10 truncated paraboloids of equal length, the volume of each section being derived by Smalian's formula from the sectional area at each end of the section. The diameters at these percentile points of measurement are referred to respectively as D_0 (at breast height), D_1, D_2, D_3, D_4, D_5, D_6, D_7, D_8, and D_9, D_{10} being the tip and having a value of zero. The corresponding sectional areas are S_0, S_1 ..... S_9. The volume of this part is given by

$$\left(\frac{(S_0 + S_1)}{2} + \frac{(S_1 + S_2)}{2} + \ldots\ldots \frac{(S_8 + S_9)}{2} + \frac{(S_9 + 0)}{2} \right) L$$

$$= \left(\frac{S_0}{2} + S_1 + S_2 + \ldots\ldots + S_8 + S_9 \right) L$$

where L is the common length of section given by $\frac{\text{total height - 4 ft 3 in}}{10}$

The volume of the whole stem is obtained by adding the volumes of the two parts. The method is illustrated in Fig. 8:2 on a pro forma found to be convenient.

The method was deliberately designed so that diameters are obtained at the same relative positions on stems of different size and stem profile equations can be developed. The method can only be applied practicably to felled trees. For standing trees, the most effective procedure is to climb and determine the correct height, then measure diameters during the return to the ground. As with the sectional method, the estimate of the volume above breast height will be unbiased to the extent that each section is equivalent to a second degree paraboloid frustum and the nominated points of measurement are representative. Assuming the part below breast height is a cylinder of sectional area equal to the basal area will almost invariably lead to a negative bias. Assuming it is a paraboloid frustum may lead to a positive or negative bias depending on its actual shape. Since the positions of measurement are fixed, the method should provide an estimate for a particular stem which is precise for the same operator and among operators. There is the same liability to mistakes as in the sectional method, perhaps more so if the operators are unskilled.

Fig. 8:2

Individual tree volume, percentile method

Location:	Mt Stromlo, A.C.T.	D.b.h.o.b:	11·4 in	Meas. by:	Black
Species:	P. radiata	Tot. ht:	68 ft	Recorded by:	White
Identity:	32			Date:	4/5/67

Below Breast Height

Diam. Meas. at	Length	Over-bark		2 BT	Under-bark	
		Diam.	Sec. area		Diam.	Sec. area
2 ft 1½ in	4 ft 3 in	11·8	·760	1·6	10·2	·568

Vol. below b.ht = Sec. area x 4ft 3in
" " " o.b. = x 4ft 3in =
" " " u.b. = ·568 x 4ft 3in = 2·41

Above Breast Height

Percentile length = L = $\frac{68'0" - 4'3"}{10}$ = 6ft 4½ in

Diam. Meas. at	Over-bark		2BT	Under-bark	
	Diam.	Sec. area		Diam.	Sec. area
d_0 4 ft 3 in	11·4	·709	1·4	10·0	s_0 ·545
					$s_0/2$ ·272
d_1 10 ft 7½ in	9·8	·523	0·7	9·1	s_1 ·452
d_2 17 ft	9·5	·492	0·6	8·9	s_2 ·432
d_3 23 ft 4½ in	8·7	·413	0·5	8·2	s_3 ·367
d_4 29 ft 9 in	8·1	·358	0·5	7·6	s_4 ·315
d_5 36 ft 1½ in	7·5	·307	0·4	7·1	s_5 ·275
d_6 42 ft 6 in	6·1	·203	0·3	5·8	s_6 ·184
d_7 48 ft 10 in	5·5	·165	0·3	5·2	s_7 ·147
d_8 55 ft 3 in	4·4	·106	0·3	4·1	s_8 ·092
d_9 61 ft 7½ in	3·1	·052	0·2	2·9	s_9 ·046
Sum					2·582

Vol. above b.ht = Sum sec. areas x L =
" " " o.b. = x =
" " " u.b. = 2·582 x 6 ft 4½ in = 16·46

Whole Tree

Total vol. o.b. = + = cu ft
= 16·46 + 2·41 = 18·87 cu ft

Other Methods Based on Volume of Sections

Various methods have been suggested based on sections of unequal

length, the sections usually being smaller near the butt where the effect of errors is greater. These are not in common use. A method outlined by Jeffers (1955) based on diameter measurements by the Barr and Stroud Dendrometer involves sections of unequal length because of the scaling of the dendrometer.

Stem Volume Derived through a Graphical Procedure

If values of diameter measured at various positions on the stem are plotted against the distance of those positions from the ground, as rectangular co-ordinates on graph paper, and then a curve is fitted to the points, a diametral outline of the stem, usually called a taper curve or stem profile, is obtained. The measurements can be taken close together or far apart and irregularities can be included or excluded at will in measurement or in fitting the taper curve. From the taper curve, values of diameter at any position can be read and stem volume calculated by sections using the Smalian or Huber formula. The advantages of this method over the sectional and percentile methods are that plotting the information graphically provides a visual check of the measurements and that the graph provides a permanent and convenient record of the stem which may find many uses such as calculation of volume of various assortments of the stem.

If sectional areas rather than diameter are plotted graphically, volume is represented directly by the area under the taper curve. The advantages of this were outlined by Reineke (1926) who recommended determining the area by planimeter. The method has been applied extensively in the U. S. A. with the use of rectangular co-ordinate paper, or paper with specially graduated axes, and the use of a planimeter or square-count method to determine area. It has also been used extensively in Australia, particularly for felled broad-leaved stems; Unwin and Bowling (1951) and Lawrence (1960) have discussed its use in Tasmania. The method has been used also for plantation conifers, standing and felled, to determine biological volume as a base against which volume by other methods could be compared in investigations such as that of Carron and McIntyre (1959).

This graphical method can be applied to trees undivided or divided from ground to tip, for total volume or volume to any particular diameter limit or between any diameter limits, over-bark or under-bark. If many measurements are taken, the method takes longer than the methods in which volume is calculated by formulae,

but many measurements should be taken to obtain the full advantages of the graphical method. If the tree is felled, the extra time involved can readily be justified in view of the relative amount of overhead time involved in applying any method. With standing trees, the extra time involved is proportionately greater but may still be justified on the grounds of the amount of time involved in getting any measurements at all. The more measurements taken, the closer is the estimate to the biological volume and the more precise the estimate for the same operator and among operators, but this depends to some extent on the prescriptions for selecting the points of measurement. Plotting each point graphically provides a visual check on both the measurement and the recording of it, since any point which varies from the general taper curve as shown by the other plotted points prompts a check. The method can readily be programmed for calculation by computer.

Gray's Taper Line Method

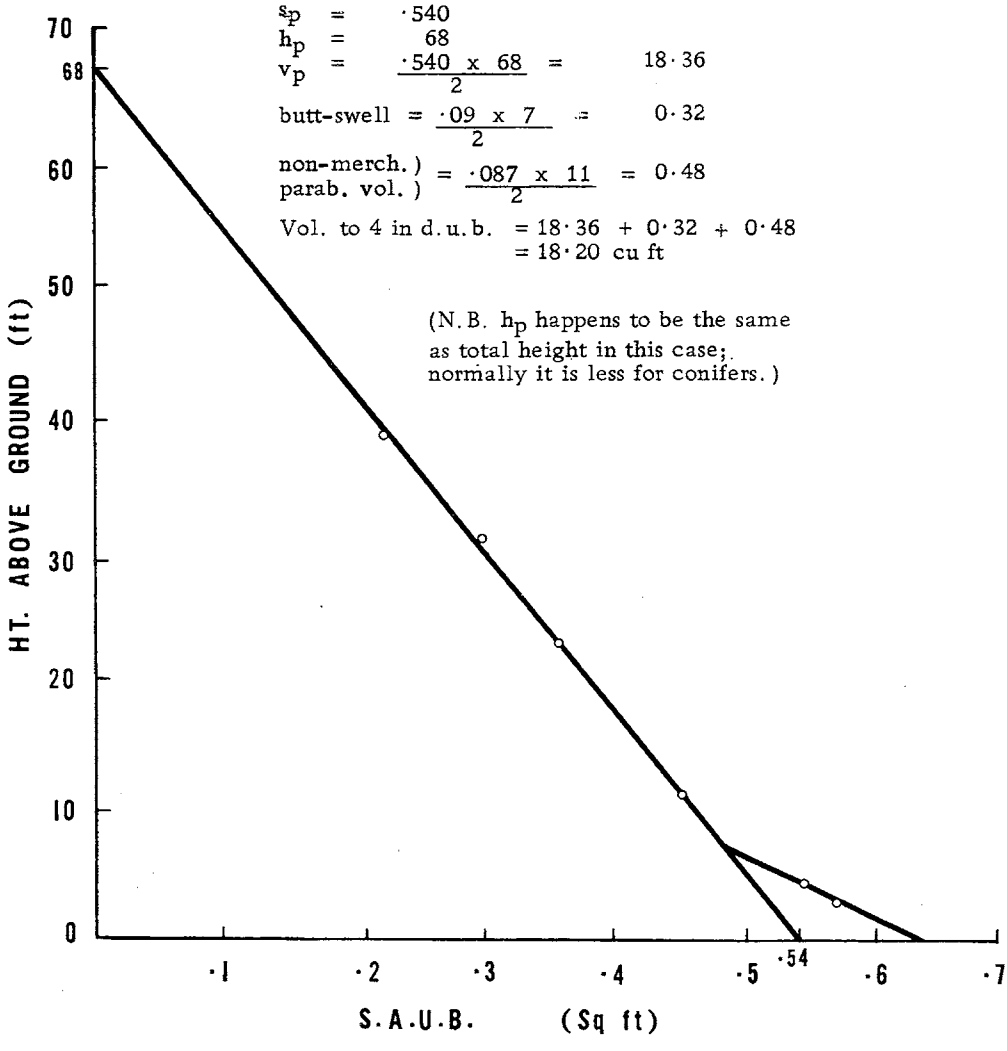
About 1940 at the Australian Forestry School, Gray was investigating the use of a standardised series of taper curves, particularly for P. radiata, so that having determined the appropriate taper curve from a limited number of measurements in the lower part of a tree the rest of the curve could be extrapolated without actual measurement to reduce the amount of climbing of standing trees; and so that there would be an objective check on measurements recorded in the field, experience having shown this to be a continual source of errors. Plotting sectional area against height showed that 'excluding a variable distance from the ground and a variable distance from the tip, sectional area under bark decreased linearly with height, at least within the limits to be expected with biological data and usual standards of accuracy of measurement'. This condition appeared to apply to a wide range of species, particularly conifers and young eucalypts. Gray (1943, 1944, 1956, 1966) then proposed the hypothesis already outlined in Chapter 6, and on the basis of this hypothesis proposed a method of deriving the volume of a tree called the taper line method. The method has most advantage when applied to a standing tree and this will be assumed in the description which follows, illustrated for a conifer in Fig. 8:3.

A measurer subjectively selects several 'representative' points for measurement, usually two in the butt-swell region, and a minimum of three and a maximum of about five along the main stem up to between a half and two-thirds the height of the tree. He measures over-bark

Individual tree volume, taper line method

Location:	Mt Stromlo, A.C.T.	D.b.h.o.b:	11·4in	Meas. by:	Black
Species:	P. radiata	Tot. ht:	68 ft	Recorded by:	White
Identity:	32			Date:	4/5/67

Ht (ft)	d.o.b. (in)	2BT (in)	d.u.b. (in)	s.a.u.b. (sq ft)
1 ft 11 in	11·8	1·6	10·2	·568
4 ft 1 in	11·4	1·4	10·0	·545
11 ft 2 in	9·8	0·7	9·1	·452
22 ft 11 in	8·6	0·5	8·1	·358
31 ft 3 in	7·8	0·4	7·4	·299
39 ft 0 in	6·8	0·4	6·4	·223



diameter at these points by girth tape and bark thickness by bark gauge. A recorder on the ground plots the equivalent under-bark sectional areas against the respective heights above ground level on rectangular co-ordinate paper as measurement proceeds. As soon as the recorder is confident of fitting a straight line to the points representing the paraboloid of the main stem the measurer returns to the ground.

The straight taper line fitted to the points of the main stem is extended to cut the sectional area axis at parabolic base s_p and to cut the height axis at parabolic height h_p. The area under this straight line represents parabolic volume v_p and being that of a triangle is computed as $\frac{s_p \times h_p}{2}$. A curve is fitted to the points in the butt-swell region, the area between this curve, the taper line, and the sectional area axis being obtained by square count or from the dimensions of the triangle formed by a straight line which approximates the butt-swell curve (as in Fig. 8:3). This butt-swell volume is added to the parabolic volume. If the top limit to which volume is required is less than parabolic height, the volume represented by the appropriate triangle is subtracted from parabolic volume. For a conifer, total height is usually greater than parabolic height, and if total volume is required a curve is run down from total height to join the taper line at an appropriate position and the volume computed in the same way as butt-swell volume; this is then added to parabolic volume and butt-swell volume.

The taper line method is thus a graphical method characterised by the assumption that the main stem approximates to a second degree paraboloid with a 'skirt' of butt-swell of varying size at the base and, in the case of conifers, surmounted by a cone-like top. This assumption leads to the practice of measuring the minimum number of points required to fit a straight line with confidence, with a saving in time, energy, and risk which may be considerable in a large measuring program, when the trees are very tall, or when climbing is difficult. In other respects, the method is like the other graphical methods - the procedure provides a visual check of measurement and recording, the graph forms a permanent and convenient record of the stem from which the volume of assortments of the stem can readily be determined at any time. Because the points of measurement are few and chosen subjectively, however, the estimate for a particular

tree is likely to be different for different operators and different for the same operator on different occasions so that the method is not precise; and any result is likely to be biased. Carron and McIntyre (1959) discuss a test of the relative precision and bias of the taper line and sectional methods applied to P. radiata.

9 Growth and Increment of Individual Trees

Though the terms growth and increment are used interchangeably by foresters, in the strict sense tree growth means the biological phenomenon of increase in size with time and increment means the quantitative increase in size over a specified time interval resulting from the phenomenon of growth. It is the phenomenon of growth which makes it possible to manage a forest as a renewable crop. The estimation of the effects of growth is therefore an important process in mensuration because management must be guided largely by forecasts of future yield from information of present rates of increment For management purposes, the main interest is naturally in the increment of a stand. Since this, however, is comprised of the increments of individual trees we need to consider how increment in an individual tree can be determined.

In general, each tree species has its own pattern and rate of growth but these can be influenced considerably in an individual by internal factors - genetic and physiological factors unique to the individual; and by environmental factors - climate, edaphic and biotic. The effects of particular factors are very difficult to isolate. The episodic growth of the main stems of trees has been commented on elsewhere. For practical management purposes and to reduce the considerable variations in increment, within-year variations are usually ignored by making the minimum period between measurements one year, and between-year variations are smoothed by considering 'current' annual increment as an average of several previous years. Because of the correlation between increment and weather over a season, it is essential that any measure of increment be related to or qualified by the weather of the period. Again, because of the asymmetrical nature of tree growth over a stem, caution must be exercised in accepting growth in one part of a stem as evidence of similar growth elsewhere on the stem.

The main tree variables whose changes with time are of interest are diameter, height, and taper. From a knowledge of increment in these variables, increment in other tree variables such as volume and bole area can be determined. To forecast increment from the past growth pattern, increment over a past period can be related to size at the beginning or end of the period whether the age of the tree is known or not. If age is known, size at a particular time can be related to age at that time or increment over a period can be related to an age which represents that period.

Determining the Age of an Individual Tree

The age of a tree can only be determined with certainty when the year of its germination is known. This is usually so for trees in artificially established forests. For natural forests, the age of individual trees can sometimes be determined from the date of a catastrophic event such as a fire or cyclone, or of a logging operation, as a result of which they developed. The age of young trees of some species can be determined from a count of annual developments of shoot. For some species, age can be determined by counting the growth rings of the stem if they are annual.

Annual growth ring development is discussed in detail in texts on that subject. Briefly, true annual rings occur in trees characterised by the formation of different early and late wood such as temperate conifers, some sub-tropical conifers, most temperate deciduous broad-leaved species, and those species characterised by a ring porous condition. Annual rings are generally not found in tropical conifers or diffuse porous non-deciduous broad-leaved species unless they are growing in sub-alpine or alpine conditions. The trees over much of the northern hemisphere form annual rings so that most mensuration texts, because they are written in that part of the world, imply that counting rings is a standard technique for determining age. There are limited conditions in Australia where trees develop truly annual rings.

The ease with which annual rings may be counted depends on the species and the environmental conditions of the particular tree. Difficulties arise when there is little colour difference between early and late wood - there does not seem to be any staining technique which gets over this problem: suppression, old age, or extreme weather conditions may cause very narrow rings or cessation of wood

formation in certain parts of the stem; false rings may be formed due to extreme weather conditions such as early or late frost or a long drought followed by rain; rings may be distorted by branch whorls or defects and the occurrence of compression wood or tension wood. Bowling (1954) has discussed counting the rings of small scrub species instead of large eucalypts of similar age for determining the age of eucalypts in southern Tasmania.

Determining the Increment of Individual Trees

Increment in height or diameter over a period can be determined by measuring the variable at the beginning and end of the period. This is done in investigations of a silvicultural nature, and is the basis of periodic inventory, to be discussed later.

If the height is measured with height sticks, the estimates of height increment will usually be satisfactory. If measurement is done with instruments based on geometrical or trigonometrical principles, the estimates may not be satisfactory; in fact, trying to get estimates of height increment by repeated measurement using such instruments over a period of years is often very frustrating despite the apparent simplicity of the operation. Errors can sometimes be reduced by having permanent positions from which instrument observations are made. Repeated measurement of diameter or girth generally gives much more satisfactory results than repeated measurement of height, provided the position of measurement on the stem is permanently marked. This is commonly done by the use of crayon, paint, or a nail of a soft metal such as aluminium or copper which will not cause problems in subsequent sawing. If the paint or nail is likely to affect growth in any way at the position it should be placed some set distance away. If a caliper is used to measure diameter the bark is sometimes scribed at the position, the bar of the caliper being set in the scribe mark.

The determination of increment of individual trees is often carried out in permanent sample plots for the measurement of which codes of procedure are generally prepared. The Forest Services of Australia have published these in various forms for domestic use. Examples for other countries are the Silvicultural Research Code (Griffith and Prasad, 1949) for India and the Code of Sample Plot Procedure (Hummel et al., 1959) for Great Britain.

Stem Analysis

The past growth history of a tree stem with truly annual rings can be read at any time by determining the position of each ring. This is known as stem analysis. If the information is obtained at only one position on a stem, for example at breast height, the procedure is called partial stem analysis. If the information is obtained at a number of positions along the stem with a view to assembling a history of the whole stem from which diameter, height, and volume increment can be determined, the process is called complete stem analysis. If the tree must be left standing, the analysis is done on cores of the stem taken horizontally from bark to pith with an increment borer. Small cores comprising the rings of the last few years may be taken with an increment hammer. There is an extensive literature on the taking, handling, storing, and measuring of increment cores - Spurr (1952) gives a good bibliography. If the tree can be felled, the counting of rings and measurement of diameters is usually done on complete sections one or two inches thick. This allows comprehensive visual inspection of the section whereas the increment borer only samples it. Depending on how many trees are to be analysed and the value of the timber, so sections may be cut to the best advantage of the analysis or to suit the requirements of utilisation. The intention of stem analysis is to reproduce, from the evidence of the sections, the under-bark outline of the stem at each of several previous ages, from which the diameter, height and volume at those ages, and their increment, can be estimated. There are various ways of tabulating and graphing the data; that outlined by Jerram (1939) is simple, practicable and effective.

The Characteristics of Growth of Individual Trees

The general trend of size with age for biological organisms is represented by a sigmoidal curve. Many attempts have been made to describe such trends mathematically, but for forestry purposes fitting curves freehand is more practicable and appears satisfactory for most purposes.

The survival and subsequent history of a tree depend primarily on its growth in height relative to that of its competitors. The trend of height with age is likely to show the inherent vigour of the tree and the environmental conditions under which it grew. For dominant trees of

an intolerant species, the relationship is usually a sigmoidal curve which shows the fairly slow initial growth of the seedling stage, an approximately linear section which represents the main life of the tree, then a flattening out at maturity. For suppressed trees or a tolerant species, the trend will be appropriately different, for example the linear main section will be less steep and the curve will flatten out much more quickly.

The relationship of d.b.h.u.b. and age is generally sigmoidal, the main section being linear or curvilinear depending on species, environment, effects of thinning and pruning, and so on. If the main section of the d.b.h.u.b.-age relationship is linear, the basal area-age relationship will be a rising curve as illustrated in Fig. 9:1 for a Eucalyptus regnans recorded by Helms (1945), an old tree by Australian standards with particularly persistent vigour. More often, the d.b.h.u.b.-age relationship is a falling curve, and the basal area-age relationship is linear or nearly so.

As discussed previously, diameter increment may be similar or different along the length of the stem depending on many factors, so

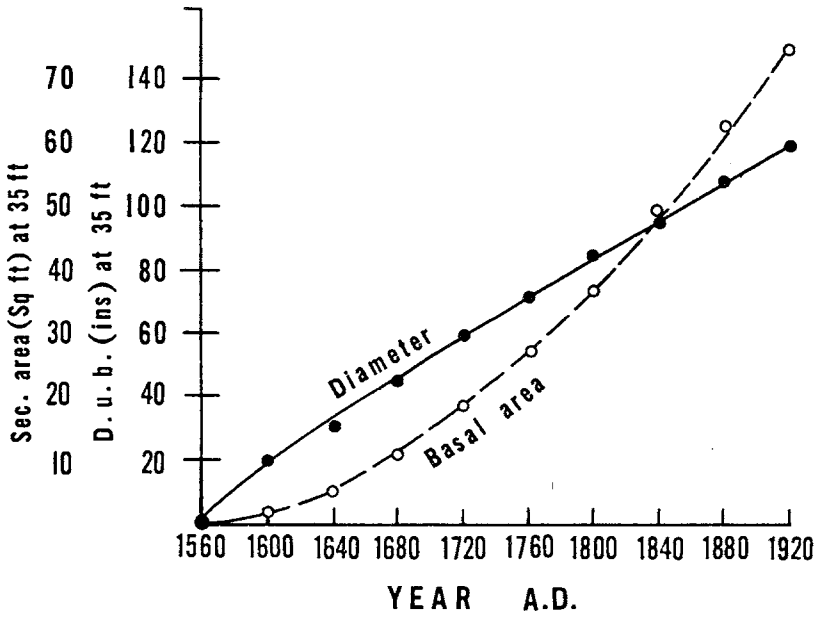


Fig. 9:1 Characteristics of growth of individual trees; E. regnans, Tasmania, 1548-1942; g.b.h.o.b. 65 ft; height to top of broken crown 257 ft; volume 64,000 sq ft (after Helms, 1945)

that it is impossible to generalise about the relationship of taper with age. Because of the effects of changing shape and rate of taper, the change of volume with age is likely to be somewhat erratic. These variations in volume are smoothed over to a large extent because changes in shape and rate of taper are not taken into detailed account in estimating volume, and the relationship of volume and age is usually sigmoidal.

Increment and the Increment-Age Relationship

There are two conventional expressions of increment. One is known as current annual increment abbreviated to C.A.I., CAI or c.a.i., which by its name implies the increment of the current year. Annual growth is often small and difficult to measure reliably, and is also subject to seasonal fluctuations. Therefore CAI is often derived as the mean over the previous several years in which case it is known as periodic mean annual increment, abbreviated to P.M.A.I., PMAI or p.m.a.i. In quoting CAI or PMAI it is essential to define the times or dates for which the increment is current and the age or size of the tree at the time. The other expression, known as mean annual increment and abbreviated to M.A.I., MAI or m.a.i., represents the average increment from origin up to a specific age and is derived by dividing the size by the number of years to produce that size. In quoting MAI it is essential to quote the age of the tree. To illustrate the trend of increment with age, values of CAI and MAI may be plotted graphically against time or age and increment curves drawn. As would be expected from their arithmetic derivation, there is an invariable relationship between these curves - they must cross when the MAI is at a maximum. As long as the CAI curve is above the MAI curve, the latter must be rising since each added yearly increment improves the average. When the CAI reaches its maximum, the improvement in the MAI will be less marked. When the CAI and MAI values are equal, the MAI curve will tend to remain horizontal or fall a little. As the CAI falls, the MAI will be reduced and the curves will cross, the MAI curve falling but remaining above the CAI curve. This description is an idealised one; there are likely to be considerable irregularities in the curves due to the variations in growth referred to previously. The interrelationship of CAI and MAI curves of a stand, their relative shape and the position of their point of intersection, are of special interest to management.

10 Stand Variables

The Forest and Stand

So far the measurement of the variables of an individual tree has been considered. This is usually only a means to the end of estimating the variables of a stand or forest of trees. Though the objectives of management must obviously be realised through the manipulation of individual trees, the only practicable unit for management planning and control is a stand or a forest. A stand is an aggregation of trees, sufficiently uniform in composition and age, or defined by natural or artificial boundaries, to be regarded as a unit for silvicultural or management purposes (B.F.A., 1953). A forest comprises a number of such stands aggregated for some purpose of management. It is convenient to talk of expressions of the combined diameters, heights, and volumes of the individual trees as stand variables.

Factors Influencing the Measurement of Stand Variables

The factors which ultimately determine what variables are measured and how they are measured are time, money, and labour. However, a number of preliminary factors have to be considered in planning the measurement.

An important factor is the purpose of the measurement. There are various reasons for wanting a quantitative description of a stand. The maintenance and development of its forests are important to the economy of a nation. To develop and implement satisfactorily a policy for that maintenance and development, the location and extent of the forest estate and its value for protection and productive purposes must be known. This information is provided by a resource inventory. To manage an individual forest efficiently more detailed information is required than is usually provided by a forest resource inventory; it is

usually provided by a management inventory or working plan inventory. Experimental investigations require even more detailed measurement. The stand description required is different for all these cases and affects what is measured and how it is measured.

The general structure of a stand also influences its measurement. This can be illustrated by contrasting the conditions in Australia of a plantation of a coniferous species with those of a native eucalypt or rain-forest stand. The former is usually of one tree species; the individual trees are in a regular pattern which allows convenient access for measurement; there is little or no other vegetation; the trees are of a size and habit such that measurements anywhere on the standing stem are practicable. The stands are even-aged and the age is known; there is a limited range of size classes within any particular even-aged stand; and, with few exceptions, all the trees are utilisable. The native forest, on the other hand, usually comprises a number of species; the trees are irregularly distributed and there is often a lesser vegetation which impedes access and makes measurement difficult; the trees are of a size and habit such that measurements up the stem are impracticable; the stand is uneven-aged and determining the age of any tree may or may not be possible; there is a wide range of sizes; not all the trees are of commercial species and many trees of commercial species are not utilisable because of defects which may not be readily discernible. Such differences in structure and composition will obviously affect what variables can be measured and how they can be measured.

Usually the population is too extensive for the measurement of even one variable on every tree. This depends, of course, on the variable and the structure of the stand. The girth of every tree in a compartment of a coniferous plantation could be measured without much trouble. Measuring the volume of every tree would, however, be a different proposition and so would measuring the girth of every tree on an equivalent area of a dense uneven-aged native eucalypt stand. As a rule, whatever the stand variable, it is measured on a sample of the stand. Some populations can be conveniently defined for sampling purposes by the number of individuals but it is usually more convenient to define the population of a stand by its area, which can be determined by surveying. Sampling is then effected through sampling units, the shape and size of the units frequently affecting what stand variables are measured and how they are measured.

11 Stand Tables and Stand Basal Area

Stand Tables

An effective way to describe a stand quantitatively is to classify the trees according to frequency of species, d.b.h.o.b., height, and the like. A frequency table of classes of d.b.h.o.b. is called a stand table. It is very useful for silvicultural and management purposes because different structures of stands are characterised by particular frequency distributions of d.b.h.o.b. A stand table is usually compiled on a per acre basis but may be compiled for the whole of a small stand. The purpose, requirements, and characteristics of stand tables are the same as those of similar kinds of frequency table for other biological data. The purpose is one of condensation or summarisation and for easier manipulation of the data. Usually equal sized classes are formed, the width and central values of which should be clearly specified. In general, for presentation and mathematical purposes, the number of classes should be from about ten to twenty. Once the table is compiled, the individual loses its identity and takes the central value of the class. If the class interval is wide and there are few individuals in the class this may give anomalous results. The manner in which the class frequencies are distributed in relation to the classes is the frequency distribution. If the values of the variable are plotted on a horizontal axis and frequency of occurrence on the vertical axis of rectangular co-ordinates, a graphical representation of the frequency table in the form of a frequency diagram can be compiled, such as a histogram, frequency polygon, and frequency curve.

The measurement of diameter and compilation of a stand table is usually referred to as an enumeration, the term implying a counting of trees of various sizes. The width of the class used varies according to the conventional practice of the forest owner in relation to the value of the stand and the purpose of the enumeration. It is important to

define the class limits in such a way that the class has an arithmetically convenient centre and to measure in a way appropriate to the class limits. For coniferous plantations in Australia, 1 in classes of d.b.h. o.b. or g.b.h.o.b. are common. For native species, classes from 4 in to 12 in d.b.h.o.b. or g.b.h.o.b. are used. In growth studies, where the trees are identified individually, diameters or girths are usually measured to 0·1 in, whatever the width of classes of the stand table, so that increment can be determined to that level. For resources inventory, management inventory, or growth studies where the trees are not identified individually, the trees may be classified directly in the field. This process is called tallying and the result is called a tally. If the data is to be processed manually, the trees are usually tallied by the gate system where 1 11 111 1111 ~~1111~~ represents 1 to 5 respectively. If compilation or computation is to be done by mechanical data processing, special methods of recording are used.

D.b.h.o.b. Distribution in an Even-aged Stand

An even-aged stand is one in which all of the trees are of identical age or, if of different age, are sufficiently close in age to be taken for all practical purposes as of identical age. The frequency curve of d.b.h.o.b. size of trees of an unthinned even-aged stand approximates a statistically normal curve for much of the life of the stand. The normal curve is bell-shaped, unimodal, and symmetrical about a central value where arithmetic mean, median, and mode coincide; the central class has the greatest number of trees, there being progressively fewer trees in classes smaller than and greater than the central class. The normal distribution is very common in many kinds of natural phenomena and much of the theory of statistics has been developed around it. How closely the stand table of an even-aged stand approximates a normal distribution depends, however, on several factors. The distribution of tree diameters is of this form because of the differences in growth of individual trees which for most stands result from a compounding of the differences in the genetical make-up, and the macro- and micro-environment, of the individual trees.

Depending on the species and general environment of the stand, the sorting of trees according to their growth rates may take place slowly or relatively quickly. If it takes place slowly, the frequency curve may in the early stages be reverse-J shaped, the greatest number of trees being in the smallest size classes with rapidly decreasing numbers in

the larger size classes. As the stand ages, the curve shifts to the right (along the abscissa of the graph) and a peak appears which is at first left of centre (positive skewness) but gets closer to the centre as the stand ages and may even move to the right of the centre (negative skewness). If the sorting out is relatively quick an approximately normal distribution may be established fairly quickly; it may remain close to normality or with time become skewed positively or negatively. The frequency curve may thus vary within a stand and between stands from symmetry to a varying degree of asymmetry, depending on the species and its growth habits, on the quality of the site, and on changing density due to natural mortality. The frequency distribution of an unthinned stand of Pinus radiata is shown in Table 11:1 and illustrated in Fig. 11:1. Where two age classes are

Table 11:1

D.b.h.o.b. frequency distribution (stand table) of an unthinned, even-aged stand of P. radiata (0·2 acre), A.C.T., planted 1943

D.b.h.o.b. (in)	Frequency			
	1956	1960	1963	1965
3	2	1	1	
4	20	10	9	8
5	41	24	19	19
6	53	44	28	26
7	21	43	43	41
8	2	14	30	28
9		3	8	13
10			1	4

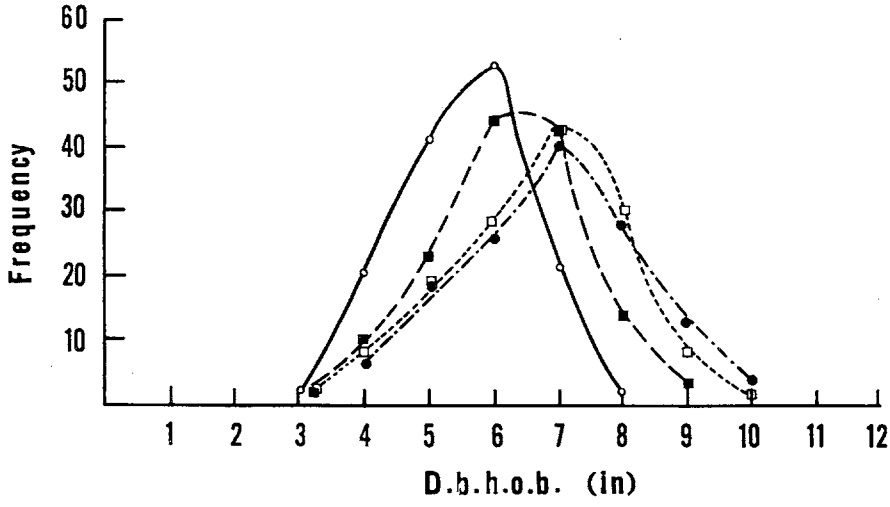


Fig. 11:1 D.b.h.o.b. distribution, unthinned, even-aged stand of P. radiata, Kowen, A.C.T (see Table 11:1)

represented separately in a stand there may be two separate normal curves. This may also be so for a suppressed even-aged stand.

