Further Reading

Avery TE and Burkhart HE (1983) *Forest Measurements*. McGraw-Hill series in forest resources. New York: McGraw-Hill.
Clutter JL, Fortson JC, Pienaar LV, Brister GH, and Bailey RL (1983) *Timber Management: a quantitative approach*. New York: John Wiley.
Lund G (1998) *IUFRO Guidelines for Designing Multiple Resource Inventories*. Vienna, Austria: IUFRO World Series.
Schreuder HT, Gregoire TG, and Wood GB (1993) *Sampling Methods for Multiresource Forest Inventory*. New York: John Wiley.
Research Working Group #2 (1999) *Code of Forest Mensuration Practice: A Guide to Good Tree Measurement Practice in Australia and New Zealand*. Available online at: http://sres.anu.edu.au/associated/mensuration/rwg2/.

Growth and Yield

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The Purpose of Forest Mensuration

Forest mensuration (the study of measurement) is the research discipline that develops and evaluates both the theoretical basis and practical application of systems for assessing the growth and yield of trees and forest stands. Originally subjective assessments and qualitative systems were used for characterizing the productivity of forest stands; however, methods of mensuration developed over the past 200 years have allowed the adoption of a strictly quantitative approach.

Forest inventory techniques are underpinned by a substantial body of research on measurement methods, and on approaches for the processing of measurements to derive summary results that provide an indication of current and potential future yield. Often the term mensuration is also used to describe the conventions adopted in standardized procedures used by forest industries for quantifying forest resources and as part of production forecasting.

A comprehensive forest mensuration research program involves developing and evaluating:

- measurement instruments and conventions for their use
- procedures for quantifying the structure and yield of forest stands
- descriptions and analyses of tree and stand growth patterns
- relationships between potential stand yield and site factors
- mathematical models of forest structure, growth and yield.

Measurement Variables, Instruments, and Conventions

The essential endeavour of mensuration involves working out how to measure variables relevant to the growth of trees and forest stands. Traditionally measurements are taken of external physical characteristics of a tree or sample of trees that are easy to measure and obviously related to growth. Notable examples of tree growth variables include:

- total height
- stem diameter, circumference, or cross-sectional area
- stem volume
- gross dimensions of the crown.

Sometimes more complex measurements are included as part of mensuration procedures, for example involving detailed assessments of tree and stand architecture. A variety of methods exists for measuring and describing the architecture of individual trees or stands, such as based on:

- the shape and size of crown(s)
- the detailed disposition of branches, foliage, and roots
- the distribution of tree species and size classes in a stand.

A wide range of instruments has been applied to the measurement of growth variables of trees as illustrated in **Table 1**.

Conventions and standards for the measurement of growth and yield variables are very important in order to ensure consistency. These need to cover not only the typical trees in a population but also give clear rules for the measurement of unusual trees (**Figure 1**). Conventions are also required for the measurement of felled trees and any cut produce such as roundwood. Consistency is important if measurements and derived results are to be repeatable. This is essential in the forest industries when buying and selling of quantities of wood. It is also important in a research context when the growth of trees or stands needs to be monitored over time, for example to find out if production is consistent with growth.

An important function of measurement conventions is to prescribe levels of accuracy for measurement. For

Table 1 Examples of tree growth variables and instruments used for their measurement. Common units of measurements are also indicated for each variable

Variable	*Examples of measurement instruments*	*Units*
Tree height	Graduated poles (on smaller trees)	
	Simple hypsometer (geometric principles)	m
	Clinometer (trigonometric principles)	
	Ultrasonic or laser-based combined range-finder and hypsometer	
Tree diameter	Tape measures (which may be calibrated in terms of diameter of an equivalent circle)	cm
	Pair of calipers (which may include digital recorder)	
	Optical dendrometer (for out-of-reach diameters)	
	Laser-based, optical scanning systems (under development)	
Tree basal area	Calculated from diameter assuming circular cross-section	m^2
Stand basal area	Sum of cross-sectional areas based on diameters of individual trees	$m^2 ha^{-1}$
	Relascope (optical device which may include digital recorder)	
Tree stem volume	Sum of volumes of short sections of tree stem calculated from the measured lengths and diameters of sections	m^3
Stand volume	Measurement of a sample of tree volumes as above; establishment of correlation between tree stem volume and diameter; sum of individual tree stem volumes based on correlation with tree diameters	$m^3 ha^{-1}$

