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# Guidelines for forest biomass inventory

A.H. Aldred and I.S. Alemdag

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Petawawa National Forestry Institute

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# FOREWORD

ENFOR is the acronym for the Canadian Government's ENergy from the FORest (ENergie de la FORet) program of research and development aimed at securing the knowledge and technical competence to facilitate, in the medium to long term, a greatly increased contribution from forest biomass to our nation's primary energy production. This program is part of a much larger federal government initiative to promote the development and use of renewable energy as a means of reducing our dependence on petroleum and other nonrenewable energy sources.

The Canadian Forestry Service (CFS) administers the ENFOR Biomass Production Program component which deals with such forest-orientated subjects as inventory, harvesting technology, silviculture, and environmental impacts. (The other component, Biomass Conversion, deals with the technology of converting biomass to energy or fuels, and is administered by the Renewable Energy Branch of the Department of Energy, Mines and Resources). Most Biomass Production projects, although developed by CFS scientists in the light of ENFOR program objectives, are carried out under contract by forestry consultants and research specialists. Contractors are selected in accordance with science procurement tendering procedures of the Department of Supply and Services. For further information on the ENFOR Biomass Production program, contact

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or a CFS research laboratory.

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ABSTRACT
The manual describes procedures for including forest biomass assessment in forest inventory. The procedures cover the collection of data in the field, laboratory analysis, development of single-tree biomass equations, and application of the equations to both current and proposed new inventories.

RÉSUMÉ
Le manuel décrit des méthodes qui permettent d'inclure une évaluation de la biomasse forestière dans un inventaire des forêts. Ces méthodes englobent la prise de données sur place, l'analyse en laboratoire, l'élaboration d'équations pour la biomasse d'arbres individuels et l'application des équations à de nouveaux inventaires en cours ou envisagés.

# GUIDELINES FOR FOREST BIOMASS INVENTORY

## I. INTRODUCTION

The purpose of forest inventory, including the appraisal of forest biomass reserves, is to provide the forest manager and others studying or concerned with the forest with a clear summary of the quantities of biomass present, and the quality and distribution of the resource over an area of interest. Frequently, a general picture is provided in the form of maps, tables, and statistics. This is supported by detailed tree data concerning species, size classes, age, productive potential, current growth and yield, stocking, and condition of the resource. The relationship of the forest to the physiography, soils, water, and other plant and animal communities may be included. Besides being an overview of what currently exists, forest inventories provide a baseline against which changes are assessed, such as those from regeneration, growth, and depletions, caused naturally or by human activity. Where man intervenes, accessibility and many economic and social issues come to the fore, particularly those concerning use and management of the resource. In this context, the baseline is needed to make supply projections, model forest stand development, and to investigate the outlook and consequences of different management options or other practices.

The principal quantities used to express the size of reserves reflect the current value and expected use of the forest. In the recent past, expressions of wood volume have predominated because of the use of the stem for conventional wood products such as lumber, plywood, poles, pilings, pulp and paper, etc. The value of these are closely related to volume. During the last decade, however, an increasing scarcity of accessible, high-quality trees has led to fuller utilization of the tree and the use of components other than the bole, as well as smaller trees, previously noncommercial species, and wood residues. Also, although the volume of the main stem is fairly easy to measure, the volume of a multitude of branches, twigs, and leaves is virtually impossible to measure. Weight is a more practical measure of such material. Measures of weight also became more important in cases where greater emphasis is given to the use of chips, particles, or ground wood for composition boards and other products or fuel. During the same period, shortages of conventional petroleum energy occurred which suggested using biomass as an alternate renewable source of energy. These trends added further impetus to include the measurement of full tree and tree component weight, hereafter called mass or biomass in these guidelines, as part of volumetric forest inventories. Accordingly, methods and techniques for carrying out forest biomass inventories needed to be developed and adapted to the current inventory practice. (An overview of forest biomass inventory, including a brief history of the development of the need for biomass information, is provided by Bonnor (1987)).

In response, many new procedures were developed and tested in Canada recently through studies conducted under the federally-funded ENFOR Program. These and related projects were concerned primarily with the collection of basic tree biomass measurements, development of species-specific tree and tree component biomass equations, and the implementation of the equations as a part of conventional forest inventory. The implementation involved several areas of application: conversion of existing inventories, biomass estimation beyond zones currently inventoried, and sampling of noncommercial species, size classes, and components.

At the early stages of the ENFOR Program, biomass studies were conducted with few terms of reference, guidelines, or standards. Although manuals with guidelines and standardization of procedures were developed as part of ENFOR, such as the field and laboratory procedures manual by Alemdag (1980), the desire or opportunity to promote or enforce standardization did not arise. Consequently, a coherent set of definitions, procedures, and standards was lacking and the results that came in from the projects, though of significant technical merit, frequently could not be compared in order to be integrated into an unified body of information. Accordingly, those wishing to plan or undertake new biomass initiatives or operational projects did not have a recognized practical reference to turn to for guidance.

The purpose of these guidelines is to take stock of many accomplishments under ENFOR, compare the results with related North American experience, and draw together an uniform set of definitions, standards, and procedures for conducting forest biomass inventories. The definitions, standards, and procedures treated in these guidelines have attempted to emphasize practicality and simplicity, and recognize current forest inventory practice.

The topics are confined to forest biomass inventory applications and do not stray into related fields such as nutrient cycling, ecological or environmental concerns, or biomass conversion technology, though the inventory procedures or results may serve these areas. The manual addresses sampling designs, which determine where to select the samples, how much data to collect, and how to use readily available data to increase efficiency of sampling. Field and laboratory procedures for measuring and recording basic data, the development of equations for estimating biomass quantities from easily-measured tree variables, and the application of biomass estimation models to forest inventory are also dealt with. The use of estimation models, in particular, had to recognize the need to tie in with established volumetric inventory methodology. In most cases, the biomass procedures parallel the volumetric counterpart to render application as direct and straightforward as possible.

The attempts to standardize are intended to help the practitioner to stay in touch with the practices of others. Standardization should also facilitate the exchange of information, comparison, and the use of inventory data in other fields where common problems are investigated. Duplication of effort should be reduced and the development of general purpose databases encouraged. For example, standardization will lay the groundwork for the development of a set of national tree biomass equations with which practitioners would become familiar and be confident in using. Uniform standards will greatly assist cooperative efforts to provide, for instance, national biomass statistics such as has been done recently in Canada by the collaborative efforts of the provinces, territories, and the federal government (Bonnor 1985).

The approach taken in this manual is to provide a general description of biomass measurement, including how it relates to the larger inventory problem. The description includes, where necessary, background, definitions of terms, equations, references, examples, and theoretical considerations. The descriptive phase is followed by a set of step-by-step procedures, checklists, etc. that the practitioner may use in carrying out biomass inventory.

# II. DATA COLLECTION TO DEVELOP SINGLE TREE BIOMASS EQUATIONS

In this chapter we define forest biomass quantities and important tree variables used to estimate forest biomass. We also detail procedures for sampling and processing such data in the field and laboratory. The collection and preparation of data leads up to the development of single tree equations (Chapter III) and their application to forest inventory (Chapter IV).

## 1. Biomass variables used in forest inventory

Two approaches can be taken to estimate biomass in inventory surveys. The &first is a direct measurement of mass (M) of a tree or tree components and the development of species-specific tree equations which use commonly measured tree variables such a diameter at breast height and total tree height to estimate biomass quantities. This approach parallels and is compatible with conventional volumetric inventories which rely on diameter and height to estimate tree volume. The second approach uses factors to convert tree or stand volume to biomass quantities and ratios in order to derive tree component estimates. The conversions employ wood density factors. Both approaches are included in these guidelines but the first is stressed because it is generally more accurate and adapts readily to most current inventory procedures. The ratio approach is generally reserved for situations where basic tree data are missing, incomplete, or out-of-date.

### a. *Measures of forest biomass*

For the purposes of this manual, forest biomass includes only the aboveground portion of living trees and woody shrubs. The distinction between woody shrubs and small trees is based upon recorded genus and species rather than size. A size distinction alone may easily lead to confusion among tree seedlings, small saplings, and shrubs. Non-woody plants and all vegetation shorter than 0.31 m are excluded.

Forest biomass can be expressed by either its green mass (GM) or ovendry mass (OM). The green mass of a tree, woody shrub, or component thereof is the growing or freshly sampled material containing variable proportions of water. It is a convenient measure to use at sampling stages before specimens are dried in the laboratory. Some scaling practices, such as the weighing of a truckload of logs, also use green mass. Ovendry mass refers to the mass of a tree, woody shrub, component,

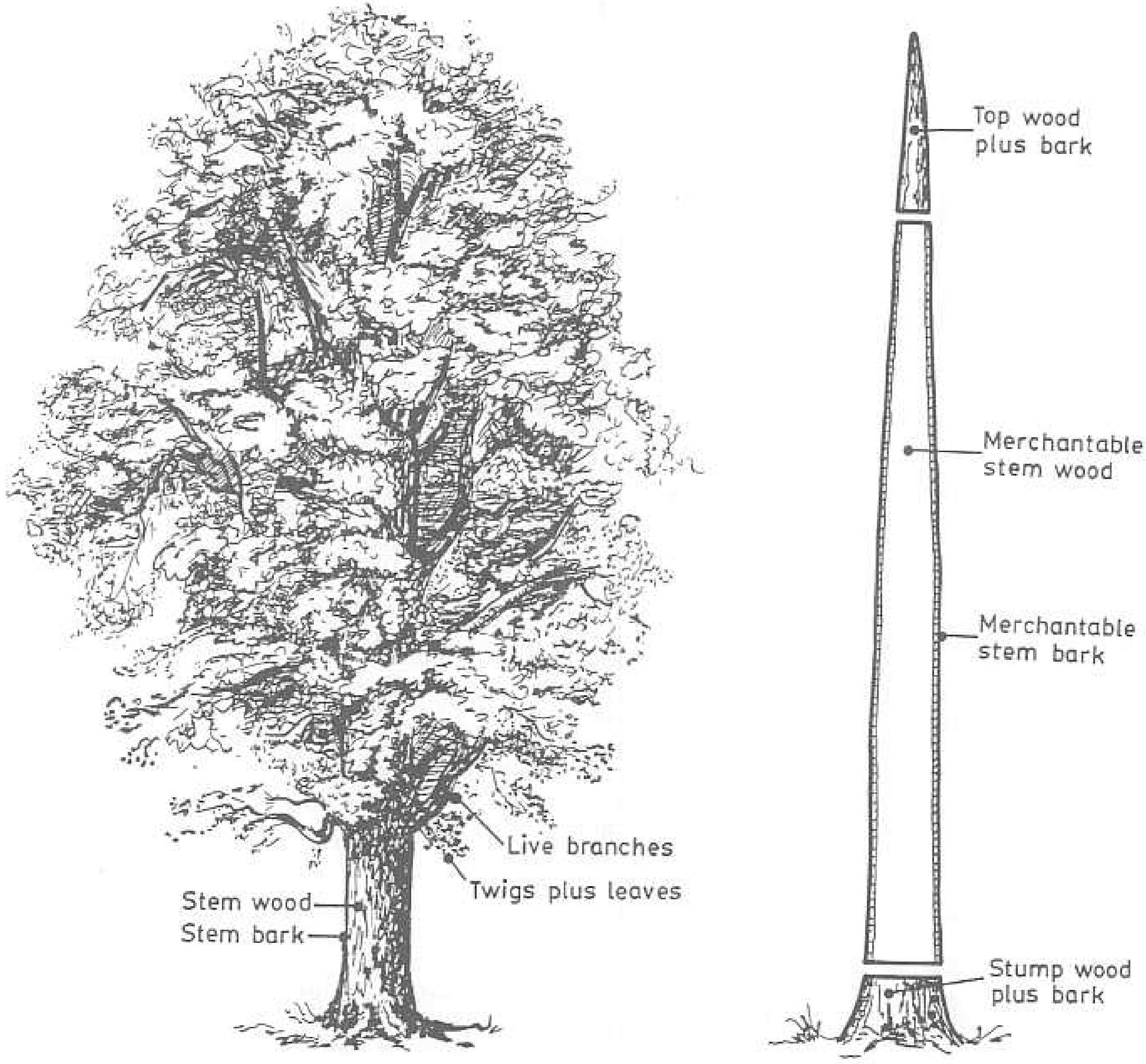


Figure 1. The tree components used for biomass estimation purposes.

or sample after drying at 105°C until the sample mass stabilizes at a constant level. The ovendry mass is the preferred expression of mass in inventory applications because of repeatibility and the closer relationship to energy potential. Unless stated otherwise, the terms mass or biomass in this manual refer to ovendry mass. Repeatibility refers to the degree of consistency of biomass measurement achieved when specimens from different trees are compared or the results of measurements by different operators, instruments, or procedures are compared. Appendices A and B provide glossary and measurement standards pertaining to field and laboratory work.

Figure 1 illustrates the important components of the tree for biomass purposes.

The definition of the components and distinguishing criteria are described in Section 3, which covers the field work instructions.

For cases where merchantability standards are imposed, the stem is subdivided into merchantable stem wood, merchantable stem bark, top wood plus bark, stump wood plus bark.

Standard stump height is usually 0.30 m above ground level but the procedures described later for developing merchantable equations allow the stump height to be varied. Merchantable diameter is a minimum allowable top diameter inside bark, usually between 7 and 10 cm depending upon the Province, wood products, and other circumstances. Merchantable height is the height from ground level to the defined merchantable diameter limit. The merchantability standards vary with product and degree of utilization of the tree and, thus, should be allowed to be set at different levels. However, many existing biomass equations and tables assume a fixed standard such as those mentioned above. The application of merchantability standards is described in Chapter III, Section 6. The standards are based on forest inventory terminology and usage edited by Bonnor (1978).

## b. *Tree variables for biomass estimation*

The common tree variables used to estimate biomass are diameter at breast &height (D), total tree height (H), and volume (V); age, site quality, crown width, crown length or crown area, and expressions of competition are used occasionally. Diameter at breast height is also referred to in the manual as tree diameter. The diameter at another height is always qualified; for example, diameter at a stump height of 0.30 m. Some of these variables are illustrated in Figure 2. The variable D is defined more specifically as the diameter of a tree outside bark at a height above ground level of 1.30 m. The determination of ground level and the treatment of sloping terrain are defined in the glossary (Appendix A) under 'ground level'. Diameter is the most commonly used variable in tree volume and biomass estimation because it is easily measured and correlated to tree and tree-component biomass. Diameter is usually measured in centimetres to the nearest millimetre. The variable is often used alone in tree equations to estimate biomass. Such equations are referred to as local biomass equations, the counterpart of local tree volume equations.

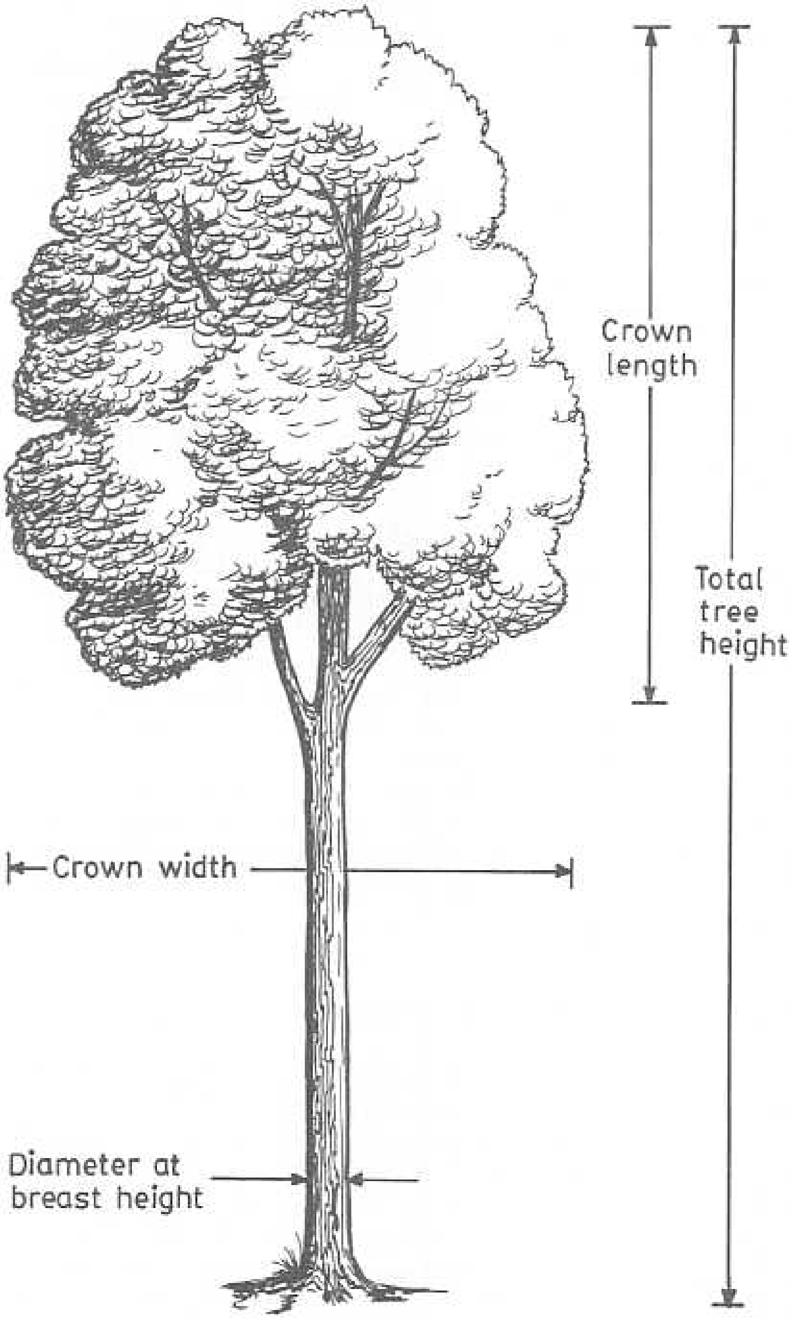


Figure 2. Tree variables used for biomass estimation.

Total tree height, defined as the vertical distance from the ground level to the extreme top of the tree, is commonly used in conjunction with D in biomass tree equations. Height is usually measured in metres to the nearest decimetre. The tree biomass equations using both D and H are referred to as standard biomass equations, analogous to standard tree volume equations.

Tree volume can be used in conjunction with wood density factors to estimate biomass (Alemdag 1984b). Component ratios can be used in conjunction with the whole tree or stem biomass estimates to derive component estimates. Unless otherwise qualified, volume refers to the gross total volume of a tree stem expressed in cubic metres, usually to the nearest three decimal places. The tree stem includes the stump, top, wood, and bark but excludes the branches and foliage. Forked trees are treated in Section 3. Expressions of merchantable volume will be referred to from time to time in these guidelines.

The remaining tree variables are less commonly used because they may not be available in conventional inventories, they are more expensive to measure, and generally are not as effective in estimating biomass quantities. Crown diameter, length, and area lend themselves to measurement on large-scale aerial photographs and can have a specialized role to play in the estimation of biomass (Alemdag 1986). The manual concentrates on the use of D, H, and V in the estimation of tree and tree component biomass quantities.

## 2. Selection of sample trees

The purpose of sample selection is to choose trees for developing biomass equations. The selection of trees should follow a statistically defensible sampling procedure and rules to ensure that the population of interest (a defined forest property or area) is properly represented. The selection task should assure that the important species and range of size classes are covered and that sufficient tree data are available for developing reliable equations. The selection procedure is also concerned with the efficiency of the sampling design and measurement procedures and the advantages of using existing data to reduce sampling effort.

The reliability and efficiency of the equations depend upon factors affecting the accuracy of equations. Regardless of whether a single characteristic is involved, such as a population mean, or more than one, such as several equation coefficients, accuracy refers to how close the estimates are to the true but unknown values. In the case of an equation, accuracy may pertain to the predicted value rather than the coefficients. The closer the estimate, the more accurate it is.

An estimate may be inaccurate for two reasons. First, an estimate may be biased, meaning that in the long run the estimate is consistently high or low by a certain amount. The bias can stem from the estimator itself; for example, ratio estimators are usually biased. Bias can arise from incorrect sampling procedures, for instance, during sample plot establishment always avoiding openings in the forest or selecting very dense stands or never going off roads by more than a few hundreds of metres. Bias can also arise from systematic errors in measurement procedures such as out-of-adjustment instruments, operator blunders, and improper recording or computation procedures. Reduction of bias to improve accuracy requires that all possible sources of systematic errors be known and controlled. Second, an estimate may be inaccurate because of random errors which, though compensated in the long run, may in particular cases cause tree estimates to be substantially different from the true value — high one time, low another. The random errors cause the estimate to be imprecise. A precise estimate is one where the random component of error is small. Sometimes good precision is referred to as high repeatibility, i.e., if a measurement is repeated over and over, the results are clustered closely about the mean. Lack of precision can stem from the sampling design (i.e., the estimator), small sample sizes (too few plots, for example), or inconsistent measurement procedures. provided the random measurement error is under control and does not overshadow sampling error, the larger the sample, the higher the precision.

An estimate will be inaccurate if either bias or lack of precision occur alone. If the height of an 18.6 m tree is measured repeatedly and found to average 14.4 m varying between 13.9 and 14.8 m, the measurements are fairly precise but very inaccurate because of the relatively large negative measurement bias of 4.2 m. Likewise, individual erratic measurement may be free of bias (when judged in the long run) but very imprecise for particular cases. Bias and precision are constant preoccupations during the consideration of the efficiency of sampling designs and measurement procedures.

### a. *Sampling rules*

Whenever a characteristic of a population is to be sampled, it is important &that a few rules be followed to ensure that the sample correctly represents the population. When the population is properly represented, then valid estimates of the required characteristics (for example, average ovendry tonnes of forest biomass per hectare or a set of regression coefficients expressing the relationship between tree mass, diameter, and height) can be made, together with statistically defensible statements about the accuracy of estimates. Valid estimates should be free of biases. Adherence to the sampling rules, judicious selection of estimators, development of good measurement procedures, careful training, and quality checking are all important in controlling bias.

The most important sampling rules are as follows:

(1) The population to be sampled must be clearly defined. In the forestry case, this generally means that the physical boundaries of a property or unit be delineated and mapped and that interior, nonforest areas such as bodies of water be recognized.
(2) Before selecting the sample, the population must be divided into parts called sampling units. In the forestry case, the sampling unit could be individual trees or, more conveniently, clusters of trees defined by one of many types of fixed-area sample plots or point samples.

(3) The sampling units must, in a conceptual sense, completely cover the population and should not overlap one another. Every element in the population should belong to only one unit. A list of all possible units is called a sampling frame.
(4) The sampling units must have a known probability of being selected.
(5) The selection process must be determined only by the choice of a valid sampling design which establishes the selection probabilities and the distribution and intensity of the sampling, and sets the rules for the random selection process, the compilation of estimates, and the accompanying reliability statements.

If these rules are followed, if an unbiased estimator is used (or estimator used with known bias which can be corrected), and if the measurement and computational procedures are free of systematic errors, then valid, statistically defensible estimates can be made. In practice, however, especially in the forestry case where access can be difficult and costly, the sampling rules often must be relaxed. In some cases, weighing schemes which modify the probability of selection can be imposed without violating the rules at all. In other cases, such as changes made to ensure that rare conditions (usually size class extremes) are covered, there may be a violation of the rules. However, with good judgment, liberties can be taken without seriously jeopardizing the results. The practitioner should be aware of the departures and potential dangers. The introductory chapter of Cochran (1963) treats the rules in greater detail; Freese (1962) provides guidance on how to apply the rules.

### b. *Sampling efficiency*

The purpose of sampling is to obtain required information without going to the &expense of measuring every sampling unit in the population. Results accurate enough to be useful can be obtained from samples of a fraction of the population. Several questions arise. What is accurate enough? How is accuracy evaluated? At what rate does an increase in the size of the sample improve accuracy? Are there other means of increasing accuracy for a given level of effort?

As described earlier, accuracy of an estimate is a measure of how close the estimate is to the true value. The lack of accuracy reflects the combined occurrence of biases in the sampling method, systematic errors in the measurement procedure, and random errors attributed to the sampling method and measurement procedures. In most applications it is assumed that sampling bias and measurement errors are held within acceptable limits and that the accuracy is adequately expressed by the random component of sampling error. Sampling error is usually expressed using calculations of variance or standard deviation of the estimator. The standard deviation is used to express either absolute or percentage limits of error allowed around the estimator with a specified level of confidence. When the level of confidence is set, a factor called the 5 value and the sample variance determine the confidence band around the estimator. For example, an estimate of mean total biomass of 153 tonnes per hectare could have a sampling error of plus or minus 5.4 tonnes plus or minus 5.4 tonnes, 95% of the time. Only the requirements of the survey will indicate what is an acceptable level of accuracy. The acceptable level goes back to the basic considerations of what the data is to be used for and the "downside" risk of being in error by a larger amount. The consequence of tightening the error tolerance too much is excessive cost. These concepts apply equally to the accuracy of equation coefficients.

Having settled on an acceptable accuracy level, what steps can be taken to change it? First, increases in sample size will increase accuracy. If a simple random sampling design were being used, sampling error is approximately proportional to the inverse of the square root of the sample size as follows:

$$S_{\bar{y}} = (S_y^2/n)^{1/2} \tag{1}$$

where $S_{\bar{y}}$ is the standard deviation of the estimator, $S_y$ an estimate of the standard deviation of the population, and n the sample size. It is assumed that the sample is taken from a large population. If the allowable error (E), the standard deviation of the population, and the required confidence level (t) were known, the size of the sample required to achieve the required level of accuracy can be determined for simple random sampling as follows:

$$n = t^2 S_y^2/E^2 \tag{2}$$

However, as the sample size is increased to achieve the required accuracy, so also cost increases, usually in direct proportion to the number of samples plus some fixed cost or overhead.

The second approach to increasing accuracy is to change the sampling design. In the case of simple random sampling, every element in the population has the same probability of being selected and, once the sample size is known, the probability is known and can be assigned (fourth sampling rule). Other designs attempt to use existing information and structural changes in the sampling unit to increase efficiency. Stratified random sampling, for example, makes use of other related information (photo-interpreted forest types, for instance) to draw together sampling elements into homogeneous groups, which when sampled are treated as subpopulations. If effective, the subpopulations will have a lower variance and, therefore, the overall sampling error should be smaller. The stratification allows different weighting schemes to be used which shift the sampling effort away from the least important strata and towards the most important or valuable strata. The weighting changes the probability of selection from one stratum to the next, but still satisfies sampling rule 4 provided the probability of selection is known. In a similar fashion the structure of the sampling unit can be changed. For example, the clustering of trees into plots already referred to is a possibility, as is the point sampling scheme where trees at a location are selected within a unit with a probability proportional to size. These structural changes raise related questions about the most efficient plot size and, in the case of variable radius plots, the best basal area factor to use. Sampling textbooks (e.g., Cochran 1963, Raj 1968) deal with these topics. All such sampling designs are valid provided the five rules are accounted for.

A large number of designs can be used which, depending upon the auxiliary data available, the nature of a population, and the cost of gain-ing access to an area and establishing a sample, will vary in efficiency. The inventory designer's job is to select the most efficient one for the particular case. The sampling handbook by Freese (1962) is a very helpful and practical guide to the choice and use of sampling designs. The classical textbooks on sampling by Cochran (1963) and Raj (1968) treat this subject in depth for those wishing to pursue other designs and the underlying principles.

### c. *Sampling procedure*

- Determine the limits of the population to be sampled. This often & involves delineation of the target area on a map.
- Assemble available data such as cover type maps, air photo coverage, field data, etc. which may be used to develop the sampling strategy, improve efficiency, and decide on sampling intensity. For example, cover type data or an existing volumetric inventory could be used to stratify the population, direct effort towards the most valuable areas, and to ensure unusual but important conditions are adequately covered.
- Select an efficient sampling design. In the case of forest inventory where cover type maps are available, stratified random sampling designs should be considered.
- Decide on the sampling unit to be used.
- Establish the sampling frame and the probabilities for selecting the sampling units. If stratified sampling were used, the strata should be assigned weights which deliberately alter the probability of selection so as to intensify the sampling of particular strata or conditions, and relax others. For example, extreme conditions are sometimes difficult to sample adequately. Weighting schemes can be used to shift the sampling into these conditions without violating sampling rules.
- Using available data on population or stratum variances, decide on the sample size needed to achieve the required accuracy and to cover important conditions.
- Using a randomization scheme appropriate to the sampling design, select and list the samples.
- Document the sampling design, the probabilities of selection, the selected samples, and the computation procedures.
- If departures are made to the sampling design, such as those that ensure population extremes are covered, record the modifications and check the consequences.

## 3. Field and laboratory procedures

The field work used to collect basic tree data for formulating single tree &biomass equations are based on procedures developed and documented by Alemdag (1980). Since Alemdag's manual was published, the procedures have been thoroughly tested on several large biomass projects. The procedures were found to be thorough, to work well in practice, and to require only a minor refinement or modification. These procedures are reproduced in this manual, incorporating the modifications.

The data collection procedures cover both sample plot measurements and sample tree measurements in the field. However, these two approaches need not be taken together; they can be combined or taken separately, depending upon the purpose of the work. Furthermore, the methods can be altered to meet local requirements.

The selection of sample locations should follow the guidelines in Section 2. The selection of sample trees and the method of subsampling and weighing in the field are explained stepwise in this section. In selecting the sample trees, emphasis should be placed on covering the full range of diameter classes for each species in the sample area and, within each diameter class, the full range of height classes. To adhere strictly to sampling rule 4, a system of weights should be used to keep track of the changes in probability of selection involved in emphasizing the extremes. In practice, the changes in probability of selection are rarely applied. A good practice however, is to at least record the changes in probability of selection used to fill out the full range of size classes. Where the sample plot procedure is not applied, the sample trees should be spread over the stands of different age, site, and density class. Although the samples may be selected from living trees that have average health and vigor and unbroken tops, some dead trees should also be included. Cones and dead branches of living trees should also be sampled for further analysis. Laboratory methods are also described in stepwise fashion.

The steps for single tree measurements are as follows; (1) selecting, (2) taking standing measurement, (3) felling, (4) collecting dimensional data, (5) separating tree components, (6) weighing green components, (7) taking samples, (8) weighing green samples, (9) ovendrying samples, (10) weighing ovendry samples, and (11) taking wood density measurements. Samples from the stem contain four disks from the merchantable trees and two from the unmerchantable trees. Three of the four disks of the merchantable trees are confined to the merchantable part of the stem because of its greater importance in the content of the whole tree. The determination of wood density, which could be regarded as an optional procedure, is not required for the development of mass/dimension tables, but it may be needed in converting volume into mass and in establishing local variances. Standards of measurement, and suggested lists of equipment for field and laboratory work can be found in Appendix B, tree species codes in Appendix C, methods of determining wood density in Appendix D, and sample recording forms in Appendix E. If desired, the data can be recorded electronically using a data logger, calculator, or portable computer. For the description and identification of tree species reference should be made to Hosie (1969). Although procedures for processing dead trees and dead branches are specified in this manual, taking measurements on such material is optional because they are not considered as a part of biomass by definition.

### a. *Sample plot field work*

When required to take sample plots in a particular forest type, follow these steps:

1.0 Establish sample plots 400 m² in size in stands of various maturity stages and site and density classes within the specified population.

2.0 Lay out circular plots with a radius of 11.28 m to achieve the 400 $m^2$ sample.

3.0 Establish two concentric subsample plots (except in plantations) with a radius of 2.82 m and 1.13 m (25 $m^2$ and 4 $m^2$, respectively).