Forecasts of the future condition of a stand should, if they are to be effective, include a forecast of the d.b.h.o.b. distribution. If the distribution is likely to be normal, forecasting the numbers of trees in the various classes is not difficult if the total number in the stand, and the mean and standard deviation of the distribution, can be forecast. Foresters have therefore sought correlations between characteristics of diameter distributions and readily measured stand variables, using both graphical and mathematical analysis of the distributions. A convenient expression of a normal distribution can be made graphically by plotting cumulative frequency per cent against size on arithmetic-probability paper; the points lie on a straight line if the distribution is normal. The methods of mathematical analysis are outlined in standard texts on statistical methods. Meyer (1930), for example, investigated the relationship between the standard deviation, the skewness and kurtosis (relative peakedness or flatness) of diameter distributions, and stand variables such as age, site, and stand mean diameter, for several North American conifers in natural stands. He showed that stand mean diameter was very satisfactory as an independent variable and that, although the absolute values were different for each species, the trend of the relationships between the characteristics of the distribution and stand mean diameter was similar. Others have demonstrated variation in the stem diameter distributions of stands with the same average diameter but of different age and on different sites. In many yield tables, however, the stand tables are harmonised through stand mean diameter rather than through age and site index.

If a stand is thinned artificially, the normal nature of the distribution is likely to be affected, depending on the kind and frequency of the thinning, particularly the size classes on which the thinning is concentrated. For a number of thinnings of P. radiata discussed by Jacobs (1962), Carron (1964) has shown that the d.b.h.o.b. distributions of the stands before thinning, the thinnings, and the stands after thinning were all sufficiently near to normal distributions for practical purposes. In other cases, particularly with fast growing species which need frequent thinning, the tendency of a thinned stand to approach normality again after thinning is continually upset by the frequency of further thinning, and at no stage is the stand distribution normal once thinning starts. Lewis (1963a) comments on the

difficulty of forecasting future diameter distributions in Australian coniferous plantations.

D.b.h.o.b. Distribution in an Uneven-aged Stand

An uneven-aged stand is one in which the individual trees cover a considerable range of age. Each tree may differ in age from its neighbours as in much single tree selection silviculture. When regeneration takes place in groups, as in group selection silviculture, the trees within a group are of the same age and, groups being regenerated at intervals, each group might be regarded as an even-aged stand; but for management purposes, the stand comprises a number of such groups and in combination they represent a range of age with a corresponding range of size from seedlings to veterans. The d.b.h. o.b. distribution of an uneven-aged stand is typically reverse-J shaped, there being a large number of small trees and decreasing frequency as diameter size increases. An example for an uneven-aged stand of mixed eucalypt species (mainly blackbutt) at Pine Creek State Forest (N.S.W.) is given in Table 11:2 and Fig. 11:2; the values are numbers

Table 11:2

Stand tables for an uneven-aged stand of mixed eucalypts, Pine Creek State Forest, N.S.W.

D.b.h.o.b. class (in)	4-8	8-12	12-16	16-20	20-24	24-28	28-32
No. per acre (actual)	48·3	22·4	14·2	9·1	4·4	2·4	1·8
No. per acre (for q=1·73)	48·3	27·9	16·1	9·3	5·4	3·1	1·8
No. per acre (from regression)	43·6	25·0	13·0	8·3	4·7	2·7	1·6

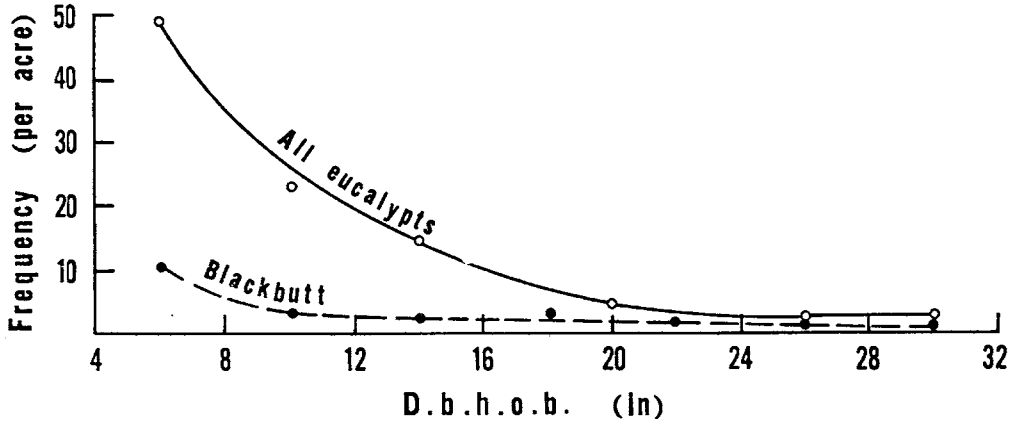


Fig. 11:2 D.b.h.o.b. distribution, uneven-aged eucalypt forest, Pine Creek State Forest, N.S.W. (see Table 11:2)

of trees per acre of all species derived from sixty-nine half-acre sample plots. The diameter distribution on small areas of uneven-aged forest may be much more irregular.

De Liocourt (1898) observed that, in certain uneven-aged selection forests in eastern France, the ratio between the number of trees in successive diameter classes was roughly constant for a particular forest, the value of the ratio differing from one forest to another. This has since been confirmed extensively in many kinds of uneven-aged forests in various parts of the world. If the ratio between the number of trees in successive classes is represented by q, the number of trees in successive diameter classes is represented by a geometric series of the form

$$a,\ aq,\ aq^2,\ aq^3,\ldots.\ aq^{n-1}$$

where a represents the number of trees in the largest size class of interest and there are n classes, n-1 being the smallest size class of interest. For the actual stand data of Table 11:2, $a = 1{\cdot}8$, $aq^6 = 48{\cdot}3$ and so it follows that $q = 1{\cdot}73$. A stand table on this basis would be as in Table 11:2. If the logarithms of the number of trees in successive classes are plotted on rectangular co-ordinate paper against the sizes of the classes, the best fit for such a geometric series is a straight line as shown in Fig. 11:3. Alternatively, the plotting may be done on semi-logarithmic paper. The regression for the data of Table 11:2 is $\log Y = 2{\cdot}000 - 0{\cdot}06014\ X$ where Y = number of trees per size class and X = the mid-point of the size class (4 in interval) in inches. Values of number of trees per size class from this regression are also shown in Table 11:2. The value of the ratio q from these values is $1{\cdot}73$. Curtin (1962a) has proposed a distribution for maximum production in an uneven-aged blackbutt forest in N.S.W. in which the q value is $1{\cdot}47$. Jacobs (1955) has used a q value of 2 in deriving simple stocking guides in uneven-aged eucalypt forests such as those at Pine Creek.

The distribution can also be represented as an exponential curve. Meyer (Meyer and Stevenson, 1943; Meyer, 1953) has done considerable work on the diameter distributions of an uneven-aged stand, characterising them by the exponential function $Y = k\ e^{-aX}$ where Y = number of trees per size class X, e = base of natural logarithms $2{\cdot}718$, and k and a are constants for a given distribution.

A stand table for an uneven-aged stand of virgin rain forest in North Queensland is illustrated in Fig. 11:4 (data by courtesy of the Queensland Department of Forestry).

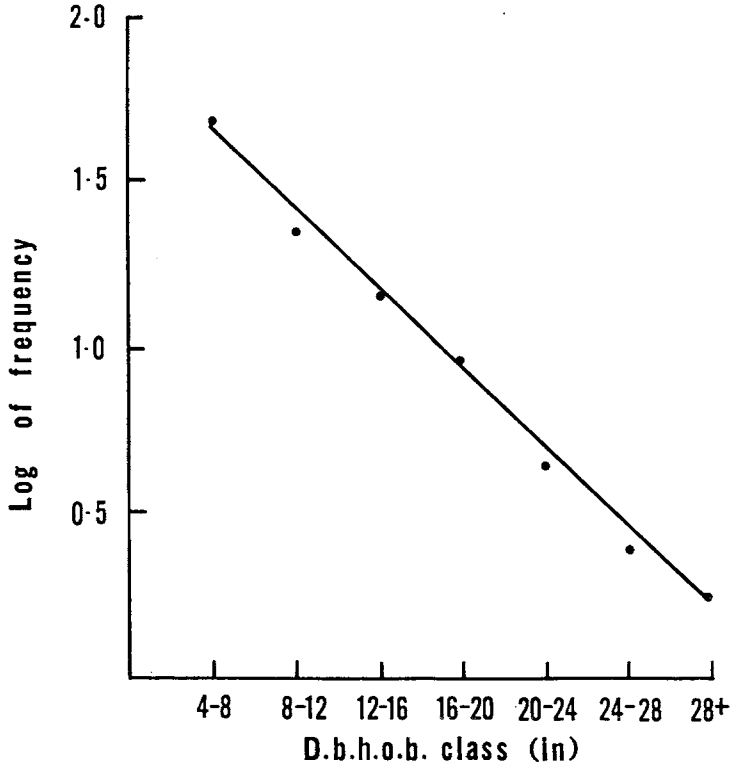


Fig. 11:3 D.b.h.o.b. distribution, uneven-aged eucalypt forest, Pine Creek State Forest, N.S.W. (see Table 11:2)

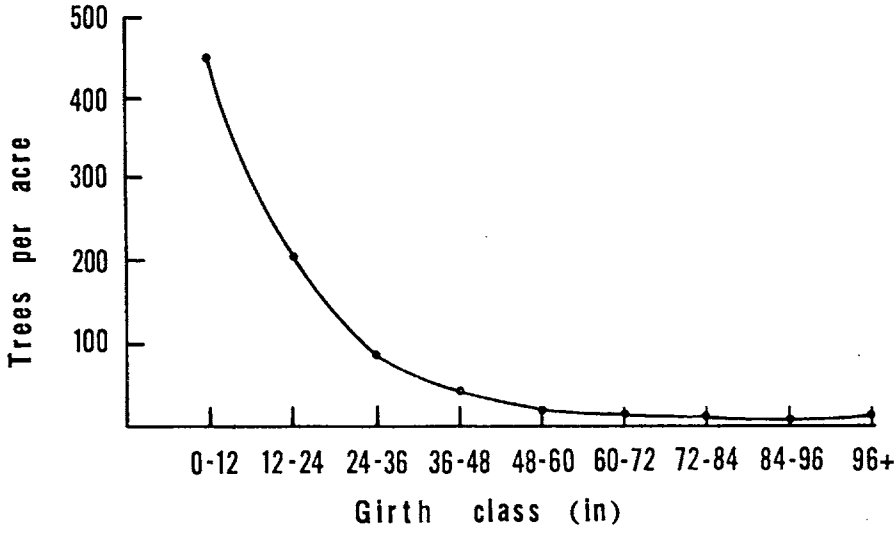


Fig. 11:4 G.b.h.o.b. distribution, uneven-aged virgin rain-forest, North Queensland, (see Table 11:3)

Table 11:3

Stand table for an uneven-aged stand of virgin rain-forest, Atherton Tableland, North Queensland

G.b.h.o.b. class (in)	0-12	12-24	24-36	36-48	48-60	60-72	72-84	84-96	96+
Number per acre	445	208	82	47	23	10	7	3	10

Stand Basal Area

Stand basal area is the sum of the sectional areas at breast height of all trees in a stand and is usually expressed on a unit area basis, for example per acre. Just as the basal area of a tree is an important reference variable for trees, so the basal area of a stand is an important reference variable for stands and is useful in quantitative description. It is usually derived over-bark. Generally, the basal area of a stand is derived directly by summing the basal areas of individual trees. Depending on the number of trees, the technique varies. For a few trees, corresponding values of basal area from prepared tables such as A. F. R. I. (1964) may be summed. For a large number of individual entries of diameter, the squares of diameter may be accumulated and multiplied by an appropriate factor. For example, if the diameter is measured in inches and basal area is required in square feet, as is conventional in Australia, the factor is 0·0054. If a stand table has been compiled, the basal area corresponding to the mid-value of each class is multiplied by the class frequency and these products are summed. If the class interval is wide and there are few trees per class, the assumption that the mean basal area of the trees in the class corresponds to that of the middle of the class may give anomalous results.

The stand mean basal area is a useful variable and is derived simply by dividing the stand basal area by the number of trees in the stand. Stand mean d.b.h.o.b. is usually derived as the d.b.h.o.b. equivalent to stand mean basal area rather than as the average of the diameters except when dealing with a diameter distribution. The quadratic mean is preferred to the arithmetic mean because of the additional weight given to the larger diameters.

Angle Count Method

Basis and Background

A variable such as stand basal area is expressed on a unit area basis, that is as a rate, for two main reasons: it is a convenient way of thinking; and the basal area of a stand can be obtained readily as the product of the rate and the area of the stand. If the basal area of a sampling unit with defined boundaries is determined by measuring the basal area of each tree, an estimate of the basal area of the stand as a rate can be obtained if the area of land within the boundaries of the sampling unit is measured. A similar sampling estimate of stand basal area as a rate is obtained by the angle count method without the need to measure the basal area of each tree, or the area of land of the sampling unit.

In 1947, an Austrian forester, W. Bitterlich, who, according to Thomson and Deitschmann (1959), had arrived at the basic method in 1931, published the first of a series of papers on 'angle count sampling'. He proposed that estimates of stand basal area per unit land area could be determined by an operator standing at each of a number of points selected by some sampling process, counting within a complete circle those trees whose diameters at breast height appeared larger than a certain reference angle projected by the operator, and multiplying the number of trees so counted by a factor appropriate to the reference angle. The simple (though not wholly satisfactory) explanation of the principle which follows is due to Keen (1950). Reference to the explanations by Cromer (1952), Kendall and Sayn-Wittgenstein (1959), and Dawkins (1965) will suitably amplify it. Suppose one stands at a point O with a piece of material 2 L in length held horizontally a distance y in front of one eye as in Fig 11:5. Assume the eye is 4 ft

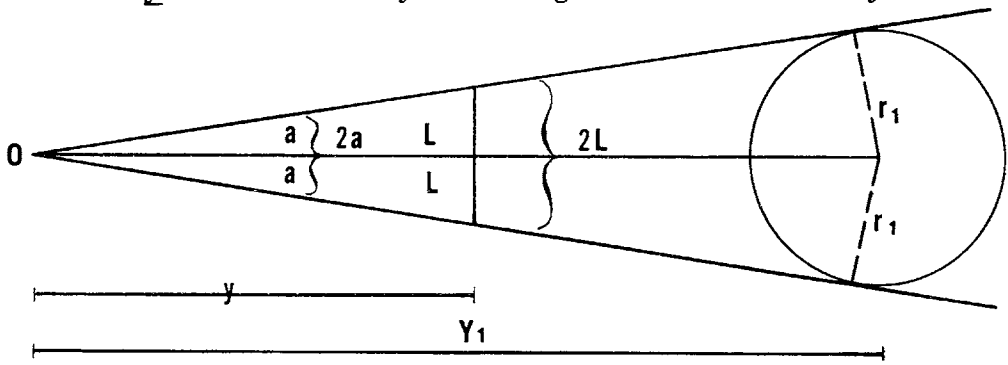


Fig. 11:5 Principle of angle count method (after Keen, 1950)

3 in above ground level and the whole ground area is level. Assume that the piece of material, held at right angles to a line of sight from the eye to the centre of a vertical tree at breast height a distance Y_1 ft away, just obscures the tree, that is the lines of sight from the eye past the ends of the material are just tangential to the tree. Assume the radius of the tree is r_1 ft. We accept as a criterion that a tree of radius r_1 will be counted if it subtends at the operator's eye the angle 2a or an angle larger than this - that is it can be any distance up to Y_1 from O but no further; so that within a circle of radius Y_1 we shall count all trees of radius r_1. The diagram shows this limiting condition.

The area of the circle of acceptance of trees r_1 in radius is $\frac{\pi . Y_1^2}{43560}$ acres. Let us assume there are n_1 trees of radius r_1 which will be counted. If n_1 trees are counted in an area of $\frac{\pi . Y_1^2}{43560}$ acres, then the number of trees of radius r_1 per acre is given by $\frac{n_1}{\frac{\pi . Y_1^2}{43560}} = \frac{n_1 . 43560}{\pi . Y_1^2}$.

The basal area of each such tree is $\pi . r_1^2$ sq. ft. The basal area (sq ft per acre) of the trees of radius r_1 ft will then be $\pi . r_1^2 . \frac{n_1 . 43560}{\pi . Y_1^2} =$

$n_1 . \frac{(r_1)^2}{(Y_1^2)} . 43560 = n_1 . \sin^2 a . 43560$ since $\frac{r_1}{Y_1} = \sin a$.

We can reason in a similar way for a tree of any radius. For each particular size tree there will be an appropriate maximum distance from O within which the tree must lie to be counted - trees of radius r_2 must lie within a distance Y_2, and so on. The basal area per acre for each size of tree will be the number of trees of that size which have been counted, multiplied by a constant $\sin^2 a . 43560$, since the ratio of tree radius to tree distance $\frac{r_1}{Y_1}, \frac{r_2}{Y_2}, \frac{r_3}{Y_3}$, and so on must always equal sin a. The total basal area per acre will then be given by $(n_1 + n_2 + n_3 + ...) . \sin^2 a . 43560 = N \sin^2 a . 43560 = N$ x basal area factor where N is the total number of trees counted and the basal area factor is $\sin^2 a . 43560$, the value of a depending on the length of the material 2 L and the distance y it is held from the eye.

In the first of several papers on the subject, Grosenbaugh (1952) pointed out that an angle gauge, the instrument used to set up the fixed reference angle, is a 'tool for selecting sample trees with probability proportional to ... size' and he developed the appropriate theory also outlined by Husch (1963).

Starting with Bitterlich's demonstration of his method to the Third World Forestry Conference at Helsinki in 1949, and the publication of what was apparently the first paper in English on the method by Keen (1950), application of the principle by foresters in western Europe was slowly recognised. After propagation of its usefulness by Cromer (1952) in Australia and by Grosenbaugh (1952) in the U.S.A., the method gradually became popular. By 1959 Thomson and Deitschmann (1959) were able to list over one hundred references to investigations into the advantages and limitations of the method for determining stand basal area under various conditions, and particularly to adaptations of the method to the measurement of other stand variables which were pioneered by Bitterlich and tried and extended by workers in other countries, most prominently western Europe, North America, and Japan. As these authors say 'foresters seldom have the opportunity to witness the development of a practical technique from its basic theory to its widely accepted application in so short a time'. Application of the method in Australia has been limited to estimating stand basal area and only this will be discussed here. Several comprehensive accounts are available, such as that by Finch (1957a). With so many foresters in different countries working with the method, it was inevitable it would be referred to by various names such as Winkelzahlprobe (angle count sampling), Winkelzahlmessung (angle count measurement), angle count method, variable plot method, plotless enumeration, plotless cruising, Bitterlich cruising, point sampling, and wedge prism method. The most common term in Australia is angle count method, the sampling point being referred to as an angle count spot.

Instruments

The object of an angle gauge is to provide at a sampling point a certain reference angle against which can be compared the angle subtended at the sampling point by the sides of each tree at breast height. The original gauge designed by Bitterlich, the 'Relaskop', consisted of a metal blade two centimetres wide mounted at one end of a rod one metre long which was held horizontally with the other end

just below the observer's eye. The reference angle was given by the lines of sight from the observer's eye to the sides of the blade. The opaque blade made it difficult to compare reliably the width of blade and tree diameter but the instrument was simple and readily made and similar instruments are still in use. Correction of the basal area on slopes to horizontal equivalent land area was made by an overall correction for average slope. In 1948, Bitterlich produced a 'Pendelrelaskop' which incorporated a pendulum device that reduced the width of the blade to account for the effect of slope in respect of each tree. Cromer (1952) in Australia combined the principle of the Relaskop with the optical properties of a reflector gunsight in an instrument he called the 'Reflectorscope'. The Relaskop blade was replaced by an illuminated image of a graticule which, by a system of lens and reflector, was seen super-imposed on the stem viewed simultaneously through the eyepiece. The main advantages were that the position of the eye could be varied without introducing parallax or altering the reference angle, and a transparent graticule made comparison of tree diameter and reference angle more efficient than an opaque blade. Correction for slope was made by correction to the basal area estimate for average ruling slope. The basal area factor was 4·356. Grosenbaugh (1952) discussed various critical angles and improvements to the Relaskop. About 1952, Bitterlich produced the 'Spiegel-relaskop', a compact optical instrument using a graticule of converging lines for various basal area factors which was free swinging and so automatically corrected for slope in respect of each tree. As versions of the blade type of instrument, Carow and Stage (1953) suggested calibration of the thumb and fingers, pieces of plastic and the like held a specific distance from the observer's eye.

A radical change in these designs was proposed by Müller (1953) in the "Baumzahlrohr' (tree count tube), using the optical properties of a wedge-shaped optical prism mounted at the end of a tube. When the stem of a tree is viewed through a prism of this type, the image of the stem is displaced laterally by an amount depending on the distance to the tree and the refractive properties of the prism. A tree is counted only when the lateral displacement of the image appears less than the width of the stem at breast height. By using prisms of different optical strength as measured in dioptres, one can have a range of basal area factors. The introduction of this principle prompted a series of modifications and developments. One was to use strips of wedge so that instead of the two parts of the stem above and below breast height being

relatively displaced, only a section at breast height was displaced. Wedges were fitted to binoculars to make easier the decision as to whether a tree should be counted or not. Various suggestions were made for incorporating mechanisms to correct for slope in respect of each tree viewed. Finch (1957a) has a comprehensive discussion of these various instruments, and techniques of calibrating them are outlined by Grosenbaugh (1952, 1958), Carow and Stage (1953), and Husch (1963). Benson (1961b) discussed supply of wedges in Australia and their calibration.

Practical Aspects

The method gives theoretically exact estimates which can be made relatively easily and quickly. There are, however, several important aspects which need consideration to ensure that the application of the method is as efficient and reliable in practice as the theory implies. One of these concerns the borderline cases - those trees which the operator cannot confidently decide should be counted or not. A rough solution is to count every second such tree, or total them and include half the total in the final count. This estimate may suffer from an operator bias. The only reliable solution is to measure the diameter of the tree and to calculate, for the factor being used, the maximum distance from the sampling spot within which a tree of that diameter should be counted, and then to compare this distance with the actual distance from sampling spot to tree centre. This procedure is, of course, somewhat tedious, but if tables or graphs of diameters and equivalent maximum distances for various basal area factors are made up beforehand, they can be applied fairly quickly.

Another aspect is that a tree wrongly counted contributes an amount of basal area equal to the multiplying factor. Some compromise is necessary between the use of a factor which gives a few trees with a minimum likelihood of wrong counting but a relatively high error from a wrong count, and the use of a factor which gives a large number of trees with a higher likelihood of wrong counting but a relatively low error from a wrong count. This matter has been investigated by various workers under various conditions and there are divergent views on it. While the process can be carried out by one person, there is usually a practical advantage in having an assistant stand behind each tree (except those trees very close to the instrument operator for which the decision is easy) with an appropriately coloured board to indicate

breast height and sharpen the tree image, and in having the assistant keep the tally.

Theoretically instruments should be designed to allow for slope in respect of each tree, to correct for a slope distance being used rather than a horizontal distance, otherwise an error is incurred. Instruments without such automatic adjustment are probably the more common, corrections to horizontal equivalent being made by multiplying the basal area estimate by an appropriate factor. The factor commonly used is the secant of the general angle of slope. Hodge (1965) argues that the secant of the maximum angle of slope should be used. As an indication of the extent of the correction the following secant values are given as percentages:

Angle of slope	5^{o}	10^{o}	15^{o}	20^{o}	25^{o}	30^{o}
Correction factor(%)	100·4	101·5	103·5	106·4	110·3	115·5

Since the process normally involves making a 360^{o} sweep, bias is likely if positions are rejected where full circle sweeps cannot be made, as on the edge of a stand. On a large area, rejecting such spots may be unimportant; on a small area, it might be quite important. A solution is half or quarter sweeps where necessary and weighting the estimate accordingly. This 'slopover' problem is discussed at length by Grosenbaugh (1958).

The process assumes that the stems are vertical and the cross-section is circular. Unless the lean is great its effect on the shape of the cross-section of view can be ignored. The effects of eccentricity may be more serious and are examined by Grosenbaugh (1958).

In dense stands, trees masked from view by intervening trees may present a practical problem. The operator should move to view any such tree so that he maintains the original distance from the centre to sampling spot.

Advantages and Disadvantages

Estimates of basal area per acre of a stand by the angle count method are sampling estimates and similar in that sense to those made from sampling units such as plots, the difference being that plots have a defined boundary and size whereas angle count sweeps do not. For that reason, to compare the determination of stand basal area by angle count sweeps with that by plots requires a comparison which takes into account the relative precision of estimate and the relative time and cost involved. The precision of estimate depends in both cases on the

variation of basal area per acre over the stand and on the size of the sampling unit, 'size' in the case of the angle count unit being reflected in the basal area factor used. Comparisons of angle count sampling and sampling using plots of various size under various conditions can be found in the literature already cited.

Trees may be counted in such qualitative categories as separate species, defective and non-defective. The method does not provide a direct estimate of number of trees per acre nor numbers by size classes. An indirect estimate can be provided by an assistant measuring with tape or caliper the d.b.h.o.b. of every tree counted in the sweep and tallying these by appropriate size classes. The basal area per acre rate of each class is then determined by multiplying the number in each class by the basal area factor. The number of trees per class, on a per acre basis, is then derived by dividing the basal area per acre rate per class by the basal area equivalent to the mid-value of the class.

The method is dependent on the operator being able to get an unimpeded view of the d.b.h.o.b. of each tree he is likely to have to consider. If pruning or clearing undergrowth has to be done for this, a balance must be struck between the effort involved in this and in establishing sampling units with defined boundaries. For permanent angle count units, in theory only a point need be marked permanently; more than this is usually needed in practice.

12 Stand Height

Stand Mean Height

The arithmetic average or mean is commonly used as a condensed expression of a set of values which vary one from another as do the heights of individual trees in a stand. A mean of this kind for height is of limited value if variation of individual values around the mean is extreme as is usually the case in uneven-aged stands where individual trees may vary from 2 in to 200 ft in height. However, mean height has considerable practical use as a variable in even-aged stands where there is usually a relatively small variation in height. Mean height at a specified age is often used as an expression of the productivity of a site. There is abundant evidence that, within fairly broad limits, there is little correlation between height growth and stand density. Height growth is likely to be reduced in extremely open and extremely dense stands but in most natural or artificially established stands it is not affected much by the density of the crop and is mainly a function of time and the factors of site. If the stand is thinned, however, and the thinning is directed particularly at removing the tallest trees or the shortest trees, mean height is artificially affected and is not effective as an index of site. Stand mean height is a logical reference variable for stand volume. The concept of stand volume as the product of stand basal area, stand mean height, and some reducing factor which might be called stand form factor, is a very old one. Stand mean height is also used as an independent variable for stand volume tables, as discussed in Chapter 13.

To derive the mean height of a stand as an arithmetic average by measuring the height of every individual tree in the stand is far too laborious and is unnecessary for most purposes. What is called mean height is normally not the average of individual tree heights but an approximation to it associated with the arithmetic mean basal area of

the stand. It is usually obtained either as the arithmetic average of the heights of a number of trees having a basal area equal or approximately equal to the arithmetic mean basal area of the stand, or by reading from a stand height curve (see p. 88) compiled for the stand, the height corresponding to the diameter equivalent to the mean basal area of the stand.

A method of deriving an expression of stand mean height based on the Bitterlich angle count principle was proposed by Hirata (1955), Essed (1955, 1957), and Strand (1957). The reference angle is held in the vertical plane and compared with the angle subtended at the sampling point by the total length of each tree sighted in turn in a full circle sweep, those trees being counted the tops of which are above the elevation of the reference angle. Mean height is derived by substituting the count number in an equation. The principles and procedure are outlined by Finch (1957a) and Grosenbaugh (1958). This method has not had more than very cursory appraisal in Australia.

Stand Top Height

For even-aged stands, an expression of the heights of the tallest trees is more often used as an index of site than an expression of mean height, since the former is less likely than mean height to be affected by thinning under most conditions of thinning, and it is a more practical index for classifying site over large areas. There are several such expressions in common use with different names. For coniferous plantations in Australia, the terms top height, predominant height, and mean dominant height are used. They are usually defined as the arithmetic mean of the heights of the tallest trees in the stand at the rate of about twenty to thirty per acre, but, in one case, in relation to the fifty largest trees per acre by diameter. In New Zealand, the term mean top height is the most common, defined as the height on a stand height curve corresponding to the mean basal area over-bark of the 100 largest diameters per acre. Because it is, when related to age, an efficient index of site, top height forms a good reference variable for other stand variables (see ch. 13). Depending on the way in which the stand has been treated, so there may be a relationship between stand mean height and stand top height which allows convenient conversion of one to the other. For example for Pinus radiata stands as they are thinned in the A. C. T., there appears to be a reasonably constant difference between mean height and top height of about 6 or 7 ft irrespective of age and site.

Stand Height Curves

A stand height curve is a relationship between the heights of individual trees in a stand and their respective diameters (or basal areas).

Even-aged Stands

If values of total height are plotted on rectangular co-ordinate paper against the corresponding values of d.b.h.o.b. for the individual trees of an even-aged stand, a trend usually emerges though it may not always be clear. Within any diameter class there is variation in the heights of individual trees since tree height and tree d.b.h.o.b. are correlated only to the extent that each is a result of tree growth in the particular environment over the particular period of time. Tree height at a particular age is primarily a product of site, time and, to a very small extent, stand density. Tree d.b.h.o.b. at that age is primarily a product of stand density on that site over the period of time to that age. However, if class mean values of height and d.b.h.o.b. are plotted, a curvilinear trend, concave downwards, is usually obtained. Over a period of time, because of the different relative growth of d.b.h.o.b. and height, the height-d.b.h.o.b. relationship for an even-aged stand generally behaves as illustrated in Fig. 12:1, that is

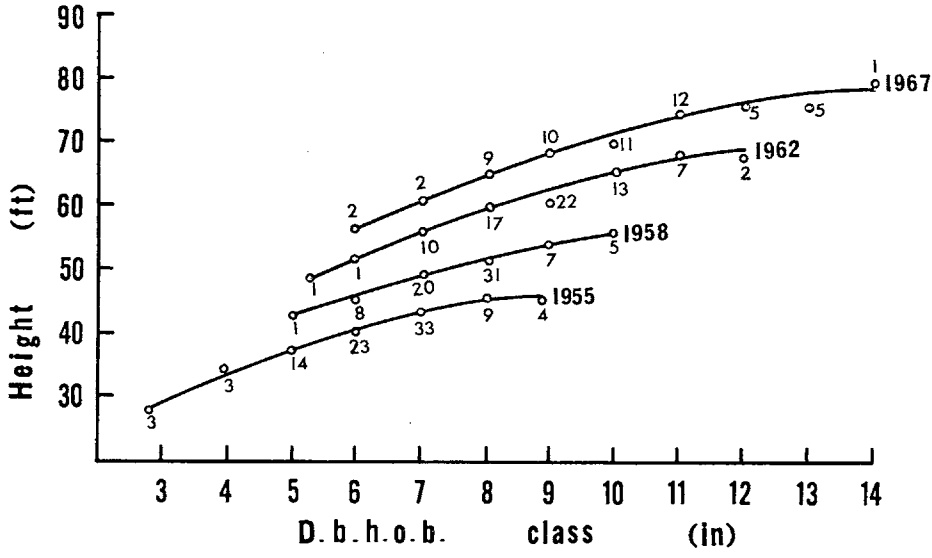


Fig 12:1 Stand height curve, even-aged P. radiata, Kowen, A.C.T. (planted 1940)

it moves upward and to the right, usually in a fairly symmetrical way.

Though height and d.b.h.o.b. are only partially correlated, the relationship between them is of considerable value. It is of silvicultural interest in that it is indicative of the stand structure. It is of practical value in measurement because a very common method of estimating stand volume is based on it. In this method heights are derived from a stand height curve corresponding to mid-values of diameter classes of a stand table. For each diameter class, the volume of a tree with class diameter and the corresponding height is read from a suitable tree volume table. The class average volume is then multiplied by the frequency of the class and the class volume then added to give stand volume.

Except for special investigation, the stand-height curve is usually determined from a sample of the stand. The most efficient sample is likely to be a stratified random sample, with d.b.h.o.b. classes as strata, the sample being allocated to the strata according to relative frequency and variation within strata, but this method is rarely employed in practice. Systematic sampling is commonly employed. This provides an unbiased estimate, in the sense of an unbiased estimate of the mean, if the start of the systematic sampling is located at random. The systematic sampling is sometimes done with the population in the order in which the individual trees are located or measured in the field; sometimes it is carried out on a stand table, in which case the sample directly reflects the d.b.h.o.b. distribution. Often the sample is selected subjectively. In a small population with which the operator is reasonably familiar, and with limited variation of height within d.b.h.o.b. classes, the bias likely to result from subjective selection may be unimportant; in other circumstances it may be quite important. Since an estimate of error of estimate is rarely made in practice, the size of sample is very often determined subjectively as one which the operator's experience suggests will give what is sometimes called a 'reasonably reliable result'. If stand height curves are compiled periodically for a particular stand, for example for deriving stand volume in periodic management inventory, growth studies, and experimental work, it is important that sensible uniformity in the position of the curves and in their change of slope be maintained. There may be an advantage in having a permanent sample. Any bias in sample selection is maintained consistently and a sensible check can be kept of the tree height measurement. A permanent sample may not, however, be at all times representative, particularly in the

case of thinned stands. If a different sample is selected on each occasion the method of selection should be objective.