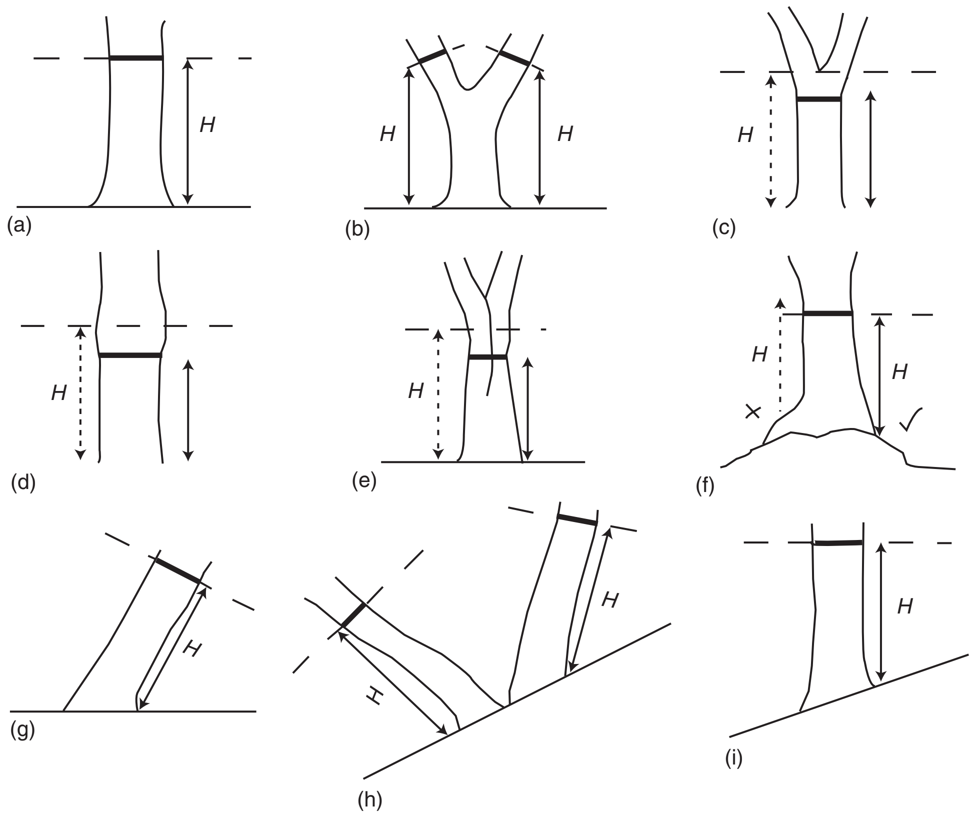

Figure 1 Illustration of conventions that may be adopted to determine a point above ground level (*H*) for measuring tree diameter. (a) Measurement of upright stem on flat ground; (b) stem forked below *H* – measure both diameters; (c) stem forked at *H* – measure diameter at smallest point below fork; (d) swelling at *H* – measure diameter at smallest point below swelling; (e) forks have fused up to and above *H* – measure diameter at smallest point below; (f) planted on plowed or uneven ground – measure from base of stem, not root buttress; (g, h) on leaning stems – measure diameter at *H* on underside of stem with smallest angle to the ground, diameter should be measured perpendicular to long axis of stem; (i) on sloping ground measure diameter at *H* on upslope side of stem.

example, a convention may require the height of a tree to be rounded down to the nearest 0.1 m to reflect the accuracy of the measurement instruments in general use.

Quantifying Stand Structure and Yield

One important aspect of mensuration methods is the requirement for efficient and cost-effective methods of measurement. For example, one of the most important variables used in describing forest growth and yield is tree stem volume which is time-consuming and expensive to measure directly. In particular, inventory systems rely on relatively quick, cheap, and reliable methods for assessment of stand structure and potential volume yield. The forest industry also uses a suite of simple mensurational methods for deciding if, when, and how to carry out thinning or harvesting of stands, as a basis for sale of timber, for planning forest operations, and ultimately as part of the development of forest design plans. These methods are thus essential tools for supporting and demonstrating the sustainable management of forest estates.

Mensuration researchers develop protocols for the assessment of stands that aim to minimize the intensity and complexity of measurements needed to obtain yield estimates of different levels of precision. Where stand structure and volume need to be quantified to high accuracy, an intensive procedure may be specified involving for example:

- counting all the trees in the stand
- measurement of a large sample of tree stem diameters
- measurement of a smaller sample of tree stem volumes.

Tree stem volumes may be measured by climbing or felling trees, or using an optical instrument such as a dendrometer.

