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Permanent-Plot Procedures for Silvicultural and Yield Research

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Abstract

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This paper reviews purposes and procedures for establishing and maintaining permanent plots for silvicultural and yield research, sampling and plot design, common errors, and procedures for measuring and recording data. It is a revision and update of a 1983 publication. Although some details are specific to coastal Pacific Northwest conditions, most of the material is widely applicable.

Keywords: Plot analysis, permanent sample plots, tree measurement, sample plot design, growth and yield.

Contents

Introduction

Rational forest management requires estimates of expected development of stands under current and future stand conditions and management regimes as a basis for managerial choices, economic decisions, and field application of chosen regimes. This information comes from observations of forest stand development and from silvicultural experiments.

Estimates of present stand volumes and growth rates usually come from forest inventories. The planned forest of the future, however, may be considerably different from the present forest. Present average growth rates do not tell us what we can expect from the future forest, nor do they provide guides to desirable management regimes or a basis for choice among possible alternative regimes. These require estimates of the behavior of managed stands, including response to such management measures as early spacing control, thinning, fertilization, control of competing vegetation, and use of genetically selected planting stock. They may also involve estimates of biomass production and carbon sequestration, development of structural features related to wildlife habitat, and visual effects. Such estimates are provided by silvicultural experiments designed to determine the relations between growth, stand conditions, and stand treatments; and by various types of yield tables and stand simulators that attempt to combine these relations into generally applicable systems for estimating behavior and production of future stands.

Background

From about 1920 to the 1940s, normal yield tables were developed for many major species. Procedures for constructing normal yield tables from temporary plot measurements in well-stocked wild stands were worked out and standardized. During the subsequent two decades, relatively little new work was done on yield tables, but many silvicultural field experiments were established.

Since the 1960s, there has been renewed interest and activity in yield research. This was stimulated by the advent of the computer, the availability of increasing amounts of data from thinning and fertilization experiments, and the need for silvicultural guides and yield estimates applicable to young stands and to increasingly intensive management. The former distinction between yield research and silvicultural research is no longer clear, and today's yield tables are in the form of various types of simulation models that use the results of silvicultural research to estimate growth rates and yields for a range of possible management regimes.

Estimates of growth rates and treatment responses are often wanted for stand conditions and stand treatments that do not yet exist on large operationally developed forest areas. These estimates must therefore be based on silvicultural

Standardization of plot data would facilitate estimation of regional growth rates for silvicultural treatments.

experiments and small experimentally treated areas. Most of the present information on thinning and fertilization has been so developed. There have been many studies showing response at particular locations, usually reported as case studies. But until roughly the 1980s, there had been relatively few attempts to combine such information into regionally applicable quantitative generalizations.

Such generalized estimates are badly needed. Few individuals or organizations possess a database adequate for the purpose, and there is much to be gained by pooling data in cooperative efforts among research workers and research organizations. This requires compatibility and comparable reliability in data collected by different individuals and organizations.

Certain defects that are repeatedly encountered severely limit or destroy the usefulness of much data obtained at high cost in time and money:

- Documentation has often been inadequate. Records of procedures, stand measurements, and stand treatments are often incomplete, poorly organized, or contradictory.
- Plots have often been excessively small, installed without buffers between adjacent treatments, or both.
- Treatments have sometimes been assigned subjectively rather than randomly, possibly biasing analyses.
- Height measurements have frequently been inadequate in number, distribution, or accuracy, and have sometimes been omitted altogether.
- Measurements have often been omitted for trees below some arbitrary "merchantable" size, which results in truncated diameter distributions and statistics that cannot be compared with other data.
- Estimates of tree and stand ages have often been inaccurate. Sampling has often been inadequate, definitions are ambiguous or inconsistent, and procedures have not been documented.
- Initial stand conditions, prior to treatment, were often not recorded.
- Plot areas may be unreliable because of poor plot surveys and poor records.
- Changes have sometimes been made in treatments, plot sizes, or measurement procedures for reasons of immediate expediency in fieldwork, without adequate documentation or consideration of effects on later analyses.
- Data codes and measurement standards have often been inconsistent or incompatible. This prevents use of a common set of computer programs or pooling of data among organizations or individuals, without costly and time-consuming conversions and loss of information.