If a mathematical model can be assumed for the stand height curve, operator bias in fitting the relationship by eye is avoided, uniformity can be maintained over periodic measurement, and calculations can be done mechanically. Many attempts have been made to find a model which describes the relationship satisfactorily yet is sufficiently simple to be calculated readily. The relationship usually appears as part of a conic section - a parabola, ellipse, or hyperbola - and many curve forms of this kind have been suggested. Trorey (1932), for example, found that for many stands in Canada the form $H = a + bD + CD^2$ where H = tree height and D = tree diameter, was satisfactory. He further assumed that since the d.b.h.o.b. of a tree of height equal to breast height is zero, then the constant a of the equation could be assigned the value of breast height. Staebler (1954) also recommended this model for certain species in North America but without the assumption that the value of the constant a should equal breast height. Many people have looked for ways of transforming the curvilinear relationship into a linear one. One way is to rearrange the variables, constants, and coefficients in the equation as exemplified by Ker and Smith (1955) who tested a number of models, concluded that the parabolic equation suggested by Trorey was the most suitable, and recommended transformation of it to a linear equivalent $\frac{H - 4{\cdot}5}{D} = b + cD$ (breast height being 4 ft 6 in). Another way of transforming the curvilinear relationship is a logarithmic transformation; the parabolic form $H = aD^b$ becomes $\log H = \log a + b \log D$. Henricksen (1950), working on Norway spruce and beech, recommended $H = a + b \log D$. Stoeffels and van Soest (1953), working with Japanese larch and Douglas fir in the Netherlands, after trying various formulae, preferred Henricksen's equation. Prodan (1965) listed a number of equations and transformations which have been proposed.

Kopezky and Gehrhardt (quoted by Prodan, 1965) suggested that a linear relationship between tree height and the reciprocal of tree basal area follows from the linearity of the tree volume-tree basal area relationship in even-aged stands, i.e. $H = a + \frac{b}{D^2}$ (sometimes called the Gehrhardt equation). As discussed in Chapter 13, the volume-basal area relationship may be linear provided the relationships of tree height and tree d.b.h.o.b., and tree height and tree form factor, take particular forms. A linear relationship between tree height and the

reciprocal of tree basal area, and a constant form factor over the range of d.b.h.o.b., comprises one of the suitable combinations for the linearity of the volume-basal area relationship. Takata (1962) and Kajihara (1966) have tested the suitability of the Gehrhardt equation, as well as a number of the curvilinear forms and their transformations, for some Japanese species.

The number of models proposed confirms what observation suggests - that the relationship probably cannot be described by one curve form which merely changes constants and coefficients according to species, locality, stand condition, and time but that it differs in curve form with time for a single stand and from stand to stand at a particular time. Under these circumstances, no single model is likely to be universally satisfactory. This, allied to the fact that even if a model has been found satisfactory it may involve considerable calculation, has promoted subjective fitting of the stand height curve in many cases such as those outlined by Hummel et al. (1959) in Great Britain and by Duff (1960) in New Zealand.

Nevertheless, experience shows that the stand height curve of a particular even-aged stand is likely to change its form and quantitative nature in a fairly regular way as illustrated in Fig. 12:1, and that a series of standard (unit) height curves, can be established to represent the likely relationships of height with d.b.h.o.b. for a stand over its life history from the information of repeated measurement, or to represent the likely height-d.b.h.o.b. relationships of all the variously aged stands of an even-aged forest from the information of a single inventory. Such a series is of particular value in applying the method of determining stand volume outlined above, that is by reference of a stand table to a tree volume table through a stand height curve. The stand height curve for a particular stand is nominated from the series instead of being compiled directly from selected and measured sample trees, through an established correlation of statistics of the stand height curves and easily measured stand variables. Work on this aspect for some Australian stands is going on at present.

Uneven-aged Stands

The relationship of total height and diameter in uneven-aged stands depends on the species composition of the stand and the treatment given to it. For an area of uniform site in an intensively managed selection forest of a single coniferous species, for example, there may be a

reasonably close relationship which can be expressed as a slightly sigmoidal curve constant with time, that is the conditions of the stand and the growth habits of the species are such that certain heights are usually associated with certain diameters as illustrated by Prodan (1965a) for a plenterwald of spruce. It is to this sort of stand that a single one-variable tree volume table may be applied throughout the life of the stand. By contrast, it may be difficult to establish any such relationship in the case of an Australian uneven-aged forest of mixed Eucalyptus species managed extensively under the group selection system, and any relationship that is established may appear to behave somewhat erratically with time, depending on the relative history of the individual trees which make up the sample selected to establish the relationship. Fortunately in this case, because it is of much more value in practice, a relationship may be more readily established between merchantable height and diameter, as shown in Figure 12:2.

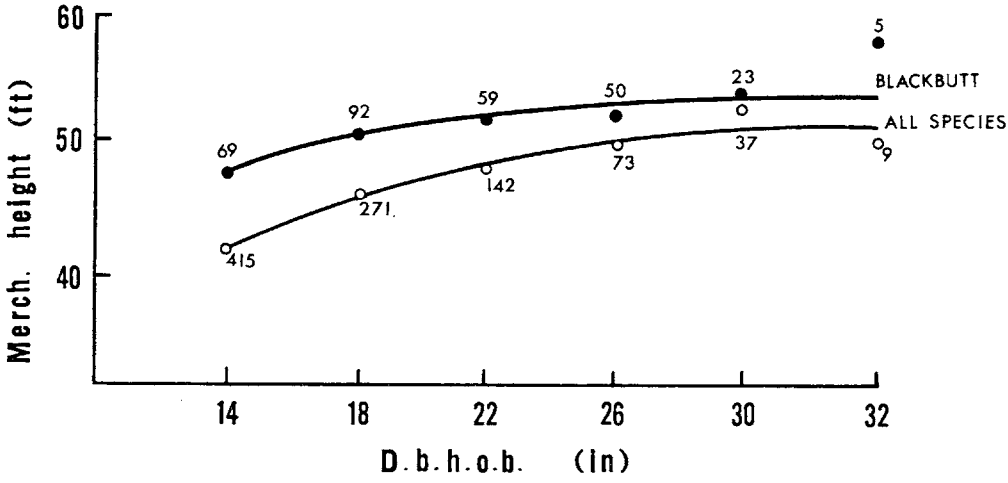


Fig. 12:2 Stand height curve, uneven-aged eucalypt forest (mixed species), Pine Creek State Forest, N.S.W.

Despite considerable variation within diameter classes, the average values for diameter classes fit a curve fairly well. If such a relationship can be accepted as constant over time, height need not be remeasured in periodic management inventory, which obviates errors in the estimate of volume increment due to errors in height measurement and difference of opinion of operators as to the merchantable limit, and allows the use of a one-variable volume table at all times.

13 Stand Volume

Determining the volume of forests of various structures, qualities, conditions, and value has been recognised as important for about two hundred years. During that time many methods, and various techniques for implementing them, have been developed and it is difficult to categorise them for purposes of description in a clear-cut way. The classification adopted here has been found convenient for academic purposes.

Sampling is an essential part of all methods of stand volume estimation and in many cases the conversion factor is very large indeed. In some methods, the final estimate of the volume of a forest is based on measurements at a sample of positions on individual trees which together form a sample of the trees in a sampling unit, one of a number of such units forming a sample of the stand which itself is one unit in a sample of the stands which together compose the forest. The forester has to keep in perspective the limitations to the inferences he can draw about the population from the information of a very small sample, and the effect of sampling error and bias at each stage of sampling, in expanding the estimate from sample to population. The discussion here will be confined to the estimation of stand volume from the ground.

SAMPLE TREE METHODS

This approach to stand volume estimation, in the form of the arithmetic mean volume tree method, is one of the oldest in forestry. The intention is to determine the arithmetic average of the volumes of the trees in the stand as simply as possible and multiply it by the number of trees in the stand. This obviously calls for sampling. For the method to give a reasonable estimate without an unduly large sample,

the stand has to be fairly homogeneous in volume. The method is therefore likely to be restricted in practice to even-aged stands of one species. Even for a small plot of an even-aged stand of one species we can anticipate having to measure the volumes of several trees to get a reasonable estimate of mean volume if we select them by an objective process. If we can 'sample' the variation by eye, however, we might get just as good a result with fewer sample trees; at best we might need to select only one tree. By such reasoning foresters developed the practice of subjectively selecting only one tree.

Because the volumes of individual trees do vary one needs clues to aid in the selection of the mean volume tree. Depending on how much information is already available - for example, usually a stand table would be compiled in any case and so mean basal area would be available - and on how much information it is worth while determining especially for the purpose - for example information on height, taper, and bark thickness - so one could have various clues to aid selection. As Chaturvedi (1926) pointed out, the mean volume tree will not have stand arithmetic mean basal area, height, and form factor, for mathematical reasons. This suggests a limit to the time involved in getting refined estimates of these values. The main question is whether there actually exists in the stand a tree with the arithmetic mean volume of the stand - there is no reason to expect one (since the arithmetic average of some quantitative measure of a population does not necessarily exist) and experience suggests there rarely is one. This suggests that two or three trees with d.b.h.o.b., height, and form factor approximating stand mean d.b.h.o.b., mean height, and mean form factor would be more suitable; or perhaps more than three trees. The larger the sample, the more the essential simplicity of the method is lost and the more information one should expect to get from it.

Variations of the simple approach developed in western Europe. The main one was to form groups (strata) on the basis of diameter classes, basal area or equal number of trees and to apply the mean tree concept to each group independently. Some of these group methods, referred to by the names of their proponents such as Urich, Hartig, Schwappach, were common in many parts of western Europe, and in other countries influenced by European practice, up to about twenty-five years ago, but have since been abandoned.

The simple method is still sometimes used in modern practice, particularly in resources inventory of even-aged stands. One example of this is the resources inventory of the radiata pine plantations in the

A. C. T. as discussed by Carron (1955) and by Cromer and Brown (1956). In the Netherlands in recent years, the method has been used for both resource and preliminary working plan inventory of even-aged stands of single species more than fifty years old.

TREE VOLUME TABLES

A tree volume table is a statement of the expected volume of a tree of particular dimensions or of a tree in a stand of a particular kind. The table may be for one species under particular growing conditions or for more than one species under different growing conditions, depending on the independent variables to which volume is referred (d.b.h. o.b., height, an expression of taper, and an expression of bark thickness) and on the extent to which variation in tree volume is accounted for by those variables. A tree volume table is compiled by procedures involving graphs or mathematical analysis from the data of sample trees. The statement may be made in tabular or graphical form, both of which allow direct reading; or it may be expressed as an equation, the volume of a tree being calculated when required by substituting in the equation the appropriate values of the dimensions of the tree which have been used as variables in the equation. The main purpose of a tree volume table is the estimation of volume of standing trees. Though tree volume tables may be used to estimate volumes of felled trees, these are more often determined by direct methods. A volume table is expected to provide a reliable estimate of the average volume of a number of trees in a diameter class; it is not expected to provide the volume of an individual tree to the same level of reliability as by direct measurement, though the more the independent variables used the closer should be the volume table estimate to the actual volume.

Volume, the dependent variable, may be total volume or volume to some diameter limit, over- or under-bark, with or without an allowance for stump, in any particular unit such as cubic foot, super foot or Hoppus super foot. The independent variables must be such that tree volume is correlated with them; and for purpose of application they must be readily identified and reliably measured on standing trees. The independent variables are therefore chosen from an expression of size over-bark at breast height; an expression of height such as total height or height to an easily identified limit; an expression of taper that can be readily measured or reliably estimated; and, for under-bark

volume, an expression of bark thickness in the vicinity of breast height.

It is most convenient to discuss volume tables according to the number of independent variables involved. There is a conventional nomenclature in which such terms as local, standard, regional, general, and universal are meant to indicate the scope of application and to imply thereby the number of independent variables involved. Scope of application and number of independent variables are, however, not necessarily connected so that this nomenclature is not convenient. If the volume statement is in tabular or graphical form, volumes are read in one way (direction) from a table with one independent variable, in a two-way fashion from a table with two independent variables, and so on. This leads to a convenient nomenclature - one-way volume tables, two-way volume tables and so on, which will be used here.

One-Way Tree Volume Tables

If there is to be only one independent variable for a volume table, the obvious choice is d.b.h.o.b. (g.b.h.o.b., b.a.o.b.). Since the volume of a tree is a function of its d.b.h.o.b., height, and form factor, a relationship of volume with d.b.h.o.b. can be established for a range of d.b.h.o.b. in a stand only if there is a relationship of height and form factor with d.b.h.o.b. for that range of d.b.h.o.b. in the stand. The trend of height and form factor with d.b.h.o.b. will influence the relationship between volume and d.b.h.o.b. The reliability of the estimate of volume of a tree of a certain d.b.h.o.b. read from a one-way table will depend on how closely the actual height and form factor values of the tree agree with those implied in the table for that d.b.h.o.b.

Even-aged Stands

The volume curve. We have already seen that for an even-aged stand there is a reasonably well defined relationship between tree height and d.b.h.o.b. at any time and that if we plot this relationship on rectangular co-ordinate paper at various ages of the stand the relationship 'moves' upwards and to the right with time (see ch. 12). The relationship between form factor and d.b.h.o.b. at a particular time is not always so well defined but in most cases some trend is evident. Where there are trends of both height and form factor with

d.b.h.o.b., the relationship of volume and d.b.h.o.b. is likely to be a curve concave upwards. The curve for the stand can be estimated by selecting appropriate sample trees, measuring their volumes, plotting the volume of each tree against its d.b.h.o.b. on co-ordinate paper and fitting the curve of best fit by eye or calculation. The volume of a tree of any diameter can be read from the curve and stand volume derived in this way through a stand table. This procedure, known as the volume curve method, has been in use in western Europe for about a hundred and fifty years. It is not in use in Australia and will not be discussed further.

The volume line. European foresters recognised that the volume curve often appeared to be parabolic. This suggested a transformation of the curve to a straight line by relating volume to basal area rather than to d.b.h.o.b. The idea of this volume-basal area line, or volume line as it has come to be called, seems to have been proposed first by Behringer in western Europe in 1894 (Chaturvedi, 1926). In 1899 it was investigated further by Kopezky and Gehrhardt, with whose names it is now mostly associated in Europe. Since then it has been investigated and used in Great Britain and Australia and recently interest has extended to certain parts of North America. The attraction of the volume line over the volume curve is its linearity - it is so much easier to fit a straight line to data, by calculation or by eye, than any other form of curve, and fewer observations are needed to establish it.

Examples of volume lines are shown in Fig. 13:1. The volume line is a simple linear regression of volume on basal area which can be expressed by the general equation

$$Y = a + bX$$

where Y represents tree volume, X represents tree basal area, a is the regression constant (the intercept of the volume line on the Y axis) and b is the regression coefficient (the 'tangent' of the angle made by the regression line with the X axis). The regression is calculated by the method of least squares which is described in standard texts on statistical methods. The variables used in Fig. 13:1 are volume under-bark from ground to 4 in and basal area over-bark.

Whether a linear relationship between tree volume and tree basal area for an even-aged stand can be assumed, and under what circumstances, has been a matter of considerable interest since it was first proposed. General experience in Australia has been that the

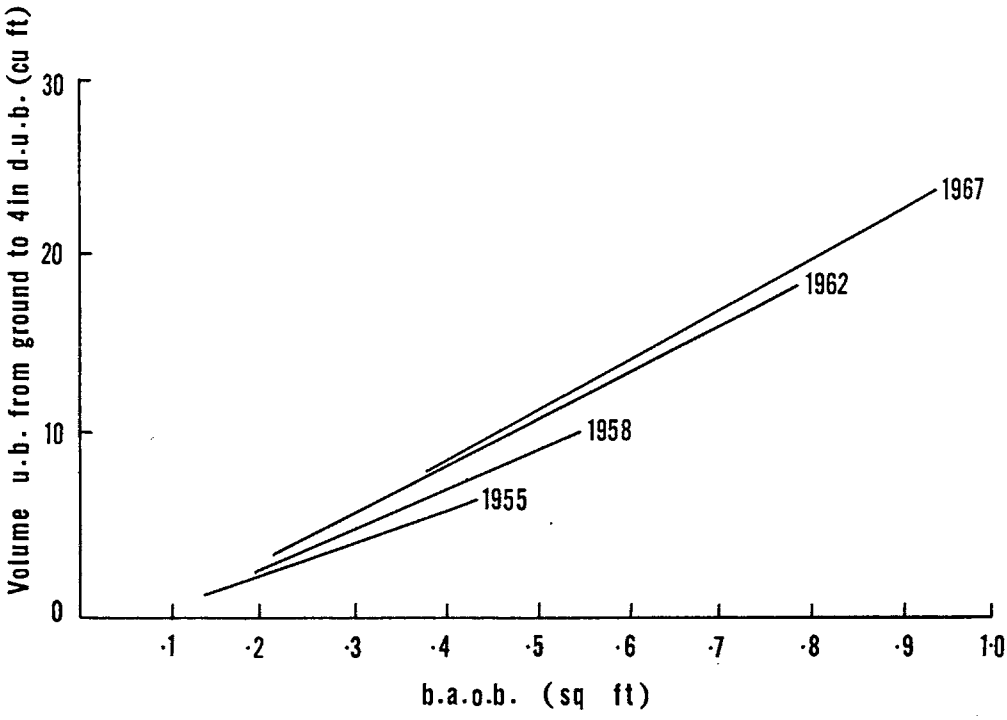


Fig. 13:1 Volume-basal area lines for an even-aged stand of P. radiata, Kowen, A.C.T. planted 1940 (see Fig. 12:1)

1955 vol. = -1·03 + 17·27 b.a.o.b.
1958 vol. = -1·55 + 21·24 b.a.o.b.
1962 vol. = -2·06 + 25·49 b.a.o.b.
1967 vol. = -3·25 + 28·14 b.a.o.b.

relationship between total volume under-bark and basal area over-bark for even-aged stands of conifers such as Pinus radiata is usually linear under most circumstances and this is also true for volume under-bark to a small end diameter under-bark limit of the order of 6 in. For young stands, particularly those of poor site quality, for old unthinned stands, and for volume to small end diameter under-bark (s.e.d.u.b.) limits greater than about 6 in, the relationship is likely to be curvilinear. The investigation by Keeves (1961) for P. radiata in South Australia supports this.

The relationship of tree volume with tree basal area at any time reflects the relationships of tree height with tree basal area and tree form factor with tree basal area at that time. The behaviour of the volume line with time reflects the behaviour of these other relationships over that period. A number of combinations of these relationships of tree height and tree form factor with basal area will produce a linear relationship between volume and basal area. For example, one which

has been demonstrated for P. radiata on many occasions has been referred to in Chapter 12. However, as volume to progressively greater s.e.d.u.b. limits is used, the relationship of this volume to basal area becomes progressively more curvilinear. Tests are readily available to determine the significance of departure from linearity.

In practice an estimate of the volume line for a stand is made from sample trees. To avoid operator bias, the sample should be selected objectively. Various methods of selection are available, the choice being influenced by whether linearity can be assumed or has to be tested. The size of sample will depend on the method of selection, the variation of volume for a particular basal area, the precision of estimate of volume of the individual sample trees, and the precision of estimate of volume required from the volume line. There is considerable variety in the manner in which the method is applied - in the number and kind of sample trees, in the method of selecting them, in the method of determining their volumes, in the method of determining the volume line and in deriving stand volume from it. Subjective selection of sample trees has been used extensively with the idea of reducing the size of the sample to a minimum; the variation of volume within d.b.h.o.b. classes is assessed by eye and average trees chosen. Hummel (1952), and McIntyre and Carron (1954), have indicated the bias to which such selection is liable but it can be kept under reasonable control if the selector is very familiar with the population. If the volumes of the sample trees are determined from a volume table rather than by a direct method of measurement, the size of the sample must be increased to obtain the same reliability of estimate. The line of best fit is often drawn by subjective judgment, rather than calculated, as a check in the field on the fit of the line at a present time relative to that at a previous time, or to save the time and trouble of calculation. The bias from this source varies according to the variability of the data and the experience of the operator. Perhaps the most suitable method is to plot the values of the sample trees on co-ordinate paper in the field as a check on the assumption of linearity, on atypical sample trees and on errors and to calculate the equation to the line in the office later.

The volume line for a particular stand represents a one-way volume table for the stand. The volume of any tree can be obtained by substituting its basal area over-bark in the equation or it can be read off the graph if the line has been determined graphically. The volume of the stand can be derived by adding the volumes of the individual

trees so determined. From the nature of the equation, however, stand volume can be obtained very readily as

$$S(Y) = a.N + b.S(X)$$

where S(Y) = the sum of the individual tree volumes and thus stand volume, N = the number of trees in the stand, and S(X) = the sum of the tree basal areas over-bark.

The volume line method has been used extensively in some parts of Australia. Gray (1966) has reviewed its introduction to Australia and developed several concepts of it. Jolly (1950), Lewis (1954), and Keeves (1961) have summarised the considerable experience of South Australian foresters. Hummel (1955) investigated the method in Great Britain and its use by the Forestry Commission was discussed by Hummel et al. (1959).

Tariffs. It has been pointed out that the volume curve or volume line for an even-aged stand is a reflection of the tree height and tree form factor relationships with tree basal area and that the behaviour of the volume relationship with time is a reflection of the behaviour of these other relationships with time. The behaviour of the stand height curve appears to be of particular importance. The graphical progression of the stand height curve with time is upwards to the right (see ch. 12). The graphical progression of the volume curve or volume line follows the same pattern as shown in Fig. 13:1, where is illustrated the progression of the volume lines equivalent to the stand height curves of Fig. 12:1. For such a series of volume curves or volume lines the name 'tariffs' has come to be used in the English mensuration literature after the use of this term in western Europe for a volume table in which volume is expressed as a function of d.b.h. only. The various kinds of tariffs have been summarised systematically by Prodan (1965a) who prefers the term 'tariff system' for a series of them (Prodan, 1965b) The great value of tariffs is that if tariffs covering the development of a stand with time can be compiled and the particular tariff applicable to the stand at a particular time can be nominated in some ready way, the need to compile the appropriate volume curve or volume line directly is obviated. Foresters have therefore looked for ways of compiling and nominating tariffs for various kinds of stands in various parts of the world.

One way is to compile from experience a series of stand height curves and the accompanying tariffs and nominate the tariff for a stand at a particular time according to its actual stand height curve at that time,

the stand height curve being easier to derive than a volume line. This approach has been used extensively in western Europe, for example by Krutzsch-Loetsch (1938). Alternatively, the tariffs are compiled directly from experience and the tariff for a stand at a particular time is nominated by the minimum number of sample trees. This was the basis of the Algan tariffs of France (Algan, 1902). Jolly (1950) found that for radiata pine in South Australia, volume lines of volume under-bark to 4 in d.u.b. over a wide range of age and stand conditions tended to converge to a value 0·09 sq ft on the b.a.o.b. axis. This led to the method, used under certain circumstances in South Australia for some time, of selecting sample trees of mean volume and drawing a line on graph paper from the plotted position of their mean to the 0·09 sq ft basal area value, equivalent to nominating one of a series of tariffs radiating from the 0·09 value.

Another way is to compile the tariffs for stands directly and then relate statistics of these tariffs to stand variables. If the volume line of a stand is a consequence of the stand height curve, the statistics of the volume line should be related to whatever controls the form of the stand height curve. If this were site quality and age, for example, then stand top height might be a logical index of the statistics of the volume line, and once their interrelationship was established one would then need only to determine stand top height to have the appropriate tariff. In the 1930s Gray demonstrated this was so for radiata pine in South Australia and later stimulated the production of similar tariffs for coniferous plantations in various parts of Australia (Gray, 1966). During the 1940s, the Queensland Forestry Department developed 'predominant height volume tables' of this kind by graphical techniques, a set of tariffs compiled from and for application to areas of certain stand top (predominant) height.

Hummel (1955) investigated the correlation between the statistics of the volume line and stand indexes for various species on various sites in Great Britain. Over a large range of species, age, site, and treatment there was a common linear correlation of the regression coefficients of volume lines with stand top height and the series of volume lines approximately converged on a value of 0·03 sq ft on the basal area axis. This led to the production of 'general tariff tables', a series of lines radiating from 0·03 sq ft basal area through successive values of volume, with one Hoppus foot interval between them at 1 sq ft basal area and identified by numbers equivalent to those values of volume. The tariffs were used to estimate volumes of thinnings, being

nominated from the volumes of felled sample trees. Finch (1957b) reported an investigation into the application of the tables to a stand through the correlation of tariff number and stand top height, and to the main crop of a stand through a correlation between tariff numbers for thinnings and main crops. The modern procedure for the use of the tariffs is outlined by Hummel et al. (1962) and the principles, applications, and limitations discussed.

Cromer and Carron (1957) carried out a similar investigation for radiata pine in the A.C.T. and established correlations between the regression coefficients of volume lines and stand top height, and between the regression constants of the volume lines and stand top height and stand mean basal area. Accepting a linear correlation of regression coefficients and constants with stand top height, the N.S.W. Forestry Commission (Henry, 1960) developed a system of harmonised tariffs by calculating a volume table based on the multiple regression

$$V = a + bB + cH + d\,B.H$$

in which V = tree volume, B = tree basal area over-bark, and H = predominant height of stand.

This equation can be written

$$V = (a + cH) + (b + dH)B$$

Since for an area of a certain predominant height H is constant, the equation can be written

$$V = a' + b'B$$

a' and b' having a linear correlation with H. This same multiple regression is also used to compile two-way tree volume tables, as discussed later, in which the height term, H, is the height of an individual tree, the equation giving the volume of a tree of a particular height and d.b.h.o.b. These two uses of the same multiple regression should not be confused. For tariffs, the regression is used to harmonise a series of volume-basal area lines for stands; for two-way tree volume tables, the regression is used to harmonise a series of volume-basal area relationships each of which is for individual trees of the same height. The Queensland Department of Forestry used the same method to improve the tariffs compiled previously by graphical methods (private communication).

Irrespective of how a tariff series is compiled and how the tariff for a particular stand at a particular time is selected, once selected stand volume is calculated from it in the same way as described above for a volume line.

Uneven-aged Stands

If the stand height curve for an uneven-aged stand remains constant with time, the volume-b.a.o.b. relationship remains constant with time (assuming tree form factor remains constant). For total height the stand height curve is usually such that the volume-b.a.o.b. relationship is curvilinear. When merchantable height can be assumed constant for all d.b.h.o.b. classes greater than a certain d.b.h.o.b. with which crown break is associated, an assumption which applies reasonably well in the case of some Australian eucalypt forests, the volume-b.a.o.b. relationship will be linear for those classes. For example, a merchantable height of about 50 ft might be assumed for all sizes of blackbutt above 14 in d.b.h.o.b. from the evidence of Fig. 12:2. If the stand height curve is not constant with time, it is necessary to apply two-way tree volume tables.

Two-Way Tree Volume Tables

Compilation

The logical independent variables for a two-way volume table are d.b.h.o.b. and an expression of height. The table is compiled from the information of sample trees. The number of sample trees which should be used depends on the variability of the material, the precision of the estimate required, and the method of compilation. Tables have been compiled in Germany using data from 30,000 trees accumulated over many years. They have been compiled for broad-leaved species in Australia from as few as 30 trees using the method proposed by Unwin and Bowling (1951). The method of selection should be objective, though there may be argument for subjective selection if the sample must be small. The population from which the sample is to be drawn should be specified clearly so the sample will be representative. The population to which the table is meant to apply should also be specified clearly so the user is not misled. The volumes of the sample trees will normally be derived by a direct method of measurement; a graphical method has the advantage that tree volume can readily be derived in assortments which may be useful at a later time if not at the present.

Compilation by graphical methods. The volume of a tree can be expressed as $V = B.H.F.$ where V = tree volume, B = b.a.o.b.,

H = height, and F = form factor. From this one would expect a volume table in which d.b.h.o.b. and height are independent variables to comprise a series of values which increase in a regular way with increase of d.b.h.o.b. for a particular height, and which increase in a regular way with increase of height for a particular d.b.h.o.b. The regularity of this increase in two directions will depend on the way form factor behaves. For a particular height, volume will bear a parabolic relationship to d.b.h.o.b. and a linear relationship to b.a.o.b., if form factor is constant over the range of d.b.h.o.b. If form factor is related in some other but nevertheless regular way to d.b.h.o.b., the volume-d.b.h.o.b. relationship may still be a simple curve, though it may not transform to linearity between volume and basal area. If form factor varies erratically with d.b.h.o.b., the curvilinear relationship of volume and d.b.h.o.b. may be complex. It may be reasonable for practical purposes in this case to assume a constant form factor. The way the volume-d.b.h.o.b. relationships for each height are related to each other depends on how form factor is related to height. There may be a symmetrical change of form factors, associated with each d.b.h.o.b., with increasing height. The change may be erratic so that there is no symmetry from one volume-d.b.h.o.b. relationship to another. It may be reasonable to ignore the erratic variation of form factor in the interests of practical compilation of the table.

The main concern in compiling a two-way tree volume table is to discover the pattern of change of volume with change of d.b.h.o.b. and height and then to express it in the simplest but most efficient way. One method is to plot the values on graph paper and fit the relationships most suitable to the data by graphical methods. This is the oldest approach. It was used in western Europe over a hundred years ago and is still used in many places today. Graphical methods have certain advantages; little mathematical knowledge is required whereas some mathematical background is required to solve equations; the relationships are determined from the graphical evidence and no assumption about the kind of relationship, or testing of the most likely relationships, is necessary as is the case with equations. On the other hand, the method is subjective and no two compilers necessarily derive exactly the same table from the one set of data, though if they are reasonably experienced the differences between their tables would usually be small enough not to invalidate the use of either table; and for subjective fitting of relationships of this kind to be satisfactory a

large amount of data is usually required. This may be difficult or expensive to collect, particularly if the sample trees are standing.

Most of the graphical methods go under the general name harmonised curve method. The basic approach appears to have been introduced to North America many years ago by Graves following experience in Europe and is often referred to under the names of the various authors who propagated it in text books. The main difficulty with the method is in trying to establish a three-dimensional relationship on two-dimensional paper. Also, there is no practicable alternative to forming the sample tree data into classes of d.b.h.o.b. and height, deriving averages, and plotting these to establish the relationship. Unless there are very many sample trees, these averages will not necessarily be the central values of the class intervals so that to the natural variability of volume due to variation in form factor is added this artificial variability which further complicates the compilation.

Various modifications have been proposed to overcome these difficulties. The simplest and most common method is to arrange the sample tree data into height classes within d.b.h.o.b. classes, and derive average volume, height, and d.b.h.o.b. for each class (cell). At an appropriate scale on rectangular co-ordinate paper, average volume is plotted against average d.b.h.o.b. for each height class separately and curves for each height class are fitted by eye, the fact that the values of average height for the cells may not be the central values of the class being temporarily ignored. For reference purposes, this graph can be called Graph 1. From Graph 1, volumes for the central value of a d.b.h.o.b. class are read in turn for each height class and these are plotted on co-ordinate paper against the average heights of the sample tree data for the appropriate cells. This is done in turn for each d.b.h.o.b. class and curves are fitted by eye. This forms Graph 2. From Graph 2, volumes for central values of d.b.h.o.b. class are read off and plotted against these values, for each height class in turn, and curves fitted by eye. This forms Graph 3 and constitutes the final volume 'table' from which values can be read and presented in tabular form.

If the trend of form factor with d.b.h.o.b. within a height class is such that volume plotted against basal area gives a linear relationship, basal area would normally be used instead of diameter throughout. If the trend of volume with height within d.b.h.o.b. class is thought to be more readily definable than the trend of volume with d.b.h.o.b. within a height class, volume is plotted against height for d.b.h.o.b.

classes in Graph 1, and Graph 2 becomes the relationship of volume against d.b.h.o.b. accordingly. The most common modification of the method is that described by Griffith and Prasad (1949), proposed originally by Dwight (1937). In this, Graph 1 is compiled as previously, and, for each height class in turn, average height is plotted against average d.b.h.o.b. in each cell and curves are fitted to these points. The equivalent to Graph 2 is compiled using volumes for the central value of a d.b.h.o.b. class for each height class in turn as read from Graph 1, but plotted against heights read from the height-d.b.h.o.b. curves; that is volumes are plotted against smoothed values of the original cell heights rather than the original cell heights themselves. Graph 3 is compiled as before. Another modification was suggested by Bowling (1951) in connection with the compilation by graphical methods of volume tables for regrowth eucalypts in Tasmania.

A number of volume tables, combined with taper tables, for various exotic conifers in New Zealand have been compiled by Duff (1954), Duff and Burstall (1955), and Burstall (1957). The method used is described as

> ... a graphical form factor method based on d.b.h.o.b. and total height. The average form factors (calculated from tree volume under-bark as a proportion of an equivalent cylinder over-bark) are plotted against d.b.h.o.b. A smooth curve is drawn through the points thus providing the first estimate volume table. Where necessary, height corrections are applied to this preliminary table. In cases where the method fails to give satisfactory results it is necessary to draw separate form factor curves for different height classes.