4.0 Within each sample 400 $m^2$ plot take the following stand and tree measurements:

4.01 Record all appropriate stand data.

4.02 Measure and record the diameter at breast height outside bark (D) at 1.30 m from ground level of all living and dead trees larger than or equal to 5.1 cm in D, by species. For the purposes of this manual, a tree is any woody perennial plant taller than 1.30 m. A woody plant equal to or smaller than 1.30 m in height is called a shrub, seedling, or sapling.

- Use a stick 1.30 m in length to find the measurement point.
- Mark each tree at breast height while taking the D measurement.
- Record the actual measured value of the D.
- Mark living and dead trees.
- Use species codes given in Appendix C.

4.03 Select at least five living trees in each D class of the predominant tree species, and measure and record their total heights (H).

4.04 Take increment cores at breast height from five living trees of the dominant and codominant classes of the predominant tree species selected randomly in an even-aged stand, except in plantations, and of all crown classes of the predominant tree species in all-aged stand (the increment core should include the pith of the tree). Count the number of rings in the core and add to it the years required to grow to breast height in order to find the total age under existing conditions. Record this total age.

4.05 Where possible, select at least two sample trees of average health and vigor and with an unbroken top from each D class of living trees and from different heights within the D classes for mass and volume sampling (destructive sampling). To achieve a complete sampling, cover the full range of existing D classes of the species sampled and, within each D class, the full range of existing height classes, distributed over several sample plots.

4.06 Identify and mark each sample tree on the aerial photograph, if required.

4.07 Measure and record the crown diameter of each sample tree.

4.08 Where possible, select one sample tree from dead trees in every second sample plot.

5.0 Within the 25 $m^2$ subsample plot proceed as follows:

5.01 Measure and record diameter at breast height outside bark at 1.30 m of all living and dead trees smaller than 5.1 cm in D, by species.

5.02 Measure and record total tree height of two to five living trees selected at random.

5.03 Select one sample tree from the living trees.

6.0 Within the 4 $m^2$ subsample plot proceed as follows:

6.01 Count all living woody plants (tree seedlings, saplings, and shrubs) 0.31 m to 1.30 m in height, and record them by species using two height classes: 0.31 m to 0.80 m and 0.81 m to 1.30 m.

6.02 Select at random one sample tree from each height class.

7.0 If the sample plot is a permanent observation plot, select sample trees from outside the plot.

## b. *Sample tree field work*

If your goal is to sample trees only, select these trees according to a weighting scheme, randomly in the natural range of the species, to include a wide range of diameters and heights. When sampling trees without using a sample plot, first measure and record the diameter at breast height outside bark and the crown diameter. Cut each sample tree at approximately 0.30 m above ground level and each sample shrub or small tree at ground level. Before cutting, clear the area around the sample tree of brush, small trees, and shrubs. Whether sampling trees within a sample plot or not, follow these steps:

### *ba.* Procedure for living merchantable sample trees

In this manual a tree, living or dead, is called merchantable if it has a diameter of 9.1 cm outside bark at or above 2.80 m from ground level (=stump 0.30 m in height + one bolt 2.50 m in length). More precisely, in this manual a merchantable tree is a merchantable-sized tree. Other trees are unmerchantable. Merchantable height is the length of the stem from ground level to where the diameter is 9.1 cm outside bark. In a particular work other values may be assigned to this diameter.

On each living merchantable tree, use the following procedures (Figures 3a and 3b):

1.0 Measure and record the following dimensions (Forms 2, 3, and 4):

1.01 Height;

Stump height;

Total height of the tree (main stem) from ground level to the tip. Place a metallic tape along the main stem so that 1.30 m on the tape coincides with the marking at 1.30 m on the bole;

Height from ground level to the point on the stem where the diameter outside bark is 9.1 cm. Mark this merchantable height point on the stem;

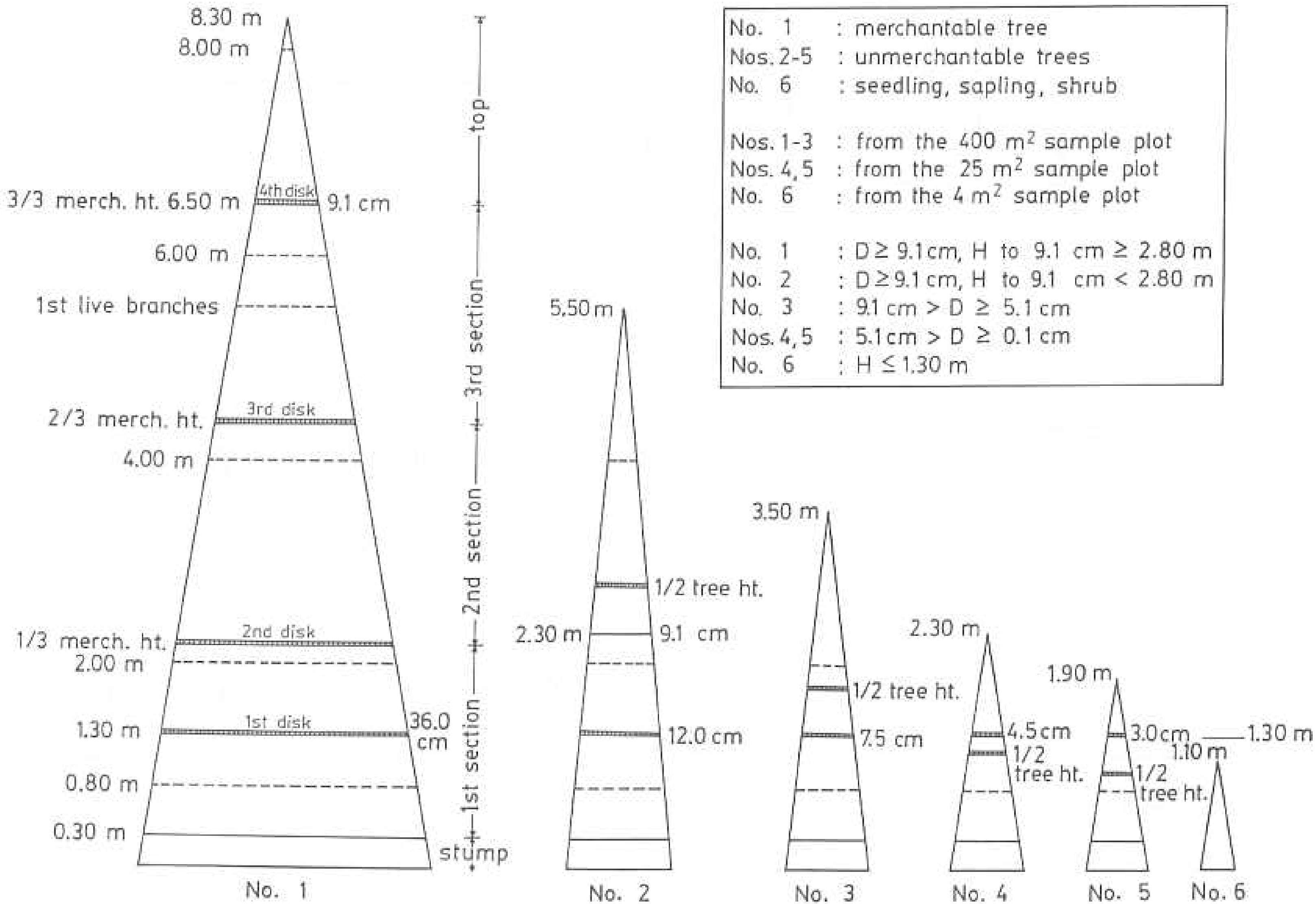


Figure 3a. A schematic instruction for the diameters measured and the sample disks taken from the merchantable and unmerchantable trees and shrubs.

| | |
|---|---|
| MERCHANTABLE | D ≥ 9.1 cm<br>Height to outside-bark diameter of 9.1 cm ≥ 2.80 m<br>Three sections and top for weighing<br>Four disks (breast height, 2nd and 3rd sections, and top) from stem |
| UNMERCHANTABLE | D ≥ 9.1 cm<br>Height to outside-bark diameter of 9.1 cm < 2.80 m<br>Total stem for weighing<br>Two disks (breast height and 1/2 stem) from stem |
| | 9.1 cm > D ≥ 5.1 cm<br>Normal size<br>Total stem for weighing<br>Two disks (breast height and 1/2 stem) from stem |
| | 5.1 cm > D ≥ 0.1 cm<br>Normal size<br>Total stem for weighing<br>Two disks (breast height and 1/2 stem) from stem |
| SEEDLING<br>SAPLING<br>SHRUB | H ≤ 1.30 m<br>Cut up for weighing: stem, branches, twigs and leaves<br>No disk |
| DEAD | Any size of D<br>Total tree for weighing<br>Two disks (breast height and 1/2 stem) from stem |

Figure 3b. Summary in words of Figure 3a.

Height from ground level to 1/3 of the merchantable height. Mark this point on the stem;

Height from ground level to 2/3 of the merchantable height. Mark this point on the stem;

Height from ground level to the base of the first whorl of live branches. Mark this point on the stem;

1.02 Diameter;

Diameter at breast height outside bark (D);

Stump diameter outside bark at ground level;

Stump diameter outside bark at the point of cut;

Diameter outside bark at 0.80 m above ground level;

Diameter outside bark at 5.0 cm below the base of the first whorl of live branches;

Diameter outside bark at each 2.00 m, starting from 2.00 m above ground level;

1.03 Double-bark thickness

Double-bark thickness (dbt) at all locations where diameters are measured;

1.04 Total age;

Annual rings on the face of the stump, plus the number of years the seedling required to reach the height of the stump (a test to determine the age of seedlings 0.30 m in height is a prerequisite).

2.0 Separate and section parts of the trees in the following way:

2.01 Cut all the branches, leaving the tree top (main shoot) on the stem; subdivide and pile the branches separately in three groups: large live branches, small live branches, and dead branches;

2.02 Remove all leaf-bearing twigs and leaves from the live branches (In this manual, the word "leaves" is used as a synonym for needles);

2.03 Collect new cones, and the old cones of the previous years, and pile them separately (In this manual, the word "cones" is used as a synonym for nuts and fruits);

2.04 Section the main stem at 1/3, 2/3, and at the full merchantable height.

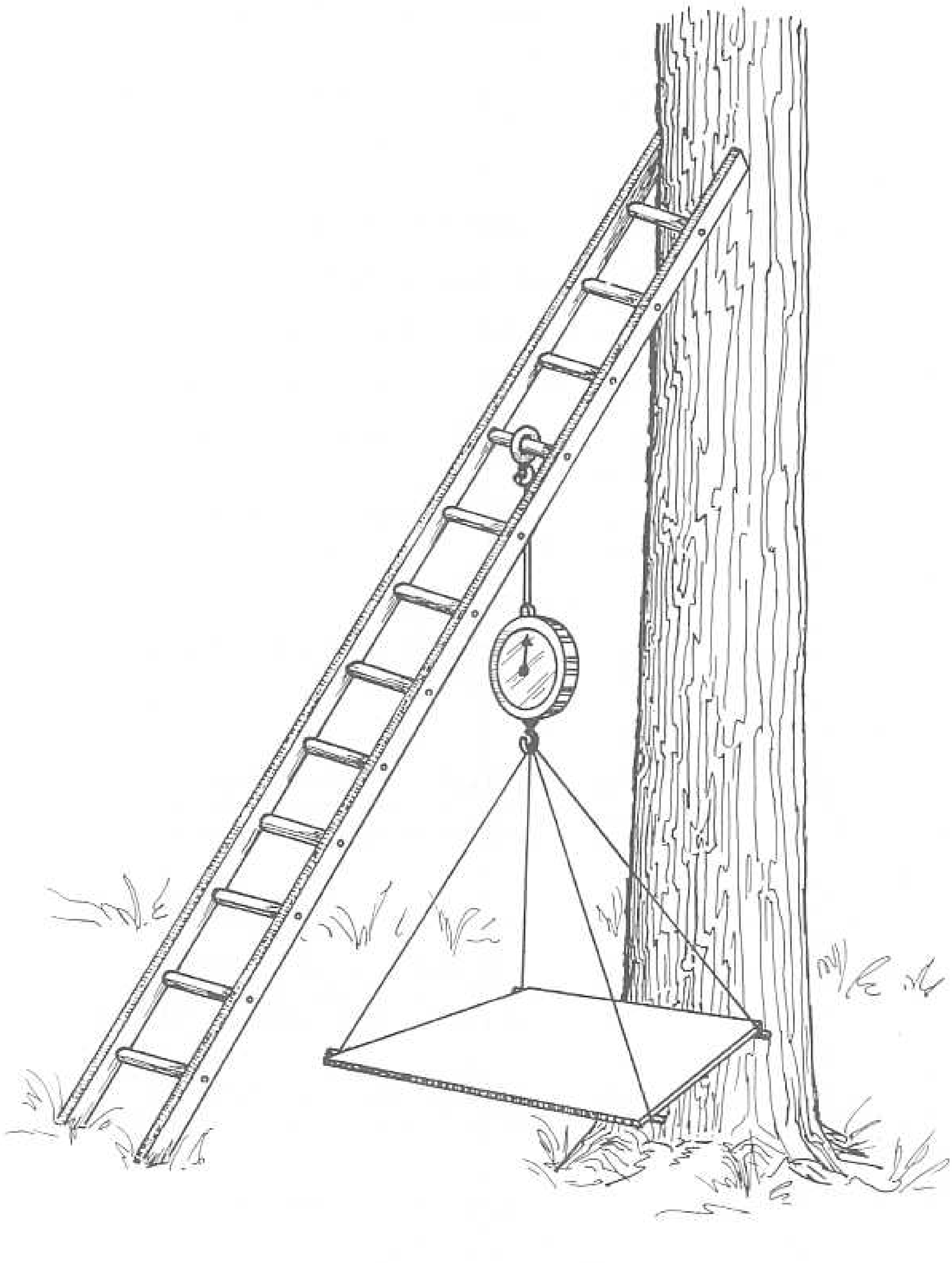

Figure 4. A way of setting up the tensiometer weighing scale in the field.

3.0 Weigh the following to establish green mass (GM), including bark; refer to Figure 4 and record results (Form 5):

3.01 Green mass of large live branches, small live branches, and dead branches separately;

3.02 Green mass of twigs and leaves together;

3.03 For conifers, green mass of new and old cones, separately; for other trees take a sample of any fruit that may be present;

3.04 Green mass of the three sections of the merchantable stem, separately (after cutting them into manageable pieces);

3.05 Green mass of the top portion of the main stem.

4.0 Collect sample material, as follows:

4.01 Take one bunch of samples of twigs and leaves (each sample being about 150 g or enough to fill a plastic bag 20 x 30 cm);

4.02 Take one sample from each pile of cones (1-3 cones) or from other fruits;

4.03 Take two samples disks (8 to 10 cm in length), one from the large and one from the small live branches; Select branches of medium length;

4.04 Take one sample disk (8 to 10 cm in length), from the pile of dead branches of every fourth tree. Select a branch of medium length;

4.05 Take one sample disk 3 to 4 cm in thickness at the breast height mark, 1.30 m from the base. Let the lower face of the disk be at the 1.30 m mark;

4.06 Take a sample disk, 3 to 4 cm in thickness, from the lower end of both section 2 and 3 of the merchantable stem (marked at 1/3 and 2/3 of the merchantable height);

4.07 Take one sample disk 3 to 4 cm in thickness from the lower end of the top;

4.08 Put each sample in a polyethylene bag labelled to indicate sample plot number (if any), sample tree number, and sample code; Identify disks by writing on their lower faces and seal the bag.

Use the following codes for the samples:

L1: bunch of twigs and leaves
C1: new cones or fruit
C2: old cones or fruit
B1: disk from the large live branches
B2: disk from the small live branches
B3: disk from the dead branches

S1: disk from breast height
S2: disk from the second section or from the middle of the stem
S3: disk from the third section
S4: disk from the tree top

Note: More sample disks from the stem can be taken while working with large trees.

*bb.* Procedure for living unmerchantable sample trees

For each living unmerchantable tree, use the following procedures (Figures 3a, 3b, and 4):

1.0 Measure and record the following dimensions (Forms 2, 3, and 4):

1.01 Height of the sample tree;
1.02 Diameter at breast height outside bark;
1.03 Stump diameter outside bark at ground level;
1.04 Diameter outside bark at the face of the stump;
1.05 Diameter outside bark at 0.80 m above ground level;
1.06 Diameters outside bark at each 2.00 m interval, starting from 2.00 m above ground level;
1.07 Double-bark thickness at all locations where diameters are measured;
1.08 Count the annual rings on the face of the stump, and add appropriate years to obtain total age (a test on seedlings 0.30 m in height is a prerequisite).

2.0 Separate, section, weigh material, and collect samples (Form 5). If a tree is very small its total components may be collected for weighting in the laboratory (Forms 2 and 6).

2.01 Do as in ba/2.0, excluding 2.04;
2.02 Do as in ba/3.0/3.01, 3.02, 3.03, and measure the total mass of the main stem;
2.03 Do as in ba/4.0, excluding 4.06 and 4.07, and take an additional sample disk, 3 to 4 cm in thickness, from the middle of the stem.

*bc.* Procedure for living shrubs and trees (below 1.30 m in height)

1.0 Measure and record the following dimensions (Figures 3a and 3b, and Forms 2 and 6):

- Total height
- Diameter outside bark at ground level
- Double-bark thickness at ground level.

2.0 Count and record the annual rings at ground level.

3.0 Cut up the whole tree, shrub, or smaller tree and place all materials in a bag for processing to determine total green and ovendry mass.

*bd.* Procedure for dead trees

Sample dead trees, using the following procedures (Forms 2, 5, and 7):

1.0 Measure and record stump height, tree height, and diameters at breast height, at 0.80 m above ground level, at the face of the stump, and at ground level.

2.0 Weigh and record the total mass of the tree including stem and branches.

3.0 Take two sample disks, one at breast height and one from the middle of the stem.

*be.* General

1.0 Check and ensure that all required measurements are taken, and taken correctly, and that there is no unusual reading for the diameters or double-bark thickness.

2.0 Check and ensure that all the required samples have been collected. These samples are as follows:

2.01 For each living merchantable sample tree four disks from the stem, two disks from the live branches, one disk from the dead branches, one bag of twigs and leaves from the crown, and cones or fruit (when available);
2.02 For each living unmerchantable sample tree, two disks from the stem, two disks from the live branches, one disk from the dead branches, one bag of twigs and leaves from the crown, and cones or fruit (when available);
2.03 For each living sample shrub or small tree, the sample comprises the whole plant;
2.04 For each dead tree, the sample comprises two disks from the stem.

3.0 Send all samples, as soon as possible, to the field laboratory for further measurements. If laboratory processing is delayed, store samples in a refrigerator at 0°C to minimize moisture loss.

4.0 After the collection of samples, dispose of all remaining material.

5.0 At the end of each day, document all sample trees to find the gaps in D and H classes using Form 8.

## c. *Laboratory work*

As with the field work procedures, the laboratory work is based on procedures developed and documented by Alemdag (1980). Use of recording forms such as those illustrated in Apendix E is suggested.

*ca.* Procedure for measuring disks from living trees

1.0 Measure and record the annual rings and diameters on the lower side of each disk taken from the stem, as follows (Form 7):

1.01 Count the number of annual rings from the edge of the wood to the pith;
1.02 Measure average diameter outside bark;
1.03 Measure double-bark thickness of the average diameter;
1.04 Measure the total width of the last 10 annual rings (the 10 outermost rings) along one radius of the average diameter.

2.0 Cut a wedge from each disk taken from the stem, and label it. Try to use a section of uniform wood, avoiding knots and other irregularities.

3.0 Take the green-mass (GM) measurements as follows (Forms 6 and 7):

3.01 Remove bark from the remaining part of the disk taken from the stem, and from the full disks taken from the live branches;
3.02 Weigh and record the green mass of the wood;
3.03 Weigh and record the green mass of the bark;
3.04 Label and store both wood and bark separately for subsequent drying.

4.0 Take the ovendry mass (OM) measurements as follows (Forms 6 and 7):

4.01 Ovendry samples (bark and wood, except wedges);
4.02 Remove from the oven, place in a desiccator until cooled, and weigh and record the ovendry mass of each sample;
4.03 Dispose of all these samples.

5.0 Take wood density measurements using wedges as follows (Form 7):

5.01 Remove the bark from the wedge;
5.02 Soak each wedge for at least one hour;
5.03 Remove each wedge, stand it on edge for 10 minutes to allow the excess water to drain away, and then pat it with a cloth or a paper towel;
5.04 Immerse each wedge in a water container for displaced volume determination, using Method 1 described in TAPPI standard T18m-53 (Appendix D), and record the volume (green volume);
5.05 Ovendry each wedge;
5.06 Remove it from the oven, place in a desiccator until cooled, and weigh and record ovendry mass of the wedge;
5.07 Dispose of samples.

6.0 If the sample is a whole shrub including stem, branches, and twigs and leaves, get the total green mass and process the sample for its ovendry mass.

*ch.* Procedure for measuring twigs, leaves, cones, and fruit of living trees

1.0 Take green mass measurements as follows (Form 6):

1.01 Strip leaves from the twigs;
1.02 Weigh the green mass of leaves and twigs separately;
1.03 Weigh the green mass of new and old cones separately;

1.04 Label and store all these for subsequent drying.

2.0 Take ovendry mass measurements as follows (Form 6):

2.01 Ovendry each sample;
2.02 Remove sample from the oven, place in a desiccator until cooled, and weigh and record the ovendry mass of each sample;
2.03 Dispose of the samples.

cc. Procedure for measuring disks from dead trees

1.0 Measure and record the length of the average diameter, and the double-bark thickness, if any.

2.0 Take the green and ovendry masses of the disk as explained earlier (but without removing the bark) and record under "wood" on Form 7. There is no need to measure wood density, to count the annual rings, or to measure the width of 10 annual rings.

# 4. Computations

Mass calculations of the tree components, and wood density and stem volume calculations, should be conducted according to procedures described by Alemdag (1984b).

## a. *Mass calculations*

First, bark per cent in terms of wood plus bark of the stem disks should be calculated using green mass obtained from the disks. Then, employing the weighted average of these percentages of the two ends of each of the bottom, middle, and upper third sections of the merchantable stem, each of these section's observed green mass of wood plus bark should be separated into wood and bark. Weighting factors should be the squares of the outside bark diameters of the disks. In the case of the bottom section, disk at breast height ought to be used as the lower-end disk, and in the case of the tree top, only one disk should be employed. Following this, the ovendry mass (OM)/green mass (GM) ratios of the above mentioned sample materials ought to be calculated. These ratios should then be multiplied by the actual measured GM values of components to arrive at the OM values. When dealing with the wood mass and bark mass of the four stem sections, a weighted average of OM/GM ratios of each section should be calculated in a fashion similar to the weighted bark percentages before applying these ratios to the sections' green masses. Ovendry mass of stump wood and of stump bark ought to be calculated by using the ratio of stump volume to the volume of the part between stump height and the top height of the lower merchantable section. After these calculations for the stem are completed, they should be added together to arrive at the ovendry mass of wood and of bark of the total stem. Then, the ovendry mass of live branches, twigs plus leaves, fruits, and dead branches should be added to this stem total to obtain the ovendry mass of the whole tree. However, when doing esti-

Table 1a. Example of computer-produced single tree summaries

## TABLE OF SINGLE-TREE SUMMARIES

PROJECT NO.: PI-12-067 STUDY NO.: ENFOR-234

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| PLOT NO. 1 | TREE NO. | 12 | SPECIES CODE | 720 | DBHOB (CM) 35.0 | HEIGHT (M) | 22.06 |
| | AGE (YR) | 94 | CR DIAM (M) | 8.5 | HT BLCR (M) 8.17 | MERCH HT (M) | 15.60 |
| | TREE STATUS | 1 | DBT AT BH (CM) | 2.0 | | | |

| ROW NO. | DESCRIPTION | SEC NO. | GREEN MASS (KG) | OVENDRY MASS (KG) | OM/GM RATIO | VOLUME (M**3) OUTSIDE BK | VOLUME (M**3) INSIDE BK |
|---|---|---|---|---|---|---|---|
| 1 | STEM WOOD | 1* | 342.468 | 186.529 | 0.545 | | 0.436 |
| 2 | | 2 | 236.462 | 127.487 | 0.539 | | 0.227 |
| 3 | | 3 | 90.256 | 48.342 | 0.536 | | 0.089 |
| 4 | | 4 | 11.650 | 6.147 | 0.528 | | 0.013 |
| 5 | ROWS 1-4 | TOTAL | 680.836 | 368.506 | 0.541 | | |
| 6 | STEM BARK | 1* | 38.232 | 21.638 | 0.566 | | |
| 7 | | 2 | 27.338 | 15.659 | 0.573 | | |
| 8 | | 3 | 13.044 | 7.305 | 0.560 | | |
| 9 | | 4 | 2.450 | 1.344 | 0.549 | | |
| 10 | ROWS 6-9 | TOTAL | 81.064 | 45.946 | 0.567 | | |
| 11 | STEM WOOD PLUS BARK | 1* | 380.700 | 208.168 | 0.547 | 0.483 | |
| 12 | | 2 | 263.800 | 143.146 | 0.543 | 0.257 | |
| 13 | | 3 | 103.300 | 55.647 | 0.539 | 0.104 | |
| 14 | | 4 | 14.100 | 7.491 | 0.531 | 0.016 | |
| 15 | ROWS 11-14 | TOTAL | 761.900 | 414.452 | 0.544 | | |
| 16 | BARK % OF WOOD PLUS BARK ** | 1 | 10.0 | 10.4 | | | |
| 17 | | 2 | 10.4 | 10.9 | | | |
| 18 | | 3 | 12.6 | 13.1 | | | |
| 19 | | 4 | 17.4 | 17.9 | | | |
| 20 | | AVG. | 10.6 | 11.1 | | | |
| 21 | BRANCHES, DEAD | | 10.100 | 7.070 | 0.700 | | |
| 38 | WOOD, LIVE BRANCHES > 9.0 CM | | 106.049 | 58.962 | 0.556 | | |
| 39 | BARK, LIVE BRANCHES > 9.0 CM | | 20.751 | 11.081 | 0.534 | | |
| 22 | BRANCHES, LIVE > 9.0 CM | | 126.800 | 70.043 | 0.552 | | |
| 40 | WOOD, LIVE BRANCHES < 9.1 CM | | 150.632 | 78.704 | 0.522 | | |
| 41 | BARK, LIVE BRANCHES < 9.1 CM | | 31.768 | 16.661 | 0.524 | | |
| 23 | BRANCHES, LIVE < 9.1 CM | | 182.400 | 95.365 | 0.523 | | |
| 42 | TWIGS | | 16.619 | 8.837 | 0.532 | | |
| 43 | LEAVES | | 20.181 | 7.266 | 0.360 | | |
| 24 | TWIGS AND LEAVES | | 36.800 | 16.103 | 0.438 | | |
| 44 | NEW CONES | | 1.700 | 0.551 | 0.324 | | |
| 45 | OLD CONES | | 0.400 | 0.181 | 0.453 | | |
| 46 | CONES | | 2.100 | 0.732 | 0.349 | | |
| 25 | STUMP WOOD | | 91.078 | 49.892 | 0.548 | | 0.116 |
| 26 | STUMP BARK | | 7.165 | 3.999 | 0.558 | | |
| 27 | STUMP WOOD PLUS BARK | | 98.242 | 53.892 | 0.549 | 0.125 | |
| 28 | TOTAL (ROWS 15,21,22,23,24,27,46) | | 1218.343 | 657.657 | 0.540 | 0.984 | 0.881 |
| 29 | MERCHANTABLE-STEM WOOD | | 669.186 | 362.359 | 0.541 | | 0.752 |
| 30 | MERCHANTABLE-STEM BARK | | 78.614 | 44.602 | 0.567 | | |
| 31 | MERCHANTABLE-STEM WOOD PLUS BARK | | 747.800 | 406.961 | 0.544 | 0.843 | |
| 32 | HARVESTING RESIDUE (28 MINUS 31) | | 468.443 | 249.964 | 0.534 | | |
| 33 | WOOD DENSITY (GRAM/CM**3) | 1 | | | 0.633 | | |
| 34 | | 2 | | | 0.620 | | |
| 35 | | 3 | | | 0.608 | | |
| 36 | | 4 | | | 0.601 | | |
| 37 | | AVG.*** | | | 0.624 | | |

* EXCLUDING STUMP
** WEIGHTED AVERAGE BY DOB**2 OF DISKS
*** WEIGHTED AVERAGE BY DIB**2 OF DISKS

## Table 1b. Example of computer-produced checking tables

**PROJECT:** PI-12-067 **STUDY:** ENFOR-234

CHECKING TABLE NO. 1
NUMBER OF TREES: 5
SPECIES CODE : 720
TREE STATUS : 1

* TOTAL OF THE COLUMN / N
** INCLUDING STUMP
*** DISREGARDING COMPONENTS WITH ZERO VALUES
**** WHOLE TREE CONTAINS DEAD BRANCHES AND CONES

| DBHOB | TOTAL HEIGHT | PLT NO. | TR NO. | OM OF COMPONENTS: STEM WOOD** | STEM BARK** | DEAD BRCH | LIVE BRCH | TWG,LVS & CONES | WHOLE TREE | OM OF COMPONENT/ OM OF STEM WOOD***: MERCH WOOD | MERCH BARK | STUMP W & BK | DEAD BRCH | LIVE BRCH | TWG,LV &CONES | STEM BARK** | WHOLE TREE | S W'S: OM** /GM** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.7 | 3.21 | 8 | 3 | 0.19 | 0.02 | 0.00 | 0.23 | 0.12 | 0.56 | 0.00 | 0.00 | 0.28 | 0.00 | 1.21 | 0.66 | 0.10 | 2.98 | 0.63 |
| 6.2 | 5.00 | 1 | 39 | 6.46 | 1.34 | 0.00 | 1.42 | 1.42 | 10.64 | 0.00 | 0.00 | 0.12 | 0.00 | 0.22 | 0.22 | 0.21 | 1.65 | 0.59 |
| 16.1 | 16.30 | 2 | 6 | 60.22 | 9.03 | 1.93 | 14.72 | 2.97 | 88.86 | 0.75 | 0.11 | 0.06 | 0.03 | 0.24 | 0.05 | 0.15 | 1.48 | 0.56 |
| 35.0 | 22.06 | 1 | 12 | 418.40 | 49.94 | 7.07 | 165.41 | 16.84 | 657.66 | 0.87 | 0.11 | 0.13 | 0.02 | 0.40 | 0.04 | 0.12 | 1.57 | 0.54 |
| 59.6 | 23.87 | 8 | 28 | 1085.32 | 201.48 | 3.69 | 649.89 | 13.75 | 1954.13 | 0.93 | 0.18 | 0.07 | 0.00 | 0.60 | 0.01 | 0.19 | 1.80 | 0.60 |
| AVG* | | | | 314.12 | 52.36 | 2.54 | 166.33 | 7.02 | 542.37 | 0.51 | 0.08 | 0.13 | 0.01 | 0.53 | 0.20 | 0.15 | 1.89 | 0.58 |

PROJECT: PI-12-067 STUDY: ENFOR-234

CHECKING TABLE NO. 2
NUMBER OF TREES: 5
SPECIES CODE : 720
TREE STATUS : 1

* TOTAL OF THE COLUMN / N
** INCLUDING STUMP
*** DISREGARDING COMPONENTS WITH ZERO VALUES
**** WHOLE TREE CONTAINS DEAD BRANCHES AND CONES

| DBHOB | TOTAL HEIGHT | PLT NO. | TR NO. | INSIDE VOL. OF 4 SECT'S: 1ST** | 2 ND | 3 RD | 4 TH | INSIDE VOLUME STEM WOOD | OM OF WOOD OF 4 SECTIONS: 1 ST** | 2 ND | 3 RD | 4 TH | INSIDE OM STEM WOOD | WOOD DENSITY OF 4 SECTIONS: 1 ST | 2 ND | 3 RD | 4 TH | AVG. | SW OM**/ S INSIDE VOLUME** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.7 | 3.21 | 8 | 3 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.188 | 0.649 | 0.687 | 0.000 | 0.000 | 0.664 | 188.0 |
| 6.2 | 5.00 | 1 | 39 | 0.000 | 0.000 | 0.000 | 0.000 | 0.008 | 0.000 | 0.000 | 0.000 | 0.000 | 6.457 | 0.602 | 0.517 | 0.000 | 0.000 | 0.574 | 807.1 |
| 16.1 | 16.30 | 2 | 6 | 0.041 | 0.026 | 0.019 | 0.018 | 0.104 | 20.678 | 15.414 | 12.309 | 11.816 | 60.217 | 0.602 | 0.527 | 0.583 | 0.536 | 0.569 | 579.0 |
| 35.0 | 22.06 | 1 | 12 | 0.552 | 0.227 | 0.089 | 0.013 | 0.881 | 236.421 | 127.487 | 48.342 | 6.147 | 418.398 | 0.633 | 0.620 | 0.608 | 0.601 | 0.624 | 474.9 |
| 59.6 | 23.87 | 8 | 28 | 1.543 | 0.506 | 0.134 | 0.005 | 2.189 | 656.491 | 321.168 | 103.205 | 4.455 | 1085.320 | 0.676 | 0.720 | 0.628 | 0.596 | 0.683 | 495.8 |
| AVG* | | | | 0.427 | 0.152 | 0.048 | 0.007 | 0.637 | 182.718 | 92.814 | 32.771 | 4.484 | 314.116 | 0.632 | 0.614 | 0.364 | 0.347 | 0.623 | 509.0 |

mation analyses, the mass of fruits and dead branches should not be included in the whole tree mass. In addition to the ovendry mass of the various tree components, the ovendry mass of the total merchantable stem wood, total merchantable stem bark, and the harvesting residue (whole tree minus merchantable stem wood and bark) should be calculated.