Purpose

This paper discusses items that should be considered by anyone planning or undertaking establishment and measurement of field plots in silvicultural experimentation or for construction of yield tables. It is concerned primarily with design and measurement of individual plots. The larger questions of experimental design in general, and of overall sampling design, are touched on only as they relate to plot procedure. Some design references specific to forestry applications include Andrew 1986, Jeffers 1972, and Stafford 1985. Important considerations in laying out plots within an experimental design are uniformity in initial conditions, randomization, and replication. Uniformity among plots allows for more efficient measurement of treatment differences. Random assignment of treatments to plots (including the control) ensures that the estimate of experimental error is valid and that differences measured are due to treatments and not to other factors. Replication (at a single location or at different locations) provides an estimate of the variation within the experiment (experimental error) to determine if differences are significant or important and expand the applicability or scope of inference beyond a single case study.

Procedures for establishing and maintaining such research plots have been discussed in a number of past publications, including Curtis 1983; Decourt 1973; Forest Productivity Council of British Columbia 1999; Forestry Commission 1979; Hummel and others 1959; Robertson and Mulloy 1944, 1946; Synnott 1979; and USDA Forest Service 1935. There are also various in-house manuals that are not widely available (for example, Bluhm and others 2003, Maguire and others 1992). These contain much valuable information; however, some procedures discussed are now out of date, and many of these manuals are oriented specifically to the needs and procedures of individual organizations and projects.

Installation and maintenance of permanent plots are not simple tasks. This paper is not intended to be a complete, detailed manual of field procedure. Rather, it is intended as an aid for those preparing procedural specifications. It should help them to avoid repetition of past mistakes by calling attention to decisions needed in the planning stage of a research study. It should help to provide some standardization and compatibility between data sets. It may give field personnel insight into the reasons behind procedures and offer possible alternatives.

Portions of the discussion may appear to be mere repetition of the obvious. But experience shows that many obvious points become obvious only in the analysis stage when it is too late to correct mistakes made in establishing and measuring plots.

The discussion is generally in terms of fixed-area remeasured plots and even-aged stands with one principal species. Historically, these are the plot type and stand condition most often used in silvicultural experiments and in construction of managed stand yield tables and simulation programs; however, many of the same ideas and principles apply to studies using variable-radius plots and to other stand conditions. Although aimed at research applications, they may also suggest possible modifications in inventory, stand examination, and monitoring procedures to make these procedures more compatible with information developed from research.

Necessarily, recommendations often represent informed opinion and the authors' best judgments rather than established fact.

Data Sources

Approaches to silvicultural and yield estimation problems are influenced by (1) specific objectives, (2) nature of the forest (even aged vs. uneven aged, pure vs. mixed species), (3) data already available, and (4) feasibility of acquiring new data. Data may come from research plots installed to secure information on a particular relation, from research plots designed to sample specified stand conditions over a region, from existing research plots originally installed for these or other purposes, from management inventories, or from some combination of these.

Inventory data are often available in large quantity, and they can provide a representative sample of the existing forest. They are usually the best data source for short-term projections; they have not generally proved satisfactory for other purposes for several reasons.

The small plots used in many inventories are subject to unknown edge effects. Usual procedures provide only rough estimates of such attributes as age and height for the individual plot and frequently omit or inadequately sample stems below some arbitrary and fairly large diameter. Such data are well suited to estimation of stratum means or existing stand conditions for specific areas (commonly their designed objective) but are poorly suited to estimation of treatment responses or the regression relations used in stand simulation.

When estimating treatment effects, comparing potential treatment regimes, and making long-term estimates for future managed stands, one is often dealing with conditions that as yet exist only on small areas and very restricted experimental installations. These are not sampled adequately, if at all, by management inventories. If sampled, the uncontrolled variation present often prevents satisfactory evaluation of treatment response.

For these and similar reasons, most silvicultural research is based on plots that are independent of management inventories. Yield research and modeling has often been based on such data, but may use some combination of inventory data and independently established silvicultural research plots (Kohl et al. 1995).

Plot Classification

Field plots used in silvicultural and yield research can be classified into three groups:

- Temporary (single-measurement) plots.
- Temporary plots, with supplementary growth information.
- Permanent (remeasured) plots.

Temporary plots—The normal yield tables of the 1930s were generally based on temporary plots. Ages, diameters, and heights were measured, but no direct information was obtained on current growth rates and mortality rates.

Such plots still have their uses, but they will not be considered here. They do not provide the information on growth and mortality required for modern yield tables and growth and yield simulators.