For tables compiled graphically it is conventional to carry out two tests of compilation. By appropriate interpolation, volume is read from Graph 3 for each sample tree according to its actual d.b.h.o.b. and height. The difference between the sum of these volumes and the sum of the actual volumes of the sample trees is expressed as a percentage of the latter. Conventionally, this aggregate difference per cent should not exceed about 1 per cent. The difference between volume table volume and actual volume for an average tree of each cell is expressed as a percentage of actual volume. These values of cell deviation per cent are tabulated and checked for unreasonably large deviations, bias in particular sections of the table, or extreme compensations. These deviations may suggest refitting of some of the curves. When the checks are satisfactorily completed, values of

volume for appropriate values of d.b.h.o.b. and height are read from Graph 3 and arranged in tabular form as shown in Table 13:1. The internal frame superimposed on the tabular layout shows the extent of coverage of sample trees. Values outside this frame are derived from extrapolation of the curves and are included in the table only as experience suggests such trees exist and their volumes may be required. Extrapolation is usually limited to one cell in each direction and the values should be used with caution.

Compilation by calculating equations. To describe a relationship amongst variables by an equation, the kind of expression which describes

Table 13:1

Tree volume table for P. radiata, Mt Stromlo, all ages and sites; volume under-bark from ground to 4 in d.u.b., in cu ft: based on 250 sample trees measured standing by the sectional method; compiled by A. Forester, 1968 by the harmonised curve method; aggregate difference 0·8 per cent (for illustration only and not for use)

D.b.h.o.b. (in)	Total height (ft) 40	50	60	70	80	90	100
5·0	1·4	2·5	3·5	4·6			
6·0	2·2	3·5	4·7	5·9	7·1		
7·0	3·2	4·6	6·0	7·4	8·8		
8·0	4·3	5·9	7·5	9·1	10·7	12·3	
9·0	5·5	7·4	9·2	11·0	12·9	14·7	
10·0	6·9	9·0	11·2	13·3	15·4	17·5	
11·0	8·5	10·9	13·3	15·7	18·1	20·6	
12·0	10·1	12·9	15·6	18·3	21·1	23·8	
13·0		15·1	18·2	21·3	24·4	27·5	
14·0		17·4	20·9	24·4	27·9	31·4	34·8
15·0		20·0	23·9	27·7	31·6	35·5	39·4
16·0		22·7	27·0	31·3	35·7	40·0	44·3
17·0				35·1	39·9	44·7	49·5
18·0					44·5	49·8	55·1
19·0						60·7	67·0

the relationship best should first be determined, then the constants and coefficients of the best fit of that expression to the particular data calculated. Considerable investigation has been carried out in various parts of the world into the kind of equation appropriate to describe the relationship of volume with d.b.h.o.b. and height. Many equations have been suggested; no one particular equation has been found suitable for all species under all conditions. Apart from the use of different standards of volume, the most likely reasons for this are the different pattern of variation of form factor within height and d.b.h.o.b. classes within a species between places, and between species within places: and variation in bark thickness, particularly at breast height.

A natural starting point in the search for an appropriate equation was the evidence, from graphical methods of compiling volume tables, of the relationship between volume and basal area within height classes and that between volume and height within basal area classes. These relationships were often linear or nearly so, and this suggested computing them separately and then harmonising these single regressions by graphical smoothing of the constants and coefficients of these regressions. This was the basis of the early investigations of the Forestry Commission of Great Britain (Hummel, 1955) and of various forest services in Australia at about the same time, for example the Tasmanian Forestry Commission (1953) and the New South Wales Forestry Commission (Henry, 1955). The technique is often referred to as compilation by harmonised regression series.

The next step was to investigate the relationship between height and the constants and coefficients of the regressions of volume on d.b.h.o.b. for height classes, and the relationship between d.b.h.o.b. and the constants and coefficients of the regressions of volume on height for d.b.h.o.b. classes. The form of these relationships indicates the most satisfactory multiple regression. For many species in various parts of the world, the constants and coefficients of the simple linear regressions of volume on basal area for separate height classes have been shown to be linearly related to height class: $a = a_1 + b.H$ and and $b = a_2 + b_2 H$. Substituting for a and b in $V = a + b B$, which is the regression of volume on basal area for height class, we have $V = (a_1 + b_1 H) + (a_2 + b_2 H)B$, that is $V = a_1 + a_2 B + b_1 H + b_2 B.H$ where V = tree volume, H = tree height and B = tree b.a.o.b. This is the Australian equation, so-called by Spurr (1952) with reference to the fact that T.N. Stoate of Western Australia had suggested it as a

likely form for volume tables (Stoate, 1945), as a means of identifying it in a comparative study Spurr carried out on various equations. A reduced form of this equation, V = a + bB.H, referred to by Spurr for identification purposes as the combined variable equation, has also been found in many cases to give a satisfactory fit. It implies a hyperbolic relationship between form factor and the product of basal area and height. If form factor is constant, there is a simple linear relationship between volume and the product of basal area and height: V = aB.H, sometimes referred to as the form factor equation. This a very old formula for compiling volume tables and was used in western Europe in the last century. If the relationship of volume on d.b.h.o.b. and height is curvilinear, or the relationship of the constants and coefficients of regressions of volume on b.a.o.b. in height classes is curvilinear, multiple regressions more complex than the Australian equation are needed and various equations have been tried incorporating further products of d.b.h.o.b. and height, and powers of height for these conditions. These include logarithmic expressions which have been particularly popular in North America. Husch (1963), following Spurr (1952), lists and comments on the various equations, arithmetic and logarithmic, which have been suggested.

Because the use of two-way tree volume tables is very common in Japan, there has been considerable investigation into equations suitable for species in that country, such as those by Ohtomo (private communication) and Takata (1962).

The introduction of high speed computers has increased enormously the scope of investigation into suitable equations. For particular data, a number of likely equations can be calculated and their efficiency compared very quickly. The most satisfactory approach, however, is likely to be that proposed by Lawrence (1965) in which equations are built up, new variables being added as calculation shows them to be effective in reducing residual variation.

Work in Australia suggests that, for plantation conifers, the Australian equation gives a satisfactory fit for total volume and for volume to small diameter limits such as 3 in and 4 in, provided the range of d.b.h.o.b. is limited. The combined variable equation is often almost as satisfactory. If the range of d.b.h.o.b. is extensive or the merchantable limit is lower down the tree, for example 6 in or 8 in, the curvilinearity is such that a more complex equation is necessary. Alternatively, techniques may be used such as that of Cromer, McIntyre, and Lewis (1955) in compiling a General Volume Table for P. radiata, where separate Australian equations were calculated for the sample tree data divided into three overlapping sections.

Methods of compilation for native broad-leaved species vary but most commonly involve fitting suitable regressions of volume on d.b.h.o.b. or b.a.o.b. in merchantable height (log length) classes, or volume on merchantable height in d.b.h.o.b. or b.a.o.b. classes, either by subjective graphical methods or by calculation, then plotting constants and coefficients of these regressions against height or d.b.h.o.b. to harmonise them. Many tables have been compiled by the method proposed by Unwin and Bowling (1951) or a modification of it. Sometimes the combined variable equation or the form factor equation has been considered to give a satisfactory fit. As for conifers, the relationships are probably basically curvilinear and appear to be linear only if the range of the data is limited. The technique of subdividing the sample tree data and computing linear relationships for each section of what is overall a curvilinear relationship has also been used in these cases as outlined by Cromer (1959).

Compilation by alignment chart methods. Many North American textbooks, for example Bruce and Schumacher (1950), refer to the use of an alignment chart to compile a volume table. An alignment chart, or nomogram, is a graphical representation of a relationship or function in which the axes representing the variables are separate straight lines or curves and do not intersect as do the axes on co-ordinate paper. The scales on the axes, and the relative position of the axes, are so arranged that a connection line across the chart intersects the axes at particular values which satisfy the function illustrated. The theory and practical construction of such charts are outlined in various texts on mathematics. The common use of such a chart is to display a relationship already established by other graphical methods or by calculating an equation. The method of compiling a volume table which is suggested by the North American texts is to prepare an alignment chart on the basis of an assumed equation and then gradually shift the scale positions of the axes in an iterative process until the volumes estimated from the chart are sufficiently close to the actual volumes. The final chart thus represents a modification of the original equation but its exact form need not be determined, since the chart forms the volume table. This method of compilation has not been used to any extent in Australia. The methods discussed previously are likely to be more efficient.

Application

The application of a two-way tree volume table to a stand to determine stand volume depends on the structure of the stand, the number of trees whose volume is to be estimated, and the standard of reliability of estimate required. When there are few trees or the variation in height between trees within a d.b.h.o.b. class is considerable, the usual practice is to estimate the volume of each tree individually through its height or log length. When there are many trees, or the variation in height within a d.b.h.o.b. class is limited, the normal practice is to compile the stand height curve, read from the volume table the volume corresponding to the tree of average d.b.h.o.b. and height for each class, multiply this average volume by the class frequency, and sum these class volumes. Sometimes the class average volumes are plotted against d.b.h.o.b. or b.a.o.b. and smoothed graphically before being multiplied by class frequency.

Freese (1960) has outlined a method of testing the 'accuracy' of a volume table in application.

Applicability

Trees of the same diameter and height differ in volume because of differences in shape and taper. The logical approach to tree volume table compilation and application is to establish the extent of such differences and the pattern of their correlation with species, provenance, and environment; to compile tables for stands of particular characteristics to which the tables can be indexed, and which have a specified error of estimate; from a range of such tables, to select one suitable to requirements. There is an unfortunate tendency for a volume table to be compiled for a forest merely because it has an entity. irrespective of whether the reasons for this are geographical. political, or administrative. This leads to quite an irrational proliferation of volume tables. Spurr (1952) has commented on the position in the U. S. A. It is hoped that a similar condition which appears to be developing in Australia can be avoided.

Malformed trees

In coniferous plantations, stems which are divided from ground to tip, usually called 'double-leaders' or 'multiple-leaders', commonly occur for various reasons. Usually the volume of such a tree is derived

by applying an appropriate correction to the volume read from a volume table for a normal tree of the same d.b.h.o.b. and total height. Depending on the size of the tree, the number of leaders, and the limit of utilisation, so the volume of such a tree is more or less than that of a normal tree. Duff (1950) has developed correction factors for radiata pine in New Zealand which seem to apply quite satisfactorily to plantation conifers in Australia.

Volume Tables with More than Two Independent Variables

From the previous discussion it will be apparent that, to improve the estimate of tree volume given by a two-way volume table, an expression of tree shape or taper must be included as a further independent variable. If this expression is to be effective as an independent variable, variation in volume must be correlated with variation in the values of the expression, and the expression must be readily identifiable and capable of reliable measurement on standing trees. The difficulty is to find an expression which satisfies these requirements. This might be forecast from a consideration of the variations in the changes in taper over the length of individual trees, particularly among trees of the same species otherwise identical in d.b.h.o.b. and height.

Towards the end of last century, the concept of form quotient was introduced in western Europe. Defined in different ways over the years it is now almost universally accepted as the ratio, usually in the form of a decimal, for example ·65, of the diameter at half the total height above breast height to the diameter at breast height, the diameters being variously over- or under-bark. Trees having the same form quotient are grouped into a form class indicated by the corresponding whole number, 65 in this case. The concept can only be applied effectively to trees which have a single stem from ground to tip. Jonson's stem profile equation (see ch. 6) incorporated constants related to form quotient. Given form quotient, relative values of diameter at percentile points on the stem could be obtained from the equation; form factor could be obtained from the relative values of diameter; and volume could be obtained from d.b.h.o.b., height and form factor. The Jonson stem profile equation thus provided both a taper table and a volume table. Since determining form quotient by direct measurement involved considerable practical difficulty on a standing tree, Jonson sought indexes to form quotient. For stands, a correlation between stand density and average form class for the stand

was developed. For individual trees, a correlation was found between form quotient and form point, the relative height of the centre of wind pressure on the crown on the basis of Metzger's theory of tree shape, the position of the form point being essentially determined by eye. The enormous amount of research into this matter in Europe and North America which Jonson's work stimulated has already been referred to. Interest in the concept has persisted to some extent but its application is limited because of the practical difficulty of determining form quotient directly, and the unreliability of estimating it indirectly for an individual tree through a subjectively estimated form point, and for stands through such indexes as stand density.

Recent interest has been concentrated on expressions of taper, or indexes correlated with taper, which are more practical than form quotient. Spurr (1952) discusses the various ratios suggested for use in the U. S. A., particularly 'Girard form class'. Volume tables have been developed in Sweden based on the ratio of the diameters at 1 metre above breast height and at breast height, and also based on the height above ground of the lower limit of the green crown as an index of taper. Ilvessalo (1947) has compiled tables using as a measure of taper the difference between the diameters at 6 metres above ground and at breast height, using pole calipers for the former measurement. Similarly, Cromer, McIntyre, and Lewis (1955) in the General Volume Table for P. radiata use the difference between the diameters under-bark at 15 ft and 5 ft above ground level, the 15 ft point being reached by ladder. This table incorporates a measure of bark thickness as a further independent variable to provide estimates of volume under-bark. It was found to have a bias in certain sections when applied to P. radiata in South Australia and a Regional Volume Table for use in South Australia was compiled (Lewis and McIntyre, 1963). During the compilation of the General Volume Table it had been noted that, for the same tree height and d.b.h.o.b., differences in bark thickness had on the average more effect than taper difference on the estimate of under-bark volume, and that using under-bark taper between 5 ft and 25 ft height offered some gain in precision of volume estimate over use of 5 to 15 ft taper. Two Regional Volume Tables were compiled of the same kind as the General Volume Table but using as entries tree height, diameter under-bark at 5 ft, and taper under-bark from 5 to 15 ft, and from 5 to 25 ft respectively. The reason for using d.u.b. at 5 ft as an entry to the table rather than a conventional breast height measurement was that there was a large number of sample trees

with under-bark measurement at 5 ft for the sectional method used for tree volume derivation, but very few trees for which d.u.b. at breast height had been measured.

Compilation

In the stem profile equation approach, the volume table is in effect compiled at the same time as the stem profile equation because the form quotient indicates the relative diameters, these indicate the form factor, and this has only to be multiplied by the b.a.o.b. and height of the tree for volume to be derived. However, form quotient can be used, as can any other measure of taper referred to above, directly as an independent variable, quite independently of any stem profile equation, in a suitable equation relating volume to d.b.h.o.b., height, and form quotient. The most commonly used equations are those of the arithmetic type like the Australian equation and combined variable equation with the expression of form included. Logarithmic types have also been tried. Because of the magnitude of the calculations, the use of high speed computers is advantageous.

Application

The inclusion of a measure of taper as a variable in the volume table is intended to improve the precision of estimate of volume of a tree. The extent to which it does so depends mainly on how well the measure of taper used describes the effect of the overall taper of the stem on the volume of the stem. For practical purposes, the measure of taper used is a simple one of ratio or difference of diameters at two places reasonably close to the ground. Tree boles are for the most part irregular and the lower part of the bole is subject to butt-swell. Such a simple measure of taper may or may not relate to the effect of the overall taper on the volume of the tree, and the estimate of the volume of an individual tree may or may not be an improvement over that from a two-way volume table - general experience is that it is likely to be an improvement. However, general experience also indicates that it is difficult to improve the precision of estimate for a stand over that from a two-way table by assuming an average taper for the stand from sampling or assuming a particular trend of taper over d.b.h.o.b. classes. This method frequently leads to biased estimates.

The determination of an expression of taper which does relate to the

effect of the overall taper on the volume of a tree and which can be measured readily is one of the most pressing mensuration problems.

STAND VOLUME TABLES

The concept of deriving stand volume directly from stand variables, instead of through individual trees as in sample tree methods and tree volume tables, has been appreciated and applied in western Europe for more than a century through the use of stand form factor. This is an abstract value, not capable of direct measurement and analogous to tree form factor, representing a correction factor to reduce the product of stand basal area and an expression of stand height to stand volume. The stand form factor for a particular stand has to be determined indirectly from correlations of stand form factors with indexes of stand structure and stand density. Estimates of stand volume by photogrammetric determinations of stand basal area and height on aerial photographs, and correlations of stand form factor with stand density, were made in western Europe and North America over thirty years ago.

Recently attempts have been made to compile stand volume tables by establishing the functional relationships between stand volume and variables such as stand basal area and stand mean height, analogous to the relationships between tree volume and tree variables such as basal area and height, by graphical solution or calculating appropriate equations. Such a stand volume table has been found to be very useful for estimating stand volume from the ground, particularly where basal area estimates can be made readily by angle count method. Stand volume tables, based on indirect estimates of stand basal area through estimates of such things as crown density, are also very useful for estimating stand volumes from air photographs. Probably the most comprehensive study of the relative efficiency of stand volume tables compiled by various methods and incorporating various stand variables is that made by Spurr (1952). He found that over a wide range of stands - even-aged and uneven-aged, of conifers or broad-leaved species, pure or mixed, good sites or poor sites, heavy or light stocking - estimates of stand volume could be made quite satisfactorily in general by a regression such as the Australian equation:

$$V = a + bB + cH + d\,B.H$$

where V = total stem volume per acre, B = basal area per acre and

H = average height per acre, the regressions of volume on basal area in height classes being linear and the constants and coefficients of these regressions being linearly related to height. He found the combined variable equation:

$$V = a + bB.H$$

was almost as satisfactory. He stressed the likely curvilinearity of merchantable volume on basal area and suggested deriving merchantable volume by applying appropriate conversion factors to estimates of total volume from a stand volume table.

Stand volume table compilation in Australia has been almost confined to even-aged stands of P. radiata. In 1953, a stand volume table for P. radiata was compiled by graphical methods by the New South Wales Forestry Commission, using data from 556 sample plots in various N.S.W. plantations, of volume under-bark per acre to 4 in d.u.b., basal area over-bark per acre, and dominant height (the average height of the tallest 20 trees per acre). There was a fairly gentle curvilinearity in the relationships of volume on basal area for separate height classes over the whole range of the data but linearity over the main central part. Cromer and Carron (1956) compiled a stand volume table for P. radiata for the Kowen area in the A.C.T. on the basis of the Australian equation, preliminary investigation having shown that linear regressions of volume on basal area in height classes were a satisfactory fit and that the coefficients and constants of these regressions showed a strong linear trend with height class. The combined variable equation was almost as satisfactory. Cromer and Brown (1956) compiled similar stand volume tables for other areas of P. radiata in the A.C.T.

If volume per acre is expressed as the product of basal area per acre, stand mean height and stand form factor:

$$V = B.H.F.$$

then volume per unit basal area is given as

$$\frac{V}{B} = H.F$$

This relationship has been investigated for various species in various countries. Krenn (quoted by Prodan, 1965b) developed mean tree tariffs, which, in the present context, are stand volume tables from relationships of form height with stand mean height. Form height for a stand being determined from stand mean height, its product with mean basal area gives mean tree volume which, when multiplied by number of trees, gives stand volume. Lewis (1954) compiled a

graphical relationship of total volume per unit basal area on stand top height for unthinned P. radiata in New Zealand which was almost linear and formed the basis of a variable density yield table from which present and future volume could be derived. A variable density yield table for P. radiata in the A. C. T. was compiled by the same method (Carron, 1967). Bedell and Berry (1955) established a linear relationship: $\frac{V}{B} = a + bH$ where V = volume from a 12 in stump to a 3 in top diameter for all trees 4 in d.b.h.o.b. and over, and H = mean stand height, for a variety of Canadian coniferous and broad-leaved species combined. Cromer (1961) carried out an extensive investigation for P. radiata from several parts of Australia. He showed that total volume under-bark per square foot of basal area over-bark bore a linear relationship to stand top height, beyond a stand top height of about 40 ft, of the form $\frac{V}{B} = a + bH$ in which the value of a could for all practical purposes be taken as zero and in which b was approximately the same over a wide range of locality, age, site quality, and density. He suggested that estimates of merchantable volume be made from estimates of total volume by the use of correction factors related to stand mean d.b.h.o.b.

Lawrence (1963) has discussed the compilation of stand volume tables by multiple regression methods for Eucalyptus obliqua and E. regnans in Tasmania.

Application

A stand volume table is a convenient and practicable tool for resource inventory and may provide sufficiently reliable estimates for periodic management inventory under certain circumstances. Where the regime of treatment is reasonably stable and future stand basal area and height can be forecast with some reliability, future stand volume can be forecast through stand volume tables. The limits of application of stand volume tables to single small stands should be recognised. Just as a tree volume table should not be expected to give reliable results for an individual tree, so a stand volume table should not be expected to give reliable results for an individual small stand.

YIELD TABLES

A yield table is a statement of variables such as volume, basal area,

height, and number of trees per unit land area for stands of various age, on sites of various productive capacity, of an even-aged forest of one species which has developed naturally, or has been maintained artificially, at a consistent density. It is a quantitative expression of the pattern of growth of a particular crop on a particular site. It is compiled from relationships, established graphically or by calculation, between the stand variables as dependent variables and age and an expression of the productive capacity of the site as independent variables. It represents a history of development of an even-aged forest and for that reason is discussed in detail in Chapter 17. It is included here as a means of estimating stand volume because it is a kind of stand volume table in which the independent variables are age and site. Once the mapping of site quality has been carried out, estimates of stand volume at any age, present or future, can be made without any further field work. If estimates of volume are required for stands of a density other than that on which the table is based, corrections to table volumes have to be made through some measure of stand density. Better results may be obtained from a yield table which incorporates a third independent variable expressing stand density. The name variable density yield table has been given to this in North America, where its compilation and application have received particular attention (Spurr, 1952; Husch, 1963).

Yield tables have been used for estimates of stand volume in resource inventory in Great Britain, West Germany, and the Netherlands and also in management inventory in some instances in western Europe. N.B. Lewis (1957) discusses the use of a yield table for inventory of radiata pine in South Australia.

COMPARISON OF METHODS

Sample tree methods can be applied satisfactorily only to even-aged stands. Tree volume tables may be applied to both even-aged and uneven-aged stands. Stand volume tables may be applied to both even-aged and uneven-aged stands; in practice, they are applied most often to the former. Yield tables are applicable only to even-aged stands.

Stand volume is determined from sample tree methods and tree volume tables by applying them to individual trees, directly or indirectly, usually within sampling units. Stand volume tables and

yield tables are applied directly to stands, usually through sampling units.

To compile tree volume tables one requires selection and measurement of volume of sample trees; for stand volume tables one requires estimates of stand volume (from sample tree methods or tree volume tables), stand basal area, and stand height; for yield tables one requires estimates of stand volume (from sample tree methods, tree volume tables or stand volume tables) at various ages on various sites periodically during the development of the crop.

To apply any method, the area of the stand must be known. If the estimate of stand volume is based on sampling units, the area of each sampling unit must be known except when stand basal area is estimated by the angle count method.

To apply sample tree methods, the d.b.h.o.b. of each tree in the stand or in each sampling unit must be measured; the height and taper of some trees may also be needed; sample trees must then be selected and their volumes determined. To apply one-way tree volume tables, the d.b.h.o.b. of each tree in the stand or in each sampling unit must be measured; for tariffs, the stand variable by which the tariffs are indexed must be measured. To apply two-way tree volume tables, the d.b.h.o.b. of every tree must be measured, and either the height of every tree must be measured or a stand height curve compiled from sample trees. To apply three-way volume tables, the d.b.h.o.b. of every tree must be measured, either the height of every tree must be measured or a stand height curve must be compiled from sample trees and either the expression of taper or form of every tree must be measured or an average determined from sample trees. To apply a stand volume table, estimates of stand basal area and stand height are required on a unit area basis. To apply yield tables, the age and site quality (site index) of the stand must be known; also the index of density for a variable density yield table.

Very few investigations have been made into the relative reliability of estimates of the volume of a particular stand by these several methods. One of local interest is that of E.R. Lewis (1957) who considered relative errors in various methods used by the New Zealand Forest Service in pure even-aged coniferous plantations. Further comments on the methods are contained in a review by the N.Z.F.R.I. (1965).

STAND VOLUME BY ASSORTMENTS: TAPER TABLES

The main stem of a broad-leaved tree is considered to end at the break of crown. For utilisation the stem is topped there and so volume is usually estimated to that level. Relationships, sometimes complex, between this 'merchantable' volume and other tree variables can be established. For conifers, the main stem is considered to extend to the tip. Relationships between this total volume and other tree variables can be established readily and are usually simple. Total volume is, however, unrealistic from a utilisation point of view since conifer stems are in practice utilised only up to certain diameter limits. Since it is difficult to relate this 'merchantable' volume to other tree variables, as for broad-leaved species, estimates of merchantable volume of conifers are often made by applying correction factors to estimates of total volume. It is found, for example, for P. radiata in an even-aged stand, that the volume of an individual tree to a particular diameter under-bark limit can be expressed as a percentage of total volume, the percentage varying with tree d.b.h.o.b., but not with height within d.b.h.o.b., as illustrated in Table 13:2. It is also found for P. radiata that the volume of a stand of trees to some upper diameter limit can be expressed as a percentage of the total volume of the stand, this percentage varying with stand mean diameter (E.R. Lewis, 1954; Cromer, 1961).

Table 13:2

Volume under-bark from ground to 4 in d.u.b. as a percentage of total volume under-bark for 200 sample trees of P. radiata, Kowen Forest, A.C.T.

D.b.h.o.b. class (in)	Total height class (ft)							D.b.h.o.b. class average
	30	40	50	60	70	80	90	
5	64	65						65
6	77	75	77	70				76
7	87	85	86	85				85
8		90	90	91	90			90
9		92	93	94	94	95		93
10			95	96	96	96		96
11			95	96	96	96	97	96
12			97	98	98	97	98	97
13				97	98	98	98	98
14						99		99
15					99	99	99	99
16							99	99

Estimates of stand volume are of greater value to management if made in terms of lengths of logs and their diameters under-bark at the small end of the log. These estimates for a stand may be provided by a combination of a stand table, a stand height curve, and a taper table. A taper table is a tabular statement which shows for a particular species, and usually under particular silvicultural conditions or for a particular locality, the over-bark or under-bark diameter at specified heights from ground for trees of specified d.b.h.o.b., total height, and perhaps form or taper. For some purposes, the height from ground to a specified diameter is given. Since the profile of the tree is defined by the taper table, so the taper table defines the volume of the tree, and tables of volume to various upper diameter limits are usually compiled in association with taper tables, exemplified by the combined taper and volume tables for various exotic conifers in New Zealand by Duff (1954), Duff and Burstall (1955), and Burstall (1957). These tables were compiled by graphical methods from data of sample trees. The means of under-bark diameters at various specific heights from ground level, within total height class within d.b.h.o.b. class, were plotted against height from ground level on rectangular co-ordinate paper and tree profiles drawn by freehand curves harmonised within and between d.b.h.o.b. classes. Two-way tree volume tables were then compiled from these generalised 'trees'. In this method of compiling taper tables, variations in taper within height and d.b.h.o.b. classes are smoothed out by averaging diameters along the tree profile within classes, and variations of these averages between classes are smoothed out by harmonising the profiles between classes.

The tables of Jonson referred to previously give diameter at percentile points along the stem, as a percentage of diameter at breast height, as derived from the stem profile equation for various values of form quotient. Once such a stem profile equation is established, the associated taper table follows simply by substitution of appropriate values of the index of form in the equation. Taper tables based on stem profile equations with form quotient as such an index were compiled in the 1920s and 1930s, when Jonson's work had attracted international attention, by various workers such as Wright (1927) in Canada and Behre (1927) in the U.S.A.

Taper tables for plantation conifers in Australia have been compiled by several Australian forest services but not published. Carron and Jacobs (1964) compiled a taper table for P. radiata which is based on Gray's hypothesis that the main stem is a paraboloid of the second

degree (see ch. 8) and which is applied to an even-aged stand through tariffs compiled by Cromer and Carron (1957). Using this taper table Carron (1964), following a procedure developed by Warren (1959) for P. radiata in New Zealand, compiled a relationship for even-aged stands of P. radiata whereby the percentage of stand volume within various log small end diameter classes can be determined from stand mean d.b.h.o.b.

14 Bole Area

The bole area of a tree is its peripheral surface under-bark. For practical mensuration purposes, the increment of wood volume over a period can be considered as a layer placed on this surface, a sheath of wood with an area equal to the surface area of the tree at the beginning of the period and a thickness which may vary over the length and around the circumference of the bole depending on where and to what extent growth takes place. The bole area of a tree can be regarded as the base for potential increase in the volume of the tree, so that the sum of the bole areas of the trees in a stand represents the base for potential increase in the volume of the stand. Since the wood producing capacity of a stand is obviously important to silviculture and management, tree and stand bole area are variables of particular interest. Surprisingly, serious attention has been given to the usefulness and estimation of this stand variable only during recent years and then only in a limited way.

The first reference in English appears to be that by Lexen (1943) who pointed out that it was then customary in the U.S.A. to describe the intensity of selective cutting by the volume of wood left in the stand and that, while this provided a measure of the wood capital left, it did not indicate the growth potential of the cut-over stand. He suggested that this shortcoming of volume could largely be overcome if it were supplemented by an estimate of bole area and illustrated this by numerical examples. He suggested calculating the bole area of an individual tree, by analogy with the calculation of volume, by substituting girth for sectional area in the Huber or Smalian formula; or by plotting girth at several positions along the stem on rectangular co-ordinate paper and computing the area below a curve fitted to the plotted points. He compiled a bole area table for individual trees, in the form of an expression involving d.b.h.o.b. and height for Pinus

ponderosa for purposes of illustration, and suggested that an approximate estimate of bole area in square feet of a P. ponderosa could be obtained by dividing 7·0 into the product of d.b.h.o.b. (in) and height (ft). (This factor 7·0 contains an element analogous to form factor used in reducing the product of tree basal area and height to tree volume. Here the value 7·0 incorporates π to convert diameter to girth, 12 to convert girth in inches to feet, and a factor to reduce the product of tree girth and height to tree surface area.) From this the bole area of a stand could be derived, either as the sum of the bole areas of individual trees so calculated, or through the bole areas of average trees by diameter classes, or as the product of the bole area of a 'mean' tree and the number of trees in the stand.

Mulloy (1944) compared, for a number of plots of red and white pine, the stand bole area calculated as the product of number of trees and the bole area for a tree of mean diameter and height, with values of Reineke's stand density index (see ch. 16) derived for the plots and concluded that 'for all practical purposes they provide the same relative measure of density index'. Lescaffette (1952) discussed the concept in general and the derivation of values of 'surface génératrice' appropriate to a 'tarif de cubage'. Hummel (1953) considered bole area as an index of stand density and drew attention to the fact that 'examination of several British and central European yield tables suggests that, above a certain age, the bole area remains more or less constant until the limit of height growth is reached and then the bole area starts to decrease ... not only for stands thinned lightly but also stands thinned heavily provided the thinning regime is consistent'. However, he rejected bole area as an index of stand density, regarding it as 'cumbersome to apply'. Briegleb (1952) also considered bole area as an index of stand density in comparing stands of Douglas fir, but found it unsuitable. Hiley and Lehtpere (1955) used an expression of bole area to illustrate how coniferous plantations in Great Britain might be thinned to produce a specific number of rings per inch. Anuchin (1962) demonstrated that, for a wide range of species in the U.S.S.R., stand bole area appears constant within a site quality over a wide range of age. On this basis, he developed from yield tables for pine stands a relationship whereby volume increment of a stand could be forecast from a knowledge of site quality, average radial increment over the previous ten years, and a measure of stand density.

Table 14:1 is a tree bole area table compiled by the writer from 229 sample trees of P. radiata from Uriarra Forest, A.C.T., which were

Table 14:1

Tree bole area table for P. radiata, Uriarra Forest, A.C.T., all ages and sites, based on 229 sample trees; values in top left corner of cell represent bole area (sq ft); values in bottom right corner represent factors whereby bole area (sq ft) may be derived by dividing the factor into the product of d.b.h.o.b. (in) and total height (ft)

D.b.h.o.b. (in)	Total height (ft) 40	50	60	70	80
6	37 6·5	46 6·6	54 6·6		
7	42 6·7	52 6·8	62 6·8		
8	47 6·9	58 6·9	70 6·9	82 6·8	
9	51 7·0	64 7·0	77 7·0	91 6·9	
10	56 7·1	70 7·1	84 7·1	100 7·0	115 6·9
11		76 7·2	92 7·2	108 7·1	125 7·1
12		82 7·3	99 7·2	117 7·2	136 7·1
13				126 7·2	146 7·1
14				135 7·3	156 7·2

selected over the range of age and site, and measured by the sectional method, for compilation of a tree volume table. The bole area of each tree has been calculated as an approximation in the way suggested by Lexen (1943) and the table compiled by the harmonised regression series method as for a two-way tree volume table (see ch. 13). Lexen's 'factor' for each d.b.h.o.b. -height class is also shown. There appears to be a correlation of factor with d.b.h.o.b. class but the values are reasonably constant over height classes and the overall variation is so relatively small that a useful approximation to the bole area (in square feet) of these and similar stands might be obtained simply by dividing the product of stand d.b.h.o.b. (in), stand mean height (ft),

and number of trees by 7·0, the same factor as Lexen found for P. ponderosa.

15 Site Quality

A forester has a broad silvicultural interest in the productivity of land - in the alternative kinds of forest an area will support and in the factors which determine the occurrence of a particular kind of forest on an area. Mensurational interest in site is much narrower. The main concern of a forester, in a stand managed for production of wood, is in its volume, present and future. Because the volume of wood in a stand at any time is largely a reflection of the site it occupies, estimation of volume is assisted if the site can be classified as one or another site quality class. As volume is the criterion of site quality, it is the logical basis for the classification. Alternatively, an index to volume production might be used - a factor of the environment or a statistic of the crop.

Since age has an important influence on production, it is convenient to consider even-aged forests of a single species separately from others.