Standardized statistical computations can be specified for processing measurements into estimates of numbers of trees, tree size class distribution, and potential volume yield (**Figure 2**). It is also possible to use statistical theory to provide guidance on the size of samples of trees measured for diameter and volume needed to achieve a required level of precision.

Often forest inventories require relatively low resolution estimates of stand structure and yield over an entire forest estate formed of hundreds (sometimes millions) of hectares. In such situations, mensuration protocols are needed that are much

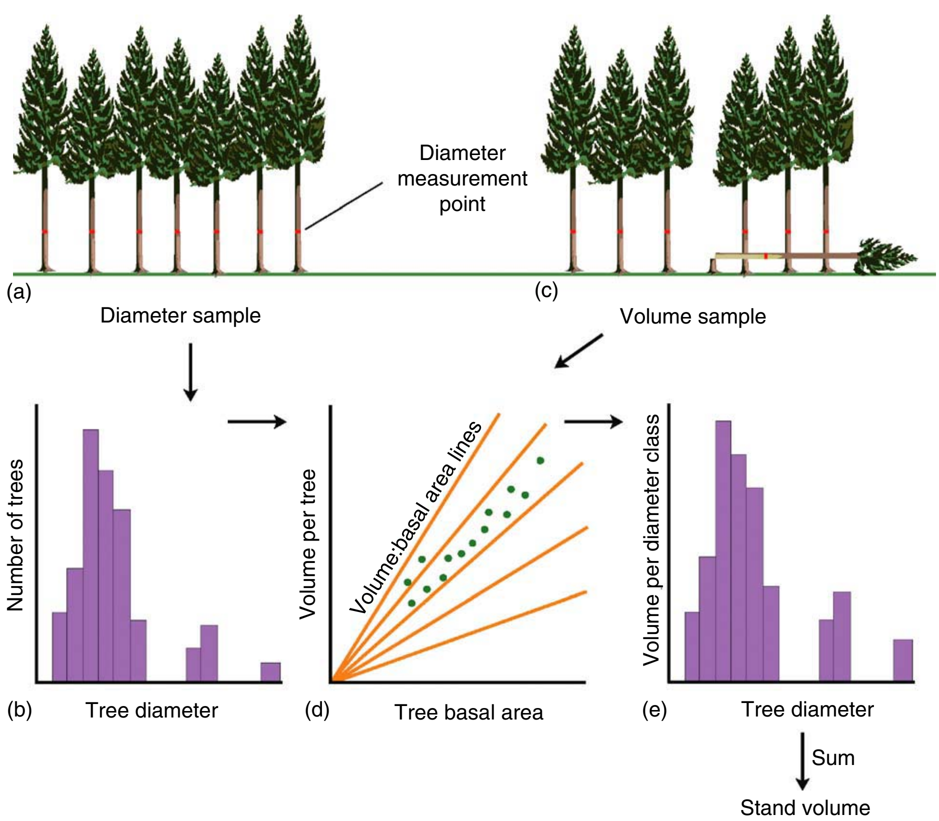

Figure 2 Illustration of intensive forest stand inventory procedure. (a) Count of all trees and diameter measurement of large sample of trees. (b) Construction of diameter frequency distribution based on diameter sample measurements and tree count. (c) Measurement of diameter and stem volume of small sample of trees (in this case by felling). (d) Measurements on volume sample trees are plotted as a scatter diagram of volume versus basal area (calculated from diameters). These are compared against a set of standard charts to determine a specific volume : basal area relationship for the stand. (e) The diameter frequency distribution is combined with the volume : basal area relationship to infer the stand volume in each diameter class, which can be summed to give total stand volume.

cheaper and more rapid to carry out than the sort illustrated in **Figure 2**. A diversity of such 'abbreviated' methods have been developed. The most obvious way is to restrict measurements (including tree counts) to small plots of known area rather than covering the whole stand. The plot level results are then scaled up to give a stand level estimate. Statistical theory can be used as the basis for guidance on the numbers of plots required to provide estimates of stand density, structure, and yield with target levels of precision.

The simplest and cheapest assessment methods dispense with plots, relying instead on 'point measurements' for example of basal area per hectare taken with an optical instrument such as a relascope. Alternatively stand density may be inferred from measurements of a limited number of measurements of distances between trees in the stand.

Simple mensuration protocols usually avoid involving intensive measurements of tree or stand stem volume. Instead these are estimated from measurements of basal area per hectare, individual tree diameters, or height by reference to standard tables or mathematical equations. Estimates may also be derived from yield tables or growth models.