### b. *Basic wood density calculations*

The basic wood density by definition is the ratio of ovendry mass of wood to its green volume, expressed in terms of mass per unit of volume. For each disk location on the stem it should be calculated by dividing the wedge's ovendry mass in grams by its green volume in cubic centimetres. The average wood density of the bole should be computed by taking the weighted averages of these wood densities, the weighting factors being the square of the inside-bark diameter of the disks.

### c. *Volume calculations*

Stem volume, from ground level to the tip of the tree, ought to be calculated for inside bark and outside bark in cubic metres. In these calculations the formula for a neiloid frustrum should be used for the stump volume, the cone formula for the tree top, and Smalian's formula for the part of the stem in between these two sections. The calculated values should be presented for the lower third (excluding stump), middle third, and upper third of the merchantable stem, for the top, and for the stump.

The results of these calculations and most of the sample tree information should then be entered into computer-produced tables called single-tree summaries. Subsequently, these processed data ought to be visually checked to see if any anomalies occurred among the calculated values, by tabulating them in an ascending order of D and H. Then, either the obvious errors ought to be corrected by referring to the field data, or the trees with these errors should be rejected. Examples of these single tree summaries and of the checking tables are provided in Tables 1a and 1b.

# III. SINGLE TREE BIOMASS EQUATIONS

The purpose of single tree biomass equations is to use available or easily-measured tree data to estimate whole tree and tree component biomass quantities. Use of equations avoids the slow, costly, and destructive process of direct biomass measurement, such as described in the previous chapter. The equations can serve in new biomass inventories, used to convert data in existing conventional forest inventories, and used for special biomass estimation problems such as handling of nonmerchantable species, size classes, and tree components. These equations can be developed either for ovendry or green mass, the former being more common because it affords more consistent mass predictions. The application of the equations to forest inventory is treated in detail in Chapter IV.

The topic of single tree biomass equations includes procedures both to develop and implement new equations and to adapt existing equations. The chapter begins by providing background and general guidelines concerning the suitability of equations and leads to specific procedures governing the development or choice of equations.

The measures of whole tree and component ovendry biomass (the dependent variables) are as defined in Chapter II. The independent variables are limited to diameter, height, and tree volume for reasons explained earlier. Linear regression techniques are relied upon heavily in the procedures needed to develop, test, and select the equations. Desirable properties of the equations are described as well as precautions in using regression analysis techniques.

The subject of linear regression and supporting principles are not treated in these guidelines. The reader is assumed to have a grasp of the topic sufficient to set up data for analysis, to use existing multiple-regression statistics packages to carry out analysis, and to understand the important assumptions underlying regression techniques and the limitations they may impose. The consequences of violations of the assumptions are, however, treated here in some detail. Most of the regression terminology is defined in the Glossary (Appendix A). Textbooks by Draper and Smith (1966), Snedecor and Cochran (1967), and Johnston (1963) are clearly written and cover the important theory. The first two chapters of Johnston (1963) provide a concise and complete review of regression techniques, as does Freese (1964).

## 1. Role of single tree equations

Several types of single tree equations are likely to be called upon in biomass inventories. The category will depend primarily on available tree data and on the sizes of the trees/shrubs involved.

Diameter at breast height outside bark (D) is almost invariably the primary tree variable used in volume or biomass inventory because it is so strongly related to volume or biomass and is easily and cheaply measured. Total tree height (H) is also important but it is less easily measured. Frequently, a fraction of sample trees are measured for H and then H-on-D equations are relied upon to estimate heights for the remaining trees. D and H are in turn used in local or standard tree volume equations to provide various expressions of stem volume (V). Thus, to estimate whole tree or component biomass, D, H, or V can be used. Because V is in most cases estimated from D and H, biomass is best estimated directly from D and H rather than by using a volume-to-biomass conversion. However, where H is largely or entirely estimated from D, the biomass equations depending on D alone are often more appropriate and are recommended when available. The discussion of single tree equations will concentrate on the use of tree D and H variables.

The tree equations vary in their effectiveness and efficiency according to the size of trees. Recent experience with the accuracy and cost of measuring different tree sizes, subsampling, experiments with effective ranges of equations, and estimation of component biomass suggest that three categories be recognized:

- Trees equal to or larger than 5.1 cm D should be served by one set of whole tree and component equations per species based either on D alone or D and H together.
- Trees and shrubs from 0.1 to 5.0 cm D should use equations based on D to estimate whole tree biomass. Component biomass should not be treated in this category. If equations are not available for this category, the equations developed for trees larger than 5.0 cm D can be substituted but may lack accuracy for trees smaller than 5.1 cm. Precautions should be taken with biomass estimates when D approaches zero.
- Trees and shrubs between 0.31 and 1.30 m in H, (ie. with no D) should be sorted and counted according to two height classes: 0.31 to 0.80 m and 0.81 to 1.30 m. For each class, the average mass per tree is used to compute the biomass estimates. Otherwise tree estimation equations are not required for this category.

Trees and shrubs 0.30 m in H and shorter should be ignored, as should dead and downed trees, litter, duff, and biomass beneath the soil surface. Special surveys such as those concerned with logging residues, lesser vegetation, peat, and fuels related to forest fires, etc., may include material in this category, but they lie outside the scope of this manual. The treatment of single tree equations to handle the biomass of merchantable and unmerchantable portions of the stem are covered separately. The desired properties of the single tree biomass equations discussed next concentrate on trees and shrubs 0.1 cm D and larger.

## 2. Properties of single tree equations

In order for the biomass equations to serve well in inventory applications, the model should be reasonable, efficient, practicable, and stand up to statistical scrutiny. The reasonableness pertains to the geometric properties of solids and their dimensions and how well the equations perform throughout the expected range of the data. Does the equation produce absurd results such as negative biomass estimates? Does biomass decline as D or H increase? The efficiency aspect concerns the accuracy of the equations, the control of bias, and balancing of the cost of measuring additional tree variables against the added gain in accuracy. Practicability concerns mainly ease of use and flexibility in deriving additional information from the equations. The statistical soundness pertains to how well sampled data represents the population being inventoried and how well the assumptions behind the development of biomass equations are satisfied. The sampling considerations have already been treated. The other requirements are described under four desired properties of the equations.

### a. *Geometric rationale*

As a tree increases in girth and height so, under most circumstances, should its volume and biomass. Therefore, equations used to estimate volume or biomass should realistically model these trends. When either H or D approaches zero, V and biomass should approach zero with some allowance for D being at a height of 1.30 m. The relationship of V or biomass to D or H alone may be curved but should be smooth and rise monotonically (without jumps or inflections). As mentioned, trees or shrubs below a height of 1.30 m present some problems best treated separately and therefore lie outside the topic of single tree equations.

The stem of a tree including the stump and top generally make up 70% or more of a tree's volume or biomass (Alemdag 1984b, Ker 1984). The stem, particularly that of trees with excurrent branching, can be regarded as a geometric solid. Using this notion, early mensurationists modelled tree volume by regarding the tree as a cylinder, cone, parabaloid, neiloid, or portions thereof called frustums (Alemdag 1978). The form of an excurrent tree can be represented quite well with the top treated as a cone, the middle section as a frustum of a parabaloid, and the stump section with some butt flare, a neiloid. The volume of the four solids can be expressed in equation form as follows:

| | | |
|---|---|---|
| Cylinder | $V=(\pi)(D/2)^2L$ | (3) |
| Paraboloid | $V=(\pi/2)(D/2)^2L$ | (4) |
| Cone | $V=(\pi/3)(D/2)^2L$ | (5) |
| Neiloid | $V=(\pi/4)(D/2)^2L$ | (6) |

where V is gross total stem volume, D is diameter at breast height outside bark, and L is length (or height) of the geometric figure.

The mensurationists proposed that a tree could be represented generally by the equation:

$$V = K\,D^2\,H \qquad (7a)$$

where K combines pi/4 and average form factor (f), and H is the total height of the tree equivalent to length. Further, the equation can be expressed in a linear equation of the form:

$$y = a(x) \tag{7b}$$

where y is exchanged for V and x for $D^2H$. Investigators could use linear regression techniques to estimate coefficient a (representing K) and find the average form factor. The technique also allowed the investigators to assess how accurately D and H could be used to estimate V. Likewise, changes in form from species to species with site, age, stand density, geographic location, and other factors could be examined. The accuracy of the model could be compared to others which, for example, might use only D.

Model 7a is intuitively attractive because it has a firm geometric basis and the equation has the property of passing through the origin when D or H approaches zero. A tree with D = 0 and H = 1.30 m actually has a measurable volume but it is insignificant in most tree measurement applications. In forest mensuration contexts the model is referred to as the stand volume equation (Husch et. al. 1982), combined variable, or constant form factor equation (Spurr 1952). Some variations of the model include a y-intercept:

$$V = a + b(D^2H) \tag{8}$$

where a is the intercept and b the slope coefficient, but the model can produce small negative volumes for small trees. However, it should be noted that where the equations are being developed for the purpose of estimating the total biomass (or volume) on an area, Model 8 may be more accurate in the end. The small negative values will be balanced against larger positive values to yield valid unbiased estimates. Still other variations of Model 7a have been used which estimate the exponents associated with D and H:

$$V = a\,D^b\,H^c \tag{9a}$$

which may be converted to a linear model using logarithmic transformation:

$$\ln(V) = \ln(a) + b\ln(D) + c\ln(H) \tag{9b}$$

where ln(V) becomes the dependent y variable in regression, ln(D) and ln(H) become two independent x variables, and ln(a), b and c are the regression coefficients. This model is sometimes referred to as the allometric equation and is frequently used in biomass estimation. The model can produce biased estimates (Baskerville 1972, Payandeh 1981) because of the log transformations, and has other drawbacks discussed later.

Honer (1967) based his volume equation on a further rearrangement of Model 7a:

$$V = D^2/(a + b\,(1/H)) \tag{10}$$

The preceding rationale and models for estimating tree volume can be extended to biomass using the stable relationship between wood volume and ovendry biomass. The relationship is based on the density of dry wood, which has been found to remain fairly constant for a given species and tree component. Much published material provides density values for different tree and shrub species and tree components. Because of the stable relationship, what applies to the modeling volume also holds reasonably well for biomass. Models 7a to 10 can be restated as:

$$OM = a\ D^2H \quad (11)$$
$$OM = a + b\ D^2H \quad (12)$$
$$OM = a\ D^b\ H^c \quad (13)$$
$$OM = D^2/(a + b(1/H)) \quad (14)$$

where OM represents whole tree or component ovendry biomass.

Other variables such as crown length, crown diameter, and crown area have been found to improve the accuracy of estimates of the crown components, but only marginally. In general, the additional time and cost is not justified by the gain in accuracy (Anon. 1982). Also, past or existing inventories generally do not include such variables, thus rendering them impractical.

Sometimes H is also not available and must be estimated from height-on-diameter equations or left out. Cunia (1979) and others have shown that the parabolic relationship between OM and D is effective:

$$OM = a + bD + cD^2 \quad (15)$$

This model performs well provided the full range of diameters is well represented in the sample used to construct the equations. If not, parabolic and other polynomial models behave erratically beyond the range of the data, especially at the bottom end. The erratic behaviour can result in negative mass with decreasing diameter such as illustrated in Figure 5. The model, however, has an important role to play for small trees, where large number of trees are involved and the measurement of H in addition to D is not feasible or efficient. The D of small trees can be rapidly measured or classified with calipers or gauges (Anon. 1982); H, on the other hand, takes more effort to measure in such cases. The y intercept is frequently retained for small trees because the biomass of a zero D tree becomes a more significant proportion of the total.

### b. *Regression assumptions*

In order for the regression technique to provide valid estimates of biomass and measures of accuracy or degree of fit, several assumptions governing the regression model should be met:

Assumption 1. The regression of y on $x_1 \ldots x_m$ is of linear form:

$$y = b_1.x_1 + b_2.x_2 + \ldots\ldots b_m.x_m$$

where $b_1$ to $b_m$ are estimates of the coefficients, y is the dependent variable and $x_1$ to $x_m$ are independent variables.

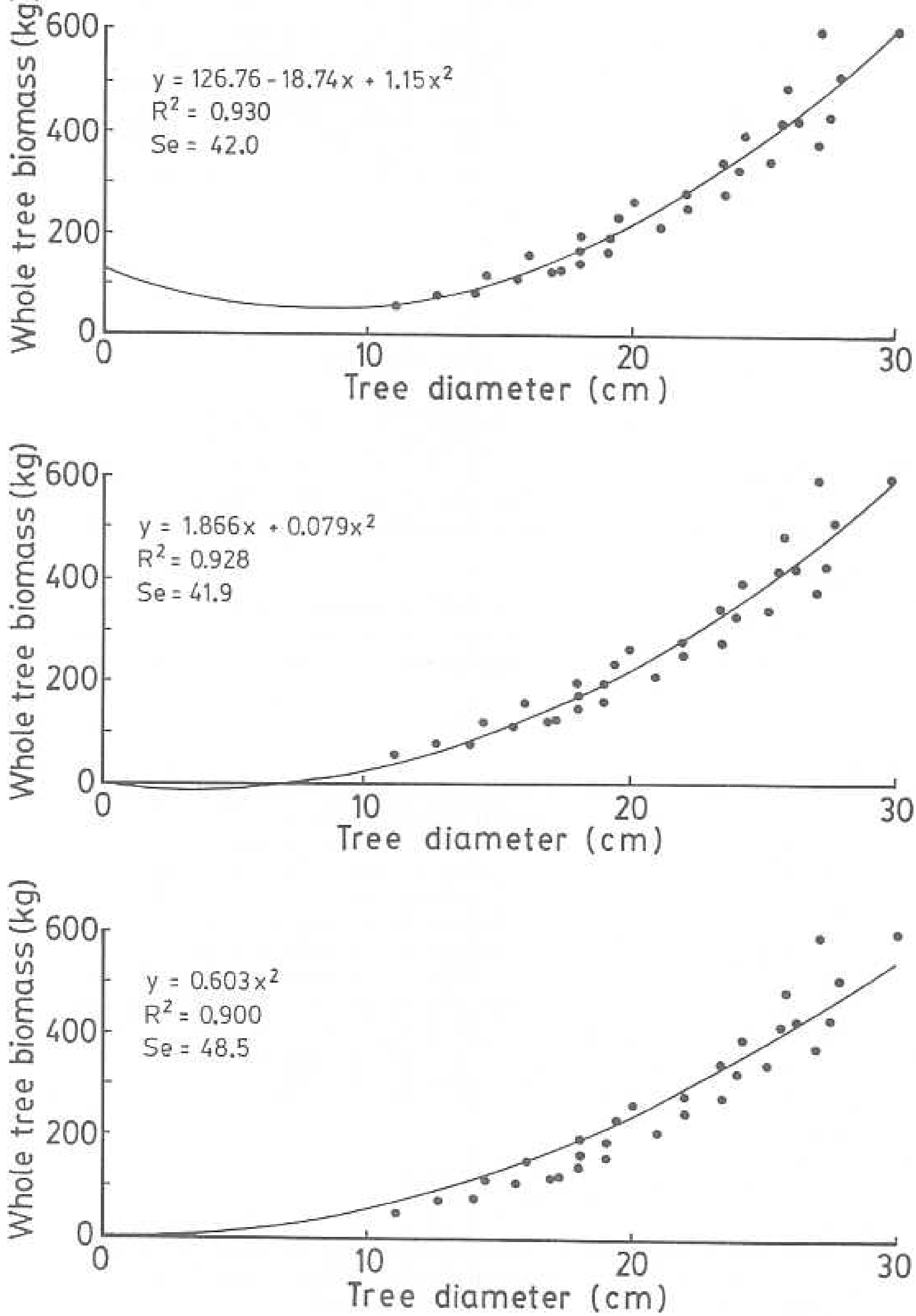


Figure 5. Three whole tree biomass models fitted to tree diameter D. The top and middle models produce unreasonable results below 10 cm D; the bottom model sacrifices some accuracy to perform better below 10 cm.

Assumption 2. The variation of y values (or residual errors around the regression function) is constant over the range of x. This is called the equal variance or homogeneity assumption.

Assumption 3. The sample values of y are uncorrelated.

Assumption 4. The independent variables $x_1 \dots x_m$ are fixed and no variable x is a linear combination of others.

Assumption 5. The probability distribution of y (or residual errors about the curve) for a given $x_1 \dots$ to $x_m$ is normal.

If inferences are to be strictly valid, there are assumptions not explicitly given which should be satisfied. For example, all variables should be measured without error. This means that the practice, for instance, of using the height-on-diameter equation to estimate height and then use the estimated height in Model 11 to estimate biomass could violate this assumption if the errors of estimate become too large.

It is generally understood that seldom if ever are the above assumptions are strictly fulfilled. The consequences of "bending" the rules are reviewed next and, where possible, some techniques for checking the degree of violation are outlined so that the user can correct the effect or judge how to proceed.

Assumption 1 states that the relationship between dependent and independent variables is linear. Nonlinear trends can lead to large biases in the coefficients and in the predictions of biomass. Considerable care should be exercised in checking for nonlinearity and restructuring the model to remove it. A plot of y on individual x's can be used to check linearity in a piecemeal fashion (Figure 6a). A plot of the residual errors about the regression on the predicted y can also be used to detect nonlinear trends left unfitted by the model (Figure 6b). In this case the performance of the model as a whole can be judged. Various transformations such as those described by Jensen (1964) can be experimented with to remove nonlinear trends.

The plot of residuals can also be used to check homogeneity (assumption 2). Ideally, the residuals should be distributed along the fitted y such that the variation of residuals is about the same across the range of the data. If the equal variance condition is not satisfied, the least squares estimates of the coefficients will still be unbiased but statements about accuracy performance will no longer be valid. Transformation sometimes can be used to correct the problem but, more commonly, weighted least squares are used. If the standard deviation of the residuals increases approximately proportional to the x variable, then the use of the weight $1/x$ should even out the residual variation. If Model 11 was used, the weight $1/D^2H$ would be appropriate. In this case, it is interesting to note that by dividing through by $D^2H$, only the coefficient a remains on the right side of the equation. As explained earlier, a consists of pi/4 and form factor f. Only f is variable, depending on average tree form, and one would expect that variation in f to be small and not strongly related to tree size. This would explain the effectiveness of this weighting scheme in improving the equality of variance condition. It is coincidental that the same weighting scheme is also effective in improv-

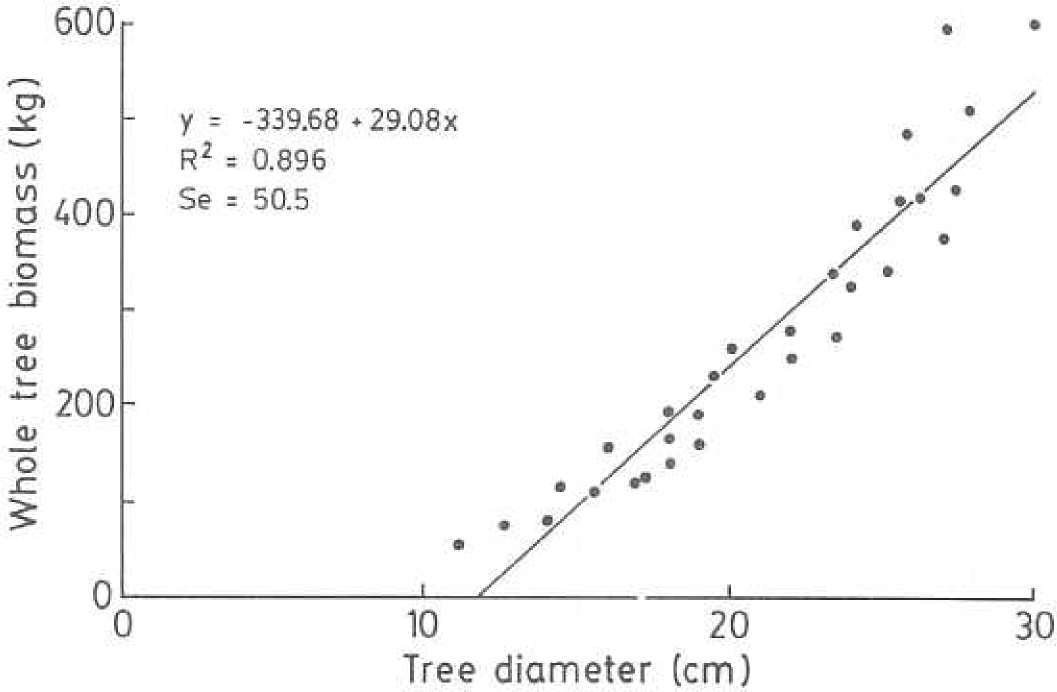


Figure 6a. A linear model fitted to nonlinear tree biomass data.

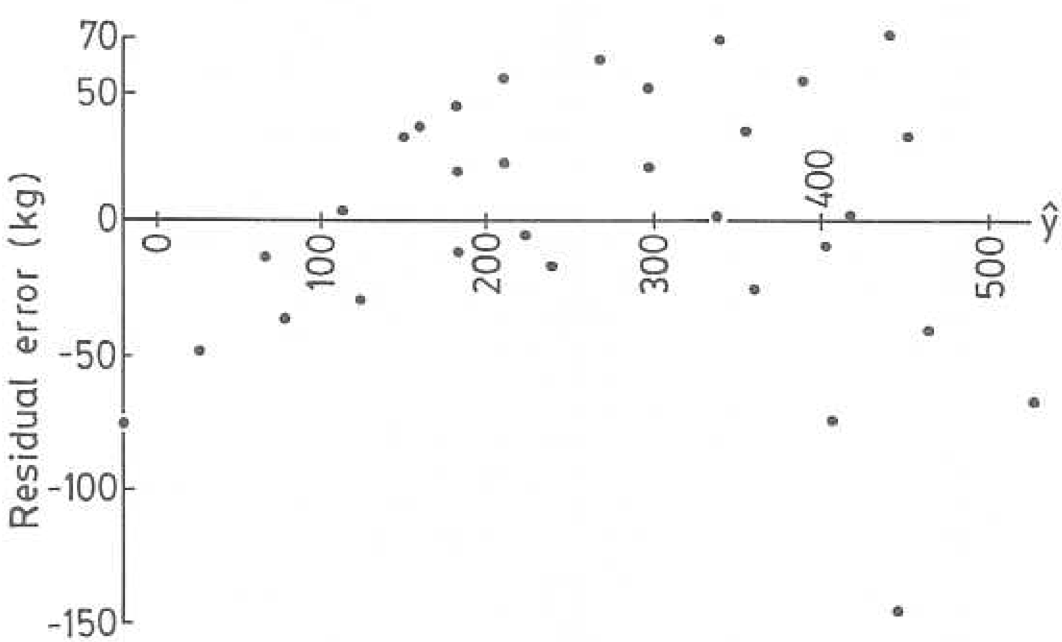


Figure 6b. A plot of the residual errors around the regression line y showing the effect of the nonlinearity.

ing the accuracy performance of biomass Model 11 for small trees. The use of weighted least squares to control the equal variance assumption is elaborated by Cunia (1986).

With regard to assumption 3, the sample values of y will be uncorrelated if individual trees are sampled according to the rules given in Chapter II. However, if plot sampling is used, even when the sampling rules are adhered to, the sample trees on a plot will almost certainly be correlated and not be independent. Large trees tend to grow in association with other large trees in a stand and vice versa. As with assumption 2, when this assumption is violated, the bias of estimates of the coefficients by least squares will be close to zero but statements of reliability of estimates may not be valid. Reducing the size of the clusters (or blocks) and increasing the number of sampling units will reduce the effect of this violation. In some cases methods can be found to modify the least square procedure but this requires the attention of a statistician specialized in sampling and least squares modeling. Cunia (1979) and Johnston (1963) shed more light on this topic.

When assumption 4 is violated, least square methods can be used but the interpretation of some of the inferences may change. When one x variable is a linear combination of another, the least squares estimation of the coefficients will not be possible. This problem, called the collinearity property, can be checked by studying the correlation or linear relationships between pairs of x variables. Where collinearity occurs, the solution is to eliminate one of the variables from the model.

Assumption 5 requires that measurements of random y variables be statistically independent and that the conditional y variable for a given x is normally distributed. This is the same as expecting the residual errors about the regression line to be independent and, at any point along the curve, normally distributed. This condition can be checked by plotting a histogram of the residual errors at an interval along the curve and confirming that the shape of the histogram follows approximately the normal distribution (Figure 7). The effect of non-normality is generally only of concern when sample sizes are small. In such cases, the effect is primarily on the reliability of the prediction interval or other measures of accuracy or goodness of fit. If the five sampling rules are followed, non-normality usually will not be of serious concern.

The main regression assumptions and consequences of violations are described in greater depth in the first two chapters of Johnston (1963).

Of the five main biomass models, only Model 13, the allometric equation, is likely to produce biased estimates. As mentioned, the effect of the biases can be corrected — and should be corrected if this model is to be used. Models 11, 12, and 15 can be expected to violate the equal variance assumption. However, the use of weighted least squares, where either $1/D^2$ or $1/D^2H$ are used as the weights, will generally correct the problem. Models 11 and 12 should be checked to ensure that no nonlinear trends are evident. A plot of residual errors around the fitted regression can be used to detect such problems (Figure 7 ). Model 15, if it reveals nonlinear trends, will tend to exhibit them near the extremes, especially the low end.

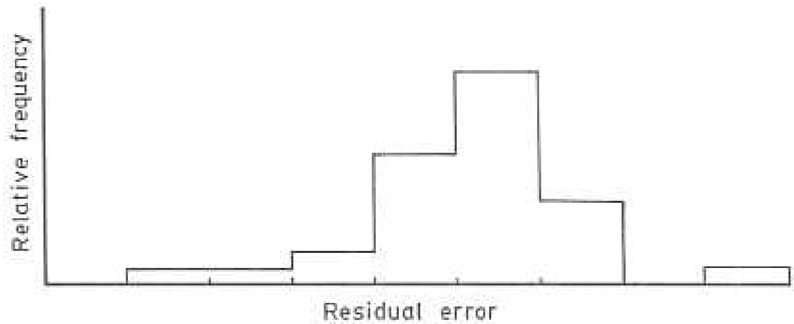


**Figure 7. Histogram showing approximately the normal distribution of residual error about the regression. The parabolic model shown at the top of Figure 5 was used.**

### c. *Accuracy*

The definitions of accuracy, bias and precision of measurements, and estimates was given and illustrated in Chapter II. Biomass equations developed from regression techniques can produce biased estimates for four principal reasons: (1) the sample data used to develop the equations were not representative of the population to which the equations are applied; (2) the linearity assumption behind the regression was violated; (3) the model itself was biased; or, (4) systematic errors occurred in the measurement process.

The first source of bias arises when the size class distribution or other properties of the population differ greatly from the population used to provide the sample data. For example, if sample data were drawn from a population with a concentration of small trees and a few large trees and applied to a population having mostly large trees, the equation could easily result in biased results at the top end, an effect which may have a drastic effect on the overall biomass estimates. This is one of the reasons why the five sampling rules given in Chapter 2 must be followed.

The effect of violation of the linearity assumptions, was treated in the previous section.

The third source of bias arises in the models themselves. Ratio estimators, for example, are usually biased. Model 13, the allometric form can be biased for the simple reason that the antilog of the average logarithmic values is not the same as the average of untransformed values. The problem can arise whenever the dependent variable y is transformed because of the role of the residual errors about the curve controlling the way the model is fitted. Baskerville (1972), Madgwick and Satoo (1975), Nielsen et al. (1979) and Anon. (1982) describe methods of removing the bias. These procedures should be followed if Model 3 is to be used.

The fourth source of bias occurs if systematic measurement errors are made in D or H. The effect of these systematic errors is to raise or lower tree or component biomass estimates which will then be reflected in the population estimates. Measurement errors can stem from improperly adjusted instruments, operator blunders, such as incorrectly judging plot borderline trees, or incorrect measurement procedures.

After the systematic errors have been accounted for or controlled, the random component of error affecting accuracy may still persist. The random errors, as explained earlier, can stem from either the measurement procedure or the equation. When measurement errors are under control, the accuracy of the equations can be judged in terms of several measures of precision or goodness of fit described next.

When the accuracy of one biomass equation is contrasted with another, three statistics are commonly used to express the expected precision of the prediction. The statistics are: the correlation coefficient (or the multiple correlation coefficient or coefficient of determination), the residual error about the regression, and the prediction interval. The correlation coefficient is useful in comparing models tested on the same data, but loses meaning when contrasting different data sets because the coefficient is sensitive to the range of data. The residual error expresses well the precision of the entire regression but does not indicate accuracy performance at particular size classes. Also, the residual error of transformed variables cannot be compared with their untransformed counterpart. The prediction interval expresses the accuracy performance at particular values of the independent variables and thus indicates accuracy performance at particular size classes but does not provide at a glance the accuracy performance of the model as a whole. The prediction interval also does not work well for transformed variables. The standard error and prediction interval are effective measures of accuracy when used together. They can be used to rate the accuracy performance of different tree models such as the five common ones given earlier. Evert (1985) described a variation on the residual error method which he called the mean square error. The measure is calculated as the mean of the squared differences between the observed and estimated biomass values. Transformed values can be converted back to the untransformed form and the mean square error calculated. The mean of the differences also can be calculated to detect the possibility of bias.