Temporary plots, with supplementary growth information—Additional measurements obtained from increment cores and stem analyses can provide information on past growth rates of trees on temporary plots. This information can be extrapolated for short periods to provide the periodic growth values or estimates of current growth rates needed for some types of analyses. This is a common procedure in inventories in which such procedures provide some growth information at less cost and without the delay involved when permanent plots are used. Similar methods can be used to obtain growth data for construction of yield tables and stand simulators, by procedures such as those discussed by Curtis (1967b), Hann and Larsen (1990), Hann and Wang (1990), Myers (1966, 1971), Vuokila (1965), and Wycoff (1990).

Although information may be obtained quickly by such methods, attaining precision comparable to that of permanent plot methods is difficult, if attainable at all. The accurate determination of diameter growth required in research studies is not easy. Except in young stands of species with annual internodes that can be directly measured from the ground, height growth estimates can be obtained only by laborious and destructive stem analyses; or by assuming (perhaps incorrectly) that pre-existing site index curves are a correct representation of height growth. Information on mortality is obtainable only in the form of subjective estimates of year of death of dead trees on the plot. Stand treatment information is usually confined to measurement of visible stumps and rough estimates of date of cutting. No information can be obtained for stand conditions and treatments not present in the existing forest, and short-term growth observations are very susceptible to the effects of weather fluctuations.

It is possible, however, to construct growth and yield models from this type of data, and such data are often useful as a means of supplementing existing permanent plot data (Stage 1977).

Permanent (remeasured) plots—Much past and present research uses "permanent" plots, which are established and measured at the start of an investigation and subsequently remeasured at intervals over a period of a few to many years. Such plots are expensive and represent a long-term commitment of resources that is unpopular with many administrators. But, permanent plots can provide data of superior accuracy and information obtainable in no other way (Curtis and Hyink 1985).

Permanent plots are expensive and a long-term commitment but can provide accurate information obtainable in no other way.

For the period of observation, permanent plots provide points in a real growth series, as opposed to artificial growth series constructed from single measurements of stands subjectively selected to represent successive stages in development. Over an extended period of years, the record of actual development of individual stands provides a standard against which estimates can be compared. Characteristics and development of individual trees can be followed over time. Such plots can provide a complete history of stand development and stand treatment, response to treatment, actual stand damage and mortality, and understory development—information not obtainable from other types of plots. When observations are continued over many years, variations in growth caused by short-term climatic fluctuations may balance out. And, for demonstration purposes, the on-the-ground examples and historical record of treatment and response they provide are more convincing to field foresters than any amount of statistical analyses and projections of temporary plot values.

This paper is primarily concerned with permanent plots, although many of the principles and recommendations given also apply to temporary plots with supplementary growth information.

Some Sampling Considerations

A first step in any sampling scheme is to define the population about which inferences are to be made, in terms of such associated characteristics as physical location, site quality, stand origin, age class, species composition, management treatment, and freedom from destructive agents. For many research studies, there is no need to sample conditions that will be excluded from the forest under anticipated future management. Thus, silvicultural experiments and yield studies rarely include very old and decadent age classes. Stands severely injured by disease, insects, or climatic agents are often excluded on grounds that, under management, such stands or conditions will be terminated. Alternatively, some studies may be specifically directed at evaluating the effects of such agents.

Sample selection is relatively straightforward in management inventories where the population consists of all presently existing stands and the primary objective is to estimate stratum or specific physical area means or totals. It is less straightforward in silvicultural studies intended to develop estimates of growth of future managed stands. In the latter case, one often seeks inferences about some largely hypothetical population of future managed stands, which may differ considerably from the present forest. The primary objective is often not to determine means or totals for some category of stands or some physical area, but to estimate coefficients of functions relating growth and stand development to current stand values and possible treatments. The conditions of most interest for this purpose may exist only on certain small areas or not at all. Some conditions and treatments must be created on newly established experimental plots. Some combinations of stand condition and treatment can be produced only by an extended period of management; these cannot be sampled directly, and estimates must be based on extrapolations from the most nearly analogous conditions available.

Yield studies often use regression analyses of unreplicated plots, established in portions of the existing forest that meet stated specifications of age, site, species composition, health, density or treatment category, and relative uniformity in stand and site conditions. Plot location within suitable areas has often been done subjectively, with the observer attempting to select a plot location representing either an average condition for the stand or the observer's conception of conditions likely under future management. A more objective and statistically more defensible approach in such studies is to select and delineate stands that meet the required specifications and then to locate the plot(s) within them by some random or systematic sampling procedure.

Stands to be used for developing regression equations should be selected to include a wide range of values for predictor variables.