As part of both simple and intensive protocols it may be necessary to estimate quantities of stemwood falling into different categories such as large diameter material suitable for sawlogs, small roundwood, and branches. Alternatively information about stand structure may need to be predicted from more simple measurement; for example, the distribution of tree diameters in a stand might be inferred using a table or statistical distribution function, selected by reference to measured stand mean diameter and assumptions about silvicultural practice. The development of reliable systems for deriving detailed estimates from more easily obtained summary measurements is one of the major tasks of mensuration research.

In all cases, the reliability of estimates derived from mensuration protocols depends crucially on the assumption that assessments are taken in a stand that is distinct in terms of area and uniform in terms of structure. The process of identifying distinct and uniform forest stands comprising a forest estate is known as stratification. Robust mensuration protocols include unambiguous rules for stratifying areas of forest.

Describing and Analyzing Growth

A significant aspect of the work of mensuration researchers involves describing and analyzing the patterns of growth exhibited by different tree species grown on different sites and according to different systems of silviculture.

Analysis of Growth Trajectories

Graphical analysis is a fundamental and frequently used technique which involves plotting sequences of measurements of selected growth variables (**Figure 3**). The sequential measurements, taken on the same tree or sample of trees over time, may be collected at intervals of less than a year or over several years, depending on the rate of growth and on the frequency of perturbations due to environment or management.

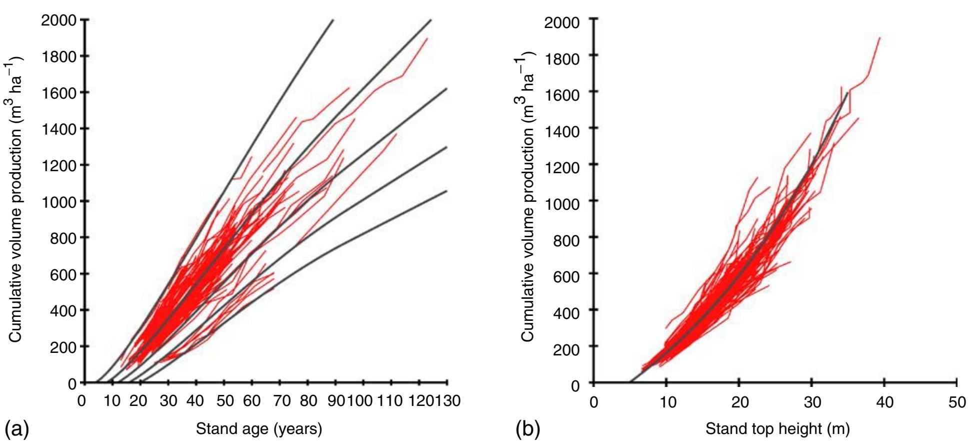

Figure 3 Examples of investigations of growth patterns by plotting trajectories. The graphs are based on assessments taken on stands of Corsican pine (*Pinus nigra* var. *maritima*) in Britain. (a) Cumulative volume production plotted against stand age. The red trajectories show sequences from different stands. The gray lines represent examples from a family of model curves describing the pattern of growth for different levels of productivity. (b) The same cumulative volume production data as in (a) but plotted against stand dominant or top height. Cumulative volume is observed to be more closely correlated with stand top height than with stand age. The gray line shows how the development of cumulative volume production might be described by a single curve with respect to top height. Mensuration researchers use results such as this to simplify the task of building growth models and yield tables.

A graph formed of lines joining the successive measurements of a given variable plotted against age is often referred to as a graph of trajectories. Trajectories may also be formed by plotting measurements of one tree or stand variable against another, in order to explore correlation between different growth variables. Tree level variables may be analyzed in this way but it is more common for growth patterns to be characterized graphically at the stand level. A range of variables may be analyzed, typically including:

- dominant or top height (the average height of dominant trees in a stand)
- mean height
- numbers of trees per hectare
- quadratic mean diameter (the diameter equivalent to a tree with average basal area in a stand)
- standing basal area per hectare
- standing (stem) volume per hectare
- cumulative basal area production
- cumulative volume production.

Traditionally, variables describing aspects of cumulative production, notably cumulative volume, are regarded as important, fundamental measures of growth performance. For an even-aged stand of trees, cumulative volume production is defined as the standing stem volume per hectare observed at a specified stand age plus the sum of all per-hectare volumes harvested as thinnings up to and including that age. Cumulative production has an obvious definition in even-aged stands but there is no widely accepted definition for application to uneven-age stands. Strictly speaking, cumulative volume production does not have any significance as a meaningful physical or biological variable, although it might be regarded as a rough indicator of ecosystem net primary production. The main applications of cumulative volume production are in economic analysis and in support of practical forest management. It has also proved useful in the theoretical development and practical construction of some types of yield models. In essence cumulative volume production represents the outturn of commercial stem volume from a stand up to a given year in the stand's development.