If one of the models is known to produce large errors in some part of its range, such as for instance at the extremes (especially the low end), weighting schemes can be used to improve accuracy. The effect of the weighting is to assign greater importance to a particular portion of the size class distribution that does not fit properly, thus forcing that part of the curve to fit better. A common means of assigning greater importance to small trees, in Model 11 for example, is to assign weighting proportional to the inverse of $D^2H$ and using weighted least squares regression. The effect is clearly illustrated by Evert (1983). The weighted least squares regression theory and practice are explained further by Cunia (1986).

## d. *Additivity*

The biomass estimation equations are required to estimate the biomass for tree &components defined earlier in addition to whole tree biomass. Furthermore, it is generally desirable for the tree component biomasses to add up to the same total as the independent whole tree biomass. This is referred to as the additivity property. A set of equations for the tree components and whole tree will only meet this requirement if the individual component coefficients add up to the corresponding whole tree coefficients as follows:

$$y_1 = a_1 + b_1x \quad (16a)$$
$$y_2 = a_2 + b_2x \quad (16b)$$
$$y_3 = a_3 + b_3x \quad (16c)$$
$$y_4 = a_4 + b_4x \quad (16d)$$
$$yt = \Sigma a_i + \Sigma b_ix \quad (16e)$$

where $y_1...y_4$ are component biomass estimates, $a_1...a_4$ and $b_1...b_4$ are component regression coefficients, $x = D^2H$ of a tree, and $y_t$ is the whole tree biomass.

The additivity condition only holds when the same independent variables are used in each equation, when the transformed variables are linear, and when all equations are fitted from the same observations. Nonlinear transformations, such as the logarithmic, will defeat the additivity condition. The additivity property is elaborated by Kozak (1970) and Chiyenda and Kozak (1984). Cunia and Briggs (1984, 1985) developed a formal breakdown of the problem and proposed procedures for assuring additivity even when different terms are used in the component equations. These references offer an excellent treatment of the topic but go beyond the immediate needs of most inventory applications.

Because some equations which may not possess the additivity property are particularly powerful, especially for a certain component, it is not always appropriate to insist on additivity. It should be regarded as a desirable property because of its contribution to internal consistency.

## 3. Evaluation of commonly used equations

A comprehensive list of biomass equations was compiled by Stanek and State (1978). The equations listed cover most important Canadian tree species and many shrubs. These equations were for whole tree biomass and components. The equations include more than 30 independent tree variables and many model forms. Equations developed in Canada since 1978 under ENFOR are listed in Appendix F.

Equations which were most widely used are listed in Table 2. In general, these were the simplest equations which used only D or H or both as independent variables. The use of other variables generally arose in specific studies where particular requirements or conditions were addressed. Such models usually will not perform well outside the conditions where they were developed and thus lack the required generality.

The equations in Table 2 were reviewed in relation to the desirable properties described earlier, and the worst cases eliminated. Model 1 was eliminated because the relationship between mass and D is generally known to be nonlinear. Models 5, 6, 9, and 10 should be treated with some caution because they can produce biased results if uncorrected (Baskerville 1972, Payandeh 1981) and because the additivity condition cannot be fulfilled easily. Of the remaining models, 3 and 4 (the parabolic form) have been found to yield the most reliable results when only D

**Table 2. Commonly used whole tree or tree component biomass equations**

| Model | Description |
|---|---|
| 1. $OM = a + b D$ | simple linear |
| 2. $OM = a + b D^2$ | basal area |
| 3. $OM = a + b D + c D^2$ | parabolic |
| 4. $OM = b D + c D^2$ | parabolic through origin |
| 5. $\ln(OM) = a + b \ln (D)$ | allometric D |
| 6. $\ln(OM) = a + b \ln(D^2)$ | allometric $D^2$ |
| 7. $OM = a + b D^2H$ | combined variable |
| 8. $OM = b D^2H$ | combined variable through origin |
| 9. $\ln(OM) = a + b \ln(D) + c \ln(H)$ | allometric D and H |
| 10. $\ln(OM) = a + b \ln(D^2H)$ | allometric combined variable |

is available. Provided a weighted least square is used, the equal variance and other assumptions behind regression should hold up well. If data are lacking for small trees, Models 2 or 4 should be favoured to avoid erratic results near zero D. If height data are available, slightly better accuracy can be expected from Models 7 or 8 (combined variable form). Model 8 is particularly attractive because it is well supported by the geometric rationale and the additivity condition is easily satisfied. As with the parabolic form, Model 7 may produce unreasonable values at the low end if little supporting data are available for small trees. Figure 6 illustrates what can occur at the low end and shows how Model 2, for example, can help. In summary: If only D is available use the parabolic model (Model 3), and set a to zero if estimates near zero D are required and the lower end of the range is not well represented. If existing equations are to be used, check that the biomass predictions are reasonable as D approaches zero. If D and H are available, use the combined variable model (Model 7), and set a to zero as for the parabolic form, if necessary. Where a is zero, the model provides a ready means of establishing component mass ratios. Furthermore, the model form can be incorporated in point sampling procedures for biomass estimation.

## 4. Evaluating existing equations

Prior to developing a new set of biomass equations, the following procedures may help decide whether or not a set of existing equations will suffice. The following steps should be checked:

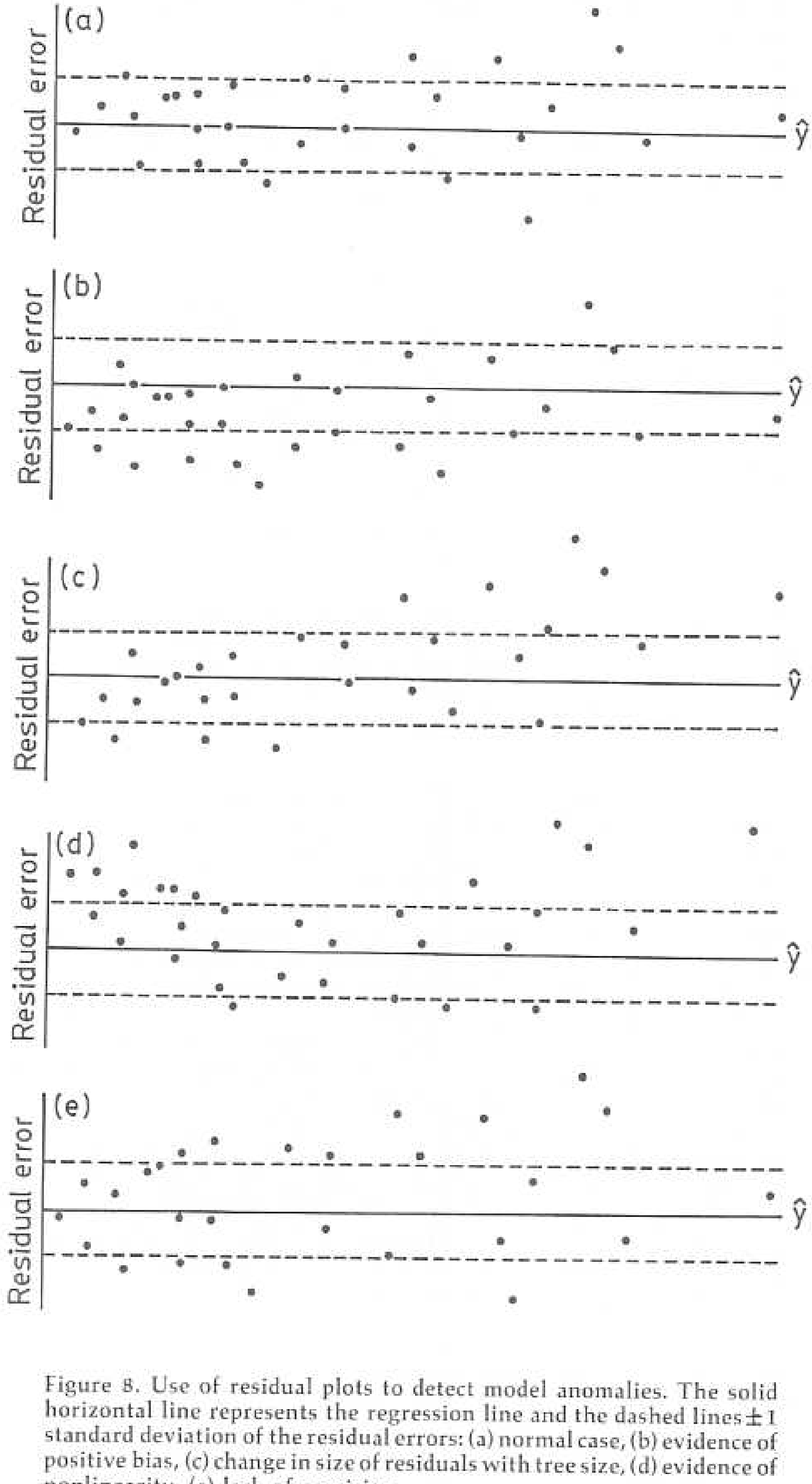


Figure 8. Use of residual plots to detect model anomalies. The solid horizontal line represents the regression line and the dashed lines ± 1 standard deviation of the residual errors: (a) normal case, (b) evidence of positive bias, (c) change in size of residuals with tree size, (d) evidence of nonlinearity, (e) lack of precision.

- Define the target population (the proposed inventory area).
- Determine the forest conditions or area to which a set of existing equations apply.
- With regard to the existing equations and new project area, compare the geographic regions and general forest types involved. Maps showing the ranges of tree species and forest classifications such as forest regions (Rowe 1972) will help. If the target area is near the margin of a species' distribution, extra care should be taken.
- Compare, as best as possible, the species composition and size class, site class, and height distribution of the forest stands involved.
- Where the match is poor or questionable, reject the equations or prepare to test them as described below.
- Check that the existing equation is one of those recommended in Table 1. If not, reject it and determine if the data used to develop the original equations are available. If so, and if the population from which the data set was sampled matches reasonably well that of the target area, develop a new set of equations using the procedures in the next section. If the match is poor, reject the existing data and prepare to sample new data and develop a new set of equations according to the procedures in the next section.
- If the suitability of existing equations still seems questionable, a small quantity of new data should be collected and compared to the existing equations. A comparison can be done effectively by listing the biomass of the test trees opposite the counterpart estimate obtained by using the equations and measured D and H of the test trees. An analysis of the differences will detect bias and trends related to the size of the tree. Five examples plotted in Figure 8 illustrated some of the possibilities. Each graph shows the differences between the biomass estimated from n equation using D and H and that measured in the field (y axis), plotted opposite tree size, expressed in terms of predicted biomass (x axis). These graphs are the counterpart of the residual plot in Figure 6b. Plot 9a is an example of a good fit, revealing little or no bias, no trend of differences with size of tree and, expressed in terms of biomass, good precision with about two thirds of the points falling within one standard deviation of the horizontal, zero error line. The residual plot in Figure 8a is based on the data and model shown in the top of Figure 5. Plot 8b illustrates evidence of a positive bias in the points, little or no trend with size, and has average precision. However, only 40% of the points fall within the one standard deviation band, leading to possible rejection. Plot 8c illustrates a distinct change in error with tree size. The equation would perform poorly in the extremes leading to probable rejection. Plot 8d, like 8a, is without much evidence of bias but shows a nonlinear, J-shaped trend with change in tree size. The equation will perform poorly near the middle of the range and would violate the linearity assumption. Plot 8e like 8a shows little evidence of bias or change in error with tree size, but it lacks precision. Only 40% of the points lie within the one standard deviation band, suggestion rejection.

The decision to accept the existing models depends upon how much error can be tolerated. The preceding procedure provides a means for detecting and rejecting badly distorted models and offers guidelines for deciding marginal cases. If the existing equations are rejected, the test data, if they are judged reliable, can be combined with new data to develop a fresh set of equations. The procedures for doing so are described in the next section.

## 5. Developing new equations

Biomass inventories may require a new set of biomass equations. Suitable &equations may not exist, or available ones may be found unsuitable, for reasons described under the previous section. The following procedure is recommended when faced with the development of new equations:

- Define the forest population to which the equations will be applied.
- If available, use existing forest cover maps or other forest stand classification to form species and size class (volume, diameter, or height classes) strata.
- According to the sampling rules and efficiency considerations described in Chapter II, assign weights to the strata to ensure that the important conditions are adequately covered. Usually the greatest difficulty arises in obtaining sufficient samples of sparsely occurring species and the upper and lower extremes of the size classes.
- Select trees or small clusters of trees (plots) according to the stratified sampling rules (Freese 1962) or, if no stratification is done, according to the simple random sampling design. Small, rather than large, clusters are suggested to minimize the correlation between closely spaced trees.
- As a basis for constructing each equation, a minimum of 30 trees per species is recommended.
- Since the stratification or use of other existing auxiliary data may not overcome the problem of adequately sampling the size class extremes, the random sample selection may be extended to fill the under-represented classes. This procedure takes some liberties with the sampling rules but, if done through a random selection process, should not seriously bias the estimates of coefficients and helps to improve the reliability of the equations in the extremes. The result should be a fairly even distribution of samples across the height and density classes.
- Once selected, the D and H of the sampled trees are measured and recorded and the biomass measurements collected according to the field and laboratory procedures given in Chapter II.
- The independent variables (D and H) and the dependent variables (whole tree and four components of tree biomass) are grouped by species and set up for regression analysis. The regression analysis should be carried out in one of a number of statistics packages used on mainframe computers, minicomputers, personal computers, or pocket calculators. Each will have its own means of entering and editing the dependent and independent variables. The software should be capable of multiple linear regression, of transforming variables (logarithms, exponentials, squares, etc.), production of residual plots such as those illustrated in Figures 7 and 9, and (preferably) residual error histograms as in Figure 8. The software should provide coefficient estimates, variance estimates of coefficients, the correlation coefficient, the coefficient of determination or R-square, the standard error of estimate of the regression, regression confidence bands, and

the prediction interval. The correlation matrix is also useful in examining the correlation between pairs of variables.

- For trees equal to or larger than 5.1 cm D, carry out regression runs by species for the whole tree biomass and each of the four components using one of the recommended models. The whole-tree biomass equation should agree with the result of adding the corresponding coefficients of the component equations. The choice of model form should depend on whether or not tree height is to be used and how well the small-tree extreme is represented. Use a model without a y-intercept if the size classes near 5.1 cm D are not well represented.
- For trees between 0.1 and 5.1 cm D, use the parabolic model with the y intercept. The y intercept is required because a tree with zero D has some positive biomass.
- Check the parabolic equations to ensure that biomass does not decline with increasing D in any part of its range. A graphical plot of mass on D is the easiest way to check this. If a decline occurs remove the linear term and rerun the regression. This is equivalent to the basal area model in Table 1 (see also bottom of Figure 5). The combined variable equation using D and H does not have to be checked in this respect.
- Check that none of the equations produces negative values in any part of its range, especially when D or H approaches zero. If negative biomass occurs, remove the constant term (y intercept) and rerun the regression.
- Check that residual errors are approximately normally distributed, by use of a histogram plot (Figure 7). The random sampling will generally assure near normality, provided the sample size is fairly large.
- Check that the equal-variance assumption is not seriously violated. Generally, the assumption will be violated if ordinary least squares regression is used with the biomass models. Weighted least squares will usually overcome the problem where weights are inversely proportional either to $D^2H$ (combined variable model) or $D^2$ (parabolic model). Cunia (1986) discusses the rationale behind weighted least squares.
- For cases where a species is so sparse in the population that size classes cannot be properly represented, the species data should be pooled with another species of similar form and size class distribution. The "pooled" equation then is used for each of two or more species in the aggregation. Similarity in form can be judged subjectively or, for particularly important species, the average form can be evaluated as described in Section 2 of this chapter and pooled on the basis of similar values.

The equations should now be ready for application to biomass inventory.

## 6. Incorporating merchantability standards

The tree equations treated so far have concentrated on the estimation of biomass of the four primary components and the whole tree. However, a common inventory problem is to estimate biomass quantities left after conventional wood products — sawlogs, poles, pilings, peeler logs, pulp wood, posts, etc. — have been extracted. In order to estimate such

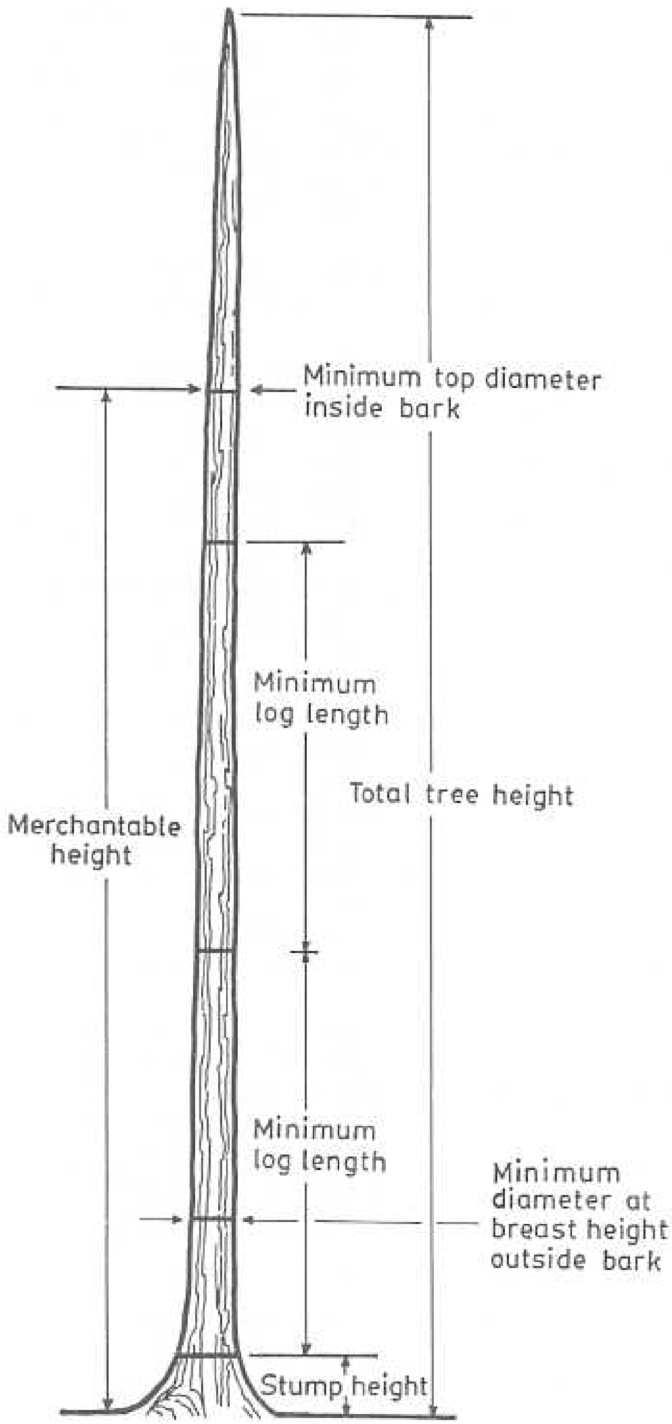


Figure 9. Diagram showing the limits which may govern the definition of the merchantable portion of a tree: minimum diameter at breast height outside bark, stump height, minimum top diameter inside bark, merchantable height and minimum log length.

biomass residuals, the biomass of the stem must be partitioned into the merchantable portion and the unmerchantable or residual portion. In order to do this, merchantability standards governing the minimum diameter and lengths of the products must be related to what can be extracted from the stem. Figure 9 illustrates the commonly used merchantability standards. The standards generally specify a stump height, which excludes the stump as a merchantable component, a minimum D, which excludes trees that are too small to yield usable products, and a minimum top diameter, which excludes the unusable top of a tree. Sometimes a minimum length of utilizable stem to a minimum height to the top diameter is prescribed (Figure 9).

The development of models to estimate merchantable components of the stem follows an approach originally described by Honer (1967) to treat merchantable tree volume, and later modified to accommodate the metric system (Honer et al. 1983) and the biomass case Alemdag (1982a). Alemdag's adaptation results in equations which estimate the proportion of stem biomass made up of the top, the stump, and the merchantable subcomponents of the stem. The proportions, expressed as percentage of ovendry mass of the stem, are used to estimate the biomass of merchantable wood, merchantable bark, top wood and bark, and stump wood and bark. Equations are used to estimate the percentages. Separate sets of equations are used for cases where minimum top diameter is a constraint or, alternatively, where height to a minimum top diameter is a constraint. Separate sets of equations are also used to estimate stump biomass where stump height is the limiting factor. Three models are recommended by Alemdag (1982a) for handling each case. The models and rationale are summarized next.

Case of merchantable top diameter: The goal is to estimate the proportions of the tree's stem when the D and minimum top diameter outside bark (Dm) are known. The model is based on the proposition that the ratio of Dm to D should equal the ratio of the volume of the top portion to the volume of the full stem. A geometric diagram and several steps described by Alemdag are used to arrive at the ratio of the biomass of the merchantable portion of the stem as a function of the ratio Dm/D. A plot of sample data revealed a well-defined curved relationship that, after testing 10 models some of which included D and H, indicated the following parabolic equation to be the most effective:

$$OM\% = a + b\,(Dm/D) + c\,(Dm/D)^2 \qquad (17)$$

where OM% is the percentage of stem biomass as merchantable wood, merchantable bark, or top wood plus bark, and a, b, and c are coefficients estimated by regression.

Case of merchantable height: A similar model was used to estimate the percentage of merchantable wood, merchantable bark, and top wood plus bark in terms of the ratio of the height between ground and the top diameter (Hm) to total tree height (H). Alemdag tested four models, some of which included D. The following parabolic model emerged as best:

$$OM\% = a + b\,(Hm/H) + c\,(Hm/H)^2 \qquad (18)$$

Case of stump height: After calculating the percentage of the merchantable portion of a stem to a given top diameter or merchantable height, a stump deduction should be applied to arrive at the net merchantable per cent. For this purpose, the average stump wood and stump bark values as a percentage of the total stem mass were calculated for each species as arithmetic means of the collected data at a 30 cm stump height. However, since stump values at different stump heights are required in practice, further analysis was done to find these percentage deductions for different stump heights of 5 cm increments. This was done by using a generalized stump diameter/breast height diameter relationship for all species (Alemdag and Honer 1977) and by considering the stump as the frustum of a neiloid (Alemdag 1978). These values are independent of the size of a tree.

## 7. Alternatives to single tree equations

The single tree equations treated up to now should be used whenever individual tree species, D, and possibly H are available. These equations can also apply to stands of average D and H in the same way that they apply to single trees. If these data are not available, two alternatives can be considered. First, if individual tree volume data are available, direct conversion to tree biomass is possible. Second, if only stand summaries or averages are available, several types of stand conversion can be made. As will be explained, stand conversions are not likely to be reliable and should be regarded as a last resort or an interim measure.

### a. *Tree volume conversions*

The conversion is based on the use of total volume or some expression of merchantable stem wood volume combined with basic wood density. Alemdag (1984a), for example, provides basic wood density values for 10 common eastern Canadian softwood species and 18 hardwood species. The conversion equations can take the following simple form:

$$OM = aV \tag{19}$$

where OM is ovendry mass, V is total stem wood volume, and a is the conversion factor equivalent to wood density. If wood density varies with size of the tree, the model can be modified to the form:

$$OM = bV^c \tag{20}$$

as was done by Singh (1984a). Examination of plots of the equations indicate that the curvature is slight and would introduce minimal error. Singh (1984b) provides conversion equations for six important prairie softwood and hardwood species.

Once the conversion has been made to ovendry mass of the stem wood, including stump and top, other tree components can be calculated using component percentages. For example, using Alemdag's (1982c) component percentages for jack pine, with a total tree volume inside bark of 0.696 $m^3$ and basic wood density of 418 $kg/m^3$, the component biomass can be calculated as shown in Table 3.

**Table 3. Biomass of components following conversion of total stem wood volume into ovendry mass**

| Components | Per cent of total stem wood | Ovendry mass (kg) |
|---|---|---|
| Stem wood | 100.0 | 290.9* |
| Stem bark | 7.9 | 23.0 |
| Live branches | 5.2 | 15.1 |
| Twigs and needles | 6.6 | 19.2 |
| Whole tree | 119.7 | 348.2 |

*290.9 kg = 0.696 $m^3$ x 418 kg/$m^3$.

If merchantable tree volume is given in place of total volume, some additional steps are involved:

- Establish merchantability standards (stump height, top diameter, or merchantable height).
- Find out the average tree size of the area under study. If it is not known, use merchantable tree volume equations such as those published by Honer et al. (1983) to approximate D to the given merchantable volume and the merchantability standards.
- Use merchantability equations such as those published by Alemdag (1982a), along with the estimated D and the merchantability standards, to find component percentages of: merchantable stem wood without the top and stump components, merchantable stem bark without the top and stump components, unmerchantable top wood plus bark, and stump wood plus bark. These will add to the stem wood plus bark.

If a jack pine had a merchantable tree volume of, for example, 0.542 $m^3$, a top diameter of 9.1 cm, and a stump height of 30 cm, the tree would, according to Honer et al. (1983), have a D of about 29 cm. Using Alemdag's (1982a) merchantability equations, component proportions and biomass can be found as shown in Table 4.

## b. *Stand volume conversions*

In the absence of tree data, occasions arise where only stand data are available. If stand volume is available, conversions can be made using basic wood density data such as those used in the preceding section, but this process has much greater potential for error. Whereas the wood density values are reasonably constant within a species, and among different size classes within a species, they are not constant between species and combinations of tree species, size classes, and components. Because stand data are usually averages drawn from sample plots or estimates made from air photo interpretation, the data are almost always an integration of many species and size classes, and involve varying stand densities. Thus, if the proportion of species or size classes in the stands used to provide the conversion factors differ from the proportions in the

Table 4. **Biomass of components following the conversion of merchantable stem wood volume into ovendry mass**

| Components | Per cent of total stem wood and bark | Ovendry mass (kg) |
|---|---|---|
| Merchantable stem wood exc. stump wood | 86.2 | 226.6* |
| Merchantable stem bark excl. stump bark | 6.0 | 15.8 |
| Unmerchantable top wood | 2.6 | 6.8 |
| Unmerchantable top bark | 0.2 | 0.5 |
| Stump wood | 4.2 | 11.0 |
| Stump bark | 0.8 | 2.1 |
| Total stem wood and bark | 100.0 | 262.8 |
| Live branches (5.2% of total stem wood) | 4.8 | 12.6 |
| Twigs and needles (6.6% of total stem wood) | 6.1 | 16.0 |
| Whole tree | 110.9 | 291.4 |

*0.542 $m^3$ x 418 $kg/m^3$.

stands to which the factors are to be applied, a considerable risk of bias arises. Consequently, direct stand conversion should be used with caution and regarded as a stopgap measure.

If other stand data are available that include species and size class distributions, such as those found in stand tables, then measures can be taken to reduce the risk of bias. Alemdag (1982b), for example, describes five techniques which make use of other available stand data such as species composition, diameter distribution, and proportions of the stand left out of stand volume estimates because of lower D and merchantability limits. The approach is to account for some of the variation by producing biomass estimates, weighted in proportion to the number of trees present by species or by diameter class, or to use ratios to account for missing stand components. However, if the proportion of trees in a stand by species and diameter class are known, more accurate methods which use stand tables can be used. For example, an effective approach referred to as the "mean tree technique" is described by Baskerville (1972); the application of this technique is demonstrated by Hitchcock (1979). The technique is applied as follows:

- Obtain a stand table giving frequencies of trees per unit area by species or species groups and by diameter class, representative of the stand in question. Most volumetric forest inventories produce such tables as a standard product of the compilation process.
- Obtain a set of whole tree and component equations for the species involved.
- For each diameter class and species, use the equations to determine the tree and component biomass quantities.
- Multiply these quantities by the frequency of trees in each diameter class/species cell.
- Sum the biomass quantities by diameter class and species category and add these subtotals to arrive at the total stand biomass by the whole tree and by component.

These steps are illustrated in Table 5.

**Table 5. Stand/whole tree biomass table of a spruce/aspen forest type**

| | Species present in stand | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Spruce | | | Pine | | | Aspen | | | |
| Diameter class (cm) | Stems per ha | Whole tree biomass (kg) | Total biomass (tonnes) | Stems per ha | Whole tree biomass (kg) | Total biomass (tonnes) | Stems per ha | Whole tree biomass (kg) | Total biomass (tonnes) | Total stand biomass (tonnes) |
| 5 | 5 | 4.6 | 0.02 | | | | | | | 0.02 |
| 10 | 60 | 23.1 | 1.39 | | | | 3 | 25.8 | 0.08 | 1.47 |
| 15 | 170 | 59.4 | 10.10 | | | | 6 | 68.0 | 0.41 | 10.51 |
| 20 | 65 | 116.1 | 7.55 | | | | 51 | 135.4 | 6.91 | 14.46 |
| 25 | 8 | 195.2 | 1.56 | 3 | 201.3 | 0.60 | 163 | 230.8 | 37.62 | 39.78 |
| 30 | | | | 8 | 296.7 | 2.37 | 280 | 356.9 | 99.93 | 102.30 |
| 35 | | | | 1 | 411.9 | .41 | 113 | 516.0 | 58.31 | 58.72 |
| 40 | | | | | | | 7 | 710.1 | 4.97 | 4.97 |
| Total (tonnes) | | | 20.62 | | | 3.38 | | | 208.23 | 232.23 |

*Whole tree equations used (Ker 1984):
Spruce $OM = 0.1077D^{2.3308}$
Pine $OM = 0.2131D^{2.1283}$
Aspen $OM = 0.1049D^{2.3910}$

Biased results can still occur with the stand table approach if the diameter classes are too broad because of wood density varying with tree size (see for example, Figure 13 in Ker 1973) and, of course, if the component equations do not represent well the stands being treated. Another drawback of the stand table approach is that valid accuracy estimates are difficult to derive. Similar "retrofit" approaches are discussed by Art and Marks (1971).

## 8. Auxiliary tables

Tree biomass equations are best suited to data processing and hand calculator applications. However, in situations where calculators or computers are not at hand, tables and occasionally graphs are a convenient substitute, especially in the field. Various forms of volume tables have had a long and useful tradition in this role. Accordingly, tables showing various tree and tree component biomass relationships and predictions may be required. Such tables are sometimes referred to as auxiliary tables because they are extensions of developed equations and conversions. Four types of tables are described: local and standard biomass tables, tree component proportions, ovendry mass/green mass ratios, and average basic wood density ratios.

### a. *Local and standard biomass tables*

Just as a local volume table provides a list of tree volumes for a range of diameter classes, a local biomass table presents whole tree or component biomass by diameter class. Likewise, a standard biomass table presents tree biomass quantities for a range of diameter and height classes. Table 6 illustrates a simple standard biomass table. Normally, such a table would have more diameter and height classes with smaller intervals which facilitate interpolation. Generally, the effective range of table entries is indicated by some means, in this case the dashed lines.