Even-aged Forests of One Species

There are many factors of the environment which influence the growth of a tree crop. They interact, and it is difficult to consider any one of them, and the relationship between it and tree growth, in isolation. Furthermore, there is a continuing reaction between the factors of the site and the stand as it develops. The environment of a forest might be regarded quite simply as the soil and the climate of its atmosphere. Criteria of climate are used successfully for broad qualitative classifications of forest but have not been found suitable for quantitative classification of stands. Many of the factors of the environment are integrated in the soil, and because reference to soil characteristics is of obvious value for qualitative site classification, considerable

attention has been given to establishing relationships between tree growth and soil characteristics such as texture, and depth and availability of water and nutrients. In many cases good correlations have been obtained. There is an extensive literature on this subject which has been summarised by Rennie (1963). However, the use of soil characteristics as an index of productivity for pure even-aged forests has been inhibited by the work involved in establishing the important soil characteristics for a particular forest, the complex nature of the relationships between growth and soil characteristics, and the difficulty of evaluating the characteristics in a particular case. Good correlations have been established between soil characteristics and statistical indexes of site (see p. 129). Work by Pegg (1967) on the relation of site index of plantations of Pinus elliottii in south-east Queensland to soil, vegetation, and climate is of interest.

A ground vegetation of mosses, grasses, ferns, flowering plants, shrubs, and small trees often accompanies a main forest crop. It might be expected that differences in site quality would be reflected in the kind and amount of this lesser vegetation. If differences in productivity of the main crop could be correlated with them, these indicator plants could be used as the index for stratifying the main crop into site quality classes. The first large-scale exposition of this concept was presented by Cajander (1926) for Finland. Statistical indexes of the main crop such as stand volume and stand height had been in use in Europe for some time. Cajander conceded these were effective for productivity classification but he sought an index whereby not only could a forest be classified into productivity classes but at the same time the land could be classified according to its potential productivity under other species. He found this index in the lesser vegetation. Ilvessalo stimulated further interest in this system by work in the northern hemisphere, and this use of indicator plants as an index for quantitative site classification has since been demonstrated in many parts of the world (Rennie, 1963). However, the system is not in common use. Lindsay (1939) was able to make a broad classification of productivity of stands of alpine ash (Eucalyptus gigantea) in southern N. S. W. on the occurrence and density of the shrub Veronica derwentii. Lesser vegetation is often used in Australia as an indication of the suitability of a certain species for afforesting or reforesting an area and as a rough guide to the potential productivity of the species. Once a coniferous plantation is established, the return of the original lesser vegetation is usually artificially discouraged.

The simplest, most effective way of classifying stands of an even-aged forest of one species into productivity classes is through a relationship between statistics of the main crop and age over the range of age and productivity. Two statistics have been found useful - stand volume and stand height. The relationship of each of these with age for a site is a curve which is in general of a sigmoidal nature. For a forest, the curves over the range of site are usually anamorphic but they may be polymorphic. For this reason, and because the exact nature of any one curve can rarely be determined with any certainty, the curves are usually drawn by hand rather than the best fit calculated for some assumed form. The way in which the curves are compiled is similar for volume and height and is illustrated for height later.

Though stand volume is the criterion of site productivity, it is influenced by stand density and its use for site quality classification is restricted to fully stocked (normal) stands. It is used for site classification in some countries of western Europe where intensive management over a long period has ensured full stocking. For example, sites are classified according to mean annual increment of volume at 100 years of age. 'Volume per acre which is produced by stands fully occupying the site' (Lewis, 1957) is used in South Australia for site quality classification of radiata pine plantations, though the actual mapping of site quality boundaries in the field is based on indexes to volume production (see p.133).

Where variation of density in stands of the same age on the same site produces variation in volume, a better classification of site may be provided by an expression of the heights of the tallest trees of the stand, since these are correlated with the productive capacity of the site but are not affected by varying density within the usual limits of the range of density found in stands in forest conditions. Various expressions of the tallest heights have been used for this purpose. For coniferous plantations in Australia stand top height (predominant height) is commonly used, being the average of the heights of the 20 to 30 tallest trees per acre. For even-aged stands of eucalypts in Tasmania, Cromer and Bowling (1961) used mean height of dominants, the average of the heights of the tallest 12 trees per acre at the rate of one tree per 1/12 acre. Lawrence (1966) also used this as mean dominant height. In Great Britain, top height is used, being the average of the heights of the 40 trees of largest girth per acre (Johnston and Bradley, 1963). It is quoted as 'corresponding conveniently with the International Union of Forest Research Organisation's recommendation of 100 per hectare

which is already in use in parts of Europe'. Mean top height has commonly been used in New Zealand for coniferous plantations, being the height on a stand height curve equivalent to the mean basal area of the 100 largest diameter trees per acre. In North America, the average of the heights of dominants or dominants and codominants is commonly used (Spurr, 1952; Husch, 1963). Spurr has discussed the disadvantages of this.

There are various ways of compiling the height-age curves, depending on circumstances. There are three likely cases. Assume a coniferous plantation in Australia in which stands vary in age from 1 to 40 years. Temporary sampling units are established over the range of site and age (down to say 8 years, since below that the factors of the site will probably not have found true expression) and stand top height is determined for each unit. Age and related top height values are plotted on rectangular co-ordinate paper giving a comet-tail scatter of points. Fitting curves to this scatter is not satisfactory because there is no way of knowing the trend of height with age. Nevertheless, height-age curves may have to be drawn from this sort of data in the preliminary stages of management, as in western Europe about two-thirds of the way through last century and in recent years in New Zealand (Lewis, 1954). If, on the other hand, permanent sampling units had been established as the stands were planted and top height continually measured, this would provide a complete height-age stand history for some stands with variously incomplete history for the others. The trend of height-age would then be clear. Complete history of this kind may also be provided from individual trees if they have annual rings and it can be assumed that the present tallest trees have always been the tallest. Alternatively, stem analysis information can be used to support periodic measurement. In the third and most common circumstance, intermediate to the two extremes discussed above, sampling units are established over the range of age and site when the oldest stand is say 30 years and top height is measured several times in 10 years. The resulting 10-year segments of the height-age history of the stands, though not as good as complete history, provide better evidence than one measurement on which to gauge the trend in height-age over the complete range of age. Whatever the data, classes have to be formed of an interval which depends on the number of site quality classes required, and on the range of height for the range of site, usually the range at what is called standard age. This age has to be such that each site has had opportunity to express itself, yet not so

advanced that the available data will be too restricted, and such that all sites are represented. If the classes are defined by height values and can be thought of in terms of mean annual increment in height, it is arithmetically advantageous to have an age which is a simple factor of the height values; for example, 20 or 25 years is commonly used in coniferous plantations in Australia. The age usually recommended is about two-thirds of rotation age. An age of 80-100 years is commonly used in Europe. In some cases, the range of height at standard age is divided into the required number of classes with an equal interval, the classes being labelled with Roman numerals (I usually the best), and referred to as site quality I, site quality II, and so on. In South Australia, for example, seven such site qualities are recognised for P. radiata (Lewis, 1963b), five of them being thinnable. Alternatively, intervals of some specific width such as 10, 15, or 20 feet are established, the classes then being called site index classes. The classes may have mid-points such as 60 feet, 70 feet, 80 feet, with limits 55-65, 65-75, 75-85 and called site index 60, site index 70, site index 80; or mid-points 65 feet, 75 feet, 85 feet with limits 60-70, 70-80, 80-90 and called site index 65 and so on - except that in Queensland they are called site index 6, site index 7. A standard age of 20 years has been adopted for P. radiata in the A. C. T. (Carron, 1955). For plantation conifers in Queensland, a standard age of 25 years has been adopted (Queensland Department of Forestry, private communication).

The means or limits of the classes then form nominated points on the height axis of the co-ordinate paper at standard age through which the curves of height-age must pass, the trend of the curves over the range of age being determined from the height-age data. Two methods are commonly used to fit the curves by hand. One method is to draw two curves based on the upper and lower limits of the data respectively and then draw a family of curves intermediate to these in position and shape passing through the obligatory points on the height axis at standard age. The shape of the family of curves is thus determined from two limiting curves based on data which, representing only the best and worst sites, are likely to be least in amount and lowest in reliability, while the more numerous and more reliable data of the most common sites are ignored. Gray (1945) recommended this method (which is often referred to as Baur's method, the limiting curve method, or the strip method and was used in western Europe last century (Jerram, 1939)) as a stop-gap method for coniferous plantations in Australia until some stand history had been recorded by periodic

measurement. He suggested getting stem-analysis information from only the best and worst sites to save time and money since any other information would not in effect be used. In the other method (often referred to as the guiding curve or directing curve method) an average of the heights over the range of site at various ages is plotted, a 'master' curve fitted to these values, and a family of curves built up by proportion. That is, the curves are located with respect to the master curve at each age in the same relative position as they are at standard age. All the data thus contributes to the shape of the curves. This is the 'harmonised or anamorphic site-index technique' described in North American textbooks such as those of Spurr (1952) and Husch (1963).

In the first method the trend of the limiting curves will not be correctly determined unless the history of height-age for the best and poorest sites is complete. In the second method, unless all sites are represented equally at all ages, the averages of height at various ages will be biased and a guiding curve fitted to them will lead to a family of curves biased in both position and shape. For natural forest, stands on all sites at all ages may not occur. In the case of plantations, it often happens that the better sites are planted first and the poorer ones later. Alternatively, poor sites may be planted for reasons other than production, for example as a conservation measure, and their success prompts extension of the plantation into better areas, as for a plantation of radiata pine in the A.C.T., the site-index classification of which is described by Carron (1967). A height-age relationship can be established with confidence only when there are height-age data for all sites and all ages. The validity of the relationship for a particular case depends largely on how well the data meets this requirement. Since the ideal is rare, the curves are usually fitted by hand. Complete data are also necessary for a reliable decision on whether the curves are anamorphic or polymorphic. Anamorphic curves are often accepted merely for convenience or through ignorance because of inadequate data.

Once the height-age relationship has been prepared, mapping of site quality or site index of a forest can be carried out. By reference to the curves, or a table compiled from them, the site quality or site index of an area can be determined from the age and top height of the stand. One method of mapping is to survey parallel lines over the forest and, while walking along them and wholly or partially covering the space between the lines, to select the tallest trees, measure their

heights, locate them on a suitable map such as a compartment plan, and draw in boundaries to define site classes accordingly. If there are fairly sharp changes in slope, aspect, and soil characteristics, and changes in site are well correlated with them, the boundaries may be located fairly readily. Otherwise it may be difficult to locate the boundaries, and various techniques within this general method have been developed to cope with this difficulty. One description is given by Carron (1955), another by the Queensland Department of Forestry (1962).

It is not always convenient to use an expression of the heights of the tallest trees as the index of site even though it is an effective one. For example, Lewis (1954, 1957) discusses the method of site quality mapping of radiata pine plantations in South Australia. Since thinning of areas of high site quality should commence at about age 11 years and a little time is needed to organise this, mapping of site quality must start at about age $9\frac{1}{2}$ years. The criterion of site quality is volume per acre, most areas being silviculturally fully-stocked. Stand top height is, however, well correlated with volume and can be used as an index to it for convenience in practice, but at age $9\frac{1}{2}$ years there are practical difficulties in measuring height in unpruned unthinned stands.

Mapping site in such stands is therefore carried out on the basis of other site indicators which are more readily seen and measured than height, such as 'vigour, form, crown density, needle length and colour, tightness and colour of bark, green level and degree of canopy formation particularly before thinning' of which height to green level is perhaps the most useful in practice. The mapping is done by running parallel lines 3 chains apart, changes in the site indicators being plotted at a scale of 10 chains to 1 inch on strip-line sheets for about 1 chain each side of the line with a minimum distance between changes along the line of about a half-chain. The boundaries are transferred to compartment plans and drawn over the 'blind' section of about 1 chain width between the strip-lines. To ensure consistency between operators, temporary test plots are established, their volumes determined, and the characteristics of the stand associated with the site quality as defined by volume are noted. These plots are then used as yardsticks in the site assessment.

The conventional practice of dividing the range of top height into a number of site quality classes with equal class intervals of height, or establishing site index classes of specific equal width, has the disadvantage that these classes of equal interval of height may not

represent classes of equal interval of volume. In some cases, the intervals of height are arranged to represent equal intervals of volume. In the Forest Management Tables of Great Britain (Bradley et al., 1966) for example, the yield classes are based on an interval of 20 Hoppus feet maximum mean annual increment in volume and the top height-age curves, on which the yield classes are determined in the field, are so positioned at unequal intervals of height to represent the equal intervals of volume MAI.

Site quality boundaries are usually not marked in the field. Compartments often assume an unjustified importance as management units in plantations because access for utilisation and protection is organised around their boundaries. Site qualities may be more important than compartments as basic units and the positions where site quality boundaries cross compartment boundaries may often with advantage be marked in the field.

Uneven-aged Forests of Mixed Species

A site quality classification of an even-aged forest of one species permits estimates of present volume to be made more efficiently than otherwise because variation in volume in each site quality class within each age class is reduced to a minimum, and the more homogeneous an area with regard to volume the more simple and efficient the method of estimation and the more reliable the statement of the estimate. Also, since the behaviour with age of a stand of a particular site quality can be forecast, estimates of future volume on a stand basis are possible. Further, since different sites have different rates of growth, they usually have to be given different silvicultural treatment and this can be organised and effected more efficiently if site classification has been carried out.

By contrast with an even-aged forest of one species for which the efficiency of both estimating volume and silvicultural treatment is enhanced by the classification of site quality within age, the most efficient stratification for volume estimation of an uneven-aged forest of mixed species is usually by species or species mixture, the proportion of various size classes and height classes, and relative crown cover, since the influence of species, age, site, and density on volume production are confounded in a complex way. For silvicultural purposes, a stratification by forest type is usually the most efficient.

16 Stand Density

One of the most important requirements in the management of a forest stand is to ensure that there is, at each stage of the development of the stand, just the right density of tree material to accord with the object of management. It is one of the fundamental laws of silviculture that there is a relationship between the development of a stand and the density of the stand. However, to define in concise terms just what we mean by the density of a stand is rather difficult and perusal of the literature on stand density suggests that foresters are far from agreement on what the term implies. The basis of our concept of stand density lies in the fact that if we look at a forest stand we get an impression of the way the tree material fills up an air space. We think of the density of the stand in terms of the amount of tree material per unit area or space. This concept of density gives us an attribute which improves the value of our description of the stand but is valuable for practical management only if we can express it in a quantitative way. If management is to ensure the right amount of material at each stage of stand development, the forester needs a schedule of reference whereby he can determine if the stand has the right density or not and regulate it artificially if necessary. An index of stand density is therefore needed, a measure of some stand variable which will indicate the amount of tree material in a stand per unit area or space. The regulation of stand density is a concern of silviculture; providing an index of stand density tends to be the concern of mensuration. In considering likely variables to describe stand density in quantitative terms we have to consider several aspects.

Firstly, we have to consider what 'amount of stand material' means because this will differ depending on what particular part of the stand one is interested in and this depends on the kind of stand, the stage of its development, and the objects of management. Interest in the stand

may range, for example, from a biological interest in the gross weight of vegetable material above and below ground, to a commercial interest in the quality of a certain part of the tree bole. We have to be sure the index implies the same thing to all people or that the different amounts they are variously interested in can all be derived from the index.

Secondly, the variable for the index of density has to be such that if two stands are otherwise the same but differ in that variable, then this difference will be reflected in a difference in their growth behaviour. If this variable is altered then the subsequent growth behaviour of the stand should reflect that alteration. This means that we shall want to use the index in a relative way. We talk, for example, of a stand as not 'fully occupying the site' when it is not using the factors of the environment to the fullest extent. We judge this by the amount of material on the site or the way the stand is behaving. To put this in quantitative terms by means of the index of density requires that this index be used in a relative way. This means setting up a standard. Establishing this standard, however, means defining what we mean by 'fully occupying the site'. Do we, for example, mean that the stand has maximum volume or is producing maximum increment in volume; and by 'maximum volume', do we mean the gross volume of the maximum number of trees or the volume of wood of a particular quality on the minimum number of trees? The standard may be based on biological or management grounds.

Thirdly, the variable for the index of density has to be one which can be measured and applied conveniently in practice so that stand density regulation can be carried out on the basis of it; or some other variable, which can be used for this purpose, has to be correlated with it.

There are some further requirements of an index of density. For obvious reasons it should be simple and objective. It should also be independent of age and site; the introduction of density as a basis for stratification of a stand further to that on the basis of age and site will not improve estimates of volume if the index of density is correlated with age and site. The index should also be a variable which lends itself to forward projection; future yield is likely to be influenced by the density at the future time which will be a reflection of the present density. Ideally, the index should be applicable to any kind of stand, from the simplest - a stand of one species, age, and site, to the most complex - a stand of mixed species, uneven-aged and with variation of site.

In summary, then, the index of density should be simple and objective, and definable in both absolute and relative terms. It should be such that quantitative differences in the value reflect different behaviour between stands at a particular time, and different behaviour within a stand during its development. It should be correlated with other stand variables. It should be independent of age and site. It should be applicable to any kind of stand. Reflecting on the complex biology of forests and the varying requirements of management, it is reasonable to assume that no single measure will meet all these requirements and that a number of different measures may be necessary to cover the wide range of conditions. Many measures have been proposed. Because they aim to describe the stand and reflect its growth behaviour, some of the measures proposed might be described as biological. Since the regulation of stand density has to be practised on the basis of the index, some indexes proposed might be described as practical, such as those referred to as 'measures of thinning grade' and 'definition of thinning treatment'. Once a schedule of regulation of density of a stand has been developed, for example by experimental trials, to suit a particular biological purpose or object of management, the density of the stand to be left as the main crop may be described in any convenient terms for practical implementation of the schedule. In even-aged stands where the tree size is reasonably uniform and where, particularly in the case of plantations, the trees are reasonably symmetrically distributed, the desirable density of a stand of a particular age on a particular site can be described by various stand variables, alone or in combination. This sort of index is derived essentially for the practical purpose of implementing a thinning schedule.

Indexes of Stand Density

Since a stand comprises a number of trees of different size distributed spatially over an area of land, its density, as amount of stand material per unit area or space, is a function of three elements - the number of trees, their respective size, and their spatial distribution. To be complete a measure of density should incorporate these elements. Number of trees can be determined, readily or otherwise, by counting. Spatial distribution of trees is not readily determined, however, and is taken into account in measures of density only indirectly, for example by assuming a generalised rectangular or triangular spacing. This is

perhaps a serious deficiency in measures of density, but the inclusion of a direct expression of spatial distribution has been generally avoided because of its complexity. There are a number of factors involved in individual tree size: the stem which can be characterised by diameter, height, and taper; the crown which can be characterised by spread and depth; and the root system which might similarly be characterised by its spread and depth except for the difficulty of measuring them. The most likely tree variables for inclusion in a measure of stand density are those which are readily measured, are intercorrelated with the other main variables of size, and in sum or average represent a stand characteristic efficiently.

Number of Trees

In many cases where the size of the individuals can be taken as constant or the difference in size of individuals can be ignored, the number of individuals serves well as a measure of density. For example, the density of human and animal populations is usually expressed as number of individuals per unit area; and for many purposes of ecology the density of small plants is defined (as by Brown, 1954) in the same terms. In young forest stands where the only concern is whether the number of trees considered necessary for the satisfactory development of the stand is present, density may also be described by the number of individuals.

Number of trees may also be used as a practical index of density for implementing a schedule of stand density regulation where the desirable number of trees, at that age on that site for that species, has been decided on. It is to this context that the term stocking, meaning number of trees per unit area, is best restricted. In this context, too, the descriptive terms of a relative kind such as under-stocked, fully-stocked and over-stocked are appropriate.

For most purposes, the variation in tree size is important in the general concept of density since the efficiency of individual trees and their contribution to the total growth of the group usually depends on their relative size, and for a satisfactory measure of density, number of trees must be combined with tree size.

Number of Trees and D.b.h.o.b.

The most commonly quoted index which incorporates directly the number of trees per unit area and a measure of d.b.h.o.b. is the

stand density index of Reineke (1933). Reineke showed that if values of number of trees per acre of even-aged stands 'at full density' were plotted on logarithmic cross-section paper against values of average diameter of the stands, a straight line relationship could be established. He found that the slope of this 'reference curve' (for maximum density) was identical for a number of species, though the heights of the curves at a given diameter varied amongst the species. He suggested a stand density index for a stand could be determined by 'plotting its number of trees and diameter, passing a line parallel to the reference curve through this point and reading the number of trees per acre at its intersection with the 10 inch ordinate' and that this expression might be used 'for comparisons between species and within a species'. He found there was 'no significant or appreciable correlation between age or site quality and the number of trees per acre for a given average diameter'. Reineke's stand density index or a related concept has been used by many workers in North America. Spurr (1952) has a critical review of it and in summary argues for stand basal area. Hall (1959) has used stand density index in investigating growth in volume in natural eucalypt forest and coniferous plantations in Victoria.

Number of trees in relation to diameter is often used as a practical index in thinning in the form of a 'rule of thumb', the required spacing of a tree being indicated by tree diameter plus or times a constant.

The stand basal area is a function of the d.b.h.o.b. of each tree in the stand, being the product of the number of trees and average basal area. On a particular site, the basal area of stands of the same age is likely to vary amongst species. For a particular species, the basal area of stands of the same age on different sites is also likely to vary. But for certain species the basal areas of stands on a particular site are likely to be reasonably constant over a considerable period of the development of the stand, particularly toward maturity, and stand basal area per unit area appears to be a good measure of the extent to which the stand is occupying the site. It is therefore a good measure of density under these conditions and, because of the greater interest of foresters in the management of even-aged stands, it has been used more than any other variable.

Basal area is a practical index of stand density; it can be obtained readily by direct enumeration of stems or by angle count method. Its use can be objected to on biological grounds in that it includes the dead wood of active trees and all the wood of suppressed trees which contributes nothing to the stand. It is, however, a natural base for

standing tree volume, and volume increment and basal area increment are usually well correlated, so that it may be satisfactory on management grounds. Though it has considerable limitations, basal area is probably applicable to more conditions than any other measure of stand density.

Number of Trees and Height

The indexes of this category are of the practical kind for implementing a schedule of stand density regulation, particularly for even-aged stands of known age and site. The commonest expression is the ratio of the average spacing of the trees to the stand height (in the same units). Such height-spacing ratios, as a fraction or percentage, have been discussed by Becking (1953) using triangular spacing, and by Wilson (1946) and Hummel (1953) using square spacing. The stand height used may be either mean or top height; it should effectively reflect site-age.

Number of Trees and Form (Taper)

Because the spacing of trees may have an effect on their rates of taper, a combination of number of trees and rate of taper should provide a measure of density. The difficulties outlined elsewhere of adequately defining taper of trees and expressing this as an average for a stand will indicate that any such measure is not likely to be successful, and none is in common use.

Number of Trees, Diameter, and Height

Briegleb (1952) showed that in young Douglas fir in western Europe and North America, crown width and length were related to both tree height and tree d.b.h.o.b., indicating that the space a young Douglas fir can utilise is related to both its diameter and height. He stressed that this relationship must be recognised when devising density standards for forests in which height at a given d.b.h.o.b. may vary greatly.

Number of Trees, Diameter, Height, and Form

The volume of a stand is a function of these four stand variables. For many purposes, volume is the essence of the concept of density and so it should provide the ideal index for those purposes. From the biological point of view, however, it has the same disadvantage as

basal area. It has the further disadvantage that it is difficult to measure, and a variable correlated with volume provides a more convenient index of density.

The bole area of a stand is also a function of these four stand variables and so is a measure of the amount of stand in the physical sense. Since the bole area of a tree can be regarded as the base for potential increase in the volume of the tree, the sum of the bole areas of the trees forming a stand represents the base for potential increase in the volume of the stand. As such it has particular biological significance. Being a measure of the amount of stand in both the physical and biological sense it should be an effective index of density but the evidence for this is conflicting. Mulloy (1944) showed that for a number of plots of red and white pine in even-aged stands, bole area and Reineke's stand density index were for all practical purposes the same. Wilson (1955) demonstrated a similar agreement between bole area and stand density index based on the ratio of average spacing on mean dominant height for even-aged stands of red pine. Hummel (1953) drew attention to the constancy of bole area over the greater part of the rotation, irrespective of kind of thinning if the thinning regime was consistent, in the case of several British and central European yield tables. Anuchin (1962) also demonstrated that for a wide range of species in the U.S.S.R., stand bole area appeared to be constant within a site quality over a wide range of age. On the other hand, Briegleb (1952) found bole area unsatisfactory as an index of stand density in well managed stands of Douglas fir in Denmark.

It has been suggested that, if the individual trees are nearly all the same height, and if variation in taper can be ignored, stand bole area can be approximated by the sum of the diameters (or circumferences). This should have the same biological significance as bole area but be easier to derive. Cooper (1961) has used sums of diameters as an index of density in investigating the relationship between growth and stand variables. Curtin (1962b) showed a linear correlation of increment in stand basal area and volume with the product of sum of diameters and mean log height for an even-aged coastal eucalypt forest in N.S.W.

Crown Canopy

Since the vigour of its crown is known to be one of the major factors influencing the growth of a tree and observation of the crowns of many species suggests that their vigour is related to aerial growing space,

the amount of space occupied by crowns in a stand might be expected to reflect the density of a stand. Thus per cent crown closure, the horizontal area of crowns as a percentage of horizontal ground area, has been used as a variable in aerial stand volume tables for various species in various countries and as an index in stratifying stands for ground sampling in resources inventory, for example stands of native eucalypts in Australia (F. and T.B., 1951). Its value in this regard depends on how satisfactorily variation of volume in stands of otherwise similar composition and structure related to variation in per cent of crown closure. Because root space may be more important than crown space, measures of stand density based on crown closure are often poorly correlated with other measures.

On the assumption that the area occupied by a single tree is proportional to its d.b.h.o.b., Chisman and Schumacher (1940) developed an equation whereby ground area was related to the number of trees and their diameters on that ground area from data of sample plots of fully-stocked, even-aged loblolly pine stands in North America, and also for uneven-aged mixed conifer and broad-leaved stands. Applied to the data for any one plot it expressed the tree area ratio, the ground area occupied by the trees of the plot as a ratio of the plot area, and the ground area occupied by an individual tree according to its d.b.h.o.b. This tree area ratio was intended as a 'measure of stocking', and 'stocking norm' for a given stand type and condition. That is the density of the trees of an area is expressed as a percentage of the average stocking of any number of sample areas, in this case the sample areas being chosen for full stocking. The ratio was considered to be independent of age and site index. Deetlefs (1953) employed a similar approach, though a more complex equation, for even-aged stands of Pinus taeda with a broad-leaved under-storey in North America whereby the ground area occupied by a single tree or by a component of the mixture can be determined. The density of any stand is determined by substituting number of trees and basal area in the equation; the average density of the stands on which the study was based being 100 per cent, the density of any individual stand may be greater or less than this. He has applied this measure of density in a study of stand density and growth relationships in P. taeda (Deetlefs, 1954).

Krajicek et al. (1961) developed a crown diameter-tree d.b.h.o.b. relationship for open-grown trees from which 'maximum crown area' of a tree could be derived. They defined crown competition factor as

the sum of the maximum crown areas of all the trees in a stand per acre, using it as a measure of density in that it estimates the area available to any tree in a stand in relation to the maximum it could use if it were open-grown. Vezina (1962) tested this in stands of various species and found it varied with age and site quality and did not show any consistent relationship with other measures such as basal area per acre and Reineke's stand density index. Curtin (1964) defined stand density index in effect as the ratio of the area of the crowns of the trees on an acre to that ground area, the crown width of a tree being given by a regression of crown width on the d.b.h.o.b. of a tree and the square of its height, for even-aged pure stands of Eucalyptus obliqua in Victoria, and considered it was independent of age and site quality.

Root Spread and Depth

The vigour of the root system of a tree is as important an influence on the growth of the tree as the vigour of the crown, so that the extent and depth of roots of the stand should reflect its density but, as pointed out previously, it is very difficult to measure.

Growth-Stand Variable Relationships

In recent years many attempts have been made to develop equations to describe relationships between stand variables and their growth under certain conditions. In these equations, various stand variables have been included to serve as expressions of stand density, the efficiency of a variable as a measure of density being judged mathematically by its contribution to the correlation.

Lemmon and Schumacher (1962), for example, studied the diameter and volume growth of P. ponderosa as influenced by site index, density, age, and size, using as expressions of density the basal area of the surrounding stands and the extent of over-storey as measured by a 'spherical densiometer' (Lemmon, 1957). They found that over-storey density was significantly correlated with periodic volume and diameter growth but basal area of the dominant portion of the surrounding stand contributed more strongly. Wilson and Brender (1963) tested four expressions of stand density for loblolly pine volume growth prediction in multiple regression in even-aged managed stands - Stahelin's 'percent of full stocking', total basal area, Reineke's stand density index, and initial merchantable cubic foot volume. They found that

essentially the same amount of variation in annual cubic foot growth was explained by each expression, in combination with age, site, and certain of their significant interactions, from data involving repeat measurements. They concluded that the choice among the variables expressing stand density is primarily at the discretion of the investigator but that basal area had the advantages of easy computation and application.

Provided the implications of judging a measure of density purely by its mathematical contribution to a correlation with stand growth are kept in perspective, we might expect the greatest contribution to the question of the relative efficiency of various measures of density to come from this approach. It is important that any measure proposed have biological significance and that the relationship make biological sense. It is also essential, as stressed by Clutter (1963) that models established to describe growth and yield separately for a stand should be compatible.

Point Density

For ecological or silvicultural purposes, it is often desirable to evaluate the effects of density on a single tree. Spurr (1962) has proposed an 'angle summation method' which involves some of Bitterlich's angle count theory but different concepts and gives an estimate of stand basal area per acre which refers to the vicinity of a particular tree. Brown (1965) stresses the need to define and measure the space available to individual trees rather than number of trees per unit area and suggests defining the area potentially available to a tree as the area enclosed by lines which bisect at right angles the lines joining the subject tree to those surrounding it.

Density and Growth

It is common observation that if the number of trees is varied in a stand of a particular age or structure on a particular site, then this variation of growing space has an effect on the subsequent growth in d.b.h.o.b. of individual trees - up to a certain point, the wider the spacing the larger the d.b.h.o.b. It is an equally common observation that density must vary considerably before it has any effect on height growth. This is the reason height growth can be used as an index of site which does affect it irrespective of density. However, whether

variation in density affects diameter growth along the stem, to what extent under what circumstances, is a matter on which there is considerable but conflicting evidence. This is one of the largest and most critical gaps in our knowledge of the behaviour of trees.

17 Increment and Yield

In mensuration we are concerned with growth not as a biological phenomenon but with the quantitative change in a tree or stand variable which is the result and expression of growth, that is increment; and in the accumulation of increment available at a particular time for a particular purpose of management, which is yield. We have already referred in Chapter 9 to the various expressions of increment in common use for individual trees - mean annual increment, current annual increment, and periodic mean annual increment. The same terms are used with reference to stands. There are many expressions of yield such as annual, intermediate, final, sustained, financial, and so on with special connotations for management. The term yield will be used here in a very general sense, merely implying an amount of wood material at a particular time.

The increment of a particular variable of a stand is the sum of the increments of that variable for the individual trees of the stand. For a tree in isolation, the main factors affecting its growth are its genetical constitution (its genotype) and its environment. When trees are in stand formation, the effect of their mutual competition is superimposed. The three factors form a complex and it is difficult for mensuration purposes to separate them and get indexes of them. We try to classify site and to index stand density. Management is usually concerned with stands composed of a number of genotypes and the effects of genetical factors on stand growth are usually unavoidably included with effects due to environment and competition.

When a species is relatively fast-growing and the period for which increment has been determined is short, often the case in Australia, the forester is sometimes inclined to forget, in extrapolating the increment into the future, that the weather over the period may not have been representative. The annual rainfall figures for Canberra

Table 17:1

Annual rainfall (in), Canberra, A.C.T.
(For. and Timb. Bur.)

1957	14	1963	25
1958	30	1964	29
1959	34	1965	16
1960	31	1966	29
1961	32	1967	14
1962	29		

in Table 17:1 serve to illustrate the point. The forester whose only knowledge of Canberra was the years 1958-64 (a seven-year period which might be thought a reasonable length on which to base an estimate of increment) would be misled unless he knew that the long-term average was 25 in and, in particular, unless he knew of the likelihood of poor years such as 1957, 1965, and 1967. An estimate of increment must always be qualified by the weather conditions of the period.

If the age of a tree or stand is known at time of measurement, we can relate size of variable at particular times of measurement to ages at those times and derive or express increment indirectly in this way. Alternatively, we can derive increment in the variable over the period between measurement directly and relate it to the average age of the period, or to the size of variable at the beginning or end of the period. If age cannot be determined, increment must be related to size of variable. Age is commonly used as an independent variable because time is a common variable in much of our general thinking. Size of variable is, however, the resultant of so many of the factors of growth, including time, that it may be more useful as an independent variable than age for many purposes.

Two phases of the development of a stand are of interest - its present condition at a particular time and its likely condition at a future time. Past increment is used to forecast the likely future condition of a stand. The history of growth of those trees which show annual rings can be determined by stem analysis. The history of growth of any kind of tree can be determined from periodic measurement. The future condition of any kind of stand can be forecast by projecting the present sizes, assuming certain increments from the record of past increments and assuming a certain frequency distribution of sizes. This is the method

of stand projection, the projection being fundamentally on an individual tree basis with the trees grouped into size classes for convenience. For even-aged stands which can be classified by age and site, the history of the stand can be compiled on a stand basis in the form of a yield table, the trends of which can be projected into the future for forecasting the future condition of that stand, or it can be applied in present or projected form to other stands of a similar nature. There are growth relationships in which independent variables other than age and site are used which can be used for forecasting future stand conditions.