Construction of Growth Curves

Graphs of trajectories are used to construct curves describing the characteristic patterns of growth for the tree species, site types, and silvicultural regimes of interest. In certain circumstances, the shapes of these curves may be established directly by visual inspection of the data and by drawing curves freehand over the trajectories.

However, in the past 40 years mathematical expressions have been formulated for describing tree and stand growth patterns. Sophisticated statistical analysis techniques have also been developed which, when combined with computer software, can be used to calibrate mathematical growth curves based on data collected from trees or stands for the variables of interest.

Parameters of growth curves, estimated for different tree species and growing conditions, may be used as summary statistics indicating the potential growth and yield of different stands. The most common of these is a parameter generally known as the site index, which is usually based on curves describing patterns of height growth in dominant trees in stands (**Figure 4**). Dominant height (sometimes known as top height) growth is often favored as a variable for indicating the influence of site on stand productivity. This is based on the assumption that the growth of dominant trees is relatively unaffected by competition within the stand and not usually influenced by silvicultural interventions,

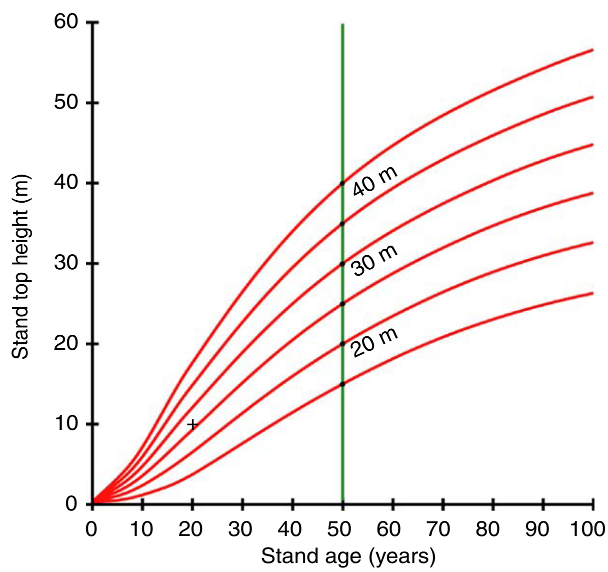

Figure 4 An example of a set of site index curves used for classifying the productivity of even-aged forest stands. The curves are based on observations of top height development with age in stands of Sitka spruce (*Picea sitchensis*) in Britain. Individual curves have been chosen to pass through specific values of top height at a 'reference' or 'base' age of 50 years. Each curve is separated at age 50 years by an interval of 5 m and the height attained at this age is referred to as the site index, for example the curve passing through 20 m represents site index 20. Measurements taken in stands of trees at varying stand ages can be compared to these curves to assess potential productivity. For example, suppose a stand of trees of age 22 years was measured and found to have a top height of 11 m, as illustrated by the black cross. This point is observed to be closest to the curve for site index 25; this curve could be used to forecast future growth potential of the stand.

notably thinning. Furthermore, the height growth of trees and stands has been observed to be much less dependent on stand density than variables such as diameter, basal area, and volume. It follows that height growth, in particular that of dominant trees, should be most strongly determined by the particular growth potential of the tree species comprising the stand in combination with site and other environmental factors.

Analysis of Increment

Mensuration researchers place emphasis on investigating increments of growth variables, indeed increments are among the most explicit representations of growth. They can be calculated for any variable of interest but cumulative volume production is often the focus of attention. Increments can be defined in different ways and three common measures are:

- current annual increment (cai)
- periodic annual increment (pai)
- mean annual increment (mai).

Current annual increment is the actual annual rate of growth of the variable of interest at a specified time. It is sometimes calculated as the difference of two values taken by a variable measured 1 year apart. Occasionally the slope of a curve fitted to a sequence of measurements over time is used to estimate cai. Alternatively periodic annual increment may be used as a surrogate. Records of cai may be used in the investigation of short-term growth trends, for example with respect to management interventions, fluctuations in climate, or episodes of pest infestation.

Periodic annual increment is the annualized growth rate of a variable over a period, typically 5 or 10 years. Measurements of pai are sometimes used in the analysis of forestry experiments for quantifying the growth response due to different experimental treatments.