**Table 6. A standard biomass table based on Alemdag's (1983) jack pine whole tree equation**

| Diameter class (cm) | Whole tree ovendry mass (kg) | | | | | |
|---|---|---|---|---|---|---|
| | Height class (m) | | | | | |
| | 5 | 10 | 15 | 20 | 25 | 30 |
| 5 | 1.98 | 3.97 | 5.9 | 7.9 | | |
| 10 | 7.93 | 15.87 | 23.8 | 31.7 | 39.7 | |
| 15 | 17.85 | 35.70 | 53.5 | 71.4 | 89.2 | 107.1 |
| 20 | 31.73 | 63.5 | 95.2 | 126.9 | 158.7 | 190.4 |
| 25 | | 49.2 | 148.7 | 198.3 | 247.9 | 297.5 |
| 30 | | | 214.2 | 285.6 | 357.0 | 428.4 |
| 35 | | | | 388.7 | 485.9 | 583.0 |

Equation used: $OM = 0.015865\ D^2H$

### b. *Tree component proportion tables*

Component proportions by species are frequently reported in the tree biomass literature. The proportions are usually presented as a percentage of ovendry stem wood mass. Table 3 in Alemdag (1984b) is a typical example.

## c. *Ovendry mass/green mass ratios*

The relationship between ovendry mass and green mass of the main tree components by tree species is of common general interest. The ratios are useful to convert green mass, which has been measured by some means, to ovendry mass. An example is the conversion of the net mass of a truck-load of logs to ovendry mass. Table 4 in Alemdag (1984b) is a good example of a table of ratios. In this case, the ovendry mass/green mass ratios of the four main components and whole tree for 19 eastern Canadian hardwood species are presented together and can be compared.

## d. *Basic wood density*

The density of wood in trees and of tree components is also of general interest. As stem volume is commonly available, it is frequently desirable to be able to convert volume to ovendry mass. The density ratios allow this. Table 5 in Alemdag (1984b) lists the basic wood density for 19 eastern Canadian hardwood species and compares them with densities obtained by another author. A range of density from about 350 $kg/m^3$ to over 650 $kg/m^3$ is evident among the species reported.

# IV. APPLICATION OF BIOMASS EQUATIONS TO FOREST BIOMASS INVENTORY

The purpose of biomass equations, whether in the form of single tree equations or of conversion factors and ratios, is to estimate the forest biomass reserves on a property by several levels of subdivision. The subdivisions are often administrative units, sampling strata, species, age and size classes, and tree components. Four methods of applying the biomass equations to forest inventory can be identified which depend primarily upon current inventory practice and the availability of data. This chapter treats these four cases in relation to the current general forest inventory practice in Canada.

The four cases can be summarized as follows:

First, if a volumetric inventory has been completed recently and the basic sample plot and tree data are intact, single tree biomass equations can usually be introduced afterwards and reliable biomass estimates compiled. The primary focus is on volume, with a tree biomass extension or "retrofit". This is likely to be the most common case. Second, if no inventory exists, a new one must be designed that will incorporate biomass estimation elements including, in most cases, the development and use of single tree equations. Examples are special biomass surveys of noncommercial forests or areas otherwise outside the inventoried zone. The primary focus is on biomass in this case, rather than volume, but volume estimation will usually be completed in conjunction with biomass. Third, if the identity of the basic tree data is lost, conversion factors and component ratios can be applied to intermediate or final volume results. This is most likely to arise with older inventories where data are incomplete, discarded, misplaced, or outdated. Fourth, if portions of the population are left out of the conventional inventory, such as noncommercial species or small size classes, adjustments may be needed to account for the missing portions. The filling in may include the use of existing data from closely related forest stand conditions or the collection of new supplementary data. Procedures for treating the four cases are described in this chapter. Dead trees, logging residues, and material below a height of 30 cm are not addressed.

The estimation of forest biomass reserves, regardless of approach, will almost always be intimately tied to an established volumetric forest inventory procedure. Many of the procedures are common to both volume and biomass estimation and, where the procedures diverge, the biomass procedure usually parallels the volumetric counterpart. The classification and mapping of forest cover types and the development of sampling strata, for example, are common to both; the development of single tree volume and biomass equations are not strictly common but are analogous. A few of the procedures may be unrelated. For example, the estimation of tree component biomass is exclusively a biomass estimation task and the use of conversion factors can be considered an extension. Regardless of the variations possible, the current inventory practices are very well established and can be expected to constrain and shape the course of most new inventory developments, including biomass estimation. Accordingly, because established procedures are so central to biomass measurement, the common procedures used in Canada, such as described recently by Smith (1975, 1976) and Bonnor (1982a, 198b) are summarized next. They provide a framework for treating the four main approaches to biomass estimation. Bonnor (1987) provides an overview of forest biomass inventory and describes how the forest biomass inventory of Canada was completed.

## 1. Summary of current volumetric forest inventory practice in Canada

### a. *Objectives*

The first step in a forest inventory is to clearly define the purpose. This begins with a decision on the type of inventory, whether general reconnaissance, regional, management, or operational. The objective should include a description of the boundaries of the property or area involved, inner exclusions, definition of the forest stand classification system, mapping specifications, levels of subdivision, strata, sampling specifications, the quantities to be estimated, the required tables of statistics, and other results. The objective should specify the accuracy requirements of key quantities, the inventory budget, a schedule for completion of the first baseline, and the required period between update cycles. The objectives ought to be defined in close relation to forest management planning, policy development, and day-to-day decision making which inventories primarily serve.

### b. *Base maps*

Forest inventories in Canada have traditionally attached great importance to maps that show the property boundary, water courses, roads, geographic features, settlements, land use, administrative units, etc. which provide a setting for forest stand data. Most management decisions are made with forest maps at hand. Considerable effort is expended in keeping such maps up-to-date. Computer-based Geographic Information Systems are assuming an important role in the production of forest maps, in updating and in the analysis and planning of forest management strategies. All such maps begin with a base map, a record of features which are generally permanent and provide background for forest resource management.

### c. *Photo interpretation*

Photo interpretation is an efficient means of delineating and describing forest units. This is usually in the form of codes. The photo scale can range from 1:10 000 to 1:50 000, but is most frequently in the vicinity of 1:15 000 to 1:20 000. The classification system determines the delineated features and the coding of the resulting lines and polygons. The forest units generally include species composition, stand height, crown cover density and, sometimes, age or maturity classes, site index, and expressions of stocking. The classification system leads to a stratification which is used later for increasing the efficiency of forest sampling and for compiling statistics and tables.

### d. *Forest sampling*

The forest stand classification and stratification system developed above is often used to establish a framework for selecting samples. The samples may be fixed-area plots of various shapes and sizes, either singly or arranged in clusters or point samples (variable radius or prism samples). The sample locations are usually selected subjectively, with consideration given to features such as accessibility and the avoidance of stand conditions considered "unrepresentative". The assignment of stratum weights may be used to intensify or limit sampling effort by stratum. Species, tree diameter, height, age, and current growth are the primary tree data recorded. In addition, supplementary stand information, topography, soil, regeneration, ground cover, stand conditions, and indications of damage, decay, and defect are frequently recorded. The data collected during the field sampling are usually used to confirm and, where necessary, refine photo interpretation.

### e. *Cartographic completion*

When photo interpretation is completed, stand delineations and coded descriptions are transferred to base maps using projection equipment or digitizers. Following transfer to map manuscripts, the data are drafted, digitized, or scanned and possibly processed through a Geographic Information System and the final map plotted. A portion of a typical forest cover type map is shown in Figure 10. The area of the stand polygons is determined and linked to the polygon description (stand attribute data) for later listing and compilation. The stand list in Table 7 illustrates a typical coded forest cover type attribute file.

### f. *Equation development*

A subsample of a few plots or special studies may be conducted to collect

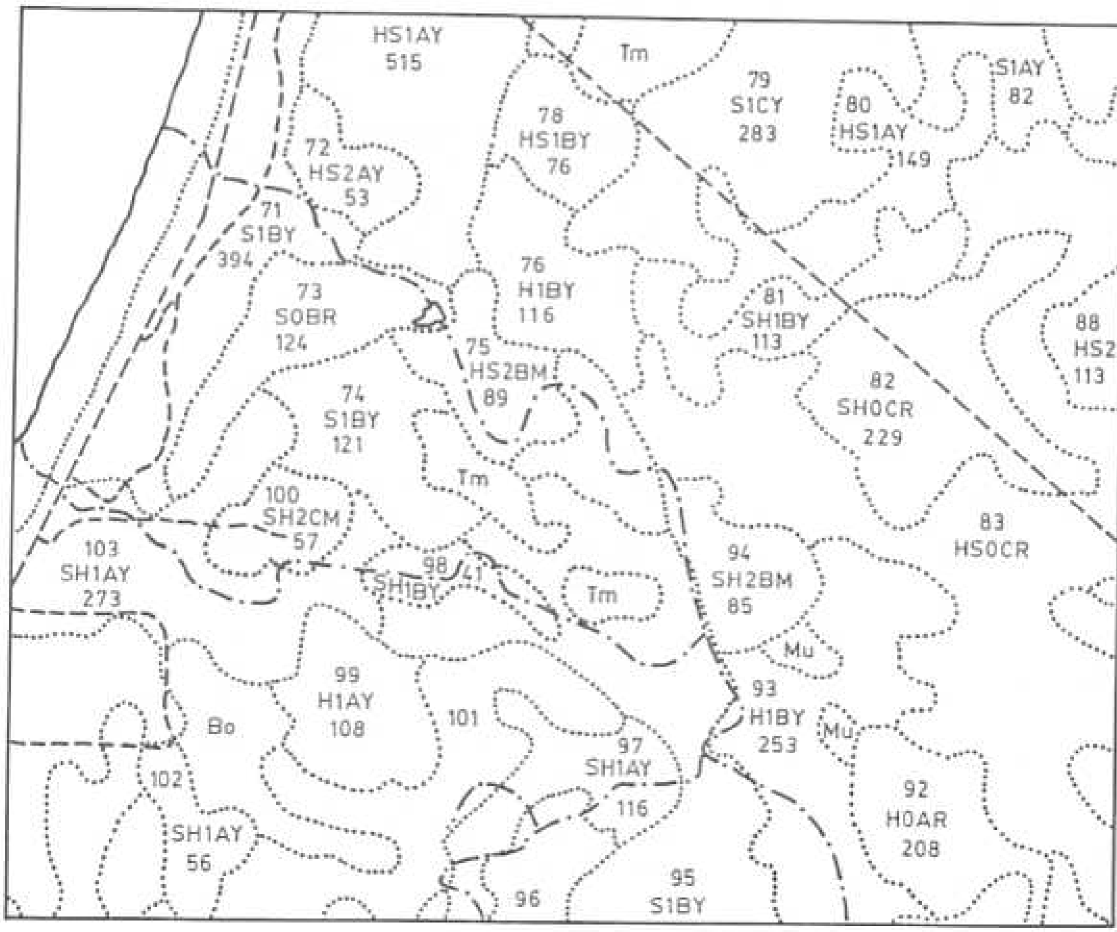


Figure 10. Example of a portion of a forest cover type map.

**Table 7. Partial list of stand attribute data in Figure 10**

| Stand No. | Cover type | Height class | Density class | Maturity class | Area (ha) |
|---|---|---|---|---|---|
| 17 | S | 1 | B | Y | 394 |
| 72 | HS | 2 | A | Y | 53 |
| 73 | S | 0 | B | R | 124 |
| 74 | S | 1 | B | Y | 121 |
| 75 | HS | 2 | B | M | 89 |
| 76 | H | 1 | B | Y | 116 |
| 77 | HS | 1 | a | Y | 515 |
| 78 | HS | 1 | B | Y | 76 |
| 79 | S | 1 | C | Y | 283 |
| 80 | HS | 1 | A | Y | 149 |
| 81 | SH | 1 | B | Y | 113 |
| 82 | SH | 0 | C | R | 229 |
| 83 | HS | 0 | C | R | 135 |
| 92 | H | 0 | A | R | 208 |
| 93 | H | 1 | B | Y | 253 |
| 94 | SH | 2 | B | M | 85 |
| 97 | SH | 1 | A | Y | 116 |
| 98 | SH | 1 | B | Y | 41 |
| 99 | H | 1 | A | Y | 108 |
| 100 | SH | 2 | C | M | 57 |
| 102 | SH | 1 | A | Y | 273 |

| Cover type | Height class (m) | Density class (%) | Maturity class |
|---|---|---|---|
| S Spruce/hardwood | 0 0 — 5 | A 0 — 30 | Y Regeneration |
| SP Spruce/pine | 1 6 — 10 | B 31 — 60 | |
| SH Spruce/hardwood | 2 11 — 15 | C 61 — 90 | |
| P Pine | 3 16 — 20 | D 91 — 100 | I Immature |
| PS Pine/spruce | 4 21 — 25 | | |
| PH Pine/hardwood | 5 26 — 30 | | M Mature |
| H Hardwood | 6 31 + | | |
| HS Hardwood/spruce | | | |
| HP Hardwood/pine | | | |

detailed tree stem profile data for developing tree volume equations or tables. Likewise, detailed measurement of trees may be carried out for growth analysis purposes. The selection procedures are generally subjective but are designed to cover the range of species and size classes as evenly as possible. The development of equations generally follows the rationale, models, and procedures described in Chapter III.

### g. *Compilation*

The final step is the compilation of the inventory results in the form of statistics and tables. The statistics include estimates of key quantities such as the mean gross total volume, merchantable volume, and net volume per hectare for the area and by strata or other subdivisions. Basal area, growth statistics, and age data may be included. Associated with the key quantities are usually statements of accuracy or reliability. The tabular reports include lists of stand attribute data with associated areas and total volumes, and stand, stock, and basal area tables which provide a breakdown by species and by diameter class.

The compilations are carried out by sorting the sample plot data according to strata or other stand attribute information. The selected sampled trees are processed tree by tree through the tree volume equations referred to earlier. The gross total tree volumes are further modified by selected merchantability standards and cull, decay, and possibly breakage factors. These constraints are closely related to the commercial wood products expected from the timber. The stem count, basal area, and various expressions of gross total, merchantable, and net volume are summed by plot to arrive at per hectare quantities which are further combined with other plots in the same stratum to produce estimates of mean per hectare quantities referred to earlier. These estimates are combined with stratum area totals to provide the overall volume summaries and the associated reliability estimates.

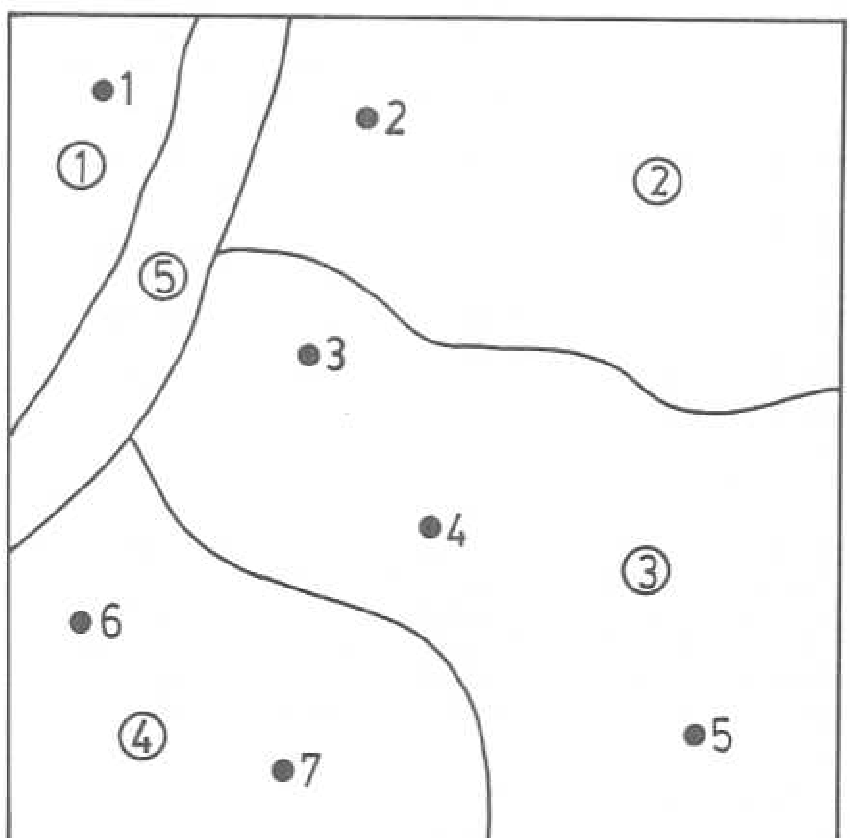


Figure 11. Forest map.

A simple example is used to illustrate the inventory compilation procedure. The example shows the input data (map data, plots, and associated trees from the field survey and volume equations), the development of strata, the compilation and the production of the inventory results. The example is unrealistically simple, involving four stands, two strata, seven sample plots, and 20 associated trees.

**Table 8. Forest stand attribute file**

| Basic data | | | Derived |
|---|---|---|---|
| Polygon No. | Cover type | Area (ha) | stratum |
| 1 | Pine | 128.1 | I |
| 2 | Aspen | 212.7 | II |
| 3 | Spruce | 381.3 | I |
| 4 | Aspen | 189.5 | II |
| 5 | Non-forest | 86.1 | |

The forest stand (or type) polygons are shown in the sketch of a forest map (Figure 11). The forest stand attribute file (Table 8) contains the basic data (polygon number, cover type, and polygon area in this case) and the stratum, which is derived from the cover type. Two strata are developed using the following rules: If the cover type is pine or spruce, assign stratum I; if the cover type is any other species, assign stratum II. The resulting stratum code is added to the attribute list as shown. The sample plots can be assigned attributes according to the polygon (stand) in which they fall (Table 9). The sample plots have trees associated with them, as shown in the tree data file (Table 10).

The following tree volume equation form was used to estimate gross total stem volume (Vt) developed by Honer et al. (1983):

$$Vt = 0.0043891\ D^2(1-0.04365a)^2/(b+(0.3048c/H)) \qquad (21)$$

**Table 9. Plot attribute file**

| Basic data | | | Derived data | |
|---|---|---|---|---|
| Plot No. | Cover type | Stratum | Total plot volume* ($m^3$) | Volume ($m^3$/ha) |
| 1 | Pine | I | 1.261 | 126.1 |
| 2 | Aspen | II | 1.307 | 130.7 |
| 3 | Spruce | I | 1.304 | 130.4 |
| 4 | Spruce | I | 1.298 | 129.8 |
| 5 | Spruce | I | 0.750 | 75.0 |
| 6 | Aspen | II | 0.058 | 5.8 |
| 7 | Aspen | II | 0.728 | 72.8 |

* Plot area assumed to be 100.0 $m^2$.

**Table 10. Tree data file**

| Plot No. | Tree No. | Species | D (cm) | H (m) | Gross volume* ($m^3$) | Merchantable volume* ($m^3$) |
|---|---|---|---|---|---|---|
| 1 | 1 | P | 21.4 | 18.6 | 0.300 | 0.256 |
| 1 | 2 | P | 27.2 | 23.1 | 0.583 | 0.493 |
| 1 | 3 | S | 24.0 | 20.3 | 0.378 | 0.331 |
| 2 | 1 | A | 26.3 | 24.7 | 0.591 | 0.503 |
| 2 | 2 | S | 12.1 | 10.2 | 0.054 | 0.021 |
| 2 | 3 | A | 28.5 | 23.6 | 0.662 | 0.581 |
| 3 | 1 | S | 23.6 | 19.7 | 0.357 | 0.278 |
| 3 | 2 | S | 24.2 | 18.1 | 0.366 | 0.281 |
| 3 | 3 | A | 22.1 | 21.6 | 0.362 | 0.280 |
| 3 | 4 | S | 19.4 | 17.4 | 0.219 | 0.182 |
| 4 | 1 | S | 32.1 | 24.6 | 0.784 | 0.710 |
| 4 | 2 | S | 26.8 | 22.7 | 0.514 | 0.462 |
| 5 | 1 | S | 16.1 | 14.1 | 0.127 | 0.081 |
| 5 | 2 | S | 19.8 | 16.0 | 0.213 | 0.187 |
| 5 | 3 | S | 21.1 | 16.1 | 0.243 | 0.212 |
| 5 | 4 | A | 18.0 | 15.2 | 0.167 | 0.121 |
| 6 | 1 | A | 13.3 | 9.8 | 0.058 | 0.022 |
| 7 | 1 | A | 22.1 | 17.6 | 0.292 | 0.271 |
| 7 | 2 | A | 21.2 | 18.0 | 0.275 | 0.234 |
| 7 | 3 | S | 8.9 | 7.3 | 0.022 | 0.000 |
| 7 | 4 | A | 17.1 | 14.1 | 0.139 | 0.083 |

* Derived from tree volume equations.

**Table 11. Coefficients of the total stem volume formula**

| Species | a | b | c |
|---|---|---|---|
| Pine | 0.151 | 0.897 | 348.530 |
| Spruce | 0.176 | 1.440 | 342.175 |
| Aspen | 0.127 | -0.312 | 436.683 |

The coefficients used with this formula are given in Table 11. Another set of equations can be used to impose merchantability constraints. Still another set of equations or factors may be used to introduce reductions for decay and defect in order to yield net total or merchantable volume. These equations are not illustrated here.

Finally, the stratum file is created, as illustrated by Table 12 using the individual plot volumes. The mean volume per hectare is calculated by stratum using the rules of stratified random sampling design. The design also will enable the accuracy of estimate to be determined. These calculations are added to the stratum file as derived values. The total volumes of the strata are calculated from the stratum areas and per hectare estimates. The stratum totals can be added to provide the total vol-

Table 12. Stratum file

| Stratum | Description | Area (ha) | Mean volume per hectare ($m^3$) | Number of plots | Accuracy* (%) | Total volume |
|---|---|---|---|---|---|---|
| I | Spruce/pine | 509.4 | 115.4 | 4 | ±23 | 58 784.5 |
| II | Aspen | 402.2 | 69.8 | 3 | ±89 | 28 073.6 |
| Total | | 911.6 | | 7 | | 86 858.1 |

* Standard error of estimate expressed as per cent of mean.

Table 13. Stand table for Stratum I

| Diameter | | | Stems per hectare | |
|---|---|---|---|---|
| class (cm) | Spruce | Pine | Aspen | All species |
| 15 | 25 | 25 | 50 | 25 |
| 20 | 75 | 25 | 50 | 150 |
| 25 | 100 | 25 | | 125 |
| 30+ | 25 | | | 25 |
| Total | 225 | 50 | 50 | 325 |

Table 14. Stock table for Stratum I

| Diameter | | | Gross total volume per hectare ($m^3$) | |
|---|---|---|---|---|
| class (cm) | Spruce | Pine | Aspen | All species |
| 15 | 3.2 | | | 3.2 |
| 20 | 16.9 | 7.5 | 13.2 | 37.6 |
| 25 | 40.4 | 14.6 | | 55.0 |
| 30+ | 19.6 | | | 19.6 |
| Total | 80.1 | 22.1 | 13.2 | 115.4 |

ume of wood on the property. The same procedure can be used to estimate merchantable and net volumes had these been included, or other quantities such as biomass (described and illustrated in the next section).

During the calculation of mean volume per hectare by strata, the compilation procedure also sorts stem counts, basal area, and the expressions of volume per hectare by species and diameter class. The results are the stand, stock, and basal area tables useful to forest management planning and decision-making. The stand and stock tables for this example are illustrated by Tables 13 and 14.

Note that the total volume per hectare for all species is the same value as in the stratum file opposite Stratum I (Table 12). The same example is used in the next few sections to illustrate the integration of biomass estimation in forest inventory.

## 2. Adaptation of single tree biomass equations to existing volumetric inventories

In the majority of cases where a biomass inventory is required, a volumetric inventory will already exist which may provide the basic data needed to compile biomass estimates. Several questions arise, however, and these should be checked. Are the basic plot and tree data complete and set up so that they can be recompiled? Are existing data sufficiently up-to-date to be useful? Will the biomass estimates be accurate enough? Is the population requiring biomass estimates properly represented and adequately sampled? Have conditions of particular importance to the biomass field been missed (e.g. noncommercial species or small material)? If not, are such conditions adequately represented in the sample? These questions should be checked using guidelines already set forth in this manual.

If volumetric inventory data can be converted after considering these questions, the following steps should be followed:

- decide whether or not the photo interpretation classes and stand descriptions suit biomass requirements. If not, the interpretation, coding, and mapping should be added to or revised. A stratification system of particular relevance to biomass may be developed and added to the forest stand attribute file for later use at the compilation stage.
- determine if a set of single tree biomass equations are available which suits the property or area in question. Use procedures in Chapter III, Section 4 to decide.
- if not, develop a new set of single tree equations using procedures in Chapter III, Section 5.
- examine compilation procedures to find where the volume equations are used to estimate tree volume based on diameter or both diameter and height. Along with the volume equations introduce whole tree and component biomass equations.
- set up procedures to accumulate biomass quantities, the equations to

calculate per hectare estimates, and the means of producing biomass estimates and tables. The biomass estimate will use estimators which are the counterpart of volume models. Likewise, the biomass tables for the whole tree and the components will parallel the volumetric counterpart.

The example in the previous section is also used to illustrate this adaptation, as follows:

First, the forest stand map and the basic data describing the forest stands will be as before (Figure 11 and Table 8). However, the derived data portion, the establishment of strata, may be altered to reflect specific biomass requirements. Suppose, from a biomass aspect, that the spruce cover type is important, perhaps because the stands are degraded or stagnant and are of interest only as a source of biomass. Spruce, then, will be treated as a separate stratum and the aspen and pine merged into one stratum. Thus, polygons 1, 2, and 4 will become stratum I, and polygon 3, stratum II.

Alternatively, three strata could have been set up, one for each of the dominant species, or other attribute data added which could be used as criteria for establishing the strata.

The basic tree data remain as before but additional columns appear to accommodate the tree component biomass estimates. Single tree biomass equations are used to provide the estimates. These could be a set of existing equations or, alternatively, a new equation. A new set of equations would have been developed using the procedures in Chapters II and III if the available equations were considered unsuitable. Here, equations from Alemdag (1981, 1983) were used in the example based on the model of

$$OM = b\ D^2H \tag{22}$$

where OM is the component or whole tree biomass. The coefficient b, specific to species and biomass component, is given in Table 15.

Equations based on these coefficients are used to produce the biomass entries opposite each tree which were listed in Table 10 as basic data, and thus Table 16 is produced. The plot's basic data remain

**Table 15. Species/component biomass equation coefficent b**

| Component | White spruce | Jack pine | Trembling aspen |
|---|---|---|---|
| OM1: Stem wood | 0.014027 | 0.015865 | 0.014755 |
| OM2: Stem bark | 0.001438 | 0.001260 | 0.003880 |
| OM3: Live branches | 0.001097 | 0.000827 | 0.003318 |
| OM4: Twigs and foliage | 0.001657 | 0.001042 | 0.000507 |
| OM5: Whole tree | 0.018219 | 0.018994 | 0.022460 |

unchanged from before (Table 9), except that the stratum column will change and additional columns will be used for the biomass quantities (Table 17). The number of biomass columns could be enlarged to include merchantable and unmerchantable components.

The tree biomass quantities are summed by plot as volume was before, converted to per hectare values, and then sorted by species and

**Table 16. Tree data file**

| Plot No. | Tree No. | Derived data: OM* (kg) | OM2 (kg) | OM3 (kg) | OM4 (kg) | OM5 (kg) |
|---|---|---|---|---|---|---|
| 1 | 1 | 135.1 | 10.7 | 7.0 | 8.9 | 161.8 |
| 1 | 2 | 271.1 | 21.5 | 14.1 | 17.8 | 324.6 |
| 1 | 3 | 164.0 | 16.8 | 12.8 | 19.4 | 213.0 |
| 2 | 1 | 252.1 | 66.3 | 56.7 | 8.7 | 383.7 |
| 2 | 2 | 20.9 | 2.1 | 1.6 | 2.5 | 27.2 |
| 2 | 3 | 282.8 | 74.4 | 63.6 | 9.7 | 430.5 |
| 3 | 1 | 153.9 | 15.8 | 12.0 | 18.2 | 199.9 |
| 3 | 2 | 154.9 | 15.9 | 12.1 | 18.3 | 201.2 |
| 3 | 3 | 155.7 | 40.9 | 35.0 | 5.3 | 236.9 |
| 3 | 4 | 91.9 | 9.4 | 7.2 | 10.9 | 119.3 |
| 4 | 1 | 355.6 | 36.5 | 27.8 | 42.0 | 461.8 |
| 4 | 2 | 228.7 | 23.4 | 17.9 | 27.0 | 297.0 |
| 5 | 1 | 51.3 | 5.3 | 4.0 | 6.1 | 66.6 |
| 5 | 2 | 88.0 | 9.0 | 6.9 | 10.4 | 114.3 |
| 5 | 3 | 100.5 | 10.3 | 7.9 | 11.9 | 130.6 |
| 5 | 4 | 72.7 | 19.1 | 16.3 | 2.5 | 110.6 |
| 6 | 1 | 25.6 | 6.7 | 5.8 | 0.9 | 39.0 |
| 7 | 1 | 126.8 | 33.4 | 23.5 | 4.4 | 193.1 |
| 7 | 2 | 119.4 | 31.4 | 26.8 | 4.1 | 181.7 |
| 7 | 3 | 8.1 | 0.8 | 0.6 | 1.0 | 10.5 |
| 7 | 4 | 60.8 | 16.0 | 13.7 | 2.1 | 92.6 |

* See Table 15 for definition of biomass components.

**Table 17. Plot attribute file**

| | | Derived data | | | | | |
|---|---|---|---|---|---|---|---|
| | | | Biomass (tonnes/ha) | | | | |
| Plot No. | Stratum | Volume ($m^3$/ha) | Stem wood | Stem bark | Live branches | Twigs and foliage | Whole tree |
| 1 | I | 126.1 | 57.0 | 4.9 | 3.4 | 4.6 | 69.9 |
| 2 | I | 130.7 | 55.6 | 14.3 | 12.2 | 2.1 | 84.2 |
| 3 | II | 130.4 | 55.6 | 8.2 | 6.6 | 5.3 | 75.7 |
| 4 | II | 129.8 | 58.4 | 6.0 | 4.6 | 6.9 | 75.9 |
| 5 | II | 75.0 | 31.2 | 4.4 | 3.5 | 3.1 | 42.2 |
| 6 | I | 5.8 | 2.6 | 0.7 | 0.6 | 0.1 | 4.0 |
| 7 | I | 72.8 | 31.5 | 8.2 | 7.0 | 1.2 | 47.9 |

diameter class. The plot biomass per hectare values by component thus compiled are added to the plot attribute file which, in turn, can be averaged by stratum to fill out the stratum file (Table 18). Though only whole tree biomass is shown here, all the components would normally appear. The stand table and the whole-tree biomass table for Stratum II were compiled and appear as in Tables 19 and 20.

As can be seen from the example, the adaptation of the single tree biomass equations to an existing volumetric inventory involves only a few changes, provided the basic plot and tree data are intact. In summary, these changes include possible alterations to the stratification sys-

**Table 18. Stratum file**

| Stratum | Description | Area (ha) | Volume ($m^3$/ha) | Mean whole tree biomass (tonnes/ha) | Number of plots | Accuracy* (%) | Total biomass (tonnes) |
|---|---|---|---|---|---|---|---|
| I | Pine/Aspen | 530.3 | 83.9 | 51.5 | 4 | 68 | 27 310 |
| II | Spruce | 381.3 | 117.7 | 64.6 | 3 | 30 | 24 556 |
| Total | | 911.6 | | | 7 | | 51 866 |

* Standard error of estimate expressed as per cent of mean.