PAST INCREMENT FROM PERIODIC MEASUREMENT

Periodic measurements are carried out for experimental growth studies, resource inventory, and management inventory.

There are two ways of determining increment depending on whether the trees are identified individually or not, discussed later.

Whether the trees are individually identified or not, the increment can be expressed in two ways. It can be considered as increment on trees of a certain size at the beginning of the period and can be related to those sizes, usually referred to as increment of the coming period. Alternatively, it can be considered as increment on trees to make them a certain size at the end of the period, and can be related to those sizes, usually referred to as increment of the past period. The purpose of the distinction is to allow a choice in projecting a stand table. The increment of trees which are a certain size now can be assumed to be, over a future length of time, the same as the increment of trees that size that length of time ago, that is the increment of the coming period is projected. Alternatively, the increment of trees which are a certain size now can be assumed to be, over a future length of time, the same as the increment in the recent period of that length to make them their present size, that is the increment of the past period is projected. For example, suppose trees respectively 8·0, 10·0, and 12·0 in five years ago have now become respectively 9·0, 12·0 and 15·0 in. Then the projected increment of the 12 in tree for the next five years could

be regarded either as 3 in, this being the increment of a 12 in tree in the coming period of the last five years, or as 2 in, this being its increment in the past period. The decision as to which of these expressions should be used for projection purposes is a silvicultural one.

Determination of increment in d.b.h.o.b. when the trees are identified individually. In this case, the increment on each tree over the period between measurements is determined quite simply by subtracting the value of the first measurement from the value of the second measurement.

Determination of increment in d.b.h.o.b. when the trees are not identified individually. In this case, the increment on each tree over the period between measurements cannot be derived. There are only two lists of tree sizes available - one at the beginning and one at the end of the period - and it is from these that increment must be derived. For this purpose, the lists are usually compiled as stand tables.

What has become known as the standard or classical method of deriving increment from stand tables of successive measurements was developed in western Europe many years ago and is outlined by Meyer (1953). It is illustrated for a small plot of Pinus radiata in Table 17:2 where two aspects have been omitted for simplicity - how to deal with natural and artificial removals, and with ingrowth (recruitment); these have been included in another illustration in Table 17:7 for cypress pine. The basis of the method (Table 17:2) is to determine for each size class of the first inventory how many trees rise into higher size classes in the second inventory and how many remain in the class. Or, put another way, to determine from what classes of the first inventory the trees in classes of the second inventory have come. Trees rise according to the amount of increment and the width of the class. If only some trees rise, some are left in the class, that is they are 'stationary'. If all the trees rise, there are no stationary trees. If the trees of a class grow through the next size class there will be a negative number of trees stationary.

The stand tables are arranged in descending order of class size. The calculation of the number of trees rising and stationary begins with

the largest class. The two 22 in class trees of the 1959 inventory are assumed to have risen from the 21 in class of the 1953 inventory. Since there were none in the 21 in class in 1953 this means -2 were stationary in that class over the period 1953-9. The six 21 in class trees of the 1959 inventory are assumed to have risen from the 20 in

Table 17:2

Increment in d.b.h.o.b. from stand tables of successive measurements; standard method; P. radiata, ½ acre plot, Mt Stromlo, A.C.T.

(1) D.b.h.o.b. class (in)	(2) No. of trees 1953 inventory	(3) No. of trees 1959 inventory	(4) Trees rising	(5) Trees stationary	(6) Double rising (DR)	(7) Double effective (DE)	(8) DR/DE (increment in units of class intervals for the period)
22	0	2	2	0	2	2	1·00
21	0	6	8	-2	10	6	1·66
20	0	3	11	-8	19	3	6·33
19	2	10	19	-9	30	12	2·50
18	6	13	26	-13	45	19	2·37
17	8	10	28	-18	54	18	3·00
16	13	13	28	-15	56	26	2·16
15	13	11	26	-15	54	24	2·25
14	20	6	12	-6	38	26	1·46
13	9	3	6	-3	18	12	1·50
12	6	0		0	6	6	1·00

class of the 1953 inventory; since there were -2 trees stationary in the 21 in class, a total of 8 trees must have risen from the 20 in class. Since there were in fact none in the 20 in class in 1953, this means there were -8 stationary in that class over the period. The three 20 in class trees of the 1959 inventory are assumed to have risen from the 19 in class of the 1953 inventory; since there were -8 trees stationary in that class, a total of 11 trees must have risen from the 19 in class. Since there were only 2 trees in that class, this means there were -9

trees stationary in the class. And so on.

The values in column 6, headed double rising, for each class are derived by adding the number of trees rising out of and into the class. For example, for the 22 in class, the value 2 in column 6 is given by 2 rising from the 21 in class to the 22 in class plus an implied zero rising out of the 22 in class; for the 21 in class, the value 10 in column 6 is given by 8 rising from the 20 in class to the 21 in class plus 2 rising out of the 21 in class; for the 20 in class the value 19 in column 6 is given by 11 rising from the 19 in class to the 20 in class plus 8 rising from the 20 in to the 21 in class. The values in column 7, headed double effective, for each class are derived by adding the numbers of trees in the class at each inventory. For example, for the 19 in class, the value 12 in column 7 is given by 2 trees in the 1953 inventory plus 10 trees in the 1959 inventory; for the 18 in class, the value 19 in column 7 is given by 6 trees in the 1953 inventory plus 13 trees in the 1959 inventory. And so on.

The values in column 8, double rising (DR) of column 6 divided by double effective (DE) of column 7, represent increments in terms of intervals of diameter class for the period. Dividing double rising by double effective is equivalent to dividing the average of the numbers of trees rising respectively into and out of the class during the period by the average of the numbers of trees respectively at the beginning and end of the period, a divisor of 2 being implied in both numerator and denominator of the fraction. Periodic mean annual increment is given by multiplying the values of column 9 by the width of the class interval (here one inch) and dividing by the length of the period in years (here 6 years); this has not been done in Table 17:2.

A modification of this method, proposed by Smithers (1949), is illustrated in Table 17:3, using the same data as for Table 17:2. In this method, the number of trees rising is determined without determining 'trees stationary'. Columns 4 and 5 represent cumulative sums of the numbers of trees from the largest size class downwards. The number of trees rising into any size class is given by the difference between the cumulative number of trees shown in the class for the two inventories, for example the value 26 shown in column 6 as rising up to the 18 inch class is given by 34 in the 1959 inventory minus 8 in the 1953 inventory. The values for double rising, double effective, and thence periodic mean annual increment, are calculated in the same way as in the standard method. These values are, of course, the same in the two methods.

Table 17:3

Increment in d.b.h.o.b from stand tables of successive measurements; Smithers's modification of the standard method; P. radiata, $\frac{1}{2}$ acre plot, Mt Stromlo, A.C.T. (same values as Table 17:2)

(1) D.b.h.o.b. class (in)	(2) No. of trees 1953 inventory	(3) No. of trees 1959 inventory	(4) Cum. no. of trees 1953 inventory	(5) Cum no. of trees 1959 inventory	(6) Trees rising	(7) Double rising	(8) Double effective	(9) DR/DE (increment in units of class intervals for the period)
22	0	2	0	2		2	2	1·00
					2			
21	0	6	0	8		10	6	1·66
					8			
20	0	3	0	11		19	3	6·33
					11			
19	2	10	2	21		30	12	2·50
					19			
18	6	13	8	34		45	19	2·37
					26			
17	8	10	16	44		54	18	3·00
					28			
16	13	13	29	57		56	26	2·16
					28			
15	13	11	42	68		54	24	2·25
					26			
14	20	6	62	74		38	26	1·46
					12			
13	9	3	71	77		18	12	1·50
					6			
12	6	0	77	77		6	6	1·00
					0			

Ferguson (1952) drew attention in English to the method proposed by Prodan (1947) which derived coming period and past period increment separately, as distinct from the standard method which provides a weighted average of the two as outlined above. The mechanics of this method are illustrated in Table 17:4 using the same data as Tables 17:2 and 17:3. The two stand tables are laid out in the fashion of Table 17:4. Lines are drawn across each column of diameter class of the first inventory opposite a position between the row of the same diameter class and the one above it in the second inventory, for example a line is drawn in the 19 in column of the 1953 inventory horizontally opposite the position between the 19 in and 20 in class of the 1959 inventory. The calculation of the movement of

Table 17:4

Increment in d.b.h.o.b. from stand tables of successive measurements; Prodan's method; P. radiata, ½ acre plot, Mt Stromlo, A.C.T.(same values as Tables 17:2 and 17:3)

Diam. dist. 1959 inventory		Diameter distribution 1953 inventory								Incrt. for past 6-year period	
		19	18	17	16	15	14	13	12		
Class (in)	No.	2	6	8	13	13	20	9	6	Tot. per class	Av. per class
22	2	2								6	3·00
21	6		6							18	3·00
20	3	—		3						9	3·00
19	10		—	5	5					25	2·50
18	13			—	8	5				31	2·38
17	10				—	8	2			22	2·20
16	13					—	13			26	2·00
15	11						5	6		17	1·55
14	6							3	3	9	1·50
13	3								3	3	1·00
12	0										

Increment for the coming 6 year period								
(i) tot. for class	6	18	19	31	31	37	15	9
(ii) av. for class	3·0	3·0	2·37	2·38	2·38	1·85	1·66	1·50

trees starts with the highest class of the second inventory. The 2 trees in the 22 in class (1959) are assumed to have come from the 2 trees in the 19 in class (1953) and are placed as shown. Since they are three 1 in classes 'above the line' they represent three 1 in increments, a total for the 19 in class of 3 in x 2 shown below as 6 in increment for the coming period. The 6 trees in the 21 in class (1959) are assumed to have come from the 6 trees in the 8 in class (1953) and are placed as shown. Since they are three 1 in classes 'above the line' they represent three 1 in increments, a total for the 18 in class of 3 in x 6 shown below as 18 in increment for the coming period. The 3 trees in the 20 in class (1959) are assumed to have

come from the 8 trees in the 17 in class (1953) and are placed as shown. This leaves 5 to account for in the 17 in class (1953). The 10 trees in the 19 in class (1959) are assumed to be that 5, and 5 of the 13 trees of the 16 in class (1953), which leaves 8 of the 16 in class (1953) to account for, these being a contribution to the 13 of the 18 in class (1959); and so on. For the 17 in class (1953), there are 3 trees with three 1 in increments (being 3 spaces or classes 'above the line') and 5 trees with two 1 in increments, a total of 19 for the class. Any trees 'below the line' indicate they are stationary in the class (there are none in this illustration).

To express increment on a past period basis, take as an example the 18 in class of the 1959 inventory: the 13 trees in the 18 in class (1959) represent 8 of the 16 in class (1953) which have moved 2 classes which equals 16 inches of increment and 5 of the 15 in class (1953) which have moved 3 classes which equals 15 in of increment. a total of 31 in of increment as shown in the second last column on the right.

All these methods are based on the assumptions that the trees are evenly distributed throughout a diameter class and that the trees in a class grow at the same rate. Meyer (1953) points out that the first of these assumptions is hardly ever fulfilled and discusses an appropriate adjustment when it is not fulfilled. The second assumption also is rarely fulfilled but leads to very little error. There is no alternative to assuming that the largest trees of the second measurement were the largest of the first measurement. The tree 'movement' must start somewhere and, lacking knowledge of how the trees actually grew, this assumption is the logical one to make. However, the assumption may be invalid as in the case illustrated in which the trees were in fact identified individually in the field; their actual movement is shown in Table 17:5 in parentheses for comparison with the assumptions of Prodan's method. The actual increment is compared in Table 17:6 with that derived by the standard method and Prodan's method. In each case the increment is in units of class intervals (1 in) for the period (6 years) which can be converted to increment per tree per year if required.

In periodic measurement, a lower limit to d.b.h.o.b. measurement is usually nominated for practical reasons. Trees of a size below this limit at one measurement may grow to a size above this limit by the next measurement. These trees are called ingrowth. Between measurements trees may die - mortality, or be removed - removals. The way in which ingrowth and removals are taken into account is

Table 17:5

Increment in d.b.h.o.b. from stand tables of successive measurements; values derived by Prodan's method (Table 17:4) compared with actual values (in parentheses)

Diam. dist. 1959 inventory Class (in)	No.	Diameter distribution 1953 inventory 19	18	17	16	15	14	13	12
		2	6	8	13	13	20	9	6
22	2	2	(2)						
21	6	(2)	6(3)	(1)					
20	3	___		3(3)					
19	10		(1)	5(4)	5(4)	(1)			
18	13			___	8(9)	5(4)			
17	10				___	8(7)	2(3)		
16	13					(1)	13(10)	(2)	
15	11						5(6)	6(4)	(1)
14	6							3(3)	3(2)
13	3								3(3)
12	0								

illustrated in Table 17:7 for cypress pine. A measurement of g.b.h.o.b. was carried out in 1946 and in 1958, the number of trees by 2 in g.b.h.o.b. classes being shown in columns 2 and 5 respectively. The number of removals due to commercial logging and treatment in each g.b.h.o.b. class during the period between the measurements is shown in column 4. Depending on when the removals are made during the period between measurements, and when trees are recorded as having died, the stand tables can be adjusted sensibly for calculation of increment. Had the removals all been made immediately after the first measurement they could be subtracted from the stand table of that measurement. Had they all been made immediately before the second measurement they could be added to the stand table of that measurement. They were made continuously over the period, so it is reasonable to subtract half the removals per g.b.h.o.b. class from the 1946 stand table and add half to the 1958 stand table. The resulting stand tables are shown in columns 3 and 6. These would then be used

Table 17:6

Increment in d.b.h.o.b. from stand tables of successive measurements; comparison of actual increment with that derived by standard method (Table 17:2) and Prodan's method (Table 17:4)

Diam class (in)	Incrt. standard method (in)	Incrt. Prodan method (in)		Actual incrt. (in)	
		Coming period	Past period	Coming period	Past period
22	1·00		3·00		3·90
21	1·66		3·00		2·91
20	6·33		3·00		2·63
19	2·50	3·00	2·50	2·35	2·49
18	2·37	3·00	2·38	3·12	2·29
17	3·00	2·37	2·20	2·69	2·27
16	2·16	2·38	2·00	2·23	2·08
15	2·25	2·38	1·55	2·30	1·51
14	1·46	1·85	1·50	1·80	1·48
13	1·50	1·66	1·00	1·91	1·13
12	1·00	1·50		1·61	

in the standard method, Smithers's method, or Prodan's method. The ingrowth is represented by the difference between the total number of trees in the two measurements, taking removals into account as shown in Table 17:7. In calculating increment by any of the methods, this value (2,017 in this case) would have to be shown as the number of trees of girth class 'less than 21 inches' for a balance to be effected.

The expression of increment in d.b.h.o.b. Whatever the method of calculating increment, a relationship is usually sought, by graphical methods or calculation of an appropriate equation, between increment and tree size (either at the beginning or end of the period), or between tree size at beginning and tree size at end of the period. These relationships are variously linear or curvilinear, with positive or negative correlation, depending on such factors as the growth habits of the species, age and structure of stand. As an example, data of an unthinned stand of radiata pine at Kowen, A.C.T., are illustrated in

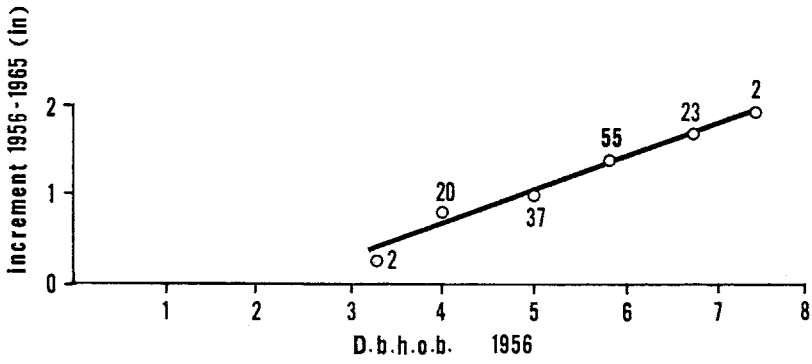
Table 17:7

Stand tables of successive measurements of cypress pine (courtesy Qld Dept For.)

(1) G.b.h.o.b. (in)	(2) No. of trees 1946	(3) No. of trees 1946 less half of removals	(4) Removals 1946-58	(5) No. of trees 1958	(6) No. of trees 1958 plus half of removals
21	1,417	1,399	36	1,527	1,545
23	1,276	1,260	32	1,455	1,471
25	1,047	1,032	30	1,311	1,326
27	871	860½	21	1,059	1,069½
29	649	639	20	804	814
31	543	534	18	733	742
33	413	404	18	572	581
35	330	325½	9	409	413½
37	231	181½	99	333	382½
39	140	100	80	170	210
41	93	69½	47	115	138½
43	62	45½	33	80	96½
45	40	29	22	48	59
47	32	24	16	31	39
49	23	18	10	21	26
51	10	6	8	12	16
53	6	2½	7	7	10½
55	8	6	4	5	7
57	7	5½	3	4	5½
59	6	4½	3	5	6½
61	4	3	2	4	5
63	0	0	2	0	2
65	2	2	0	1	1
67	0	0	0	0	0
69	1	½	1	0	½
71	0	0	0	0	0
73	0	0	0	0	0
75+	1	½	1	1	
	7,212		522	8,707	

Total 1958 + removals	8,707 + 522	
	9,229	
less total 1946	7,212	
	2,017	= ingrowth

Figs. 17:1 a and b. The relationships between increment in d.b.h.o.b. and d.b.h.o.b. at the respective measurements, and between d.b.h.o.b. at each measurement, are linear with a high positive correlation. As a further example, a curvilinear relationship of



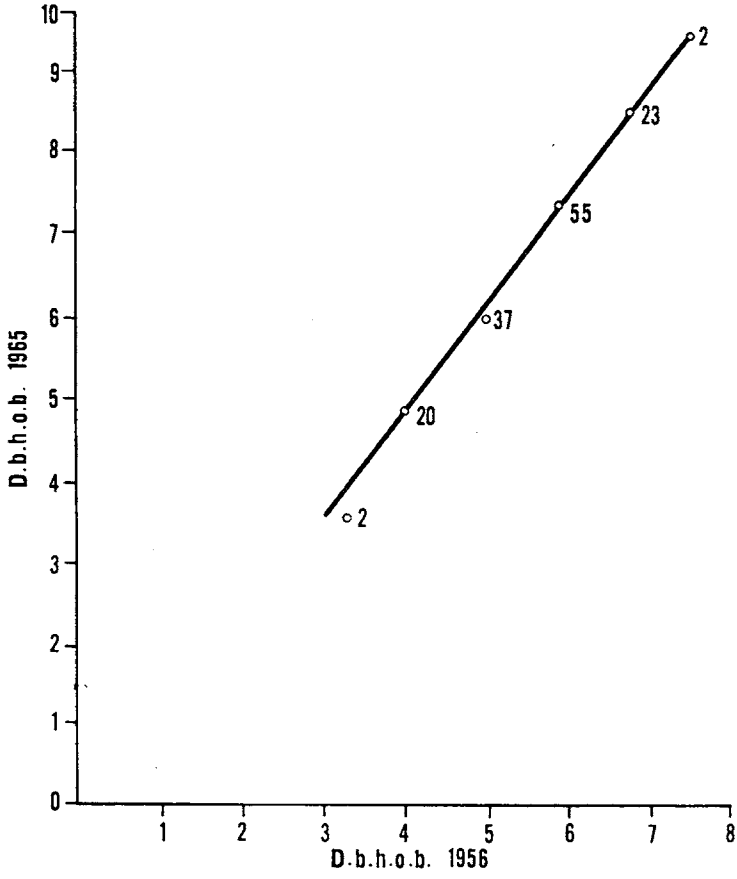


Fig. 17:1 Increment in d.b.h.o.b. of P. radiata, Kowen, A.C.T.
(a) Increment 1956-1965 (in) = -0·75 + 0·36 d.b.h.o.b. 1956 (in)
(b) d.b.h.o.b. 1965 (in) = -0·75 + 1·36 d.b.h.o.b. 1956 (in)

d.b.h.o.b. increment and d.b.h.o.b. for several eucalypt species combined (red and white mahogany, tallow wood, and blue gum) from Pine Creek State Forest, N.S.W. is shown in Fig. 17:2.

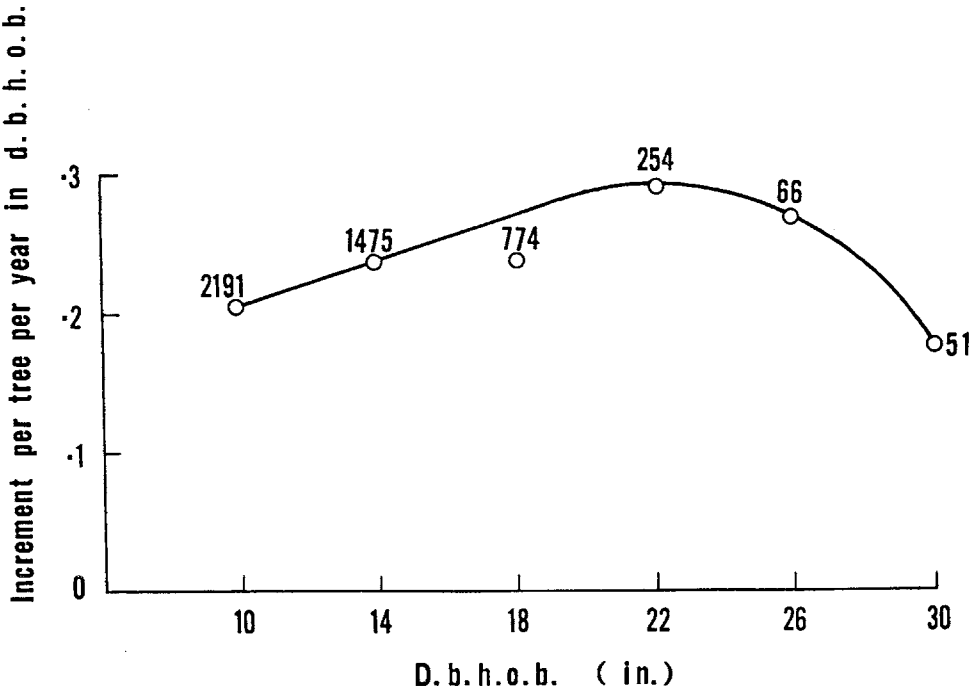


Fig. 17:2 Increment in d.b.h.o.b. of red and white mahogany, tallow wood, and blue gum, Pine Creek State Forest, N.S.W.

When d.b.h.o.b. increment is related to d.b.h.o.b. on a diameter class basis and trees grow more than the width of a class interval during the period between measurements, a decision has to be made on the size class to which the increment should be credited. If these trees are classified according to size at the beginning of the period like the rest, this keeps the procedure consistent, but there is an argument for classifying them according to size at the middle of the period.

Decrement in d.b.h.o.b.

One would expect a tree to increase in d.b.h.o.b. between measurements except that in old age it might remain static. Sometimes, however, the d.b.h.o.b. at a second measurement is less

than at the previous measurement. For plantation conifers in Australia, this may be the result of an actual decrease in the d.b.h. of the wood due to lack of water and the over-bark measurement may truly reflect the present d.b.h.u.b. The difference in the two measurements must be regarded as a negative value in deriving average increment for a class. For many eucalypts, the decrease is the result of loss of bark due to annual or periodic shedding and measurement must be timed to suit this. It may, however, be an accidental loss and nothing can be done about it. Loss of bark due to sudden change of environment, abrasion by understorey plants, deliberate burning of the litter or wild fire makes it difficult to get reliable estimates of increment for many eucalypts.

Increment in Basal Area

If the increment in basal area is required by diameter class or basal area class, increment in d.b.h.o.b. is derived as discussed above and then converted to basal area increment. Usually basal area increment is required on a stand basis. It is then immaterial whether the trees are individually identified or not, since the stand basal area is the sum of the basal area of all the trees in the stand. It can be readily derived by determining the b.a.o.b. of each tree and relating the sum of the individual basal areas to the size of the stand; or on a per acre basis using angle count method. Since it can be determined simply and reliably and forms a good independent variable for relationships with other stand variables, stand basal area is almost invariably measured in growth studies and for resource and management inventory. Increment in stand basal area is therefore one of the most common expressions of increment.

Increment in Height

Estimates of height increment are necessary for a study of the growth pattern of stands, their response to treatment, and the effects of site; also for estimates of future volume by separate projection of diameter and height. Increment in height is usually related to increment in d.b.h.o.b.

The relationship of height and diameter, the stand height curve, was discussed in Chapter 12. In well balanced uneven-aged stands of conifers a stand height curve which does not change with time may sometimes be assumed. This may also be a reasonable assumption

for a stand height curve of merchantable height for certain uneven-aged eucalypt forests in Australia. For these cases, a particular height increment is regarded as associated with particular changes in d.b.h.o.b. In even-aged stands the stand height curve is continually changing and the height increment associated with increment in diameter in trees of a particular size varies according to the age and structure of the stand.

If the trees are identified individually, the height increment of each tree can be determined and related to it directly. Usually average height increment per d.b.h.o.b. class is calculated and related to the d.b.h.o.b. of the first or second measurement, depending on whether coming period or past period increment is required. Generally the increment is determined as the difference between heights measured on successive occasions. Jacobs (1939) describes an instrument for measuring height increment directly where this can be recognised, for example as an internode or annual shoot on Pinus species.

If the trees are not identified individually, one way of determining increment in height for any d.b.h.o.b. class is as follows:

1. Compile a stand-height curve for the first measurement.
2. Relate d.b.h.o.b. increment to d.b.h.o.b. for the d.b.h.o.b. classes of the first measurement.
3. Compile a stand-height curve for the second measurement.
4. For any particular d.b.h.o.b.:
   (a) read its height from 1
   (b) determine the corresponding d.b.h.o.b. at time of second measurement from 2
   (c) read the height corresponding to (b) from 3
   (d) get the difference between the heights of (a) and (c).

Increment in Volume

Increment in volume is the difference in volume at successive measurements.

If a sample tree method is used it is applied directly and independently on each occasion.

There are several possibilities if a one-way volume table is used: either a unique volume-basal area line may be compiled independently, or an appropriate tariff may be used on each occasion, or a single tariff may be used as illustrated by Meyer (1953) for the method of control.

If two-way volume tables are used, volume is derived each time for each tree through its d.b.h.o.b. and height, or through a stand table and a stand height curve.

If a stand volume table is used it is applied directly and independently on each occasion.

Volume may be estimated from a yield table each time but a yield table is usually so arranged that the increment in volume for a particular age and site can be estimated directly.

Yield Tables

Normal Yield Tables

A yield table (see p. 117) is a statement of variables such as volume, basal area, height, and number of trees per unit land area for stands of various ages, on sites of various productive capacity, of an even-aged forest of one species which has developed naturally, or has been maintained artificially, at a consistent density. It is a statement of the history of development of the stands of an even-aged forest of one species, compiled from relationships, established graphically or by calculation, between the stand variables as dependent variables, and age and an expression of the productive capacity of the site as independent variables. The statement is usually presented in tabular form but since it is derived by graphical methods or formulae it may be left in graphical or algebraic form for convenience. Depending on the amount of information available for the compilation of the table, on the purpose of the table and the stand variables considered of most interest to management, so the form of the table varies. It may be a simple statement of stand volume per acre produced to various given ages on various site qualities such as that by Lewis (1957) for radiata pine in South Australia. It may be a comprehensive statement of number of trees, mean d.b.h.o.b., stand basal area, height, volume of main crop and thinnings, and increment in variables by age and site quality such as that by Hummel and Christie (1953) for various species in Great Britain.

The first step in compiling a yield table is to establish a system of classification whereby the forest can be divided into areas of different productivity - site quality or site index classes. Data are then obtained from stands on the various sites at various ages for the stand variables which are to be included in the table. Relationships between

the variables and age are then established directly, or indirectly through top height. The validity and efficiency of these relationships depends on the historical extent of the information in the same way and for the same reasons as the relationship of top height and age as discussed in Chapter 15. The most satisfactory information comes from periodic measurement, the least satisfactory from a single measurement. Stem analysis information may be used to support either. The relationships are usually established by subjective graphical methods in the same way and with the same problems as the top height-age relationships discussed previously. A good example of this approach is that described by Hummel and Christie (1953, 1957). A number of attempts have been made to calculate relationships of best fit to formulae and are reported in the literature. They are not very successful unless the relationship is of a simple type - which is not common, and the information is particularly comprehensive - which is not usual.

The purpose of a yield table is to provide estimates of present yield and future increment and yield. There are two ways in which a yield table for a particular species can be used to estimate future yield. If a species is in the first rotation in an area and has not completed that rotation, which is the case with most plantations of coniferous species in Australia, its history of growth up to the present time can be compiled in yield table form. Likely future yields can be established by extrapolating the relationship of volume on age and site, guiding this extrapolation by the form of the past trends, or perhaps supported by some information on the development of the species elsewhere. For safety, such forecasts should be short-term ones, about 5 years. As the future becomes the present the actual development of the forest is recorded. This becomes the basis for future forecasts by further extrapolation. Eventually the whole history is recorded. If now a second rotation of the species is established, the yield table of the first rotation can be used for long-term forecasts of the likely history of the second crop, assuming there is no change in the productivity of the site, or that the growth trends of the various site qualities are not affected if there is a change in productivity.

Yield tables are of practical value in management as a means of quantitative estimates. Since they afford ready comparison of the development of a species under a particular silvicultural regime in a country with its development under similar or different regimes in that country or elsewhere, they are also of interest in national and

international aspects of policy and economics. Even if a yield table has limitations as a means of estimate, it may have considerable value as a compact history with implications of importance to silviculture and management.

Volume per acre on a particular site at a particular age varies according to stand density. If stand density varies, it is difficult to establish relationships of volume with age for each productivity class for the yield table, even if the site classification has been successfully established on the basis of stand top height - which is not affected by varying density. Stand basal area is of course also affected by varying density and, as discussed in Chapter 16, is used as a measure of it. The solution to this problem in the early development of yield tables in western Europe last century was to restrict the compilation of a yield table to stands which were fully stocked and to which the name normal was given - unfortunately, because this term in general usage implies the usual condition when in fact fully stocked stands are rather unusual. An estimate for a stand which was other than fully stocked was then obtained by applying a correction factor to the yield table according to the density of the stand, basal area commonly being used as a measure of density for this purpose. This approach was used for forecasting increment of eucalypt regrowth stands in southern Tasmania (Lawrence, 1965).

Variable Density Yield Tables

Except in certain forests in western Europe which were fully stocked after a long history of intensive management, foresters often found it difficult to get enough data from fully-stocked stands on which to base a normal yield table. Or, if they were able to compile a normal table, they found that correcting the values for densities other than that implied in the table often led to unsatisfactory results. Techniques had also been developed whereby relationships with more than two independent variables (age and site) could readily be handled. This led to the development of yield tables incorporating a third independent variable expressing stand density to which the name variable density yield tables was given (Spurr, 1952) and which have received particular attention in North America. A yield table incorporating age, site, and density can be compiled for practically any kind of even-aged forest. Spurr (1952) and Husch (1963) discuss the compilation and application of variable density yield tables in the U.S.A.

Stand basal area is the most commonly used index of stand density for even-aged stands. A suitable way of expressing the volume-growth relationship is a stand volume table in which stand volume per unit stand basal area is related to stand top height. Lewis (1954) compiled a variable density yield table on this basis for radiata pine in New Zealand. Cromer (1961) discussed the matter for radiata pine over a wide range of conditions and suggested 'the growth rate of Pinus radiata stands is approximately constant under a wide range of site, density, treatment and locality, when such rate is expressed as the increase in under-bark volume per square foot of basal area for unit increase in top height'. Carron (1967) compiled a variable density yield table for a plantation of radiata pine in the A. C. T. on the basis of this relationship of volume per unit basal area and stand top height. One advantage for radiata pine is its apparent linearity over a wide range of conditions. Cromer and Bowling (1961) found that volume per acre of even-aged stands of Eucalyptus obliqua regrowth in Tasmania could be satisfactorily estimated from a curvilinear relationship established between volume per unit basal area and mean height of dominants. Since mean height of dominants by age could also be used to classify site index, this allowed estimates of volume per unit basal area by age and site index to be made from the relationship - in effect, a variable density yield table.

Other Solutions for Modification of Normal Yield Tables

Johnston and Bradley (1963) discuss the use of a secondary classification of stands into yield classes according to maximum MAI of volume through top height-age curves 'to enable local growth differences to be taken into account and thereby to convert the general yield classification into a local yield classification'. For each general yield class there are three production classes, one with the same rating as the general yield class, the others being respectively below and above the general yield class by one yield class. The production class of a particular stand is assessed, after its general yield class has been determined by the top height-age curves, by the relationship for the stand between top height and (a) total basal area production or (b) total volume production or (c) the mean girth of the 40 largest girthed trees per acre.

Forecasting the Stand Table

The variables of a yield table are stand variables. The value of a forecast of future volume from a yield table may be enhanced if it is supported by a forecast of the d.b.h.o.b. distribution. If the distribution is normal projection may not be difficult. If it is skewed and changes the extent and direction of skewness with time projection may be quite difficult. Lewis (1963a) has referred to this for radiata pine in Australia. Considerable work has been done on the matter, some of which is listed by Spurr (1952). In Australia at present projections are usually made by subjective graphical methods.