Mean annual increment is probably the most important of the increment variables and is usually most relevant to the analysis of cumulative volume production. This may be defined as the average rate of cumulative volume production up to a given year. The development of mai follows a characteristic pattern with respect to stand age (**Figure 5**). In the early years of stand development, mai rises steadily from zero to a maximum value. From this point on mai declines steadily, although the rate of decline may be slight in the years immediately following

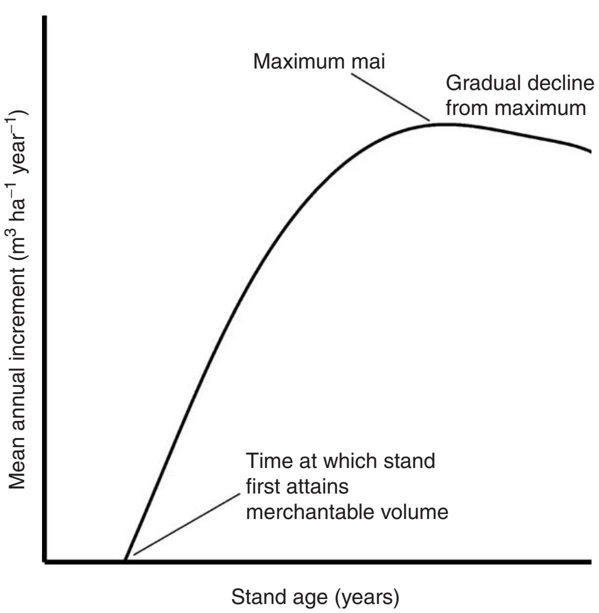

Figure 5 Illustration of the characteristic pattern of development of mean annual increment of cumulative volume production with respect to stand age in even-aged forest stands.

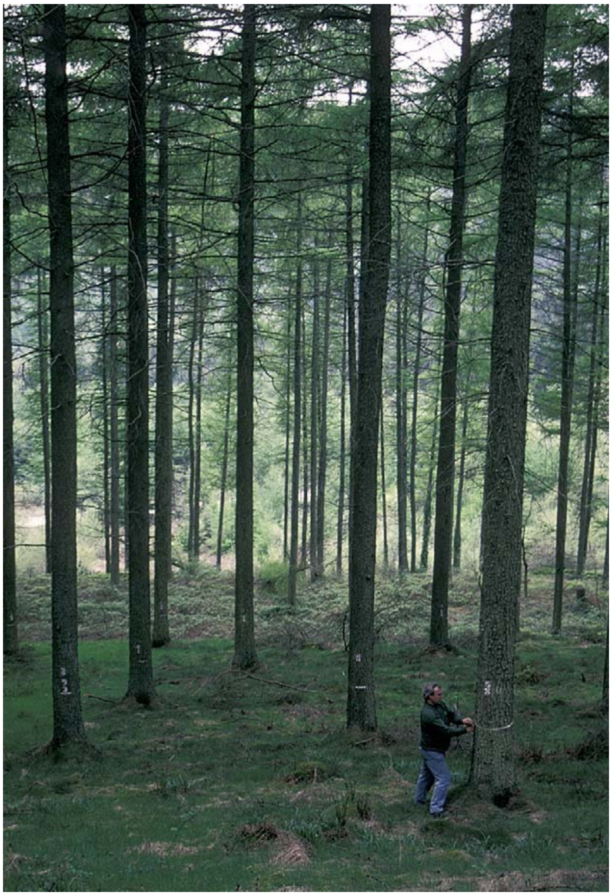

Figure 6 Measurements being taken in a mensuration permanent sample plot. Painted numbers identify the trees in the plot and allow successive measurements to be compared. The horizontal bands on the trees indicate the reference height at which diameter measurements should be taken. Sample plots have been a vital source of data on the structure, growth, and yield of forests. Courtesy of Forest Research Photo Library.

attainment of maximum mai. The existence of a stand age for which mai takes a maximum value may be regarded as being of great commercial significance in the management of even-aged stands particularly if the aim is to maximize sustainable volume production. Specifically, if the maximum value of mai occurs at a predictable stand age then a forest manager may choose to clear-fell the stand at this age. The average rate of volume production over the rotation period will then be equal to the maximum. The forest manager can then replant or regenerate a new stand on the clear-felled site. If this new stand is also grown over the same rotation period then average rate of volume production of the new stand will again be maximal, provided that the fertility of the site has not been depleted and environmental conditions have not changed. Clearly, managing a stand on this site using any other rotation period will result in a lower average rate of volume production.