**Table 19. Stand table for Stratum II**

| Diameter class (cm) | Stems per hectare | | | |
|---|---|---|---|---|
| | Spruce | Pine | Aspen | All species |
| 15 | 3 | | | 3 |
| 20 | 10 | | 7 | 17 |
| 25 | 10 | | | 10 |
| 30+ | 3 | | | 3 |
| Total | 26 | | 7 | 33 |

**Table 20. Biomass table for Stratum II**

| Diameter class (cm) | Stems per hectare | | | |
|---|---|---|---|---|
| | Spruce | Pine | Aspen | All species |
| 15 | 2.2 | | | 2.2 |
| 20 | 12.1 | | 11.6 | 23.7 |
| 25 | 23.3 | | | 23.3 |
| 30+ | 15.4 | | | 15.4 |
| Total | 53.0 | | 11.6 | 64.6 |

tem, the addition of biomass equations to the compilation procedures, the addition of columns of biomass quantities to the output of results, and the addition of a few new biomass tables. The procedure is also well illustrated by MacQuarrie (1983).

## 3. Incorporation of biomass estimation in new forest inventories

The development of a new forest inventory allows several tasks of biomass measurement and estimation to be planned and incorporated before the inventory is actually carried out. The planning and integration eliminates most of the "retrofit" problems discussed in the preceeding section. The procedures, however, will follow most of the inventory steps outlined so far in this chapter. In particular the base mapping, photo interpretation, stand classification, and forest mapping phases will not change except that the stand attribute data may have biomass-related information added and the stratification system may be modified to reflect the characteristics or particular needs of the biomass application. For example, whereas noncommercial or degraded forest stands are usually excluded or de-emphasized in conventional volumetric inventory, such stands may be of particular interest in a biomass context and stressed.

The chief departures in the procedures occur in the field sampling, development, and adaptation of the tree biomass equations and in the compilation phases. These departures are described next so that biomass measurement and estimation can be implemented in a planned new forest inventory. The execution and results of an integrated biomass and volume inventory of a forest property in Ontario can be found in Alemdag and Bonnor (1985).

### a. *Field sampling*

The addition of biomass requirements to a forest inventory imposes a few modifications to field sampling procedures. The modifications pertain primarily to the treatment of small material and the collection of tree data for checking or developing single tree biomass estimation equations.

Biomass estimation generally places greater emphasis on small material and on species that are regarded as noncommercial in conventional surveys. Accordingly, some means are required to control the quantity of small trees and shrubs sampled. In response, use of subplots and other sampling manipulations, such as larger basal area factors in point sampling, have evolved. Common practice, as already introduced in Chapter II, was to use two levels of subplots: for example a 25 $m^2$ circular plot (radius = 2.82 m ) for trees 0.1 to 5.1 cm in diameter, and a 4 $m^2$ circular plot (radius = 1.13 m) for trees 0.31 to 1.30 m height. In the first case, species, diameter, and other tree data are recorded; in the second case the trees are tallied and sorted by species and two height classes: 0.31 to 0.80 m and 0.81 to 1.30 m. The purpose of the subplots and measurements procedure is to limit the amount of field sampling work for small material. Exclusion of trees and shrubs below 0.31 m in height is also intended to limit field effort. Trees larger than 5.0 cm in diameter can be treated as in a volumetric inventory, although the height of every sample tree would have to be measured or estimated if the biomass equations require both diameter and height. In Chapter II, a circular fixed area plot (radius 11.28 m) was recommended. Variable radius plots (prism samples) increase sampling efficiency where the emphasis is on large, commercially valuable trees for conventional wood products. Fixed area plots come into their own when small trees are of greater interest or the frequency distribution of trees across the size classes (as in stand tables) assumes greater importance. In other respects the field sampling procedure will be nearly identical to that of a conventional inventory.

The procedures for selecting and measuring trees to develop biomass equations differ somewhat from that of the volume counterpart. The differences pertain mainly to the tree dimensions measured and the division of the tree into components. The procedures are elaborated in Chapter II.

### b. *Equation development*

As with the sampling and measurement of trees for equation development, the difference between volume and biomass equations relates primarily to the variables involved and the tree components. The equation development procedures are treated in detail in Chapter III.

### c. *Compilation*

A primary purpose of compilation is to estimate key statistics, such as total volume and biomass per hectare, from plot data by strata and to combine them with the stratum area statistics to produce required totals. This procedure was illustrated in Sections 1 and 2. The compilation will generate many other results such as tree component biomass estimates, and stand, stock, basal area, and biomass tables which highlight stand structure, the frequency distribution of trees, and the distribution of volume, basal area, and biomass by species and by diameter class. Such tables typically show the average structure of stands by stratum and become key elements in forest management planning and decision-making. The compilation procedure produces area, volume, and biomass tables and accuracy estimates of the key statistics.

As illustrated in the example in Section 2, the tree biomass equations and procedures for compiling per hectare estimates parallel the volume counterpart. The only changes involved are the redefinition of strata to reflect biomass requirements, and the processing of tree data.

## 4. Conversion of existing volumetric data to biomass

Conversion refers to the use of factors or ratios to transform wood volume estimates into biomass equivalents. Since stand aggregations or averages are involved, conversion is risky and should be treated as a last resort. The procedure is followed only when the original sample tree data are not available, are lost, or are too out-of-date or incomplete to be recompiled as described in Section 2 of this chapter. The conversion process is described in this section along with reasons why large biases can be expected. Some means of controlling bias are described, followed by a recommended procedure for using conversion factors.

### a. *Conversion principle*

The use of conversion factors is based on the simple process of finding the ratio between a difficult-to-measure quantity and an available or easily-measured quantity. For example, some available data may be used to estimate the ratio between the ovendry mass of the stem of a tree and stem volume:

$$R_s = OM_s/V_s \tag{23}$$

where $R_s$ is the ratio, $OM_s$ the ovendry stem mass, and $V_s$ the volume of the stem. This ratio may then be used to estimate the ovendry stem mass of other trees given that their volume is known or can be easily determined:

$$OM_i = R_s \,.V_i \tag{24}$$

where $OM_i$ is the estimated stem ovendry mass of another tree, and $V_i$ is its stem volume. The estimation, however, depends upon the ratio (a measure of wood density) being stable from tree to tree. In practice stem wood density is fairly constant for a given species of a given size. But the wood density of other tree components such as branch or foliage biomass may vary considerably with tree form and degree of crowding of surrounding trees. Likewise, variations in wood density can be expected with changes in tree size and among different species.

Other conversion factors may be used which depend on the same simple notion. For example, if the ovendry mass of a tree stem is divided by its green mass, the resulting ratio will reflect moisture content. Using this ratio, the green mass of a truckload of logs, for example, can be converted to ovendry mass. However, since the moisture content is affected considerably by growing conditions, time since cutting, and microclimate in the vicinity of the logs, the ratio is virtually useless unless the moisture content is sampled and adjustments made. In general, great caution must be taken in the use of ratio conversions.

### b. *Application of conversion factors to forest industry*

Under some circumstances only the forest inventory results may be reported. The basic sample data used to compile results are generally too numerous and cumbersome to report. Moreover, after a few years the tree data become lost and only documented results remain intact. If biomass estimates are required under these circumstances, we must resort to conversion factors for biomass estimates, and component ratios must be used to partition the whole tree biomass quantities into the components. This section reviews how the biomass estimates can be made and indicates how serious bias problems may arise. Some means of alleviating potentially severe biases are suggested, followed by a recommended procedure.

Total gross timber volume on a property or area can be converted to biomass estimates as follows. Because aggregate volume estimates were based originally on individual sample trees, the actual tree volume quantity estimated should be checked: is it gross total volume or an expression of merchantable volume where the top and stump are excluded? Were trees below a minimum diameter excluded? Find the volume-to-biomass conversion factor that suits the tree volume specifications. Having a measure of the tree component (usually stem) involved, convert aggregate volume to aggregate biomass for that component and use average tree component ratios to find the whole tree biomass and other components as described and illustrated in Chapter III, Section 7. Using the above procedures, quick and rather crude biomass estimates can be made.

Such estimates can be very unreliable. Both the volume estimate and conversion factors are estimates based on sample data. The sample data may involve species and size classes that are different from those making up the particular inventory in question.

For instance, the total volume of 86 858 $m^3$ in the example in Section 1 could be converted to whole-tree biomass using an average wood density value and the average percentage of stem wood biomass making up the whole tree. Thus, if an average wood density of 390 $kg/m^3$ were assumed and stem wood made up 80 percent of the mass of the whole tree, the total stem wood volume could be converted to total whole tree biomass as 86 858 x 390 x 100/80 = 42 344 tonnes. This estimate is about 18 percent lower than the 51 866 tonnes compiled from basic tree data given in Section 1. The accuracy depends entirely on the choice of the average wood density value and the stem wood percentage. The conversions are known to be strongly influenced by variations in species composition and size class. As the basic tree data used in the inventory are unavailable to check the match, the size of the biases cannot be gauged without gathering new data.

If a species breakdown, however, has been made in the reporting of inventory results, species specific conversion factors can be used which will alleviate the problem to some extent. This is illustrated using the sample again from Section 1. The results shown in Table 12 are frequently reported and available, but the plot and tree data discarded or misplaced. Thus, rather than using procedures in Section 2 to produce biomass estimates, conversions of the stratum volume method would be resorted to, using the following procedure:

- locate volume results such as given in Table 12 (Section 2);
- if possible, make a breakdown by species (Table 21);
- find a set of species conversion factors. In this example, basic wood density factors from Alemdag (1981, 1983) were used (Table 22);
- find a set of ratios that express tree component biomass as a percentage of stem wood mass. Stem wood mass is used because it is the counterpart of gross total volume which does not include the bark,

branches, twigs, and leaves. The data again were taken from Alemdag (1981, 1983) as in Table 23;

- convert gross total stem volumes to stem wood ovendry mass (Table 24);
- partition the stem wood mass into the tree component mass using the species component percentages (Table 25). All values are in tonnes.

**Table 21. Breakdown of strata by species**

| Stratum | Species | Per cent of total volume | Pro-rated volume ($m^3$) |
|---|---|---|---|
| I | Spruce | 69 | 40 562 |
| | Pine | 19 | 11 169 |
| | Aspen | 12 | 7 054 |
| | | | 58 785 |
| II | Spruce | 2 | 561 |
| | Aspen | 98 | 27 513 |
| | | | 28 074 |

**Table 22. Basic stem-wood densities**

| Species | Stem-wood density ($kg/m^3$) |
|---|---|
| Spruce | 386 |
| Pine | 412 |
| Aspen | 406 |

**Table 23. Tree component biomass as a percentage of stem wood biomass**

| Species | Stem wood | Stem bark | Live branches | Twigs and leaves | Whole tree |
|---|---|---|---|---|---|
| Spruce | 100 | 10 | 8 | 12 | 130 |
| Pine | 100 | 8 | 5 | 7 | 120 |
| Aspen | 100 | 26 | 23 | 3 | 152 |

Table 24. **Converting total stem volume to total ovendry mass**

| Stratum | Species | Total volume ($m^3$) | Conversion factor ($kg/m^3$) | Total ovendry mass (tonnes) |
|---|---|---|---|---|
| I | Spruce | 40 562 | 386 | 15 657 |
| | Pine | 11 169 | 412 | 4 602 |
| | Aspen | 7 054 | 406 | 2 864 |
| II | Spruce | 561 | 386 | 217 |
| | Aspen | 27 513 | 406 | 11 170 |
| Total | | | | 34 510 |

Table 25. **Biomass of tree components (tonnes)**

| Species | Stem wood | Stem bark | Live branches | Twigs and leaves | Whole tree |
|---|---|---|---|---|---|
| Spruce | 15 874 | 1 587 | 1 270 | 1 905 | 20 636 |
| Pine | 4 602 | 368 | 230 | 322 | 5 522 |
| Aspen | 14 034 | 3 649 | 3 228 | 421 | 21 332 |
| Total | 34 510 | 5 604 | 4 728 | 2 648 | 47 490 |

As can be seen, the total whole-tree biomass of 47 490 tonnes is a reasonable approximation of the total biomass of 51 866 tonnes compiled from the basic tree data in Table 10. The use of species proportions helped control variations which may have been introduced by differences in wood densities among the three species involved in the example. As illustrated next, use of diameter distribution data should provide further control over potential bias in estimates that use conversion factors.

## c. *Recommended procedure*

Experience has shown that large biases can occur in the direct conversion of total property volume to biomass. However, if species and diameter distributions are known, much greater control over bias can be expected, provided the species and diameter distributions of the "model" match that of the target population. If the original sampling of the population, and later compilation, produced a species-based stand and stock table such as illustrated in Table 5, then an excellent model is at hand, assuming a representative sampling design was used in the first place. This approach, described in detail by Baskerville (1972), is applied as follows:

- for each species select a suitable set of biomass equations based on D or D and H;

- for the midpoint of each D class, estimate its corresponding height using a height-on-diameter equation. The midpoint is assumed to represent the class mean;
- using the set of biomass equations, enter with the midpoint of D and if necessary the corresponding H to calculate whole tree and component biomass;
- multiply these estimates by the number of trees per hectare opposite each diameter class and species to arrive at a set of per hectare estimates;
- sum estimates by diameter class and by species to generate marginal totals;
- add along margins to find the per hectare totals;
- multiply the per hectare estimates by area to estimate target population whole tree and component biomass.

The above procedure is illustrated using the examples in Sections 1 and 2.

First, obtain a stock and stand table for each stratum or for the population as a whole. For simplicity's sake, we developed the latter (Table 26) from basic data in Table 10.

**Table 26. Stand table for sample population**

| Diameter class (cm) | Stems per hectare | | | |
|---|---|---|---|---|
| | Spruce | Pine | Aspen | All species |
| 10 | 29 | | | 29 |
| 15 | 29 | | 14 | 43 |
| 20 | 44 | 14 | 57 | 115 |
| 25 | 57 | 14 | 14 | 85 |
| 30+ | 14 | | 14 | 28 |
| Total | 173 | 28 | 99 | 300 |

Next, arrange data so that component biomass quantities can be calculated. Single tree biomass equations from Section 2 are used in this illustration. Use an available height-on-diameter equation to estimate the tree height corresponding to each diameter class. Use the single-tree equations for each species to calculate whole tree biomass (Table 27).

The whole tree biomass values are multiplied by stems per hectare and scaled from kilograms to tonnes. The total is multiplied by the area to yield another estimate of total whole tree biomass, i.e., 53.8 x 911.6 = 49 044 tonnes, somewhat closer to the total compiled from the basic tree data.

The recommended procedure helps to control bias by using the stand table to supply information on the distribution of trees by diameter class and by species. The procedure, however, may still provide unreliable

Table 27. Calculation of whole tree biomass

| Species | Diameter (cm) | Height (m) | Whole tree biomass (kg) | Stems per ha | Whole tree biomass (tonnes/ha) |
|---|---|---|---|---|---|
| Spruce | 10 | 9.1 | 16.6 | 29 | 0.5 |
| | 15 | 13.5 | 55.3 | 29 | 1.6 |
| | 20 | 16.1 | 117.3 | 44 | 5.2 |
| | 25 | 21.2 | 241.4 | 57 | 13.8 |
| | 30 | 24.0 | 393.5 | 14 | 5.5 |
| Pine | 20 | 18.1 | 137.5 | 14 | 1.9 |
| | 25 | 22.8 | 270.7 | 14 | 3.8 |
| Aspen | 15 | 13.0 | 65.7 | 14 | 0.9 |
| | 20 | 17.5 | 157.2 | 57 | 9.0 |
| | 25 | 23.3 | 327.1 | 14 | 4.6 |
| | 30 | 24.6 | 497.3 | 14 | 7.0 |
| Total | | | | | 53.8 |

estimates, mainly because the stand table is the result of sampling and, accordingly, represents an average condition based on data taken from stands varying considerably in species composition and structure. The reader is cautioned again not to place too much confidence in the results determined through the use of conversion factors.

## 5. Adjustments for missing data

In the course of reprocessing sample plot data to produce biomass estimates (Section 2) and converting volume results to biomass (Section 4), several significant parts of the population may not have been included in the sample. The original sample plots may have excluded trees below a prescribed diameter threshold or left out trees and shrub species having little or no commercial value. Such exclusions are imposed in the first place to reduce the cost of collecting and processing material of little interest. However, in terms of biomass, the material may assume greater significance and should be accounted for. Likewise, when volume data are converted to biomass, small material and certain species may have been left out of the estimates. Further, when merchantable volumes are reported, rather than gross total volumes, unmerchantable portions of the stem will be lacking in much the same way that total volume results do not include foliage, twigs, live branches, and bark components. Net volumes likewise are the results of deductions for decay, defect, and (possibly) breakage. This section outlines approaches to account for these exclusions.

## a. *Exclusions of small trees*

The frequency distributions of trees in a stand can be characterized by the form shown in Figure 12. If trees below 9.1 cm D were not sampled, the biomass of trees and shrubs of this proportion would be lacking. Two approaches can be taken to estimate the biomass of the excluded portion and to add it to the included portion: subsampling the target population to cover the missed portion or use of existing data from a similar population.

The subsampling consists of re-sampling the population to pick up the missed portion. Because the missing quantity is generally less important than the included portion, only a proportion of the original sample would be re-sampled, a smaller subplot may suffice, or both. The re-sampling is basically straightforward, following most of the original sampling procedure. It is, however, costly and seldom used in practice.

The second approach uses existing data, usually from other inventories or studies, as a substitute or "model" for the missing data. Alemdag (1982b), for example, describes and illustrates a method which finds the ratio of the missing portion of biomass to the included portion for varying diameter cut-off limits. In Alemdag's example, a diameter limit of 5.1 cm for a particular jack pine stand indicates that the excluded portion was 0.43 per cent of the included portion; a 9.1 cm limit excludes 1.53 per cent. The approach assumes that the structure (that is, size class distribution of trees in the stand) of the model is similar to that of the stand condition being adjusted. However, because ratios were used, the total biomass or volume of the respective stand conditions do not necessarily have to be alike.

Stand structure is critical to the success of the adjustment; hence, stand tables or a tree frequency graph, such as shown in Figure 12 and expanded in Figure 13, can be of considerable help in judging how well a model and a particular case match.

Suppose that the stand structure shown in Figure 12 is used as the model for estimating the proportion of biomass below a diameter limit of 9.1 cm. The model is reproduced in Figure 13, along with two additional stands having trees below 9.1 cm presented for discussion purposes but which are assumed to lack data in practice. What are the consequences of using this model to estimate proportion? In the case of Stand 1, Figure 13 shows that the proportion of small trees is greater than that of the model. This is also reflected in the stem counts in Table 28, which shows the stem wood biomass for each diameter class. The ratio of biomass below 9.1 cm to that above for the model is 2.3 per cent. Even though the model and Stand 1 have a similar total biomass, the ratio for Stand 1 is 11.5 per cent. Accordingly, the model will greatly underestimate biomass below a diameter of 9.1 cm. However, Stand 2, which has a much lower total biomass than the model, has a similar size class distribution (structure) and a ratio that is close to that of the model. Consequently, the model will provide a fairly good estimate of Stand 2's biomass below a diameter of 9.1 cm. Both histograms in Figure 13 and

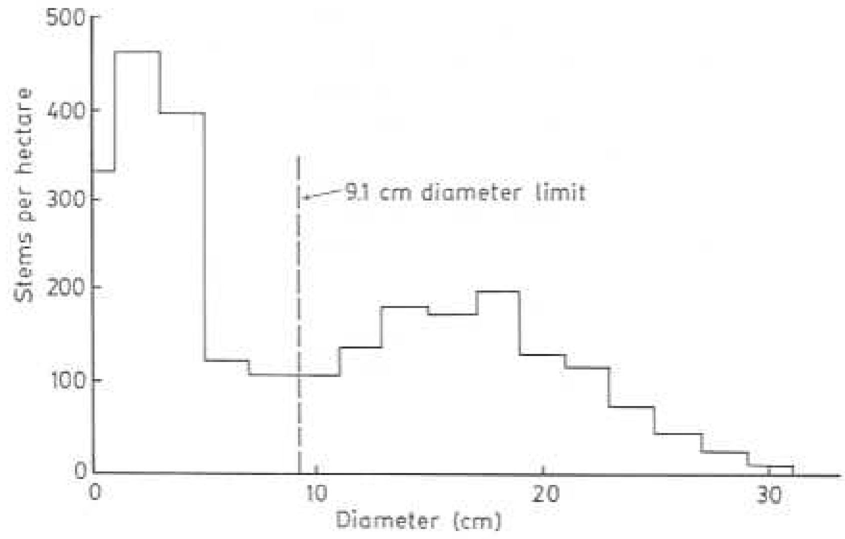


Figure 12. Example of the frequency distribution of trees in a stand by diameter classes.

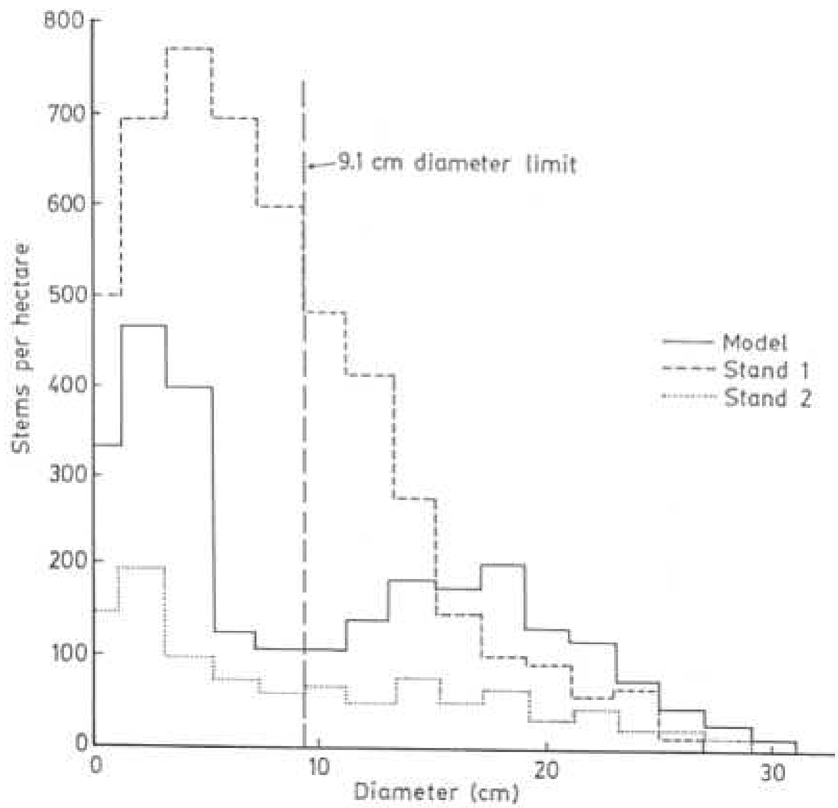


Figure 13. Frequency distribution of three stands by diameter class: the model stand shown in Figure 12 and two stands of different structure.

the stand tables in Table 28 provide an useful guide to whether or not a particular model can be used. Of course, the stands in question will lack small trees and, thus, part of the structure, but the user can extrapolate the general form drawing on experience with data from similar stands. The use of such data is really a verification procedure which is extremely important in any kind of modelling exercise. The user should constantly pursue the question, is the model a reasonable representation of the case being treated? How realistic is it?

Alemdag (1982b) describes and illustrates other variations of using ratios to cope with missing portions. The examples reveal, incidentally, that for trees 5.1 cm D or less, the proportion of biomass missed is usually small.

**Table 28. Frequenct and stem wood biomass distribution of three stands**

| | | Model | | Stand 1 | | Stand 2 | |
|---|---|---|---|---|---|---|---|
| Diameter class (cm) | Height (m) | Trees per ha | Stem wood biomass (kg/ha) | Trees per ha | Stem wood biomass (kg/ha) | Trees per ha | Stem wood biomass (kg/ha) |
| 0 | 1.3 | 333 | 55 | 500 | 30 | 150 | 10 |
| 2 | 3.5 | 467 | 83 | 700 | 125 | 200 | 53 |
| 4 | 5.5 | 400 | 443 | 775 | 858 | 100 | 249 |
| 6 | 7.2 | 100 | 328 | 700 | 2 287 | 75 | 408 |
| 8 | 8.7 | 108 | 758 | 600 | 4 210 | 60 | 526 |
| 10 | 10.0 | 108 | 1 363 | 481 | 6 068 | 63 | 794 |
| 12 | 11.2 | 138 | 2 795 | 407 | 8 242 | 48 | 972 |
| 14 | 12.2 | 183 | 5 498 | 372 | 11 176 | 75 | 2 253 |
| 16 | 13.1 | 175 | 7 364 | 147 | 6 185 | 51 | 2 146 |
| 18 | 13.8 | 200 | 11 279 | 101 | 5 696 | 62 | 3 496 |
| 20 | 14.5 | 171 | 12 487 | 92 | 6 718 | 31 | 2 264 |
| 22 | 15.1 | 138 | 12 689 | 58 | 5 333 | 40 | 3 677 |
| 24 | 15.6 | 71 | 8 035 | 63 | 7 130 | 19 | 2 150 |
| 26 | 16.1 | 46 | 6 286 | 11 | 1 503 | 21 | 2 869 |
| 28 | 16.5 | 25 | 4 069 | 0 | 0 | 11 | 1 786 |
| 30 | 16.8 | 8 | 1 523 | 0 | 0 | 0 | 0 |
| Total | | 2 671 | 75 000 | 4 704 | 65 561 | 1 396 | 23 663 |
| Summary | | | | | | | |
| 0 — 9.0 cm | | | 1 667 | | 7 510 | | 882 |
| 9.1 — 30.0 | | | 73 333 | 65 561 | 22 841 | | |
| Ratio (%) | | | 2.3 | | 11.5 | | 3.6% |

### b. *Exclusions of noncommercial species*

Adjustments for noncommercial species lacking in an inventory can be approached in the same way as missed trees. Either the population must be re-sampled to pick up the noncommercial portion or a search made for an existing substitute or analogue. In this case, the use of an analogue is unlikely to be reliable. A particular cover type or stand having minor noncommercial species may not have them in another case, or the proportions could vary greatly. Stands purely or predominantly of noncommercial species will be very difficult to estimate accurately using projections from other inventories or studies. Consequently, a re-survey is recommended as the only reliable means of handling noncommercial species. However, the original cover type map may be a great help in directing sampling effort to areas most likely to have noncommercial species. Certain stands may be known to have a very low possibility of containing noncommercial species, others known to have a higher chance. Some areas, perhaps classified and mapped generally as brush areas, slides, abandoned fields, etc. may have a high likelihood of having a large proportion of noncommercial species. Accordingly, weights could be assigned to the cover types and used to increase the efficiency of sampling. Otherwise, the re-survey will follow most of the procedures of a conventional field survey (Section 1).

### c. *Exclusion of unmerchantable components*

The problem of recovering excluded unmerchantable components of a tree applies only to the case where all basic sample tree data are unavailable and merchantable volume-to-biomass conversions must be used. If the sample trees are available, then all tree components can be estimated through the single tree equations, including the unmerchantable components (Chapter III, Section 6).

As in the preceding two cases, if the unmerchantable fraction is not determinable directly, two options can be considered: re-sampling to estimate the proportions, and approximation using a closely related analogue. If re-sampling is to be followed, the procedures will be similar to that of a new survey. The results will be reliable but the survey will be too expensive in most cases. The use of related inventory data to provide a model estimating unmerchantable proportion should, in most cases, turn to the use of stand tables. Otherwise global proportions are too susceptible to bias because the merchantable and unmerchantable proportions are sensitive to tree size. Therefore, the diameter distributions, such as in a stand table, are the least that can be accepted. The procedure for using a stand table draws on the merchantability equations developed by Alemdag (1982a) and the procedure described in Chapter III Section 6.

## 6. Summary

When designing a forest biomass inventory, the planner should be fully conversant with the current forest inventory procedures used in Canada. These are primarily designed, developed, and carried out by the provinces and territories. Although the procedures vary among them, considerable progress towards standardization has been brought about by metric conversion, by activities of the joint federal/provincial Canadian Forest Inventory Committee, and by developing new technology such as Geographic Information Systems which already play an important role in forest inventory. Company practices largely follow those of the province or territory in which they operate. Biomass inventory should generally take advantage of and be integrated with current inventory practice.

If plot sample data are kept intact, most of the costly work — photo interpretation, mapping, field sampling, and compilation — will have already been done. The development or adaptation of existing single-tree biomass equations and minor modification of compilation procedures will be the main areas of work. Much duplication of effort can be avoided by integrating biomass inventory with current forest inventory methodology.

Whenever possible, the use of single tree biomass equations of an appropriate model for each species should be favoured over the use of conversion factors or ratios. Proper sampling procedures concerning the selection of trees for developing or validating single-tree equations and statistically defensible sampling designs will do much to ensure the reliability of the biomass estimates, especially the control of bias which may distort estimates. The use of volume to biomass conversions should be regarded as a last resort because of the difficulty of employing conversions which include all important stand components and which adequately represent the forest area being inventoried.

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# APPENDIX A

## Glossary

The definitions in the Glossary are based mostly on terminology from the following sources:

Alemdag 1980, 1981, and 1982a
Anon. 1973
Bonnor 1978, 1982a, 1982b, and 1985
Freese 1962
Keays 1971

The above are listed in the References. In some cases the definitions were copied verbatim from the source; in others we altered the definitions to suit the biomass context. In a few cases we made our own definitions to fill our the meaning of terms.

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Aboveground biomass: biomass of a living tree including stem wood, stem bark, live branches, twigs and leaves or needles, and fruits or cones. c.f. forest biomass, whole tree.

Accuracy: a measure of the distortion of estimates of a parameter (characteristic) from the true value of the parameter. The mean square error is a common expression of accuracy. c.f. bias, precision.

Basal area:

a) of a tree, the area in square metres of the cross section at breast height of the stem.
b) of a stand, the area in square metres per hectare of the cross section at breast height of all the trees.

Basal area factor: the basal area per unit of stand area corresponding to the angle of projection of a gauge, prism, or other angle instrument.

Base map: a map which displays basic planimetric information (drainage and cultural features) and which is used as a base for the forest map.

Basic wood density: the ratio of ovendry mass of wood to the green volume of the same quantity of wood expressed in $kg/m^3$. c.f. density.

Bias: the difference between the expected value of an estimate and the true value of the quantity being estimated. c.f. accuracy, precision.

Biomas: quantity of living matter in a given ecosystem expressed in terms of its mass. c.f. mass.

Biomass components: see tree components, stem components, primary division of components, secondary division of components.

Bole: a tree stem once it has grown to a substantial thickness, capable of yielding saw timber, veneer logs, larger poles or pulpwood.

Bottom of stump: the place where the stump meets the general ground level. c.f. ground level.

Branches: the wood and bark of a tree extending from the main stem(s) to the foliage, excluding twigs. c.f. large branch, small branch.

Brush: shrubs and stands of short, scrubby tree species that do not reach merchantable size.

Cluster: a statistical sample unit comprising two or more sample plots or other elements.

Collinearity: in a system of linear equation, a condition where one independent variable is perfectly correlated with another.

Commercial species: a tree species for which there is a current market.

Cones, nuts, and fruits: reproductive parts of a tree.

Confidence limit: during the estimation of one or more parameters, a statement of the limits around the estimate within which the parameter can be expected to fall with a prescribed level of confidence. For example, the true height of a tree may be estimated to be 17.2 m within limits of $\pm$1.6 m with a 95 per cent probability.

Crown area: the area covered by the vertical projection of a tree crown to a horizontal plane.