The Usefulness of Yield Tables in Australia

Normal yield tables are suitable for many conifer plantations in Australia. Variable density yield tables may be necessary for some time for plantations where the effects of early establishment troubles, drought, insect and fungal depredation have caused variation in density; where fluctuating demand affects the planned thinning schedule; or where thinning schedules cannot yet be defined or the treatment regime stabilised. Whatever the kind of yield table, it provides a very useful means of estimating future increment and yield, especially for management purposes and policy planning. Age and site quality are the most important variables influencing production and the silvicultural regimes to achieve it. The age of a stand is usually known from the records and the site quality of a stand can be readily determined once a system of site classification has been compiled and mapping of site quality, which becomes a permanent stratification for management purposes, has been carried out.

Stand Projection

To forecast the probable yield from a stand at a future time we can forecast the condition of the stand at that time by stand projection. By this is meant determining its present condition by an inventory, forecasting increment in the future period on the basis of increment in the past period which has been derived by periodic measurement or stem analysis, and adding this future increment to the present condition of the stand. Whereas yield tables can be compiled for and applied to even-aged stands only, stand projection can be applied to any kind of stand.

Projection of D.b.h.o.b.: Stand Table Projection

There are a number of different procedures for stand table projection but with a common principle which involves the compilation of a stand table for the present stand and adding to the d.b.h.o.b. values the appropriate increments to forecast the stand table at the future time, taking into account ingrowth, artificial removals, and mortality. These steps are discussed in detail by authors such as Wahlenberg (1941) and are outlined here only in broad terms.

The present stand table is obtained by an inventory. A decision is needed on the increment values to be used - whether on a diameter or basal area basis, whether coming or past period, what further adjustments are necessary. There are no general rules for this, the chief factors being the stage of stand development, the growth habits of the species and the effects of artificial treatment. The increment for each class has then to be added to the present stand table. The simplest way is to add the diameter increment to the mid-points of the diameter classes forming the stand table. Unless the diameter increments are exact multiples of diameter class interval, which is most unlikely, this procedure leads to a stand table with classes of unequal width and mid-points which are not round numbers. This is an awkward form of stand table but forming a conventional stand table with equal class intervals and round number mid-points from it may destroy its validity.

An alternative is to assume that the trees in classes are evenly distributed throughout the classes, a certain proportion will move out of the class into higher classes, and a certain proportion will stay in the class, these proportions depending on the ratio of the increment and the width of the diameter class. This ratio is called the movement factor. For example, assume there are 10 trees in the 6·0 in class (5·50–6·49) with diameters respectively 5·5, 5·6 ..... 6·3, 6·4; assume the increment is 0·7 in; these trees will become respectively 6·2, 6·3, 6·4, 6·5, 6·6, 6·7, 6·8, 6·9, 7·0, 7·1; the ratio is $\frac{0·7}{1·0}$; therefore 70 per cent should move up 1 in class and 30 per cent stay in the class - this is so as seen in the actual distribution. Assume the increment is 1·4 in with 1 in classes; the ratio is $\frac{1·4}{1·0}$; then 40 per cent will move up two classes and the remaining 60 per cent will move up one class, as seen from the distribution which would be 6·9, 7·0, 7·1, 7·2, 7·3, 7·4, 7·5, 7·6, 7·7, 7·8, that is 4 trees (40 per

cent) are now in the 8 in class, the other 6 are in the 7 in class. Some common sense modification of this percentage has to be adopted when there are only a few trees per class or one tree per class. The use of this movement factor is discussed by Wahlenburg (1941) and Meyer (1953). Two assumptions are involved. One is that all the trees in a class grow at the same rate, whereas there is usually a variation of increment within a class. The other is that there is an even distribution of trees around the centre of the class, whereas an even-aged stand has an approximately normal distribution over all the classes and an uneven-aged stand has a reverse-J shaped distribution. The effects of these on the validity of the projection are discussed by Meyer (1953).

The main problem in forecasting a stand table is to forecast what shape the distribution is likely to take.

Projection of Basal Area

Future basal area can be determined indirectly through d.b.h.o.b. classes by stand table projection, or directly by graphical projection or merely adding basal area increment to present basal area.

Projection of Height

If a stand height curve for a future even-aged stand is required from which stand volume can be determined by reference to a two-way volume table, the future height of a d.b.h.o.b. class of a certain size now can be determined by adding appropriate increment to its present height, the future d.b.h.o.b. can be determined by stand table projection, the future height can be plotted against future diameter and a stand height curve fitted. If future stand mean height or top height is required it can be forecast by adding appropriate increment to present height.

For an uneven-aged stand with a constant stand height curve, present d.b.h.o.b. can be projected and the equivalent height read from the stand height curve.

Projection of Volume

If a one-way volume table is applicable on successive occasions, the volume on successive occasions can be determined by projecting the

stand table and applying it to the volume table. If different one-way tables are applicable, projection of both the stand table and the variables with which the tariffs are correlated is necessary. To apply a two-way volume table, d.b.h.o.b. and height must be projected separately. For a stand volume table, stand basal area and stand height are projected separately.

Ingrowth

For stand table projection, information must be obtained about the frequency and increment of classes just below the size class set as the lowest for enumeration purposes if a reliable estimate is to be made of ingrowth.

Removals and Mortality

The number and sizes of artificial removals can be anticipated from the intended treatment.

Information on past mortality must be obtained and taken into account in stand table projection. The general procedure is to deduct forecasted mortality from the present stand table prior to projecting it or after projecting it. The procedure is simple, the difficulty is to forecast the mortality.

Growth Percentage

The increment of a tree or stand may be considered as a form of interest on capital. It is natural to consider increment in this way as a basis for comparing the rate of interest of production with the rate of interest chargeable against money invested for that production. Methods of calculating increment as interest on a percentage basis, that is as growth percentage, have been considered for a long time. The large number of formulae proposed bears witness to the limited use of the concept. Expression of increment as growth percentage appears to have some merit when it is used for illustrative purposes, for example to express a particular growth condition by a rate so as to make comparison with some standard or expected rate more clear. It has considerable limitations in forecasting the future condition of the forest (see Wahlenburg, 1941 and Spurr, 1952).

Other Growth Projections

As an alternative to stand projection for uneven-aged stands, there is the possibility of forecasting future volume through equations, using as independent variables those stand characteristics with which volume is correlated and which can be projected readily and reliably. Turner (1966) developed a multiple regression in which volume and basal area growth of an uneven-aged eucalypt forest of mixed species on the coast of N. S. W. are forecast from various stand characteristics, and provided a comprehensive bibliography of work of this kind for both even-aged and uneven-aged forests in the northern hemisphere.

18 Forest Inventory

A forest resource inventory is a qualitative and quantitative investigation and record of the location, ownership, extent, nature, condition, purpose, and capacity of forest estate on a broad scale, for example an inventory of the forest area of a country, a state of the country, or part of a state. Its purpose is to provide information to the government for formulating a land-use and forest policy and for general development, and the government is responsible for it. To plan the use of a country's resources and to develop and control trade in forest products, the government needs to know where the forests are, who owns them, how much there is of what type and in what condition, the role they play or can play in protection and production, amounts of present production and potential production, rates of growth and loss. A management inventory is a qualitative and quantitative investigation and record of a particular forest sufficiently detailed for efficient planning and implementation of management; the owner is responsible for it.

There are certain similarities between these two kinds of inventory and in practice they grade into each other. Resource inventory covers such a comparatively large area that at least the quantitative investigation, and usually the qualitative investigation, is based on sampling. Management inventory in certain limited cases is based on a complete d.b.h. enumeration of the forest but in most cases, as with resource inventory, at least the quantitative investigation is based on sampling. The same kind of sampling units may be used in resource and management inventory. If the resource inventory is intensive and the management inventory not very detailed, practically the same kind of information may be recorded. Again, the information from one kind of inventory may be used in place of that from the other because of lack of funds, staff, or time for the other.

The ideal sequence of events in the development of forestry in a

country would start with a preliminary reconnaissance of the location and extent of the forested area which would indicate the most efficient design of resource inventory. After this resource inventory had been done, the areas for intensive management could be nominated and management inventories of them carried out. Unfortunately, there is probably no country in the world where this ideal sequence of events has been possible and in some cases the information from a resource inventory has to serve temporarily for the management of an area; in others, the information from management inventory of typical areas may be extrapolated to estimates of the whole country at a resource level.

Again, foresters in most countries have had to start managing individual forests before a resource inventory of the whole forest estate of the country has been carried out. Management inventory therefore has a longer history than resource inventory, and some of the techniques of resource inventory have come from management inventory rather than the other way around as one might expect. Further, knowledge of the forest resources of the country and intensity of management varies from country to country, so that the two kinds of inventory may usually be distinguished fairly readily within a country but often appear indistinguishable between countries.

For these reasons there seems at times to be little difference between these two kinds of inventory. In ideal circumstances, at least, they are essentially different. They differ in function, in the kind of information obtained, and in the size of area involved. The primary stratification for resource inventory is by broad forest type, use and ownership. For management inventory it is usually by object of management or the requirements of silviculture. The level of precision of the quantitative estimates required is usually higher for management than resource inventory, necessitating more intensive sampling. Because the differences are greater than the similarities, the two kinds of inventory will be discussed separately.

FOREST RESOURCE INVENTORY

A few countries of the world began organised forest resource inventory about 1920. Finland has carried out four successive inventories and Norway and Sweden have each done three (Nyssonen, 1964). At that time, an Empire Forestry Conference stressed the need for

inventory in Commonwealth countries such as Australia but little action followed. An impetus to inventory in many countries of the world, however, occurred about 1946 for reasons mainly connected with World War II. One reason was that aerial photographs had played an enormous role during the war in mapping and interpretation for military purposes. Foresters were aware of their value for forest resource study and were able to take advantage of the considerable amount of aerial photographic coverage, equipment, knowledge, and trained manpower which was available after the war. Another reason was that damage to the forest estate in many countries and cutting for the needs of war, voluntary or under occupation, prompted national appraisal for planning post-war development. A further reason was that the establishment of the United Nations Organization strengthened the concept of forests as an international resource and stimulated forest resource studies, particularly through agencies such as FAO. About this time, and to some extent stimulated by the need for censuses of various kinds including that of forest resource, extensive developments began in the theory of sampling.

The decision to carry out a forest resource inventory is the government's responsibility, prompted by the forest authority, which is then made responsible for its implementation. There are many factors involved in this decision, but these are not of present interest and only the technical aspects of the inventory will be discussed.

Modern forest inventory is the application of mathematical statistics, aerial photogrammetry and photo-interpretation, land surveying, tree measurement, and data processing. Loetsch and Haller (1964) devote 400 pages to the first two aspects only and as they say 'forest inventory methodology ... [is now] a specialised branch of forestry science'. The treatment of the subject here must necessarily be both brief and general, and some familiarity with the various aspects involved is assumed.

Mapping

The standard of mapping needed for resource inventory depends on the scope and objectives of the inventory. Planimetric detail is necessary for planning the sampling and executing the field work. The addition of topographic detail makes the map much more valuable for both these purposes. If the estate is to be classified by ownership, cadastral detail is necessary. The map supporting the final statement should

include planimetric, topographic, and cadastral information if at all possible. The position will vary from that where adequate map coverage is available to that where there are no maps at all. Mapping is usually the responsibility of specialist organisations. If maps are not already available for forest inventory, they may be specially prepared, or maps may be provided with a common planimetric, topographic, and cadastral base to organisations interested in resource studies such as forestry, agriculture, geology, and hydrology, each superimposing its own particular information. In some cases, forestry has to provide its own maps for inventory.

For general planning, the scale of mapping is usually 1 in 250,000, 1 inch to 4 miles or even 1 in 1,000,000. The working maps on which the stratification is recorded and the sampling units selected, and from which the units are located in the field, are usually at a scale of 1 in 25,000 or 1 inch to 20 chains. The maps presented with the final report are usually the common civil or military map of the country at a scale of 1 in 50,000 or 1 inch to 1 mile.

Classification and Stratification

The main purpose of a resource inventory is to provide a statement of the various kinds of forest in the country, how much of each kind there is, where it is, who owns it, what condition it is in and what role it is playing or can play; and, for the production forest, a statement of present volume and rates of growth and loss. A system of classification is needed for this. There are strong arguments for adopting an international classification which would provide estimates on an international basis, modifying it if necessary to suit domestic classification rather than the reverse procedure. The first step is to nominate the 'forest' or 'forested land', second to classify it into classes of present or potential use and into categories of ownership. The third step is a classification into broad forest types which may be a simple division into broad-leaved or coniferous forest, or a more detailed one to suit the particular conditions of each country - for example, the types suggested for the national inventory of Australia (F. and T.B., 1951) are 'coniferous plantation, cypress pine, rain forest, mixed forest, eucalypt forest, mallee, and miscellaneous'.

For some policy purposes, the classification might stop at this stage but usually estimates of volume of wood of the productive forest are required and these can be made and used more efficiently if some sort

of stratification of broad forest types is carried out. Under certain circumstances of sampling, even a geometric stratification may improve the efficiency of the sampling, but the greatest contribution to efficiency is usually given by a stratification which reduces the variance of volume within strata to a minimum. The best basis for stratification for this purpose is generally a natural one. The best stratification for estimating volume is often, but not necessarily, the best for making statements about volume. The stratification suggested for the indigenous eucalypt forest for the Australian national inventory suits both purposes, comprising a preliminary division into stand size class (regeneration, saplings, poles, mature and over-mature), then stand height class (170 ft and over, 130-169 ft, 90-129 ft, 50-89 ft, 10-49 ft, and under 10 ft) and density class (open, scattered, moderate, dense).

Considerable thought has to be given to the kind and number of criteria used in the classification and the stratification. There should be enough classes and strata to be of practical value but not so many that time is spent unprofitably delineating them. If the classification and stratification are based on interpretation of aerial photographs, the criteria should be readily distinguishable both on aerial photographs and ground. The minimum area of each class and stratum which should be delineated must be defined in terms of the area which will represent it at the scale of the map for the final record. For the Australian national inventory, minimum areas of 80-160 acres for forest types and 320-340 acres for density classes were recommended for final maps at a scale of 1 mile to 1 inch. If possible, the stratification should be capable of expansion for subsequent management inventory if so required.

Sampling for Quantitative Estimates

Quantitative estimates in forest resource inventory are almost invariably determined by sampling. Estimates of area of the various classes of forest may also in certain cases be determined by sampling. In any discussion of inventory, a consideration of the theory and application of sampling is therefore necessary. Sampling is an extensive and complex subject and will be discussed here only in elementary terms. There is a vast literature of which Yates (1949), Cochran (1963), Finney (1947, 1948), and Loetsch and Haller (1964) provide good references.

There are three general objectives in sampling for estimates of a

variable such as stand volume in inventory: that the sample should provide an unbiased estimate of the mean of the population; that this estimate of the population mean should be as precise as possible for the time and money expended; and that the sample should provide an unbiased estimate of variance from which the precision of the estimate (usually the standard error of the mean) may be assessed. If the inventory is to be carried out periodically to get information on change (growth and loss) at national level, an unbiased and precise estimate of change may also be required. The requirements of sampling for this may conflict to some extent with the requirements for the other objectives.

As a preliminary classification it is convenient to consider sampling methods, or the methods of selecting a sample, as of either a subjective or objective kind.

Subjective Selection

In subjective, purposive or judgment selection, or selective sampling, the selector studies the population and then by personal judgment selects what he considers to be typical, representative, or average units of the population. This method of selection is obviously liable to personal bias, the extent of which is not readily evaluated. Subjective selection may produce unbiased results when the population is small, the variation is limited, average values exist, and the selector is sufficiently experienced with the population to nominate them. These conditions do not obtain in inventory. Because it does not have the necessary element of randomness in the selection essential to the basic mathematical principles of sampling methods for which theories have been developed, 'it is not amenable to the development of a sampling theory' (Cochran, 1953) so that no assessment of precision of estimate can be carried out. But a knowledge of the precision of the estimate is often as important in inventory as the estimate itself. Haphazard selection, in which the operator does not make a deliberate choice but employs devices such as sticking a pin into a map or a list while blindfolded, has the same disadvantages as purposive selection. However well intentioned, the selection is liable to the personal bias of the selector; and the method is not 'amenable to the development of a sampling theory'.

Subjective and haphazard selection are therefore not common in inventory but have been used sometimes with satisfactory results.

Seely (1961, 1964), for example, discusses the advantages, disadvantages, tests, and results, of using subjective selection of sampling units within strata on air photographs; and of using the 'selected line' method whereby 'easily identifiable map features are selected at some distance from the stands and straight lines joining them are drawn through the stand or stands to be sampled. Sample plots may be selected at random on the lines or may be placed at regular intervals thereon'. The selected line method has been used in Australia. Harrison (1950) discusses the advantages and disadvantages of selective sampling of areas of a particular classification on a map compiled from stratification of aerial photographs and then sampling such areas by sampling units.

Objective Selection

In objective selection, the individual sampling units are selected by a method in which chance may or may not play a part but which is not influenced by the personal judgment of the selector. This group includes all those methods which can be considered as basically either random selection or systematic selection.

Random selection. If a population for inventory is considered as having a finite number of units, say N, simple (unrestricted) random sampling is a method of selecting n units out of the N units so that every possible sample of n units has an equal chance of being chosen. In practice, the sampling units are selected unit by unit independently with equal probablities of selection. The most satisfactory way is to assign to each unit a number if the units can be listed, or a set of rectangular co-ordinates if they compose an area, and then to select the appropriate quota of numbers mechanically from a table of random numbers such as that of Fisher and Yates (1943) which is an artificially compiled population of randomly distributed elements from which mechanical selection gives a random sample. The sampling units with numbers corresponding to those chosen then make up the sample. For inventory purposes the selection is usually done without replacement, that is a number drawn previously is ignored if drawn again subsequently, on the grounds that there is little point in having the same unit more than once in the sample. This method of selection provides an unbiased estimate of the mean and of the variance but unless the sample is well distributed over the population the precision of the estimate of the mean may be low, particularly if there is

considerable variability in the population and if, as is usually the case, the sampling intensity is low.

Stratification of the population and drawing an appropriate proportion of the sample randomly from each stratum, called stratified (restricted) random sampling, is likely to be more efficient than simple random selection from the whole population because it ensures a more effective distribution of the sampling units. The stratification may be based on artificial grids, geographical divisions or cadastral boundaries, but since the efficiency of the sampling increases as the variation of volume within strata is reduced, the most effective stratification is usually one of a 'natural' kind using criteria with which volume is correlated. For precision of estimate to be assessed, there must be at least two sampling units per stratum, since no estimate of variation can be made from the evidence of one unit.

A major advantage of stratified sampling is that a variable sampling intensity amongst strata may be employed, a fraction of the sample being allotted to each stratum by some system of weighting. In proportional allocation, the sample is allotted to each stratum in the proportion which the number of units in the stratum bears to the total number of units, that is the sample distribution is weighted purely by area. In optimum allocation, the sample is allocated so as to give the smallest standard error of the estimate of the population mean (the highest precision of estimate) possible for the particular size of sample, the sample distribution being weighted by the product of the area of stratum and the within-stratum standard deviation of volume. This expression of variation within strata is estimated from whatever evidence is available, such as previous sampling of similar populations, or by preliminary sampling. If cost of sampling varies from one stratum to another, as is normally the case, a further weighting involving cost per sampling unit in each stratum can be used to derive the allocation which gives most information for the money to be spent. For various reasons, overall estimates may be of less importance than estimates for particular strata in which case optimum allocation is ignored and emphasis placed on sampling those particular strata so as to obtain a desired degree of precision of estimate for them. There are also practical advantages in sampling strata separately - priority of work may be varied as the inventory proceeds to suit the weather, the availability of men for field and office work, or a change of interest in strata as information is accumulated.

Systematic selection. In systematic sampling, the pattern of the

position of the units of the sample relative to one another is determined in advance. Usually the pattern is a regular one, the units being spaced an equal distance apart in one-dimensional pattern on a list or in a line, or spaced in a square or rectangular grid system in a two-dimensional pattern. By the nature of such a pattern, the position of every unit is determined once the position of one unit is determined. It is therefore essential that the framework of the sample be placed by random selection from all possible positions (that is, the systematic selection should have a 'random start') otherwise the estimate of the mean is liable to bias.

If a stratified random sample may be expected to show an improvement in precision over a simple random sample because of the improved distribution of the sampling units, it might then be expected that a systematic distribution of units would also show an improvement, at least over simple random sampling, and perhaps would be as precise as a corresponding stratified random sample with one unit per stratum. This has been investigated for artificial and natural populations as discussed by Cochran (1963). Nevertheless, whatever the relative precision of the estimate of the mean from systematic sampling as compared with that from simple or stratified random sampling, a single systematic sample does not provide an unbiased estimate of variance and so the precision of the estimate of the population mean cannot be calculated. The conventional method of calculating the error of estimate requires the assumption that every possible sample of the size chosen has an equal chance of being chosen, whereas there is a definite restriction to the repetition of the systematic sampling process according to the pattern and the sampling intensity. Systematic sampling has practical advantages and under certain conditions the precision of the estimate of the mean may be relatively high. Statisticians have therefore investigated ways in which an approximate estimate of precision might be made from a single systematic sample and the extent of the bias in an estimate of precision calculated from a systematic sample as if the sample had been randomly selected (Osborne, 1946; Yates, 1949; Finney, 1947, 1948, 1950, 1953; and Matern, 1962). Various workers such as Shiue (1960) have suggested establishing a number of systematic samples, each being regarded as a cluster of sampling units, and estimating sampling error from these clusters.

For forest inventory, strips are usually spaced equidistant on a base line and plots are spaced equidistant in terms of rectangular

co-ordinates. Seely (1961) describes tests in Canada of sample plots equi-spaced in terms of polar co-ordinates, the design being 'of most use when it is desirable to penetrate the stands as far as possible from the starting point [of the day's work] and return directly to that point instead of making long offsets between the radiating location lines with consequent limited penetration during a day's work'.

A comparison of stratified random and systematic sampling. One of these two methods of sample selection is normally used in resource inventory. Several factors influence the choice.

In resource inventory, information on the composition of the forest is usually wanted and sometimes topographic information as well. If aerial photographs are not available or are not adequate for interpretation of forest composition and for mapping topography, this information can best be obtained by systematic sampling. After map compilation, quantitative estimates might be obtained by stratified random sampling but it may be more economic and convenient to make quantitative estimates while systematically sampling the forest composition and topography. Even if photographs are available, the forest may not lend itself to stratification, or boundaries of strata may not be readily discernible on the photographs, or the establishment of random units within strata may be difficult, in which cases systematic sampling would be more practicable.

For practical location of units on the ground, the direct nature of a systematic layout makes it easier under most forest conditions to prescribe, execute and check the location of units, and to re-locate them. Various sources of bias in the estimates, which may arise due to problems of locating randomly selected units, may be avoided.

Provided the framework of selection is located by random choice of all possible positions, an unbiased estimate of the mean of the population can be obtained from a systematic sample as with a stratified random sample - one of the major objectives of sampling.

A second objective, that the evidence of a single sample provide an unbiased estimate of variance from which the precision of the estimate of the population mean may be calculated, is met by stratified random sampling but is not met by systematic sampling, though an approximation to the estimate of precision may be obtained in certain circumstances.

A further objective is that the estimate of the population mean should be as precise as possible for the time and money expended. It has

been shown that under certain circumstances the precision of estimate may be higher for systematic sampling than stratified random sampling. There is, however, no way of forecasting these circumstances.

Sample Structure

If each unit in a population can be divided into a number of smaller elements each of which can be further subdivided, the sampling may be done by multi-stage sampling. At the first stage, primary units or locations are selected by some suitable method of selection; then a sample of the second-stage units of the primary units is taken by the same or a different method of selection; a sample of third-stage units of the second-stage units is then selected; and so on. Yates (1949) discusses the advantages and disadvantages of multi-stage sampling.

In some cases the required information is determined from several samples. If the first sample provides the basis for the rest, so that certain information is obtained from all the units of the sample, other information from only a sample of these, and other information from only a sample of these latter, each sample represents a phase of the collection of the wanted information and this is called multi-phase sampling.

The Sampling Units

Kind of unit. Three main kinds of units are used - the strip, the plot, and the point (spot) of the angle count method. The term strip (stripline, transect) is given to an area enclosed between parallel straight lines stretching from some reference boundary to another, the distance between the lines (width of strip) depending on the method of sampling, the sampling intensity, the nature of the topography and the forest composition, being from $\frac{1}{4}$ to 2 chains wide. Usually, for quantitative estimates, the strip is laid down by establishing one survey line, then offsetting the whole prescribed width on one side or half the prescribed width on each side of the line; the offset must be exact because the quantity is related to area. For qualitative information such as topographic and forest type boundaries, the survey line merely acts as a reference for location. The strip is sometimes broken up into recording units by a break in the record of the information to allow easier supervision and checking. This may also assist in mapping types. Rectangular plots may have external boundaries cleared and marked. They may also be established by the same technique as a

strip, that is a single line is surveyed and the boundaries of the plot offset from it, the conventional limit to the length being 10-15 chains - anything longer is called a strip. Circular plots may not have any external boundaries cleared, though they may be indicated by marks on boundary trees. Often the units are not regular but of varying size with irregular boundaries such as small ridges, creeks, tracks, and rides. For the angle count method, the sampling unit is identified merely by a point or spot from which the circular sweep, characteristic of the method, is made.

Various factors influence the choice of kind of unit. If information on topography and forest composition cannot be obtained from aerial photography and ground sampling is necessary, strips are most convenient, the quantitative estimates usually being made at the same time. Because the ratio of working time on units to travelling time between units is greater for strips than plots, a forest can usually be sampled to a greater intensity (by area) by strips than by plots in a certain time. However, the number of units, and so the number of degrees of freedom in calculating sampling error, is likely to be less and this may not be balanced by the reduction in the between-unit variation. Where the forest composition is such that establishing plots, particularly randomly selected plots, involves a disproportionate amount of time and difficult 'navigation', then strips are generally used. A combination of strip lines and plots is sometimes used, topography and type information being recorded along systematically located strips, and quantitative estimates being made at intervals within portions of these strips. The term line plot is often used for this arrangement. The same term is sometimes used to indicate a systematic location of plots which is better described as an aligned arrangement of plots.

Size of unit. Size of unit has an effect on precision of estimate. A compromise is usually necessary between a certain number of large units which would provide a certain variance between the units and a greater number of smaller units which would increase the variance between units but might decrease the variance of the estimate of the mean. For a given number of units, the larger the individual unit the more precise is the mean likely to be on a unit area basis, but this depends on the way the unit is increased in size - generally, increase in the long dimension will give the greatest gain, particularly if a fertility gradient exists and if the unit is oriented along it as it should be. The size of the unit should bear a sensible relationship to the size

of the elements of the population. For example, a unit of one acre may be necessary in a stand of mature eucalypts carrying 10-15 trees per acre, but one-tenth acre may be more suitable for a stand of poles and a mil-acre unit may be adequate for regeneration. In a forest composed of mixed species and range of sizes, concentric units are commonly used. Too many concentric units may lead to undue complications in field work and office computations and about three seems a desirable limit in practice.

Though it is often stated that in principle the smaller the unit the more reliable measurement is likely to be through reduced opportunity for making mistakes and through more intensive application by the measurers, it seems in practice that the unconscientious operator is not affected by the size of the plot and that the conscientious operator is only affected adversely if the size of the unit is such as to promote mistakes however conscientious he might be.

The relationship between size of unit and time-cost of measurement is often but not necessarily a direct one. Once operators are on the spot and organised, increasing the amount of measurement usually does not proportionally increase the cost.

If single plots are used there are many advantages in handling the data if they are all the same size, and a compromise is often made between the largest unit which is practicable in densely stocked stands of small sizes and the smallest worthwhile unit in sparsely stocked stands of large sizes. There may be particular advantages in the field, however, in having units of varying size and irregular shape bounded by natural features, particularly if the units are permanent, and these advantages may outweigh awkwardness in handling the data.

Where time to get to a unit is disproportionate to the time spent in establishing and measuring it, cluster sampling is often employed, a number of sub-units being established as a group or cluster around a primary sampling point. There are other advantages as outlined by Loetsch and Haller (1964). Various patterns are used. For example, Loetsch (1957) describes the use in Thailand of a number of 'camps', each camp comprising a cluster of seven camp units, each camp unit comprising a cluster of seven tracts, each tract being a square each side of which was formed of twelve plots each 0·05 hectare. Tracts of this kind had been used in the Swedish National Inventory (Matern, 1962).

Shape and orientation of unit. Sampling units are usually regular in

shape. Strips are long rectangles, plots are usually rectangular or circular. The last have the least perimeter for a specific area and so reduce the likelihood of wrong inclusion or exclusion of trees on the boundary. In some cases there are practical advantages in establishing and identifying circular rather than rectangular plots. Where there are silvicultural as well as practical advantages in identifying units by topographic and artificial boundaries, irregular shaped units of varying size are sometimes used.

Where fertility gradient can be recognised, units with a long axis in the direction of the gradient can usually be expected to give greater precision than plots of other shape and equal area. Where fertility gradient cannot be recognised, establishing square or circular plots avoids the risk of bias which might otherwise arise by orienting long units other than along the gradient. Strips for qualitative description are usually directed at right angles to the contours of the main topography of an area since there is usually a good correlation between kind of forest and its position on a slope. This usually suits quantitative description as well because of a correlation, positive or negative, between the carrying capacity of a forest and its position on a slope.

Permanence of units. Changes in the forest estate are just as important as its state at any time. Resource inventory, to be effective, needs to be carried out periodically. Whether the sampling units should be permanent or not for this purpose is of similar but possibly greater concern in management inventory and is discussed later in that connection.

Size of Sample

The size of the sample may be expressed either as the number of units, or as sampling intensity - the area of the sample as a percentage of the area of the population. The former expression is generally preferable because if two areas of different size have the same mean and variance they will require the same number of units for a particular precision of estimate but this will represent quite different sampling intensity.

The variability of the variable being estimated, the size and shape of the sampling units, and the method of selecting them, determine the number of units needed for a particular precision of estimate.

Time, money, and labour available determine the number of units which can be established. A compromise is often necessary between what is desirable and what circumstances permit.

Standard texts on statistical methods illustrate the method of calculating the number of units needed for a particular precision of estimate if the extent of the variability is known. Information about the variances of various classes and strata of an inventory is accumulated to this end. In stratified random sampling, the best allocation of the sample to the various strata can be determined, taking into account both relative variability and the relative cost of establishing units in the various strata.

A decision has to be made on the precision required. This is an administrative decision and the factors affecting it will not be discussed here, but the point is made that the decision seems far too often to be made without sufficient rationale and a higher precision is called for or expected than is really necessary for the purpose of the inventory.

Establishing the Sampling Units on the Ground

Operator Bias in Locating the Units

In the systematic location of units, the randomly chosen starting point of the systematic pattern is established by survey method, using as a datum some point which has been or can be referenced on a map. Strips are set out equidistantly along a surveyed base line and plots are laid out at prescribed spacing along surveyed parallel lines. The prescriptions for the location of units are well defined and easy to follow and there is little source of bias in location.

Units selected randomly are usually selected on paper (a map or aerial photograph), and their positions must be translated into the field by survey method, using reference points which can be identified both on paper and in the field. In random location there are various sources of bias. Strips can be located by prescribed distances along a surveyed base but exact location of plots is often difficult - maps lack sufficient detail, the forest composition prevents location of features apparent on photographs, the quality of the photographs prevents reliable interpretation of them, or the forest shows no distinguishing features. There are two common cases. In one, the operator can locate himself near the required position but not exactly on it. If he then decides to locate the unit at a certain distance in a

certain direction from where he stands without deliberately trying to influence the location thereby, he can minimise subjective bias in location. In the other case, location must be made by survey method over a considerable distance, from an identifiable feature, the prescription for location by bearing and distance being determined in advance. If the operator adheres faithfully to that prescription he can avoid subjective bias even if factors outside his control prevent exact location of the unit.

The prescriptions must anticipate circumstances where the operator may feel prompted to substitute positions with good intention but which will be a source of bias. For example, a unit may fall in a 'minimum area' - an area of one kind, within a larger stratum of a different kind, which is too small to be worth delineating on aerial photograph or map. The operator should be instructed to locate the unit as planned but to record the circumstances as an explanation of why the unit might appear atypical. Again, access to private land to establish a unit may be denied, in which case the operator would normally be instructed not to substitute a position but to omit it and record the circumstance as explanation of the omission.

Edge Effects

The outer edge of a forest stand surrounded by open land has different micro-locality conditions from those within the stand which may be reflected in different species, different growth rates of the same species, and different tree taper. The change may be of a continuous or discontinuous nature and extend over a few feet or hundreds of feet. This fringe usually cannot be readily identified as a sub-population for sampling purposes and the extent to which it should be taken into account in sampling has to be considered. In selecting units, some are likely to fall so that they lie partly within and partly outside the stand. If the fringe area is small relative to the area of the main population, these units might be rejected without the bias being serious. To avoid bias the units should be established up to the external boundary of the stand as partial units and appropriate adjustments made to estimates in these partial units to bring them to whole unit equivalents. This is not inconvenient if the fringe area is relatively small.

In an extensive inventory of small isolated stands, however, the fringe area is likely to represent a large proportion of the total area and must be taken into account in the sampling. Units cannot be

rejected but establishing partial units may be inconvenient in both field and office. In such a case it may be desirable to modify the prescriptions of establishment of units in the perimeter to avoid this inconvenience without biasing the estimate. The solution to this problem in the Census of Woodlands of Great Britain, where it was of particular importance, is discussed by Hummel (1949) and Finney and Palca (1950). The matter will need attention in a resource inventory of Australian native forest which includes private property.