Applications of Trajectory and Increment Analyses

Analyses of growth trajectories can be applied in some circumstances without further interpretation. For example, suites of curves describing cumulative production and the development of other growth

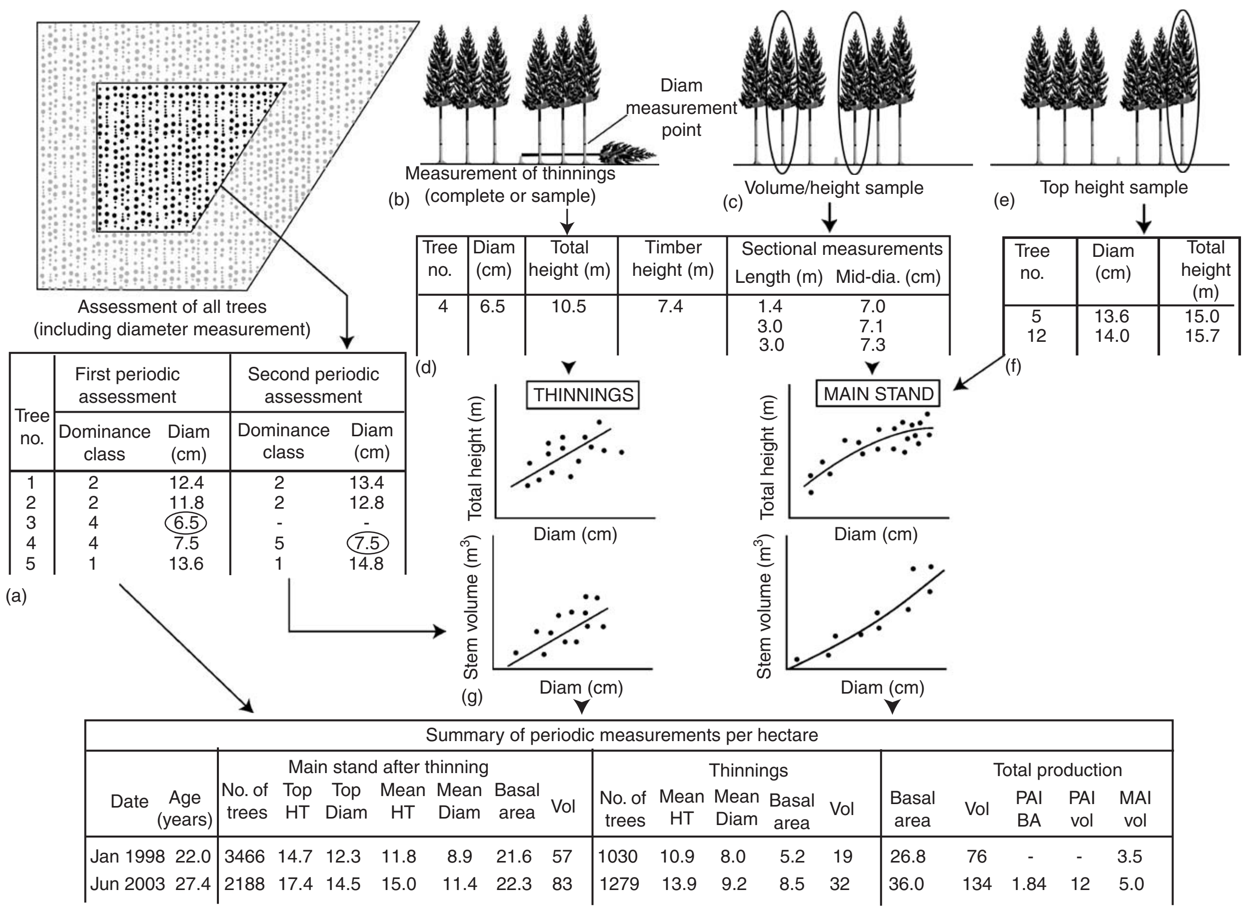

Figure 7 Illustration of the types of measurements taken in mensuration sample plots and how they can be summarized. Standard protocols for measurement and calculation procedures are very important to ensure consistency and quality of data. (a) The sample plot is marked out on the ground with clear boundaries and protected by a marked surround of protecting trees. All trees in the plot are checked, and classified (for example for dominance or form), and diameter is measured. Standard forms or computer programs are used for collecting the assessments. (b) A sample of trees removed as thinnings is measured for diameter and stem volume. (c) A sample of trees remaining in the stand is measured for diameter, height, and stem volume. Measurements of crown architecture may also be collected. (d) The detailed measurements on sample trees are recorded in a standard format. (e) A sample of dominant trees (which may be used for establishing stand top height) is measured for diameter and height. (f) The measurements on the top height sample are recorded in standard format. (g) The detailed measurements of thinnings and standing trees are analyzed to establish correlations between key tree variables specific for the current assessment of the sample plot. For example, the correlation between tree stem volume and diameter is established separately for the standing trees and any thinnings. (h) The full diameter assessment and analyses of sample trees are combined in the calculation of summary estimates of key variables for the sample plot. Measurements taken at different stand ages can be displayed in a standard format and compared.

variables can be used to construct a range of simple yield tables for direct application to forest management. Summary parameters from these analyses, such as site index, can be used for classifying yield potential of real stands, either as part of stand management and production forecasting or as part of a more general inventory system. Sometimes, individual curves and equations developed to characterize particular growth variables are used to support inventory systems, for example in the form of volume tables or equations. Supplementary analyses may also be carried out that extend beyond direct assessment of stands, for example measurements of site index in stands may be analyzed with respect to site and environmental variables so that the potential growth of trees can be predicted for unplanted sites.

Models of increment are useful in a commercial context for very short-term forecasting. However, the main application of increment studies is in a research context, for example, for understanding relationships between tree and stand dynamics and environmental and management factors. As such, the study of increment has in effect developed into the science of dynamic growth modelling.

Sample Plots