Crown diameter: the horizontal distance between two extremities of the crown on opposite sides of the tree.

Crown length: the vertical distance from the top of a standing tree to the base of the crown, measured either to the lowest live branch or to the lowest live branch-whorl.

Cull: trees or logs or portions thereof that are of merchantable size but are rendered unmerchantable by defects.

Cull factor: the percentage of a standing tree's gross volume rendered unmerchantable by defects.

Dbh: see diameter at breast height.

Density: the ratio of mass of a substance to the volume of the quantity. c.f. basic wood density, stand density, specific gravity.

Dependent variable: in linear regression, the variable which is predicted or estimated from a linear combination of independent variables. Usually designated by the symbol y.

Depletion: the decrease in volume on a managed forest area. The decrease may be due to logging, fire, insect and disease damage, and other causes.

Diameter at breast height: the stem diameter outside bark of a tree measured at breast height (1.30 m above ground level). c.f. ground level.

Diameter class: any interval into which the range of stem diameters of trees or diameters of logs is divided for classification and use. Also the trees or logs falling into such an interval.

Diameter inside bark (dib): the diameter of a tree or log excluding double bark thickness.

Diameter limit: the minimum, and occasionally the maximum diameter to which trees or logs are to be measured, cut, or used. The limits generally refer to the breast height, the top, or the stump.

Diameter outside bark (dob): the diameter of a tree or log including bark.

Even-aged: of forest, stand, or forest type in which small age differences exist between individual trees.

Foliage: organic tree material capable of photosynthesis. The component foliage also includes twigs. c.f. twigs.

Forest: a community of trees having a minimum crown closure of 10 per cent.

Forest biomass: the total mass of living woody plants growing on an area including stem wood, stem bark, live branches, twigs, leaves or needles, and fruits or cones. Usually measured in tonnes per hectare. May also include roots. c.f. aboveground biomass, whole tree.

Forest map: a base map to which forest data have been added.

Forest type: a group of forested areas or stands of similar composition which differentiates it from other such groups. Forest types are usually separated and identified by species composition and often also by height and crown closure classes. In detailed typing, age, site and other classes may be recognized. The typing is usually done on aerial photos and may be supplemented by field data. Type symbols and boundaries are marked on the photos and transferred to the forest map.

Forked tree: a tree which is forked above 1.30 m from the ground level. If the fork occurs at or below 1.30 m, the tree is considered to be actually two trees.

Form factor: the ratio between the inside bark volume of a tree stem and the volume of cylinder having the same diameter and height.

Full tree bole: tree stem including wood and bark from stump to the tip of the tree.

Green mass: the mass of a tree or a biomass sample measured immediately after cutting.

Gross merchantable volume: volume of the main stem excluding stump and top but including defective and decayed wood of trees or stands.

Gross total volume: volume of the main stem including stump and top as well as defective and decayed wood of trees or stands.

Ground level: the point where the tree touches the ground on the uphill side. c.f bottom of stump, diameter at breast height.

Hardwood(s): trees belonging to the botanical group Angiospermae with broad leaves usually all shed annually. Also, stands of such trees and the wood produced by them.

Hardwood type: a forest type in which 0.25% of the canopy is coniferous. c.f. softwood type, mixedwood type.

Height class: any interval into which the range of tree or stand heights is divided for classification and use.

Immature: in even-aged management, those trees or stands that have grown past the regeneration stage, but are not sufficiently developed to be harvested.

Independent variable: in linear regression the variable which, often in combination with other independent variables, is used to predict or estimate a dependent variable. The independent variable is often designated by the symbol x or $x_1, x_2, \ldots, x_n$, where there are several.

Large branch: live branch segment of at least 2.50 m with a diameter at the small end of at least 9.1 cm. c.f. branches, small branch.

Leaves and needles: the photosynthesizing portion of a tree.

Management inventory: a detailed, intensive forest inventory for management purposes, of an area managed as one unit.

Mass: the numerical measure of the property of a body by which it requires force to change its state of motion. The unit of mass is the kilogram in the International System (SI), and the pound in the imperial system. c.f. biomass.

Mature: stands or forest types past rotation age. Growth has culminated.

Merchantable diameter: a specified tree diameter at breast height below which trees will generally not be harvested.

Merchantable height: the length of stem from the ground to merchantable top diameter. c.f. merchantable top diameter.

Merchantable stem bark: the bark portion of a tree stem between stump height and the height on the stem of a minimum top diameter.

Merchantable stem wood: the wood portion of a tree stem between stump height and the height on the stem of a minimum top diameter.

Merchantable top diameter: of a standing tree, the diameter at merchantable height, i.e. at the smaller end of the uppermost merchantable log. Measured inside bark. c.f. merchantable height.

Merchantable tree: a tree having a diameter at breast height equal to or larger than the merchantable diameter.

Minimum top diameter: see merchantable top diameter.

Mixedwood type: a forest type in which 26%-75% of canopy is coniferous. c.f. hardwood type, softwood type.

Mortality: death or destruction of forest trees as a result of competition, disease, insect damage, drought, wind, fire, and other factors, excluding harvesting.

Net merchantable volume: volume of the main stem, excluding stump and top as well as defective and decayed wood of trees or stands.

Non-commercial species: a tree species for which there is no current market.

Non-forest land: land not primarily intended for growing forest, or not supporting it.

Non-stocked forest land: land capable of producing forest but generally lacking in tree growth.

Operational inventory: an intensive forest inventory of a small area for harvesting purposes.

Ovendry mass: the mass of a tree or biomass sample which, when dried in an oven, has attained a constant minimum moisture content.

Overmature: stands or forest types past rotation age. Openings in canopy as a result of mortality becoming apparent.

Photo interpretation: the extraction of information from photos or other recorded images.

Phototyping: the delineation and labelling of natural or cultural features on aerial photos.

Point sample: a sample unit or element in which trees are selected for inclusion from a point with probability proportional to their basal area.

Point sampling: a method of selecting trees for measurement, and for estimating stand basal area, at a sample location or point sample. Also called plotless cruising, angle count method, or Bitterlich method. In point sampling, a 360 degree sweep is made with an angle gauge such as a prism about a fixed point. The stems whose breast height diameters appear larger than the fixed angle subtended by the angle gauge are included in the sample.

Population: the aggregate from which the sample is chosen. In forest inventories, the population is usually trees or clusters of trees in a forested area for which information is required.

Precision: the variability of a series of sample estimates — the difference between a sample estimate and the estimate obtained from a complete enumeration using the same method and procedures. Generally, random deviation from the sample mean. The mean square error (MSE), a measure of accuracy, illustrates the relationship between precision and bias:

$$MSE = \text{Precision squared} + \text{Bias squared}$$

The precision or sampling error is usually expressed as the standard error of the sample estimate, either as an absolute value or as a percentage of the estimate. c.f. accuracy, bias.

Primary division of components: of a tree, stem wood, stem bark, live branches, twigs and leaves (or needles), and fruits (or cones). c.f. tree biomass, tree components, secondary division of components.

Prism: an optical instrument used as an angle gauge, consisting of a thin wedge of glass which established a fixed (critical) angle of projection in a point sample.

Productive forest land: land that is capable of producing a merchantable stand within a reasonable length of time.

Reconnaissance inventory: an exploratory, extensive forest inventory with no detailed estimates obtained.

Regeneration: the renewal of a forest crop by natural or artificial means.

Regional inventory: a detailed extensive forest inventory for planning on a regional or provincial basis.

Relascope: an angle gauge, used in point sampling, in which bands of different widths are viewed through an eyepiece, resulting in corresponding angles of projection.

Sample: a subset of one or more of the sample units into which the population is divided. The samples are selected to represent the population and examined to obtain estimates of population characteristics.

Sample plot: a sample unit or element of known area and shape.

Sample unit: one of the specified parts into which the population has been divided for sampling purposes. Each sample unit commonly consists of only one sample element which may be a sample plot, a point sample, or a tree. If the sample unit contains more than one sample element, it is termed a cluster. In probability sampling, the sample until are selected independently of each other while the sample elements within a sample unit (cluster) are not.

Sampling: the selection of the sample unit from a population and the measurement and/or recording of information contained therein to obtain estimates of population characteristics.

Sampling error: see precision.

Sampling frame: a list or accounting of all sampling units that make up a population. In most applications the list is conceptual rather than actual because of the large number that may be involved.

Sapling: a young tree having a diameter at breast height greater than 10 cm and less than the smallest merchantable diameter.

Sawtimber: trees that will yield logs suitable in size and quality for the production of lumber.

Scrub: inferior growth consisting chiefly of small or stunted trees and shrubs.

Secondary division of components: of a tree stem, merchantable wood, merchantable bark, stump wood, stump bark, top wood plus bark. c.f. stem components, primary division of components.

Seedling: a young tree having a diameter at breast height equal to or less than 10 cm.

Shrub: any woody perennial plant species which according to recognized taxonomy tests is defined as a shrub. c.f. tree.

Site: the complex of physical and biological factors for an area which determines what forest or other vegetation it may carry. Sites are classified either qualitatively by the climate, soil, and vegetation or quantitatively by relative productive capacity.

Site capability classes: and interval into which the site capacity range is divided for classification and use.

Site capacity: the mean annual increment in merchantable volume that can be expected for a forest area, assuming it is fully stocked by one or more species best adapted to the site, at or near rotation age.

Site class: any interval into which the site index is divided for classification and use.

Site index: an expression of forest site quality in terms of height, at a specified age, of dominant and codominant trees in a stand. May be grouped into site classes. Usually refers to a particular species.

Site quality: a measure of the relative productive capacity of a site for one or more species.

Slash: the residue left on the ground after felling, tending, and simple accumulation as a result of storm, fire, girdling, or poisoning. Includes unused logs, uprooted stumps, broken and uprooted stems.

Small branch: live branch segments with a diameter less than 9.1 cm at the large end. c.f. branches, large branch.

Softwood(s): Cone-bearing trees with needle or scale-like leaves belonging to the botanical group Gymnospermae. Also, stands of such trees and the wood produced by them.

Softwood type: a forest type in which 76-100% of the canopy is coniferous. c.f. hardwood type, mixedwood type.

Specific gravity: the ratio of a quantity of mass to the mass of an equal volume of water. c.f. density.

Stand: a community of trees possessing sufficient uniformity in composition, age, arrangement, or condition to be distinguishable from the forest or other growth on adjoining area, thus forming silvicultural management entity.

Stand components: the division of trees in a stand into merchantable trees and submerchantable trees.

Stand density: a quantitative measure of tree cover on an area, in terms of crown closure, number of trees, basal area, or volume. In this context, tree cover includes seedlings and saplings, hence the concept carries no connotation of a particular age. Expressed on a per hectare basis. c.f. density, stocking.

Stand height:

a) in mensuration: the average height of dominant and codominant trees of the main species forming the stand.
b) in remote sensing: the average height of dominant and codominant trees in a stand.

Stand table: a summary table showing the number of trees per unit area by species and diameter classes, for a stand or forest type. The data may also be presented in the form of a frequency distribution of diameter classes.

Stem: the principal axis of a plant from which buds, shoots, and branches are developed. In trees, it may extend to the tip of the tree as in some conifers, or it may be lost in the ramification of the crown, as in most deciduous trees.

Stem bark: the bark of a tree stem from ground level to the tip of a tree.

Stem components: the segments into which a tree stem has been divided conceptually, for classification and use. c.f. secondary division of components.

Stem wood: the wood of a tree stem from ground level to the tip of a tree.

Stocking: a qualitative expression of the adequacy of tree cover on an area, in terms of crown closure, number of trees, basal area, or volume, in relation to a pre-established norm. c.f. stand density.

Stock table: a summary table showing the volume of trees per unit area by species and diameter classes, for a stand or forest type.

Stratum: a subdivision of a forest area to be inventoried. The division of a population into strata (stratification) is usually done to obtain separate estimates for each stratum.

Stump bark: the bark portion of a tree stem between ground level and a specified stump height.

Stump height: the vertical distance between ground level and the top of a stump. On slopes, ground level is generally taken on the upper side of the stump. Stump height may be the actual height of a cut stump, or some arbitrarily selected standard.

Stump wood: the wood portion of a tree stem between ground level and a specified stump height.

Top bark: the bark portion of a tree stem from a specified stem diameter (minimum top diameter) to the tip of a tree.

Top diameter: see merchantable top diameter.

Top wood: the wood portion of a tree stem from a specified stem diameter (minimum top diameter) to the tip of a tree.

Tree: any woody perennial plant species which according to recognized dendrology texts is defined as a tree. c.f. shrub.

Tree biomass: the mass of the aboveground portion of a live tree. c.f. whole tree.

Tree components: the segments into which a tree has been divided conceptually, for classification and use. c.f. primary division of components.

Twigs: the leaf-bearing sections of live branches with a diameter equal to or less then 0.5 cm outside bark. c.f. foliage.

Type map: a map showing the distribution of various environmental types such as soil, vegetation, or site throughout a forest area.

Uneven-aged: of a forest, stand, or forest type in which intermingling trees differ markedly in age.

Unmerchantable: of a tree or stand that has not attained sufficient size, quality and/or volume to make it suitable for harvesting.

Unmerchantable top: the wood and bark of a tree stem from a specified stem diameter (minimum top diameter) to the tip of the tree.

Unproductive forest land: land that is incapable of producing a merchantable stand within a reasonable length of time.

Volume: the amount of wood in a tree, stand, or other specified area, according to a given unit of measurement or some standard of use. The unit of measurement may be cubic metres or cubic metres per hectare. The standard of use may be pulpwood or sawtimber. Usually refers to the volume inside bark, and is according to different specifications which include stump height, minimum diameter at breast height and minimum top diameter.

Volume equation: a statistically-derived expression of the relationship between volume and other tree or stand variables. Used to estimate volume from more easily measured variables such as diameter at breast height, tree or stand height, and crown closure.

Volume table: a table showing the estimated average tree or stand volume corresponding to selected values of other, more easily measured, tree or stand variables. Used in the same way as the volume equation, from which it generally is constructed. Occasionally constructed from a graphically-derived relationship between volume and other tree or stand variables. Constructed for individual species or species groups.

Whole tree: includes all component parts such as stem wood with stump and top, stem bark with stump and top, live branches, twigs and leaves (or needles), and fruits (or cones). Roots may be included under certain circumstances. c.f. aboveground biomass, forest biomass, tree biomass.

Yield table: a summary table showing characteristics at different ages for stands (usually even-aged) of one or more species on sites of differing qualities. The stand characteristics usually include average diameter, average height, total basal area, number of trees, and volume per hectare.

# APPENDIX B

## Standards of measurement and suggested equipment

## A. Standards of measurement relating to field work

1. The diameter (D) and height classes specified in this manual are for sampling purposes only. Because the trees are recorded by their actual diameters and heights, any grouping most appropriate for a particular situation can be formed at a stage later on during the analyses.

2. If a knot is encountered at a point on the stem (including breast height) where the diameter is to be measured, the diameter directly below the knot should be recorded, but there should be no corresponding adjustment in length.

3. Sample disks should be taken so as to avoid branch stubs.

4. Weighing should be done immediately after felling.

5. Green mass of a component of a sample tree is the mass taken in the field after felling, or in the laboratory if the tree or shrub is very small.

6. Other descriptions, measurement standards, and codes are as follows:

   (a) Age

   Number of annual rings at the place of measurement;

   (b) Diameter (stem or branch)

   To the nearest 0.1 cm (1 mm);
   By circumference;
   With a record of one measurement (actual value);
   By the use of diameter tape;

   (c) Diameter (crown)

   To the nearest 0.5 m (50 cm);
   In two directions (north-south and east-west) on the perpendicular projection of the crown on the ground;
   With a record of the average (actual value);
   By use of metallic measuring tape;

   (d) Diameter (D) classes

   0.1 — 5.0 cm code: 1
   5.1 — 10.0 cm 2
   10.1 — 15.0 cm 3
   15.1 — 20.0 cm 4
   20.1 — 25.0 cm 5
   25.1 — 30.0 cm 6
   30.1 — 35.0 cm 7
   35.1 — 40.0 cm 8
   40.1 — 45.0 cm 9
   45.1 — 50.0 cm 10
   etc.;
   (2 cm classes are recommended for plantations);

(e) Double-bark thickness

To the nearest 0.1 cm (1 mm);
At one diameter direction taken randomly (total of two readings);
With a record of the total of two measurements (actual value);
By use of a Swedish bark measurer at 1.30 m and at uncut sections, and using a ruler at cut surfaces;

(f) Width of annual rings

To the nearest 0.1 cm (1 mm);

(g) Total tree height (standing)

To the nearest 0.1 m (10 cm);
From the ground level to the tip of the main stem;
With a record of one measurement (actual value);
By use of a Haga height measurer or aluminum poles;

(h) Shrub height

To the nearest 0.01 m (1 cm);
From the ground level to the tip of the main stem;
With a record of one measurement (actual value);

(i) Section length (including stump and top)

To the nearest 0.01 m (1 cm);
With a record of one measurement (actual value);
By use of metallic measuring tape;

(k) Height classes

| | |
|---|---|
| 0.01 — 0.30 m code: | 1 |
| 0.31 — 0.80 m | 2 |
| 0.81 — 1.30 m | 3 |
| 1.31 — 5.00 m | 4 |
| 5.01 — 10.00 m | 5 |
| 10.01 — 15.00 m | 6 |
| 15.01 — 20.00 m | 7 |
| 20.01 — 25.00 m | 8 |
| 25.01 — 30.00 m | 9 |
| 30.01 — 35.00 m | 10 |
| 35.01 — 40.00 m | 11 |
| etc.; | |

(l) Crown (social) classes

| | |
|---|---|
| Dominant | code: 1 |
| Codominant | 2 |
| Intermediate | 3 |
| Suppressed | 4 |
| Dead | 5 |

(m) Mass (tree components, before samples are removed)

To the nearest 0.1 kg (100 g) (However, if the total mass of a tree component is under 1 kg, record to the nearest 0.001 kg [1 g], using lab scale);
With a record of one measurement (actual value);
By use of a tensiometer weighing scale.

(n) Tree status

| | |
|---|---|
| Living | code: 1 |
| Dead | 2 |

(o) Crown closure

| | |
|---|---|
| 1 — 25% | code: 1 |
| 26 — 50% | 2 |
| 51 — 75% | 3 |
| 76 — 100% | 4 |

7. For terminology refer to Appendix A.

8. The tally sheets and the other recording forms are as per examples provided with this manual (Appendix E).

## B. Checklist of suggested equipment and instruments for field work

Forms, paper, pencils
Compass
Stereoscope
Right-angle prism
Pickets (range poles)
Metallic tapes (30 m and 2 m)
Diameter tape (with mm divisions)
Increment borers (25 cm and 40 cm)
Haga height-measurer
Swedish bark-measurer
F-shaped caliper for 9.1 cm diameters
Magnifier
Flagging tape (plastic or cloth)
Marker (felt-tip, for writing purposes)
Timber scribe
Axe with blade guards and extra handles
Sandvik clearing axe with spare blades
Chainsaw with spare chains
Chain-sharpener kit
Gasoline and oil containers
Fire extinguisher for gasoline fires
Gloves
Safety pants
Chainsaw earmuffs
Bow saw (45 cm) with spare blades
Pruning saw
Pruning clippers (secateurs)

Plywood platform (about 75 cm x 75 cm)
Tensiometer weighing scale (a direct-reading scale) with ladder and ropes
Polyethylene covers (3 m x 3 m)
Polyethylene bags (20 cm x 20 cm, and 30 cm x 50 cm)
Metal strings for sealing the bags or masking tape
Metal garbage cans with handles
Stapler and staples
Clipboards (metal with cover)
Balls of string (for making plot perimeters etc.)
Rechargeable pocket calculator
Walkie-talkie
First aid kit

## C. Definitions and standards of measurement relating to laboratory work

1. The samples should be dried in a forced-air oven at 105°C ± 3°C for 24 to 48 hours or until no change in sample mass is noted.

2. The green mass of a sample is the mass measured in the laboratory immediately after the polyethylene bag is opened.

3. The ovendry mass of a sample is the mass recorded immediately after the sample is removed from the dessiccator when there is no change in the mass of sample material.

4. Wood density is the ratio of the mass of a quantity of a substance to the volume of that quantity and is expressed in terms of mass per unit volume (in this manual, ovendry mass/green volume in terms of $g/cm^3$ at room temperature).

5. The green or ovendry samples should be weighed to the nearest 0.1 g.

6. The diameter and width of annual rings on the disks should be measured to the nearest millimeter.

7. Examples of recording forms are provided with this manual (Appendix E).

## D. Checklist of suggested equipment and instruments for laboratory work

Forms, paper, pencils
Wax pencil
Indelible copying pencil
Aluminum trays or foil pans (various sizes)
Paper towels (low-quality, brown)
Magnifier
Stapler and Staples
Sander (belt type)
Mallet and 3.8 cm chisel

Vise (for wood disks)
Handsaw
Pocket knife
Sturdy hunting knife
Water container and necessary attachments (a standard laboratory metal-stand with a metal arm and moving ring clamps)
Oven (thermostatically controlled and fan-vented)
Dessiccators
Silica gel for desiccators
Precision balance (capacity of at least 4.0 kg)

# APPENDIX C

Tree species codes

# Canadian Forestry Service numerical codes for tree species (Established in the 1950s)

| Code | Species Common Name | Species Botanical Name |
| --- | --- | --- |
| 010 | Pine | *Pinus* L. |
| 020 | Eastern white pine | *Pinus strobus* L. |
| 030 | Red pine | *Pinus resinosa* Ait. |
| 040 | Jack pine | *Pinus banksiana* Lamb. |
| 050 | Lodgepole pine | *Pinus contorta* Dougl. var. *latifolia* Engelm. |
| 060 | Shore pine | *Pinus contorta* Dougl. var. *contorta* |
| 070 | Ponderosa pine | *Pinus ponderosa* Laws. |
| 080 | Western white pine | *Pinus monticola* Dougl. |
| 090 | Miscellaneous pines | |
| 091 | Limber pine | *Pinus flexilis* James |
| 092 | Pitch pine | *Pinus rigida* Mill. |
| 093 | White bark pine | *Pinus albicaulis* Engelm. |
| 094 | Scots pine | *Pinus sylvestris* L. |
| 095 | Austrian pine | *Pinus nigra* Arnold |
| 096 | Mugho pine | *Pinus mugo* Turra var. *mughus* Zenari |
| 100 | Spruce | *Picea* A. Dietr. |
| 110 | Black spruce | *Picea mariana* (Mill.) B.S.P. |
| 120 | Red spruce | *Picea rubens* Sarg. |
| 130 | White spruce | *Picea glauca* (Moench) Voss |
| 131 | Porsild spruce | *Picea glauca* (Moench) Voss var. *porsildii* Raup |
| 132 | Western white spruce | *Picea glauca* (Moench) Voss var. *albertiana* (S. Brown) Sarg. |
| 140 | Engelmann spruce | *Picea engelmannii* Parry |
| 150 | Sitka spruce | *Picea sitchensis* (Bong.) Carr. |
| 190 | Miscellaneous spruce | |
| 191 | Norway spruce | *Picea abies* (L.) Karst. |
| 192 | Colorado spruce | *Picea pungens* Engelm. |
| 200 | Fir | *Abies* Mill. |
| 210 | Balsam fir | *Abies balsamea* (L.) Mill. |
| 211 | Bracted balsam fir | *Abies balsamea* (L.) Mill. var. *Phanerolepis* Fern. |
| 220 | Alpine fir | *Abies lasiocarpa* (Hook.) Nutt. |
| 230 | Grand fir | *Abies grandis* (Dougl.) Lindl. |
| 240 | Amabilis fir | *Abies amabilis* (Dougl.) Forbes |

| Code | Species Common Name | Species Botanical Name |
| --- | --- | --- |
| 250 | Douglas-fir | *Pseudotsuga menziesii* (Mirb.) Franco |
| 251 | Blue Douglas-fir | *Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco |
| 300 | Larch | *Larix* Mill. |
| 310 | Tamarack | *Larix laricina* (Du Roi) K. Koch |
| 311 | Alaska larch | *Larix laricina* (Du Roi) K. Koch var. *alaskensis* (Wight) Raup |
| 320 | Alpine larch | *Larix lyallii* Parl. |
| 330 | Western larch | *Larix occidentalis* Nutt. |
| 390 | Miscellaneous larches | |
| 391 | European larch | *Larix decidua* Mill. |
| 392 | Siberian larch | *Larix sibirica* Ledeb. |
| 400 | Cedar (Arbor-vitae) | *Thuja* L. |
| 410 | Eastern white cedar | *Thuja occidentalis* L. |
| 420 | Western red cedar | *Thuja plicata* Donn |
| 430 | Yellow cypress | *Chamaecyparis nootkatensis* (D. Don) Spach |
| 440 | Eastern red cedar | *Juniperus virginiana* L. |
| 450 | Rocky mountain juniper | *Juniperus scopulorum* Sarg. |
| 500 | Hemlock | *Tsuga* (Endl.) Carr. |
| 510 | Eastern hemlock | *Tsuga canadensis* (L.) Carr. |
| 520 | Western hemlock | *Tsuga heterophylla* (Raf.) Sarg. |
| 530 | Mountain hemlock | *Tsuga mertensiana* (Bong.) Carr. |
| 600 | Aspen or poplar | *Populus* L. |
| 610 | Trembling aspen | *Populus tremuloides* Michx. |
| 620 | Largetooth aspen | *Populus grandidentata* Michx. |
| 630 | Balsam poplar | *Populus balsamifera* L. |
| 640 | Eastern cottonwood | *Populus deltoides* Bartr. |
| 650 | Plains cottonwood | *Populus deltoides* var. *occidentalis* Rydb. |
| 660 | Lanceleaf cottonwood | *Populus* × *acuminata* Rydb. |
| 670 | Narrowleaf cottonwood | *Populus angustifolia* James |
| 680 | Black cottonwood | *Populus trichocarpa* Torr. and Gray |

| Code | Species Common Name | Species Botanical Name |
|---|---|---|
| 690 | Miscellaneous poplars | |
| 691 | Carolina poplar | *Populus × canadensis* Moench |
| 692 | Silver poplar | *Populus alba* L. |
| 693 | Lombardy poplar | *Populus nigra* L. var. *italica* Muenchh. |
| 700 | Birch | *Betula* L. |
| 710 | White birch | *Betula papyrifera* Marsh. |
| 711 | Western white (paper) birch | *Betula papyrifera* Marsh. var. *commutata* (Reg.) Fern. |
| 712 | Mountain white (paper) birch | *Betula papyrifera* Marsh. var. *cordifolia* (Reg.) Fern. |
| 713 | Alaska birch | *Betula neoalaskana* Sarg. |
| 714 | Large-fruited white birch | *Betula papyrifera* Marsh. var. *macrostachya* Fern. |
| 715 | Silver (weeping) white birch | *Betula pendula* Roth |
| 716 | Northwestern white birch | *Betula papyrifera* Marsh. var. *subcordata* (Rydb.) Sarg. |
| 717 | Gaspe white birch | *Betula papyrifera* Marsh. var. *elobata* (Fern.) Sarg. |
| 720 | Yellow birch | *Betula alleghaniensis* Britton (*Betula lutea* Michx. f.) |
| 730 | Grey birch | *Betula populifolia* Marsh. |
| 790 | Miscellaneous birch | |
| 791 | Water birch | *Betula occidentalis* Hook. (*Betula fontinalis* Sarg.) |
| 792 | Blueleaf birch | *Betula caerulea—grandis* Blanch. |
| 793 | Kenai birch | *Betula kenaica* Evans |
| 794 | Cherry birch | *Betula lenta* L. |
| 800 | Maple | *Acer* L. |
| 810 | Sugar maple | *Acer saccharum* Marsh. |
| 820 | Red maple | *Acer rubrum* L. |
| 830 | Black maple | *Acer nigrum* Michx. f. |
| 840 | Silver maple | *Acer saccharinum* L. |
| 850 | Manitoba maple | *Acer negundo* L. |
| 851 | Inland Manitoba maple | *Acer negundo* L. var. *interius* (Britt.) Sarg. |
| 860 | Bigleaf maple | *Acer macrophyllum* Pursh |
| 890 | Miscellaneous maple | |
| 891 | Mountain maple | *Acer spicatum* Lam. |
| 892 | Striped maple | *Acer pensylvanicum* L. |
| 893 | Vine maple | *Acer circinatum* Pursh |

| Code | Species Common Name | Species Botanical Name |
|---|---|---|
| 894 | Douglas maple | *Acer glabrum* Torr. var. *douglasii* (Hook.) Dipp. |
| 900 | Other hardwoods | |
| 901 | White alder | *Alnus rhombifolia* Nutt. |
| 902 | Red alder | *Alnus rubra* Bong. (*Alnus oregona* Nutt.) |
| 903 | Speckled alder | *Alnus rugosa* (Du Roi) Spreng. (*Alnus incana* [L.] Moench) |
| 904 | Mountain alder | *Alnus tenuifolia* Nutt. |
| 905 | Wild crab apple | *Malus coronaria* (L.) Mill. |
| 906 | Pacific crab apple | *Malus diversifolia* (Bong.) Roem. |
| 907 | Arbutus | *Arbutus menziesii* Pursh |
| 908 | Cascara | *Rhamnus purshiana* DC. |
| 909 | Chestnut | *Castanea dentata* (Marsh.) Borkh. |
| 910 | Ash | *Fraxinus* L. |
| 911 | White ash | *Fraxinus americana* L. |
| 912 | Black ash | *Fraxinus nigra* Marsh. |
| 913 | Red ash | *Fraxinus pennsylvanica* Marsh. |
| 914 | Northern red ash | *Fraxinus pennsylvanica* Marsh. var. *austini* Fern. |
| 915 | Green ash | *Fraxinus pennsylvanica* Marsh. var. *subintegerrima* (Vahl) Fern. |
| 916 | Blue ash | *Fraxinus quadrangulata* Michx. |
| 917 | American mountain-ash | *Sorbus americana* Marsh. |
| 918 | Showy mountain-ash | *Sorbus decora* (Sarg.) Schneid. |
| 920 | Basswood | *Tilia americana* L. |
| 921 | Kentucky coffee-tree | *Gymnocladus dioicus* (L.) K. Koch |
| 922 | Cucumber-tree | *Magnolia acuminata* L. |
| 923 | Alternate-leaved dogwood | *Cornus Alternifolia* L. f. |
| 924 | Roughleaf dogwood | *Cornus drummondii* C.A. Meyer |
| 925 | Eastern flowering dogwood | *Cornus florida* L. |
| 926 | Western flowering dogwood | *Cornus nuttallii* Audubon |
| 927 | Black gum | *Nyssa sylvatica* Marsh. |
| 928 | Hackberry | *Celtic occidentalis* L. |
| 929 | Golden-fruited hawthorn | *Crataegus chrysocarpa* Ashe |

| Code | Species Common Name | Species Botanical Name |
|---|---|---|
| 930 | Beech | *Fagus grandifolia* Ehrh. |
| 931 | Blue-beech | *Carpinus caroliniana* Walt. |
| 932 | Columbia hawthorn | *Crataegus columbiana* Howell |
| 933 | Black hawthorn | *Crataegus douglasii* Lindl. |
| 934 | Hop-tree | *Ptelea trifoliata* L. |
| 935 | Honey-locust | *Gleditsia triacanthos* L. |
| 936 | Red mulberry | *Morus rubra* L. |
| 937 | Pawpaw | *Asimina triloba* (L.) Dunal |
| 938 | Redbud | *Cercis canadensis* L. |
| 939 | Sassafras | *Sassafras albidum* (Nutt.) Nees |
| 940 | Cherry | *Prunus* L. |
| 941 | Wild plum | *Prunus americana* Marsh. |
| 942 | Bitter cherry | *Prunus emarginata* Dougl. |
| 943 | Canada plum | *Prunus nigra* Ait. |
| 944 | Pin cherry | *Prunus pensylvanica* L.f. |
| 945 | Black cherry | *Prunus serotina* Ehrh. |
| 946 | Choke cherry | *Prunus virginiana* L. |
| 947 | Western choke cherry | *Prunus virginiana* L. var. *demissa* (Nutt.) Torr. |
| 948 | Black choke cherry | *Prunus virginiana* L. var. *melanocarpa* (A. Nels.) Sarg. |
| 950 | Elm | *Ulmus* L. |
| 951 | White elm | *Ulmus americana* L. |
| 952 | Slippery elm | *Ulmus rubra* Mühl. |
| 953 | Rock elm | *Ulmus thomasi* Sarg. |
| 954 | Saskatoon-berry | *Amelanchier alnifolia* (Nutt.) |
| 955 | Downy serviceberry | *Amelanchier arborea* (Michx. f.) Fern. |
| 956 | Pacific serviceberry | *Amelanchier florida* Lindl. |
| 957 | Allegheny serviceberry | *Amelanchier laevis* Wieg. |
| 958 | Staghorn sumac | *Rhus typhina* L. |
| 959 | Sycamore | *Platanus occidentalis* L. |
| 960 | Hickory | *Carya* Nutt. |
| 961 | Bitternut hickory | *Carya cordiformis* (Wang.) K. Koch |
| 962 | Pignut hickory | *Carya glabra* (Mill.) Sweet |
| 963 | Big shellbark hickory | *Carya Laciniosa* (Michx. f.) Loud. |
| 964 | Red hickory | *Carya ovalis* (Wang.) Sarg. |
| 965 | Shagbark hickory | *Carya ovata* (Mill.) K. Koch |
| 966 | Ashleaf shagbark hickory | *Carya ovata* (Mill.) K. Koch var. *fraxinifolia* Sarg. |
| 967 | Mockernut hickory | *Carya tomentosa* Nutt. |
| 968 | Tulip-tree | *Liriodendron tulipifera* L. |
| 970 | Hop-hornbeam (Ironwood) | *Ostrya virginiana* (Mill.) K. Koch |
| 971 | Butternut | *Juglans cinerea* L. |
| 972 | Black walnut | *Juglans nigra* L. |
| 978 | Chinquapin oak | *Quercus muehlenbergii* Engelm. |
| 979 | Chestnut oak | *Quercus prinus* L. |
| 980 | Oak | *Quercus* L. |
| 981 | White oak | *Quercus alba* L. |
| 982 | Swamp white oak | *Quercus bicolor* Willd. |
| 983 | Red oak | *Quercus rubra* L. |
| 984 | Scarlet oak | *Quercus coccinea* Muenchh. |
| 985 | Black oak | *Quercus velutina* Lam. |
| 986 | Bur oak | *Quercus macrocarpa* Michx. |
| 987 | Pin oak | *Quercus palustris* Muenchh. |
| 988 | Northern pin oak | *Quercus ellipsoidalis* E.J. Hill |
| 989 | Garry oak | *Quercus garryana* Dougl. |
| 990 | Willow (all species) | *Salix* L. |

# APPENDIX D

## Determining wood density

# EXCERPTS FROM TAPPI'S[1] PAPER T18M-53, DATED MARCH 1953

## Specific Gravity (Density) and Moisture Content of Pulpwood

(The Standard is under jurisdiction of the Fibrous Materials Testing Committee)

This method is applicable to pulpwood chips and disks from the cross section of logs.