Units Overlapping Strata Boundaries

A similar problem arises in stratified random sampling where units fall so that they overlap the boundary between two different strata. A method of moving such a unit so that it lies wholly within one stratum with appropriate weighting of the quantitative estimate was suggested by G.A. McIntyre for the Australian national inventory (F. and T.B. MSS.).

Fertility Gradient

Units with one dimension longer than the other should have that dimension directed along the fertility gradient. This is usually across the line of topography, that is at right angles to the contours. When strips are established so that information on forest types and topography can be obtained at the same time as quantitative estimates, they are oriented at right angles to the contours to get a representative sample of this information also. In large areas with an irregular topographic pattern, this may necessitate survey sub-division. In any case, strip length should be restricted to about one mile for control of direction. The direction of the strips is usually prescribed beforehand and there is no source of operator bias in locating the unit relative to fertility gradient.

If long narrow plots are used purposely to take advantage of their increased efficiency if they are oriented along the fertility gradient, it is essential that they be oriented correctly. It is preferable not to leave it to the operator in the field to decide the orientation. If the area is essentially of one topographic form, or is known to be of variable form but no detailed plan is available a meridional direction common to all units in the area is often prescribed. If the topography varies by zones, a fixed direction for all units in a particular zone may be prescribed. The prescriptions for orientation of units which

were used for inventory of an area of known broken topography are described by Carron and Hall (1954).

The Quantitative Estimate

Tree and Stand Variables

The objectives of the inventory will determine what tree and stand variables are measured or estimated. How this might be done forms the previous part of this text.

The scope of an extensive inventory and the fact that time, funds, and labour are usually limited, often prompt substitution of ocular estimate for measurement of tree variables. Ocular estimation is often a serious source of bias. The capacity of operators to estimate tree dimensions tends to be grossly exaggerated, and if the inventory is serious in intention and not just a cursory reconnaissance, ocular estimation should not be considered except where a regression of ocular estimates on measured values is a part of the inventory design.

The Area of the Unit

Any error in determining the area of sampling units has a direct effect on the overall estimate. When the complete boundaries of units are established by surveying methods and measured, the determination of area is under control. When strips or long plots are used, it is common to establish only a centre line by survey. In this case the determination of area may or may not be under strict control and this source of error may be serious. For narrow units (2 metres, 10 ft, or a quarter-chain in width), a pole is often used to determine from the centre line whether trees are within or outside the unit. For wider units, operators frequently estimate by eye whether trees are 'in' or 'out' of the strip because the difficult forest conditions which prompt the choice of such units are by their very nature those which prompt estimation rather than measurement. If strips are used and the operator is collecting qualitative information at the same time as quantitative information, he may also tend to forget, in collecting the qualitative information as far on each side of the centre line as he can, that he should collect quantitative information within only a very strictly defined distance of the centre line. The argument is often advanced that a certain amount of error in strip width estimation can be permitted because trees wrongly included are likely to be balanced by trees

wrongly excluded, particularly over long strips.

An investigation into this matter was carried out by students of the Australian Forestry School at Roses Tier, Tasmania, in 1951. On an area of 240 acres of eucalypt forest (mainly E. obliqua), 30 contiguous strips were established, each 40 chains long, making a total of 15 miles of stripline. The centre lines were surveyed and cleared and parties required to assess 1 chain each side of the centre line. The trees were recorded merely by an identifying number and their volumes derived later. The area was at an elevation of about 3,000 ft and varied from flat to steep; the undergrowth was dense in most places, of high bladey grass in the flat dry areas and mixed species in the wetter areas, particularly thickets of myrtle beech in the gullies. The weather varied from hot and dry to cold and wet, with snow on two occasions and heavy hail on another. The bush was always wet for the early part of the morning's work. In short, the general conditions were reasonably typical for stripline work in many Australian forests. Four parties each assessed the 15 miles of stripline, three parties working in the common fashion of measuring strip width only when in real doubt about a boundary tree. The fourth party was instructed to check the strip width except when there was no doubt at all, and subsequently went over the strips again to determine the exact population of each strip and to analyse errors the party had made. A tree was considered within the strip if its geometric centre at ground level was within the strip. The results are shown in Tables 18:1, 18:2, and 18:3.

The general conclusion is that without continuous check of strip width by measurement, the error in the estimate of volume may be high. The errors in individual strips are likely to vary in size and sign depending on the operators, as seen in Table 18:1. The summary of these errors by classes in Table 18:2 shows the extent to which the errors can be reduced by conscientious measurement of strip width (operator 4). Table 18:3 shows that there was no balance between trees wrongly included and those wrongly excluded. Even where the numbers of trees closely agree for operator 3, there is a very big difference in volume. Analysis showed that there was a marked tendency to include trees doubtfully in or out if they were large and to exclude them if they were small. Operator 4 wrongly included only 6 trees in the 15 miles of strips, all of which were due to confident but wrong estimate of strip width. Of the 49 wrongly excluded (a surprisingly high figure in the circumstances), 23 were excluded because of confident but wrong estimate of strip width; 13 were missed

because of the nature of the undergrowth around the trees, weather, and topographical conditions; and 13 were missed for no valid reason. The evidence suggests that to estimate the contents of a strip correctly,

Table 18:1

Strips, Roses Tier; error as per cent of true volume for striplines by four operators

Strip no.	Oper. 1	Oper. 2	Oper. 3	Oper. 4
1	3·4	-4·6	17·5	-2·0
2	4·7	-3·7	5·8	nil
3	12·4	20·2	19·6	-0·4
4	0·7	3·3	7·9	-0·4
5	11·0	2·7	15·0	-0·4
6	3·8	-5·3	-1·3	-1·7
7	-0·1	-0·3	-3·7	nil
8	3·8	12·6	7·7	-0·5
9	1·5	11·4	-7·3	-0·2
10	-0·7	8·8	1·8	-1·7
11	1·0	3·6	-1·8	-0·8
12	-4·4	15·6	-2·8	-1·4
13	-1·7	7·1	-4·2	0·2
14	-4·2	-2·0	-0·3	nil
15	-4·6	-2·7	-5·1	-0·8
16	-0·1	9·5	1·2	-0·8
17	11·2	4·4	7·2	-3·5
18	7·1	5·9	5·2	0·9
19	6·0	-1·3	-1·2	-1·2
20	6·0	3·3	7·2	-0·3
21	-0·9	3·0	-2·6	-2·4
22	-0·7	16·9	-3·9	-2·0
23	2·4	4·4	1·3	-1·3
24	-7·8	3·3	-4·2	-3·8
25	-7·9	3·5	3·4	1·7
26	-2·2	1·0	-2·6	0·2
27	-2·0	8·1	3·6	nil
28	-9·8	-9·9	-5·3	-3·0
29	-1·7	-3·5	5·8	-0·7
30	0·6	-6·8	2·5	-0·1

Table 18:2

Strips, Roses Tier; distribution of error as per cent of true volume for striplines by four operators

Class	Oper. 1	Oper. 2	Oper. 3	Oper. 4
Nil	0	0	0	4
1·0 and less	8	2	1	14
1·0 - 5·0	13	15	17	12
5·0 and greater	9	13	12	0
No. of + ve errors	15	20	16	4
No. of - ve errors	15	10	14	22

Table 18:3

Strips, Roses Tier; error as number of trees and as volume of whole area for striplines by four operators

	Oper. 1	Oper. 2	Oper. 3	Oper. 4
		Number of trees		
Wrongly excluded	156	145	162	49
Wrongly included	136	185	164	6
Difference	-20	40	2	-43
Difference as per cent of total	-0.7	1.2	0.07	-1.4
		Volume		
Difference (cu ft)	6406	33866	16696	-10029
Difference as per cent of total	0.6	3.2	1.6	-0.9

considerable care generally and continual measurement of strip width is necessary.

Species Identification

It is usually important that tree species be correctly identified in inventory and special instruction of operators before an inventory and frequent checking during the inventory to ensure consistent and correct species identification is generally necessary. This is particularly the case where certain species have special qualities, trees look alike but have wood of quite different quality and value, and there are a number of species not regarded as useful at present but which may be so regarded later.

Processing and Analysing the Data

Because the amount of data collected is usually such that it poses great difficulty in handling it manually, most modern inventory involves the use of automatic data processing methods. This is a specialist field of study and application and no attempt will be made to discuss it here. There is extensive literature on the subject because of the fast advances in the development and application of automatic equipment in the last decade. Furnival (1962) and Husch (1963) provide good outlines from which the forester can obtain background of a general nature. The authority organising an inventory will either have its own specialist

staff to deal with processing the data, or will have it done by another organisation. In either case it must be recognised that the processing of the data is an essential part of the planning of the inventory as a whole; the requirements of processing will influence what data are collected and how they are collected. Advice on data processing must be sought before an inventory, not afterwards.

The nature of the statistical analysis for estimates of means and sampling errors depends on the method of sampling. This is covered in standard texts on the subject.

Forest Resource Inventory in Australia

Australian forestry authorities have agreed on the desirability of an inventory of the indigenous forest of the country on a national scale but for various reasons no comprehensive inventory has been carried out.

The general pattern in Australia up to the late 1940s was assessment of areas of local management interest by ground surveying. Sampling units were usually strips from which forest type and topographical maps were prepared and estimates made of quantities of wood available, usually including only the species then utilisable and by the criteria of economic accessibility and utilisation of the time. Some State forest services had by that time mapped and assessed a large proportion of the forests of the State of interest to management on this basis. Other State services had covered only a small proportion.

After World War II, interest in a resource inventory on a national scale was stimulated by various foresters for several reasons. Some had been involved in the use of aerial photographs during the war and the application of aerial photographs to forest inventory had already been confirmed before and during the war; there was a considerable reservoir of maps, photographs, and expertise available which had not been available before; automatic data processing equipment, by which the vast amount of data collected in inventory could be conveniently handled, was becoming available and exciting new developments were promised; other countries were commencing comprehensive inventories and the sense of internationalism which was being generated after the war prompted a sense of national responsibility to survey natural resources.

Those State services with a large proportion of their forests already assessed began to use aerial photographs to modify assessment

information from low intensity and faulty sampling and to enhance further strip assessments. Other State services began to use aerial photographs in a comprehensive program of inventory. Tasmania, for example, had already investigated the usefulness of aerial photographs before World War II and Hemmings (1949) was able to report a considerable amount of research into interpretation for forest classification and stratification. Cromer (1949) outlined the progress that had been made in photo interpretation of various forest types in Australia but emphasised the necessity for photographs taken especially for forestry purposes. He also emphasised that basic mapping, on which foresters could superimpose information of special interest to them, was inadequate and might have to be provided by the forest services themselves.

In 1951, a conference was held of Commonwealth and State forestry authorities and a framework which was suitable to a national inventory was agreed on (F. and T.B. MSS., 1951). Definitions were adopted, mainly following those of Harrison (1950) which had been proposed as an international standard. It was recommended that mapping be on the basis of 1 mile to 1 inch military sheets with a classification of land and forested land as discussed earlier in this chapter. It was suggested that, wherever possible, the estimation of volume be carried out by stratified random sampling using plots as sampling units. The sampling intensity of the strata was to depend on the area and importance of the strata and the precision desired, and tentative suggestions were made as to the appropriate precision for estimates of gross bole volume and commercial volume for various purposes and strata. It was recommended that certain plots be made permanent for determination of increment. To test the practicability of the prescriptions, they were applied by students of the Australian Forestry School to an area in Victoria as reported by Carron and Hall (1954), and an inventory of the A.C.T. was also carried out (Rodger, 1953).

However, the inventory on a national basis did not eventuate and the various State services have continued independent inventories which vary from resource type to management type, with various levels of classification and stratification based on various criteria, and at varying intensity of sampling. The 'forest inventory surveys' of State forest areas of Queensland are intended as management inventories but the areas of the western cypress pine-eucalypt and some of the coastal eucalypt forests are so large that these inventories are almost resource type inventories in scope. In New South Wales, 'classification

surveys' have been carried out over a considerable part of the State based on a classification such as outlined by Byles (1958). These are resource type inventories in scope and purpose. Though the main purpose of the assessments carried out in Tasmania, as reported by Lawrence and Walker (1954) and Lawrence (1963), has been for management planning, they have followed fairly closely the prescriptions for national forest inventory as have the assessments of Western Australia as discussed by Nunn (1959). Some authorities have claimed that the various inventories carried out in the States have sufficient in common for satisfactory national estimates to be derived from them. Other authorities such as Cromer (1960) deny this.

Cromer (1949) has drawn attention to the limitations to the application of photo-mensuration techniques to the eucalypt forest of Australia. For many years these techniques have formed the basis of much of the resource inventory of forests of the northern hemisphere. The history of a considerable part of the eucalypt forest is one of selective logging, and the present forest has a legacy of large faulty trees. Many species also develop the typical central pipe which is hollow or not utilisable, or have been subject to insect and fungal attack particularly after fire. The occurrence or extent of one of these faults cannot be determined by aerial photograph interpretation - even on the ground estimation of these faults is notoriously unreliable. The major contribution of aerial photographs to inventory in the eucalypt forest is to allow fast and reliable mapping of the location and extent of forested areas, classification into productive and non-productive forested land, and stratification into various strata which improve the efficiency and practicability of sampling for quantitative estimates on the ground. The efficiency of this kind of stratification was tested in Tasmania as reported by Lawrence (1957). Attention has been given to photo-interpretation techniques, particularly the use of stereograms and density scales (Aitken and Hall, 1951), and to the cause, effects, and avoidance of 'shadow point' (Sims, 1954; F. and T.B., 1955). Sims and Hall (1955) considered various requirements for interpretation of aerial photographs in Australia and in particular outlined prescriptions and criteria for the selection and training of aerial photograph interpreters which have been applied to a large number of people undertaking courses in interpretation at Canberra in the last decade.

Forest Resource Inventory Elsewhere

Much has been written on forest resource inventory in various countries of the world. There is no point in summarising any of it here. The reader's interest will be better served by direct reference to the literature listed below, which has been chosen because it explains the intentions of the inventory and methods and techniques used (rather than statements of resources) or has itself the most comprehensive bibliography on the particular inventory.

A start was made on a forest resources inventory of Papua-New Guinea during World War II for military purposes and for planned post-war development. Various aspects of the military survey were outlined by Shillinglaw (1945) and Luke (1946). Post-war inventory is discussed by Womersley and McAdam (1957).

A description of the national forest inventory of New Zealand which had then recently commenced was given by Thomson (1946). A general outline was given by Masters, Holloway, and McKelvey (1957).

There is a long history of resource inventory in Canada, where many aspects of the use of aerial photographs were pioneered. Seely (1957) has given a summary of the inventories of the various provinces, and also an outline of technical aspects (Seely, 1960). There is a similarly long history of resource inventory in the U.S.A. Spurr (1952, 1960) has provided an extensive bibliography on the various methods and techniques; Wilson (1962) lists 'criteria useful in appraising the relative merits of a survey design' and evaluates a number of the designs used in North America on the basis of them. Inventories of South American countries are much more recent and limited. Heinsdijk (1961, 1962) has discussed inventories in Brazil.

In Europe, the Scandinavian countries are noted for the number of successive national forest inventories they have carried out, based on field observations only. The inventory of Sweden was outlined by Hagberg (1957), that of Norway by Langsaeter (1949), and that of Finland by Ilvessalo (1952). In other countries of Europe, the inventories are basically of management rather than resources type.

The methods and techniques of the Census of Woodlands of Great Britain were described by Hummel (1949) and further by the Forestry Commission (1952, 1953).

For Asian countries, Mathauda (1957) outlined methods used for inventories in India, basic research on methods of sampling forests in India having been reported by Griffith (1945-6). de Rosayro (1962)

discussed inventory in Ceylon and refers to inventories in other tropical forests. Loetsch (1957) described a forest inventory in Thailand. Francis and Wood (1955) discussed a classification of vegetation in North Borneo from aerial photographs. Brunig (1963) has reviewed the history of forest inventory in Sarawak. Kinashi (1954) and Kinashi et al. (1962) discussed the development of sampling designs for forest inventories in Japan.

Nyssonen (1961) has discussed inventories of tropical forests in general and particular.

FOREST MANAGEMENT INVENTORY

The measurement or estimate of stand variables over the whole or a sample of a forest or stand so that present yield can be determined and its utilisation regulated has always been the basis for management of the forest or stand. It has therefore been carried out in some parts of the world for a very long time. Historically, this kind of inventory preceded resource inventory, which borrowed many of the methods and techniques of management assessment. Much of what has been said about methods of making quantitative estimates under the heading of resource inventory is applicable here and need not be repeated. The main differences between resource and management inventories, already mentioned, are the basis of classification and stratification, the kind of information collected, and the precision of the quantitative estimates required. Characteristically this kind of inventory of an area is carried out once, the information obtained by a single inventory being regarded as sufficient for implementing a managerial control over operations on the area.

There has been a long history of such assessment in Australia, the main function of which in earlier times was to provide information for timber operations to meet the demands of an established and expanding industry, but which in later times was to provide information for management in the stricter sense. The history of assessments of this kind in New South Wales forests was outlined by Henry (1955) and in Western Australian forests by Nunn (1957). Recent assessments of eucalypt forests in Tasmania for management planning were described by Lawrence (1963).

There is an extensive literature on assessments in various countries of the world. Some of the more interesting references are those

describing investigations in tropical high forest in Africa by Dawkins (1952, 1957).

Periodic Management Inventory

If estimates of future yield are required, the estimates of a single inventory can be adjusted by information about likely growth in the future period drawn from special investigations. There are, however, many advantages in repeating an inventory of a forest so that the repeated inventories provide information about yield available at the time of inventory and also about changes during the period between inventories that are directly related to the forest and so provide a better basis for extrapolation. This system of repeated inventory is known by various names, among them periodic management inventory, working plan inventory, continuous forest inventory and forest inventory survey.

The earliest example of importance is the periodic management inventory of the control method which was first applied in western Europe over seventy years ago. There has been effective periodic inventory, on which management has been based, in some Australian forests for a little over thirty years. In the last ten or fifteen years there has been an increased interest, both public and private, in repeated inventory in many parts of the world. This is due to both an increasing awareness of the need for management and so of the need for quantitative data on which to base it and to the development of data processing, which has given the forester means to handle the enormous amount of data usually involved. This expansion of interest, with concomitant spate of literature, has been particularly marked in the U. S. A.

The general principles of periodic management inventory can be applied to any forest or stand whether even-aged or uneven-aged, of coniferous or non-coniferous species, pure or mixed, virgin or cut-over, though the method and technique of applying the principles differ according to the objective of management and the kind of forest. The information required for the particular purposes of management, and the required levels of reliability of the quantitative estimates, are nominated. This information is sometimes obtained by complete enumerations but more often by sampling, which involves consideration of the size of the sample, the method of selecting the sampling units, number, size, shape and orientation of the sampling units, their establishment in the field, their maintenance if permanent, and their

representativeness at all times. The stand variables are measured or estimated on the sampling units and a field record made. The data is then analysed, manually or by some system of data processing, to provide information on the present stand condition and changes in the stand over the period between measurement. On the basis of this information, management decisions are made.

The purpose of a management inventory being to provide the manager with information to make rational decisions on the management of a forest, the logical starting point of any management inventory is for the manager to nominate what information he needs, and at what level of reliability. This may require some preliminary investigation. Usually the manager will know enough about a forest to decide the sort of information he needs to choose the objects of management. If, having decided on the object of management, he needs further information to implement it, this may have to be determined by extra work. Usually the inventory can be arranged to obtain not only the right kind of information on which to decide on the best object of management but also the kind of information needed to implement it. If the inventory cannot be so arranged it is far better to carry out an appropriate preliminary investigation, on which an efficient inventory can be based, than to carry out an inventory which gives more information than is needed to decide on the object of management but less than is needed to implement it.

The level of reliability at which the manager needs the information is important. To a large degree it determines the method and intensity of sampling and so the amount of work to be done in the inventory. In deciding this level the manager should be mainly concerned with balancing it against the consequence of a wrong decision. The usual position in which the manager finds himself is that the level of reliability he would like to have costs more than the revenue of the forest (or other sources of funds) can support and the inventory which the forest can support will not give him a level of reliability which will enable him to make his decisions with appropriately comforting confidence. He must effect what to him is an uneasy compromise between these two. One of the main difficulties in this is that, whereas confidence limits can be readily set to quantitative estimates, it is not comparably easy to nominate 'consequence limits' in decision making. Forest managers do not appear to have given sufficient attention to this latter aspect and as a consequence the level of reliability required for most management inventories, like that for

most resource inventories, is rarely nominated in a rational way and very often is likely to be higher than is necessary.

The design of a management inventory may be considerably affected if the inventory is to provide information on where cutting operations should be carried out at a particular time as well as information on how much is available for cutting at that time. A separate operational inventory may be necessary for the former.

Because inventory is an information-gathering procedure and management involves devising and controlling operations, there is a tendency to think of it as something apart from management. Inventory is an essential part of management. It is best designed and supervised by the manager, or, if management and inventory require different skills, they should be in complete sympathy with each other.

Paine (1966) has illustrated the use of linear programming in management planning of a eucalypt forest in Victoria. McGrath and Carron (1966) have suggested a method of determining the yield of an uneven-aged mixed eucalypt forest on the coast of New South Wales, the information necessary for this, and the problems of obtaining the information by periodic inventory.

Complete Enumerations

As interest in management inventory has developed in recent years so has reference to the control method (méthode du contrôle, Kontrollemethode) increased in the literature. The term is associated with the management of some forests in western Europe, particularly in Switzerland, along lines suggested by Gurnaud in France about 1878 and further developed by Biolley in Switzerland about 1890. Detailed outlines of the method were given by Schaeffer et al. (1930) and Knuchel (1953). There has been considerable discussion at various times on whether the control method is a method of management, a silvicultural system, or a method of mensuration. It is convenient for present purposes to regard it as of three components: carrying out periodic inventory from which the present state of the stand and past increment are determined; prescribing present and future yield on this basis; obtaining this yield through a particular silvicultural system. The reason for the particular mensuration interest in the control method is that, when the procedure for the inventory of the particular forests was established over seventy years ago, far-sighted attempts were made to ensure that the successive inventories would be comparable

so as to give reliable estimates of increment. This comparability has been ensured and the records, kept meticulously over this long period, are of particular interest as an example of a long-term inventory project.

The several important features are briefly as follows. The d.b.h.o.b. of every tree in the stand on each occasion is measured by caliper, and measured consistently by placing the beam of the caliper in a permanent scribe mark. The trees are not identified individually. They are tallied in fairly wide (for example, 5 cm) classes; there is a lower limit to the enumeration (for example, 20 cm). D.b.h.o.b. class volumes are derived by reference to a tariff which is used on each occasion of measurement to keep the estimates of volume comparable, the unit of volume of the tariff being called a silve. The volume of trees harvested is derived both in silves and in terms of the utilisation conditions of the time. This provides a factor whereby the standing volume in silves can be corrected to equivalent present commercial volume. Increment is derived from the differences of the estimates at the periodic measurements, taking into account natural mortality and artificial removals, and ingrowth. Growth is usually computed for the stand and by d.b.h.o.b. classes which are often simplified into three broad classes - small, medium, and large.

Complete enumeration is carried out in management inventory in some other forests of western Europe not managed by the control method. Where the stands are relatively small and management very intensive, the cut and treatment are prescribed by compartments, the timber has a high value, and the silviculture is such that a continually changing stand composition presents practical problems in sampling. A traditional resistance to sampling and the ready availability of a low-salaried but well-trained labour force are further reasons in some cases.

Sampling

In most countries periodic management inventory is carried out by sampling. In Australia, for example, the forests are too large in extent for complete enumerations to be practicable; because of relatively fast growth rates frequent inventories are required and the forest revenue could not support frequent full enumerations. In any case, the information required for management can be obtained at an appropriate level of reliability by properly designed sampling - which

is also the case for the forests under the control method except where continual change in stand composition makes sampling difficult.

The Sample

The usual method of selecting the sample is stratified random or systematic. The sampling units are usually plots or angle count spots; strips are not commonly used. Aspects of size, shape, and orientation of unit discussed under resource inventory also apply to management inventory. Sampling for management inventory is usually of much greater intensity than for resource inventory. The intensity for resource inventory is usually less than one per cent and may be as low as one tenth of one per cent. For management it is usually greater than one per cent and may be as high as ten per cent.

Sampling on Successive Occasions

There are two essential functions of periodic management inventory: to record the condition of the forest at each inventory and from these records to determine the changes over the period between inventories. For example, stand volume may be determined on each occasion and net increment for the period in between. For such sampling on successive occasions there are several alternative designs. These are discussed in standard texts, such as Yates (1949), because they are applicable to any kind of census or inventory which is carried out to give information on both the state of a population on occasions and the changes in the population in between those occasions. In the present context, for a sample of units established in a forest and measured on one occasion, there are three possibilities for measurement on a subsequent occasion. The first possibility is to remeasure all the units; the units are permanent, the samples are dependent or the sample is fixed; 'this is formally equivalent to the observation of different characters (variables) on the same sample' (Yates, 1949). The second possibility is to remeasure none of the units; the units are temporary, a new sample is chosen on each occasion, the samples are independent, 'this is formally equivalent to interpenetrating samples' (Yates, 1949). The third, intermediate possibility is (a) to remeasure only some of the units, some of the original units having been made permanent and the others temporary; this is sub-sampling, 'formally equivalent to a two-phase sample' (Yates, 1949); or (b) to remeasure only some of the units, some of the original units having

been made permanent and the others temporary, but to replace the temporary ones not remeasured with new units (which may be temporary or permanent for a subsequent occasion). This is sampling with partial replacement and 'has no formal equivalent .... These equivalences are of importance in that the methods of estimation will be the same for formally equivalent sampling processes' (Yates, 1949). In choosing one or another of these designs, the manager must consider several factors.

One factor involves statistical aspects. Foresters have appreciated for a long time that the precision of estimate of increment in a stand variable was higher (other things being equal) for dependent samples than independent samples for reasons emphasised by Hall (1959) and this has been one of the important statistical aspects influencing them in deciding which of the two alternative designs to use. In recent years, there have been several papers on the subject of sampling with partial replacement of units in forest management inventory in North America, particularly by Bickford (1959, 1963), Bickford, Mayer, and Ware (1963), Ware and Cunia (1962) and Cunia (1964, 1965). The alternative designs will all provide unbiased estimates of stand variables and of sampling errors associated with those estimates, but one of the designs will provide best estimates at least cost (usually the major criterion of efficiency of sampling design). This will depend on the method of sample selection, the extent of the correlation between the estimates of the stand variable on the successive occasions, the actual stand variables estimated, the relative precision required of the estimate of the stand variable and the estimate of the change in the stand variable, the relative cost of establishing new units and of finding and remeasuring permanent units and the percentage of permanent units which cannot be found.

Another factor is d.b.h.o.b. increment. It can be calculated reliably only when trees are identified individually and this is feasible only on permanent units. In many kinds of forest, too, the most reliable guide to silvicultural treatment is from the performance of individual trees and this can only be studied on permanent units. Again, it is essential that a comprehensive and reliable record of treatment, removals, and mortality be kept between measurements and this is usually much more practical on permanent units. Against this, changes of a qualitative kind may better be brought to notice through a different sample.

A third factor is the representativeness of the sample. There are two main points for concern. One is that particular sampling units do

represent what they purport to represent - that they do not get biased treatment. This may present difficulties. If units are permanent they must be so identified that exact relocation does not cause any problems. However, if they are clearly marked, there is the danger that operators will give them biased treatment and temporary units may be more satisfactory. The other point of concern is that the relating of sampling units to sub-populations be correct. In stands of even-aged coniferous plantations in Australia, for example, thinning is usually carried out on a compartment basis or within site quality class within a compartment. The areas to which sampling units refer can be fairly readily defined and measured. On the other hand, in those native eucalypt forests where a silvicultural system such as the Australian group selection system is applied, it may be quite difficult to define the stand areas to which particular units refer and quite impracticable to measure them. Nor is it practicable to carry out complete enumerations, the solution resorted to for similar problems in certain parts of western Europe.

Another factor is the effect of mistakes and biases in measurement of units. Permanent units give both operators and supervisor the opportunity to pick up mistakes and biases, and the fact that they can be picked up may prompt operators to be conscientious. An important factor here is ready identification of sampling unit and individual trees so that there is no problem in reconciling the record. It is sometimes argued that the difficulties of reconciliation and the errors discovered in remeasurement are such that it is better to have temporary units - which is equivalent to arguing that errors are acceptable if we are ignorant of them.

Practical Aspects

In artificially established plantations, permanent units can be established at any time after establishment. Unless information is required on early growth or there are practicable advantages in establishing the units before establishing the crop, a suitable time is just prior to first thinning. If the sample is to be a stratified random one, using sites as strata, establishment of units must await the mapping of site quality boundaries, which cannot be done until the crop has settled down after establishment troubles and its condition is truly reflecting the site. Even for a systematic sample, it may be wiser to wait some years so that the population can be clearly defined. In

natural stands, units are established as soon as management interest requires it.

Frequency of measurement depends on the variables being measured; the stage in the crop rotation, and rate of growth of the crop; the relationship between time of measurement and cutting cycle, thinning, working plan revision; staff and funds available. For first rotation conifers in Australia, a common pattern of measurement has been every 2-3 years up to 20-30 years and about every 5 years thereafter. In natural forests in Australia, remeasurement about every 5 years is more appropriate. Once sufficient increment data are available, measuring for working plan revision about every 10 years may be sufficient.

If the units are to be temporary, only the minimum trouble is usually taken in identifying the plot location. For permanent units, the maximum trouble should be taken. Every attention must be paid to ensure easy re-location of units by appropriate unit location plans and location marks. If individual trees are to be identified, they can be numbered by painting numbers on the trees, by a system of tagging, or they can be identified by some appropriate system of recording such as serially from a specified starting point in a specified direction in plantations, or by tree location plans using measured co-ordinates from some defined axis of co-ordinates in natural forest. Clear, concise practical prescriptions for the establishment, maintenance, and measurement of the sampling units are essential, particularly for consistent procedure. The originators of the control method recognised this and it has been the strength of the method. Since methods and techniques of measurement are continually being improved, some compromise has to be found between continuing to use a primitive method which gives consistent estimates and changing the procedure every time an improvement is possible, with consequent likelihood of bias in the estimate of increment. The way in which the Code of Sample Plot Procedure of the Forestry Commission (Hummel et al., 1959) was prepared might well serve as a model.

Periodic Management Inventory in Australia

The main aspects of periodic management inventories carried out in coniferous plantations by the State Forest Services have been summarised by Lewis (1963a).

The prescriptions of the forest inventory surveys of the coniferous

plantations, rain forest areas, coastal eucalypt forests, and the cypress pine-eucalypt forests of the State are outlined by the Queensland Department of Forestry (1962). In each case the sample comprises systematically located plots but their size and sample intensity varies with kind of forest. Some of this inventory has been carried out for over thirty years.

'Continuous forest inventory' has been implemented by the New South Wales Forestry Commission in recent years in various native forests as described by Forrest (1961), Curtin (1962b), and Turner (1966), as well as in the coniferous plantations. As a result of considerable investigation in earlier assessments into the relative efficiency of various methods of sample selection, sampling intensities, and sizes and shapes of units in various kinds of forest, there is no single standard procedure. The use of aerial photographs is an integral part of the inventory. Humphreys (1961) has discussed the reliability of and limits to photo-interpretation of species associations for management planning in eucalypt forests of the north coast of New South Wales.

A periodic inventory of the plantations of P. radiata in the A.C.T. is based on a stratified random sample of angle count spots with age and site index as strata.

Hall and Neal (1966) have outlined the method of processing data for management and research from periodic inventory used by Australian Paper Manufacturers Limited for both coniferous plantations and native eucalypt forest, mainly in Victoria. The Forests Commission of Victoria carries out periodic management inventory in the coniferous plantations, the overmature and second-growth eucalypt forests, and the foothill forests.

The Woods and Forests Department of South Australia has a large number of semi-permanent 'yield plots' in the coniferous plantations which are measured periodically to provide information appropriate to determining material available from thinnings and clear fellings. Lewis (1963a) has discussed the problems of forecasting future yield from these inventories.

Periodic management inventory is carried out by the Forestry Commission of Tasmania in coniferous plantations.

Nunn (1957) refers to the periodic inventory carried out in Western Australia in a general outline of the history of assessments in that State.

Periodic Management Inventory Elsewhere

The various conservancies of the New Zealand Forest Service carry out periodic management inventory in coniferous plantations as do many of the private forestry organisations. The methods are summarised by N.Z.F.R.I. (1965).

Much has been written on the subject for the northern hemisphere. Prodan (1965a) discusses it for various European countries. The Forestry Commission of Great Britain has scrutinised the usefulness of periodic inventory to management fairly thoroughly and discussions by Johnston (1960), Waters (1961), and Johnston and Bradley (1964) are of particular interest. Jack (1962) outlines the method used in Northern Ireland. Some of the great interest in the matter in North America is outlined by Purdue University (1960) and Putman, Furnival, and McKnight (1960).

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Index

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Forest mensuration is the starting point of organised forestry and is essential to efficient management. This book outlines the fundamental principles and their application to practice in Australia.

Many of the methods and techniques of forest mensuration in Australia have been adapted from those of northern hemisphere countries, but they have been so modified to suit Australian conditions that the available textbooks are not suitable for Australian students. This is the first book to provide a basic text for a university undergraduate in Australia. In addition the clear descriptions of forest mensuration practice will make it of use as a reference for practical foresters and forest owners, in Australia and in other countries with similar conditions.