Mensuration research depends on high-quality, comprehensive data on the growth and yield of forest stands. Internationally there has been considerable effort over the past 150 years to collect such data either as isolated assessments or through the long-term monitoring of research plots (**Figure 6**). Such research plots are generally known as 'mensuration sample plots' and are categorized as either temporary (one-off measurement) or permanent (repeated, long-term measurements). The data obtained from sample plots have been vital to the understanding of forest growth dynamics, for mensuration research and for development of models of stand structure and yield (**Figure 7**).

Future Developments in Mensuration Research

Although now a well established discipline, mensuration remains an important, arguably fundamental, element of forest research. Research will continue on development of inventory methods and growth and yield models but this is likely to be carried out in a more integrated context. For example, significant scope exists for integrating networks of mensuration sample plots with other forest monitoring networks addressing subjects such as forest condition, biodiversity, or carbon balance. Extension of the research to cover such integration would require the development of a more comprehensive range of measurement protocols and supporting equations and models. Rapid developments in the fields of geographic information systems (GIS) and remote sensing offer opportunities for combining traditional, intensive mensurational assessments with extensive, state of the art technologies such as satellite imagery.

See also: **Inventory**: Forest Inventory and Monitoring; Multipurpose Resource Inventories. **Mensuration**: Forest Measurements; Timber and Tree Measurements; Yield Tables, Forecasting, Modeling and Simulation. **Resource Assessment**: GIS and Remote Sensing.

Further Reading

Adlard PG (1995) Myth and reality in growth estimation. *Forest Ecology and Management* 71(3): 171–176.

Assmann E (1970) *The Principles of Forest Yield Study*. Oxford, UK: Pergamon Press.

Carron LT (1968) *An Outline of Forest Mensuration, With Special Reference to Australia*. Canberra, Australia: Australian National University Press.

Chapman HH and Meyer WH (1949) *Forest Mensuration*. New York: McGraw-Hill.

Hallé F, Oldeman RAA, and Tomlinson PB (1978) *Tropical Trees and Forests: An Architectural Analysis*. Berlin, Germany: Springer-Verlag.

Husch B, Beers TW, and Kershaw JA (2003) *Forest Mensuration*, 4th edn. New York: John Wiley.

Philip MS (1994) *Measuring Trees and Forests*, 2nd edn. Wallingford, UK: CAB International.

Tesch SD (1980) The evolution of forest yield determination and site classification. *Forest Ecology and Management* 3: 169–182.

Vanclay JK (1992) Assessing site productivity in tropical moist forests: a review. *Forest Ecology and Management* 54(1–4): 257–287.

Vanclay JK, Skovsgaard JP, and Pilegaard Hansen C (1995) Assessing the quality of permanent sample plot databases for growth modelling in forest plantations. *Forest Ecology and Management* 71(3): 177–186.

Yield Tables, Forecasting, Modeling and Simulation

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Introduction

Growth is usually defined as the net periodic annual increments of forest variables and the yield is their summation. Yield tables typically present the amount