Specific gravity (sp. gr.) is the ratio of the mass of a quantity of a substance to the mass of an equal volume of water. It is an absolute value and, since it is a ratio of similar quantities, is expressed without units. Density is the ratio of the mass of a quantity of a substance to the volume of that quantity and consequently is expressed in terms of weight[2] per unit volume.

Since wood swells or shrinks, respectively, with absorption or loss of water, it is necessary to express the specific gravity under specified conditions of moisture content and volume. The most usual conditions are the moisture-free weight[3] and the maximum (green) or the minimum (moisture-free) volume. For most purposes, the maximum volume basis is sufficient. In the method described here, the specimen is considered to be swelled to its maximum volume when its moisture content exceeds the "fiber-saturation point," which lies between 18 and 26% by weight (wet basis) for most species. Procedures for obtaining the volume on both the green and moisture-free bases are described in this method.

## Apparatus

1. Weighing Scales: A balance with a capacity of 14 to 16 kg (30 to 35 lb) and sensitive to 0.5 g, preferably with a sliding-weight beam graduated in grams (or 0.001 lb).

2. Drying Oven: A drying oven maintained at 105 ± 3°C (220 ± 5°F).

3. Disk Holder: A suitable holder consists of a 3/16-inch-diameter rod, 8 to 10 inches long, with one end fitted into the center of a brass or bronze disk about 4 inches in diameter and 1/4 inch thick. The side of the disk opposite the rod is fitted with three prongs about 11/4 inches long and 1/8 inch in diameter. The sharpened points of the prongs are equidistantly spaced about 3 inches. Variations in design of the disk holder are permissible.

4. Auxiliary Apparatus: Ring stand and clamps. Pans and other containers for use in soaking samples and obtaining their submerged weights.

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[1] Technical Association of the Pulp and Paper Industry, One Dunwoody Park, Atlanta, Ga. 30338.

[2] Authors' note: The term weight in this paper is equivalent to the term mass in the manual.

[3] Many wood technologists believe that the specific gravity of wood is truly expressed only on the basis of moisture-free weight and maximum (green) volume.

## Specific Gravity or Density

1. Soaking: Submerge the sample in water at room temperature for at least 1 hour, or longer if necessary.
   The purpose of soaking the wood is two-fold: first to insure that the specimen is swelled to its green volume, and second to eliminate an error which occurs if the wood absorbs water during the weighing operation for obtaining its volume. Thus, it is necessary to insure that the internal cavities be practically filled with water prior to weighing when submerged, so that further absorption during this weighing is negligible. When the moisture content is above the fiber-saturation point, a 1-hour soaking period is usually sufficient to accomplish both these conditions; otherwise, the soaking should be prolonged until (cracks), if any, are closed.

2. Draining: Let the free water drain from the soaked disks by standing them on edge for a short time and then patting with a cloth or piece of blotting paper just prior to weighing. While draining, the disks should not be exposed to a draft, fan, or direct heat. Disks whose surfaces show signs of drying out before the weighings can be completed should be returned to the soaking vessel.

3. Determination of Green Volume: In determining the volume of the specimen it is the outside boundary, exclusive of surface depressions, that is required. For this reason the disks should be cleanly cut and all cracks and checks swelled with water until they are closed.
   One of the most accurate methods of obtaining the volume of an object is by displacement in a liquid, usually water. The procedures given below may be varied both as to apparatus and operation. Variations are permissible so long as they adhere to the fundamental principle involved. Two procedures are described as Method 1 (On the Balance) and Method 2 (Off the Balance).

## Method 1 (On the Balance)

Place a vessel holding enough water at room temperature to completely immerse an 8- or 9-inch diameter disk on the left-hand pan of the scales, and counterbalance the weight of the container and water. Keep the counterbalance on the pan throughout all subsequent operations.

Impinge a drained disk on the three-pronged rod and carefully lower the disk into the vessel so as not to entrap bubbles of air. In a completely submerged position and not touching either sides or bottom of the vessel, clamp it by means of the ring stand and clamp. If not more than 1/2 inch of the prongs are immersed, the volume of water displaced by them will be negligible. Again balance the scales. The weight added to restore balance is the weight, C, of the volume of water equivalent to the volume of the specimen.[4]

Note: Disks too large for the container should have been cut into two or more pieces and properly identified prior to soaking. The above operations are performed on each piece separately and the weights added to obtain the weight, C, for the whole disk.

Remove the disk and add water to the vessel until it is counterbalanced again before immersing the next specimen.

[4] Authors' note: The weight added, if read in grams, is equal to the volume of the specimen in cubic centimeters.

# APPENDIX E

Recording forms for field and laboratory work together with recorded examples

STUDY No.: DATE: NAME:

FORTRAN CODING FORM No.1

# FIELD DATA: SAMPLE–PLOT MEASUREMENTS AND TALLIES

| Plot No. | Area (m²) | Forest type | Crown closure (%) | Structure | Origin | Maturity | History | Site class | Elevation | Aspect | Slope position | Slope percent | Soil type | Soil moisture | Province | Latitude (° ′) | Longitude (° ′) | Tree No. | Species code | dbhob (cm) | Total height (1) (m) | Total age (yr) | Tree status | dbhob class | Height class (1) | Crown class (2) | Card No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 207 | 400 | 1 | 42 | 1 | 2 | 3 | 1 | 2 | 2 | 4 | 2 | 1 | 5 | 3 | 2 | 4556 | 7725 | 1 | 40 | 142 | 1180 | 35 | 1 | | | | 10 |
| | | | | | | | | | | | | | | | | | | 2 | 40 | 87 | 770 | 24 | 2 | | | | |
| | | | | | | | | | | | | | | | | | | 3 | 40 | 319 | 1976 | 58 | 1 | | | | |
| | | | | | | | | | | | | | | | | | | 4 | 40 | 224 | 1690 | 48 | 1 | | | | |
| | | | | | | | | | | | | | | | | | | 5 | 40 | 96 | 1227 | 40 | 1 | | | | |
| | | | | | | | | | | | | | | | | | | 6 | 40 | 176 | 1442 | 38 | 2 | | | | |
| | | | | | | | | | | | | | | | | | | 7 | 40 | 345 | 2280 | 74 | 1 | | | | |
| 207 | 25 | | | | | | | | | | | | | | | | | 8 | 40 | 27 | 310 | 12 | 1 | | | | |
| | | | | | | | | | | | | | | | | | | 9 | 40 | 32 | 190 | 11 | 1 | | | | |
| | | | | | | | | | | | | | | | | | | 10 | 40 | 11 | 140 | 6 | 1 | | | | |
| | | | | | | | | | | | | | | | | | | 11 | 40 | 49 | 650 | 20 | 2 | | | | |
| | | | | | | | | | | | | | | | | | | 12 | 40 | 36 | 490 | 16 | 1 | | | | |
| 207 | 4 | | | | | | | | | | | | | | | | | 13 | 40 | | | | 1 | | | 2 | |
| | | | | | | | | | | | | | | | | | | 14 | 610 | | | | 1 | | | 1 | |
| | | | | | | | | | | | | | | | | | | 15 | 40 | | | | 1 | | | 1 | |

(1) For the height-measurement trees and the mass-sampling trees only and for shrubs.

(2) For the five age-measurement trees only.

STUDY No.: DATE:

NAME:

FORTRAN CODING FORM No. 2

## FIELD DATA: MASS AND VOLUME SAMPLE–TREE MEASUREMENTS (BASICS)

| Plot No. | Tree No. | Species code | dbhob (cm) | BH dbt (cm) | Total age (yr) | Total height (m) | Merch. height (m) | Height to first live br. (m) | Stump height (m) | Crown diam. (m) | Ground level dob (cm) | Ground level dbt (cm) | Stump height dob (cm) | Stump height dbt (cm) | Height: 0.80m dob (cm) | Height: 0.80m dbt (cm) | Merch. ht dob (cm) | Merch. ht dbt (cm) | Base of live br. dob (cm) | Base of live br. dbt (cm) | Tree status | dbhob class | Height class | Crown class | | Card No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 207 | 3 | 40 | 319 | 22 | 58 | 1976 | 1617 | 1075 | 30 | 50 | 411 | 42 | 391 | 36 | 355 | 29 | 91 | 7 | 225 | 11 | 1 | | | | | 20 |
| 207 | 5 | 40 | 96 | 8 | 40 | 1227 | | 782 | 30 | 25 | 140 | 20 | 122 | 17 | 107 | 12 | | | 66 | 5 | 1 | | | | | |
| 207 | 9 | 40 | 32 | 2 | 11 | 190 | | 85 | 30 | 6 | 67 | 5 | 58 | 4 | 45 | 3 | | | 43 | 3 | 1 | | | | | |
| 207 | 10 | 40 | 11 | 2 | 6 | 140 | | 65 | 30 | 5 | 43 | 3 | 34 | 3 | 22 | 2 | | | 26 | 2 | 1 | | | | | |
| 207 | 6 | 40 | 176 | | 38 | 1442 | | | | | 241 | | 210 | | 193 | | | | | | 2 | | | | | |
| 207 | 11 | 40 | 49 | 3 | 20 | 650 | | | | | 74 | 6 | 65 | 5 | 57 | | | | | | 2 | | | | | |

STUDY No.: DATE: NAME:

FORTRAN CODING FORM No. 3

## FIELD DATA: 2m SECTION–DIAMETER MEASUREMENTS [1]

| Plot No. | Tree No. | Species code | Number of 2m sections | Diameter outside bark at: 2 m (cm) | 4 m (cm) | 6 m (cm) | 8 m (cm) | 10 m (cm) | 12 m (cm) | 14 m (cm) | 16 m (cm) | 18 m (cm) | 20 m (cm) | 22 m (cm) | 24 m (cm) | 26 m (cm) | 28 m (cm) | 30 m (cm) | 32 m (cm) | 34 m (cm) | 36 m (cm) | 38 m (cm) | 40 m (cm) | | Card No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 207 | 3 | 40 | 9 | 307 | 288 | 258 | 233 | 207 | 186 | 131 | 74 | 32 | | | | | | | | | | | | | 30 |
| 207 | 5 | 40 | 6 | 92 | 85 | 77 | 64 | 42 | 15 | | | | | | | | | | | | | | | | |

(1) For trees larger than or equal to 5.1 cm dbhpb only.

STUDY No.: DATE:
NAME:

FORTRAN CODING FORM No.4

## FIELD DATA: 2m SECTION—BARK MEASUREMENTS (1)

| Plot No. | Tree No. | Species code | Number of 2m sections | Double-bark thickness at: 2 m (cm) | 4 m (cm) | 6 m (cm) | 8 m (cm) | 10 m (cm) | 12 m (cm) | 14 m (cm) | 16 m (cm) | 18 m (cm) | 20 m (cm) | 22 m (cm) | 24 m (cm) | 26 m (cm) | 28 m (cm) | 30 m (cm) | 32 m (cm) | 34 m (cm) | 36 m (cm) | 38 m (cm) | 40 m (cm) | | Card No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 207 | 3 | 40 | 9 | 20 | 19 | 17 | 16 | 11 | 10 | 8 | 7 | 4 | | | | | | | | | | | | | 40 |
| 207 | 5 | 40 | 6 | 7 | 6 | 5 | 5 | 3 | 1 | | | | | | | | | | | | | | | | |

(1) For trees larger than or equal to 5.1 cm dbhob only.

STUDY No.: DATE:

NAME:

FORTRAN CODING FORM No.5

# FIELD DATA: GREEN–MASS MEASUREMENTS

| Plot No. | Tree No. | Species code | Twigs and leaves (kg) | Large live branches [1] (kg) | Small live branches [1] (kg) | Dead branches [1] (kg) | New cones (kg) | Old cones (kg) | Stem sections [1]: lower ⅓ [2] (kg) | Stem sections [1]: middle (kg) | Stem sections [1]: upper ⅓ (kg) | Stem sections [1]: top (kg) | Card No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 207 | 3 | 40 | 63900 | 20000 | 64200 | 40700 | 500 | 300 | 280900 | 207900 | 99500 | 6400 | 50 |
| 207 | 5 | 40 | 4800 | | 2300 | 2800 | | | 48300 | | | | |
| 207 | 9 | 40 | 60 | | 350 | 40 | | | 1500 | | | | |
| 207 | 6 | 40 | | | | | | | 80100 | | | | |
| 207 | 11 | 40 | | | | | | | 3100 | | | | |

(1) Including bark.

(2) Total mass for the whole *stem* of the tree (less stump) if there is no merchantable bole, or total mass for the whole tree if the tree is dead.

STUDY No.: DATE:
NAME:

FORTRAN CODING FORM No. 6

## LAB DATA: TWIG, LEAF, AND BRANCH MASS MEASUREMENTS ON SAMPLES

| Plot No. | Tree No. | Species code | Twigs (1) | | Leaves | | Large live branches | | | | Small live branches | | | | Dead branches | | New cones | | Old cones | | Card No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wood | | Bark | | Wood | | Bark | | | | | | | | |
| | | | GM(g) | OM(g) | GM(g) | OM(g) | GM(g) | OM(g) | GM(g) | OM(g) | GM(g) | OM(g) | GM(g) | OM(g) | GM(g) | OM(g) | GM(g) | OM(g) | GM(g) | OM(g) | |
| 207 | 3 | 40 | 537 | 259 | 495 | 240 | 750 | 310 | 84 | 36 | 788 | 328 | 87 | 36 | 1482 | 936 | 915 | 302 | 557 | 481 | 6 0 |
| 207 | 5 | 40 | 549 | 250 | 507 | 230 | | | | | 284 | 134 | 31 | 15 | 646 | 434 | | | | | |
| 207 | 9 | 40 | 195 | 92 | 144 | 53 | | | | | 566 | 258 | 206 | 87 | 122 | 65 | | | | | |
| 207 | 10 | 40 | 155 | 90 | | | | | | | | | | | | | | | | | |

(1) Total mass for plants equal to or smaller than 1.30m in height.

STUDY No.: DATE:
NAME:

FORTRAN CODING FORM No. 7

## LAB DATA: STEM–DISK MEASUREMENTS ON SAMPLES

| Plot No. | Tree No. | Species code | Number of stem disks | Wood GM (g) | Wood OM (g) | Bark GM (g) | Bark OM (g) | Wedgewood Volume (cm³) | Wedgewood OM (g) | Number of annual rings | Avg. dob (1) (cm) | dbt (2) (cm) | Width of 10 annual rings (cm) | Card No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 207 | 3 | 40 | 4 | 20236 | 8217 | 1378 | 797 | 2983 | 1010 | 48 | 319 | 22 | 32 | 7 1 |
| 207 | 3 | 40 | | 20464 | 8520 | 1198 | 662 | 2306 | 742 | 43 | 272 | 18 | 30 | 2 |
| 207 | 3 | 40 | | 13096 | 6412 | 861 | 439 | 1295 | 617 | 36 | 210 | 11 | 27 | 3 |
| 207 | 3 | 40 | | 1343 | 438 | 175 | 69 | 512 | 165 | 17 | 91 | 7 | 25 | 4 |
| 207 | 5 | 40 | 2 | 1234 | 542 | 103 | 48 | 402 | 152 | 30 | 96 | 8 | 14 | 1 |
| 207 | 5 | 40 | | 685 | 251 | 97 | 42 | 270 | 90 | 21 | 75 | 5 | 12 | 2 |
| 207 | 9 | 40 | 2 | 104 | 61 | 14 | 7 | 102 | 38 | 6 | 32 | 2 | 25 | 1 |
| 207 | 9 | 40 | | 182 | 84 | 25 | 11 | 148 | 66 | 8 | 40 | 3 | 26 | 2 |
| 207 | 6 | 40 | 2 | 1865 | 1044 | | | | | | | | | 1 |
| 207 | 6 | 40 | | 823 | 496 | | | | | | | | | 2 |
| 207 | 11 | 40 | 2 | 120 | 60 | | | | | | 49 | 3 | | 1 |
| 207 | 11 | 40 | | 37 | 32 | | | | | | 32 | 2 | | 2 |

Enter disk number in column 80

(1) Diameters outside bark of the first and the fourth disks are the same as the dob at breast height and at merchantable height, respectively.
(2) Double-bark thicknesses of the first and the fourth disks are the same as the dbt at breast height and at merchantable height, respectively.

# FORM No. 8: SAMPLE-TREE INFORMATION SUMMARIES

SPECIES: 40

| Diameter class | | | Diameter class | | | Diameter class | | | Diameter class | | | Diameter class | | | Diameter class | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.1cm - 5.0cm | | | 5.1cm - 10.0cm | | | 10.1cm - 15.0cm | | | 15.1cm - 20.0cm | | | 20.1cm - 25.0cm | | | 25.1cm & over | | |
| Plot No / Tree No | dbhob (cm) | ht (m) | Plot No / Tree No | dbhob (cm) | ht (m) | Plot No / Tree No | dbhob (cm) | ht (m) | Plot No / Tree No | dbhob (cm) | ht (m) | Plot No / Tree No | dbhob (cm) | ht (m) | Plot No / Tree No | dbhob (cm) | ht (m) |
| 207/9 | 3.2 | 1.90 | 207/5 | 9.6 | 12.27 | | | | | | | | | | 207/3 | 31.9 | 19.76 |
| 10 | 1.1 | 1.40 | | | | | | | | | | | | | | | |

# APPENDIX F

## References for biomass equations developed under ENFOR

| SPECIES | BIOMASS COMPONENT* | LOCATION | REFERENCE |
|---|---|---|---|
| Alder | 5 | Prairie | Peterson et al. (1982) |
| Alder, red | 1 2 4 | British Columbia | Standish et al. (1985) |
| Ash, black | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| Ash, red | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| Ash, white | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| | 1 2 3 4 5 | New Brunswick | Ker (1980b) |
| Aspen, largetooth | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| | 1 2 3 4 5 | Ontario | Alemdag & Horton (1981) |
| | 3 4 5 | Nova Scotia | Freedman et al. (1982) |
| | 1 2 3 4 5 | Ontario | Horton (1981b) |
| Aspen, trembling | 1 2 3 4 5 | Ontario | Alemdag (1981) |
| | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| | 1 2 3 4 5 | Ontario | Alemdag & Horton (1981) |
| | 1 2 3 4 5 | Newfoundland | Anon. (1982) |
| | 5 | Western Canada | Bella & Franceschi (1980) |
| | 1 5 | Canada | Evert (1983) |
| | 1 2 | Canada | Evert (1985) |
| | 3 4 5 | Nova Scotia | Freedman et al. (1982) |
| | 1 5 | Ontario | Horton (1981a) |
| | 1 2 3 5 | Nova Scotia | Ker (1980a) |
| | 1 3 4 5 | Maritime | Ker (1984) |
| | 1 2 3 4 5 | Newfoundland | Lavigne (1982) |
| | 3 4 5 | Newfoundland | Lavigne & Nostrand (1981) |
| | 1 2 3 4 5 | Yukon | Manning et al. (1984) |
| | 5 | Prairie | Peterson et al. (1982) |
| | 5 | Quebec | Quellet (1983b) |
| | 1 2 | Prairie | Singh (1982) |
| | 1 2 | North West Territories | Singh (1984b) |
| | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Basswood | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| Beech | 1 2 3 4 5 | New Brunswick | Ker (1980b) |
| Beech, American | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| Birch, grey | 1 2 3 5 | Nova Scotia | Ker (1980a) |
| Birch, white | 1 2 3 4 5 | Ontario | Alemdag (1981) |
| | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| | 1 2 3 4 5 | Newfoundland | Anon. (1982) |
| | 3 4 5 | Nova Scotia | Freedman et al. (1982) |
| | 1 2 3 5 | Nova Scotia | Ker (1980a) |
| | 1 3 4 5 | Maritimes | Ker (1984) |
| | 1 2 3 4 5 | Newfoundland | Lavigne (1982) |
| | 3 4 5 | Newfoundland | Lavigne & Nostrand (1981) |
| | 1 2 3 4 5 | Yukon | Manning et al. (1984) |
| | 5 | Quebec | Ouellet (1983b) |
| | 5 | Prairie | Peterson et al. (1982) |
| Birch, white | 1 2 | Prairie | Singh (1982) |
| | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Birch, yellow | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| | 1 2 3 4 5 | Ontario | Alemdag & Horton (1981) |
| | 3 4 5 | Nova Scotia | Freedman et al. (1982) |
| | 1 2 3 4 5 | New Brunswick | Ker (1980b) |
| | 1 2 3 4 5 | Newfoundland | Lavigne (1982) |

| SPECIES | BIOMASS COMPONENT* | LOCATION | REFERENCE |
|---|---|---|---|
| | 5 | Quebec | Ouellet (1983b) |
| | 1 2 4 5 | Ontario | Thomas (1981) |
| Cedar, E. red | 1 2 3 4 5 | Ontario | Alemdag (1983) |
| Cedar, W. red | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Cedar, E. white | 1 2 3 4 5 | Ontario | Alemdag (1983) |
| | 1 2 3 4 5 | New Brunswick | Ker (1980b) |
| Cherry, black | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| Cottonwood, black | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Elm, white | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| Fir, alpine | 1 2 | Prairie | Singh (1982) |
| Fir, balsam | 1 2 3 4 5 | Ontario | Alemdag (1983) |
| | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| | 1 2 3 4 5 | Newfoundland | Anon. (1982) |
| | 1 2 3 4 5 | Nova Scotia | Freedman et al. (1982) |
| | 1 2 3 5 | Nova Scotia | Ker (1980a) |
| | 1 3 4 5 | Maritimes | Ker (1984) |
| | 1 2 3 4 5 | Newfoundland | Lavigne (1982) |
| | 3 4 5 | Newfoundland | Lavigne & Nostrand (1981) |
| | 5 | Quebec | Ouellet (1983b) |
| | 1 2 | Prairie | Singh (1982) |
| Fir, Cstl. Douglas | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Fir, grand | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Fir, Pacif. silver | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Fir, subalpine | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Fir, yellow | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| | 1 2 4 5 | Ontario | Thomas (1981) |
| Hardwoods | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| Hemlock, E. | 1 2 3 4 5 | Ontario | Alemdag (1983) |
| | 1 2 3 4 5 | New Brunswick | Ker (1980b) |
| Hemlock, W. | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Hickory | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| Ironwood | 1 2 3 4 5 | Ontario | Alemdag (1981) |
| | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| Larch, E. | 1 2 3 4 5 | Ontario | Alemdag (1983) |
| | 1 2 3 4 5 | Newfoundland | Anon. (1982) |
| | 1 2 3 5 | Nova Scotia | Ker (1980a) |
| | 1 2 3 4 5 | Newfoundland | Lavigne (1982) |
| | 3 4 5 | Newfoundland | Lavigne & Nostrand (1981) |
| | 5 | Quebec | Ouellet (1983b) |
| | 1 2 | Prairie | Singh (1982) |
| | 1 2 | North West Territories | Singh (1984b) |
| Larch, W. | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Maple, hard | 1 2 4 5 | Ontario | Thomas (1981) |
| Maple, red | 1 2 3 4 5 | Ontario | Alemdag (1981) |
| | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| | 3 4 5 | Nova Scotia | Freedman et al. (1982) |
| | 1 2 3 5 | Nova Scotia | Ker (1980a) |
| | 1 3 4 5 | Maritimes | Ker (1984) |
| Maple, red/sugar | 5 | Quebec | Ouellet (1983b) |
| Maple, silver | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| Maple, sugar | 1 2 3 4 5 | Ontario | Alemdag (1981) |
| | 1 2 3 4 5 | Ontario | Alemdag (1984b) |

| SPECIES | BIOMASS COMPONENT* | LOCATION | REFERENCE |
|---|---|---|---|
| | 3 4 5 | Nova Scotia | Freedman et al. (1982) |
| | 1 2 3 4 5 | New Brunswick | Ker (1980b) |
| Oak, red | 1 2 3 4 5 | Ontario | Alemdag (1981b) |
| | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| Oak, white | 1 2 3 4 5 | Ontario | Alemdag (1984b) |
| Pine, E. white | 1 2 3 4 5 | Ontario | Alemdag (1983) |
| | 1 2 3 4 5 | New Brunswick | Ker (1980b) |
| | 5 | Quebec | Ouellet (1983b) |
| Pine, jack | 1 2 3 4 5 | Ontario | Alemdag (1983) |
| | 1 2 3 5 | Nova Scotia | Ker (1980a) |
| | 1 3 4 5 | Maritimes | Ker (1984) |
| | 5 | Quebec | Ouellet (1983b) |
| | 1 2 | Prairie | Singh (1982) |
| | 1 2 | North West Territories | Singh (1984b) |
| Pine, lodgepole | 1 2 3 4 5 | Yukon | Manning et al. (1984) |
| | 5 | Prairie | Peterson et al. (1982) |
| | 1 2 | Prairie | Singh (1982) |
| | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Pine, mountain | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Pine, ponderosa | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Pine, red | 1 2 3 4 5 | Ontario | Alemdag (1983) |
| | 1 2 3 4 5 | Ontario | Alemdag & Stiell (1982) |
| | 1 2 3 5 | Nova Scotia | Ker (1980a) |
| | 5 | Quebec | Ouellet (1983b) |
| Pine, shore | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Pine, W. white | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Poplar, balsam | 5 | Western Canada | Bella & Franceschi (1980) |
| | 1 2 3 4 5 | Ontario | Horton (1981b) |
| | 5 | Prairie | Peterson et al. (1982) |
| | 1 2 | Prairie | Singh (1982) |
| | 1 2 | North West Territories | Singh (1984b) |
| | 1 2 4 5 | Ontario | Thomas (1981) |
| Softwoods | 1 2 3 4 5 | Ontario | Alemdag (1983) |
| Spruce, black | 1 2 3 4 5 | Ontario | Alemdag (1983) |
| | 1 2 3 4 5 | Newfoundland | Anon. (1982) |
| | 1 2 | Canada | Evert (1985) |
| | 1 2 3 4 5 | Nova Scotia | Freedman et al. (1982) |
| | 1 2 3 4 5 | Nova Scotia | Ker (1980a) |
| | 1 2 3 4 5 | Newfoundland | Lavigne (1982) |
| | 3 4 5 | Newfoundland | Lavigne & Nostrand (1981) |
| | 1 2 3 4 5 | Yukon | Manning et al. (1984) |
| Spruce, black | 1 2 5 | Quebec | Ouellet (1983a) |
| | 1 2 | Prairie | Singh (1982) |
| | 1 2 | North West Territories | Singh (1984b) |
| | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Spruce, red | 1 2 3 4 5 | Nova Scotia | Freedman et al. (1982) |
| | 5 | Quebec | Ouellet (1983b) |
| Spruce, red/black | 1 3 4 5 | Maritimes | Ker (1984) |
| Spruce, sitka | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Spruce, white | 1 2 3 4 5 | Ontario | Alemdag (1983) |
| | 1 2 3 4 5 | Newfoundland | Anon. (1982) |

| SPECIES | BIOMASS COMPONENT* | LOCATION | REFERENCE |
|---|---|---|---|
| | 1 2 | Canada | Evert (1985) |
| | 1 2 3 4 5 | Nova Scotia | Freedman et al. (1982) |
| | 1 2 3 5 | Nova Scotia | Ker (1980a) |
| | 1 3 4 5 | Maritimes | Ker (1984) |
| | 1 2 3 4 5 | Newfoundland | Lavigne (1982) |
| | 3 4 5 | Newfoundland | Lavigne & Nostrand (1981) |
| | 5 | Quebec | Ouellet (1983b) |
| | 1 2 | Prairie | Singh (1982) |
| | 1 2 | North West Territories | Singh (1984b) |
| | 1 2 4 5 | British Columbia | Standish et al. (1985) |
| Willow | 5 | Prairie | Peterson et al. (1982) |

*1 = Stem wood
2 = Stem bark
3 = Live branches
4 = Twigs and leaves (foliage)
5 = Whole tree