Such stands should be deliberately selected to obtain as wide a distribution of the predictor variables as possible, consistent with study objectives and expected application of the model. As an example, many predictors of growth are regression models that involve age, site productivity, and some measure of density. A statistically desirable selection would insure that the plots include a wide range of densities for each age and site productivity class. As sample selection proceeds, the distribution of age, site productivity class, and density can be indicated in a three-way table and an effort made to fill all cells as equally as feasible. In subsequent regression analyses, a sample so selected will provide a better assessment of effects of the predictor variables, and better predictions near the margins of the range of data.

In silvicultural experiments, treatments are usually replicated at a given location or locations in accordance with some specified experimental design. This provides an estimate of experimental error and allows statistical analysis of results at that location. Often, the experimenter's primary interest is in defining some specific relationship, such as response to fertilizer dosage or to density level. To minimize the experimental error, the experimenter will then impose stringent requirements on initial homogeneity and comparability of plots within that installation. Meeting this requirement of close comparability of initial conditions among plots generally requires that the plots be subjectively located, with subsequent random assignment of treatments.

Many yield studies use regression analyses of plots selected in chosen strata of the existing population, supplemented with plots from silvicultural experiments. The latter furnish information on conditions and treatments not available in the existing forest and may provide guides to the form and nature of certain relationships. Considerations of time, cost, and availability of data often force the analyst to use data that are not completely comparable or compatible in method of plot selection and standards of measurement, and treatments may or may not be replicated at a particular location. Stringent stand uniformity requirements and close control of treatments, which are necessary for identification and measurement of treatment effects in silvicultural experiments, may lead to estimates that require adjustment for operational use (Bruce 1977).

It is risky to base estimates of expected growth on measurements in a single, short period.

Valid conclusions applicable on a regional basis also require that additional installations be distributed over a range of site conditions, initial stand conditions, and geographic locations that include various unmeasured and possibly unrecognized factors affecting growth. Most silvicultural experiments and yield studies recognize the need for replication at a given location if conclusions are to be drawn for that location, and the need to sample the range of stand and site conditions if conclusions are to be drawn on a regional basis. The need to include a range over time is less generally recognized.

Growth of forests varies from year to year and decade to decade because of variation in weather conditions and sporadic occurrence of widespread stand injuries and cone crops. In some instances, these fluctuations can be extreme (Keen 1937, Reukema 1964). Mortality tends to be clustered in both time and space because it is associated with climatic extremes and with the occurrence of windstorms and insect and disease outbreaks.

It is therefore risky to base estimates of expected growth on observations of growth, mortality, and treatment response made in a single short growth period. Although little can be done to allow for possible long-term trends, data that represent a series of periods rather than a single short growth period will be less influenced by short-term weather fluctuations. This is one major value of long-term permanent-plot observations and of the accumulation over time of compatible data collected by consistent procedures.

Plot Installation

Well-designed permanent plots maintained and repeatedly remeasured over time become more valuable with increasing length of record. They are often found valuable for purposes other than the study for which they were installed, and for purposes not anticipated by the person who installed them.

Long-term permanent-plot data are often analyzed by someone other than the original investigator. Analytical techniques and objectives change over time, and there can be no certainty that the computational procedures and analyses foreseen at the time the plots were established will be those judged most suitable at the time of later analyses. Therefore, procedures and data should be as complete and general as possible. Shortcuts that will later limit analyses to specific summarization and analysis procedures should be avoided. Experience shows that such shortcuts usually result in later costs and loss of information far more important than small immediate savings in field time. It should be anticipated that details of site classification, volume computation, and similar procedures will change, and the data should be adequate to permit summarization and analysis by any generally applicable procedure.

Procedures and data should be complete and general, as data are often analyzed by different people than the originators, for different objectives than originally intended, and by using new analytic procedures.

Plot Configuration

The plot is the basic unit of observation. It is usually a single area delineated on the ground, and is usually the experimental unit to which treatments are applied. It may consist of a cluster of subplots (or points, if variable-radius plots are used) arranged randomly or systematically within the treatment area or stand, with cluster totals treated as the basic values for analysis. In clumped or irregular stands, such clustered subplots may be preferable to single larger plots and more consistent with later management application of results.

Fixed-area plots can be any shape but are usually circles or squares, which minimize perimeter per unit area and, hence, edge effects and required area of buffer. Circles are convenient for very small plots, but accurate location and marking of the perimeter becomes difficult for larger plots; especially on steep slopes, if there are large numbers of trees, or trees and vegetation interfering with visibility. The straight borders of squares and rectangles lend themselves to accurate location and marking of corners and borders. Corners of squares are easily located with compass

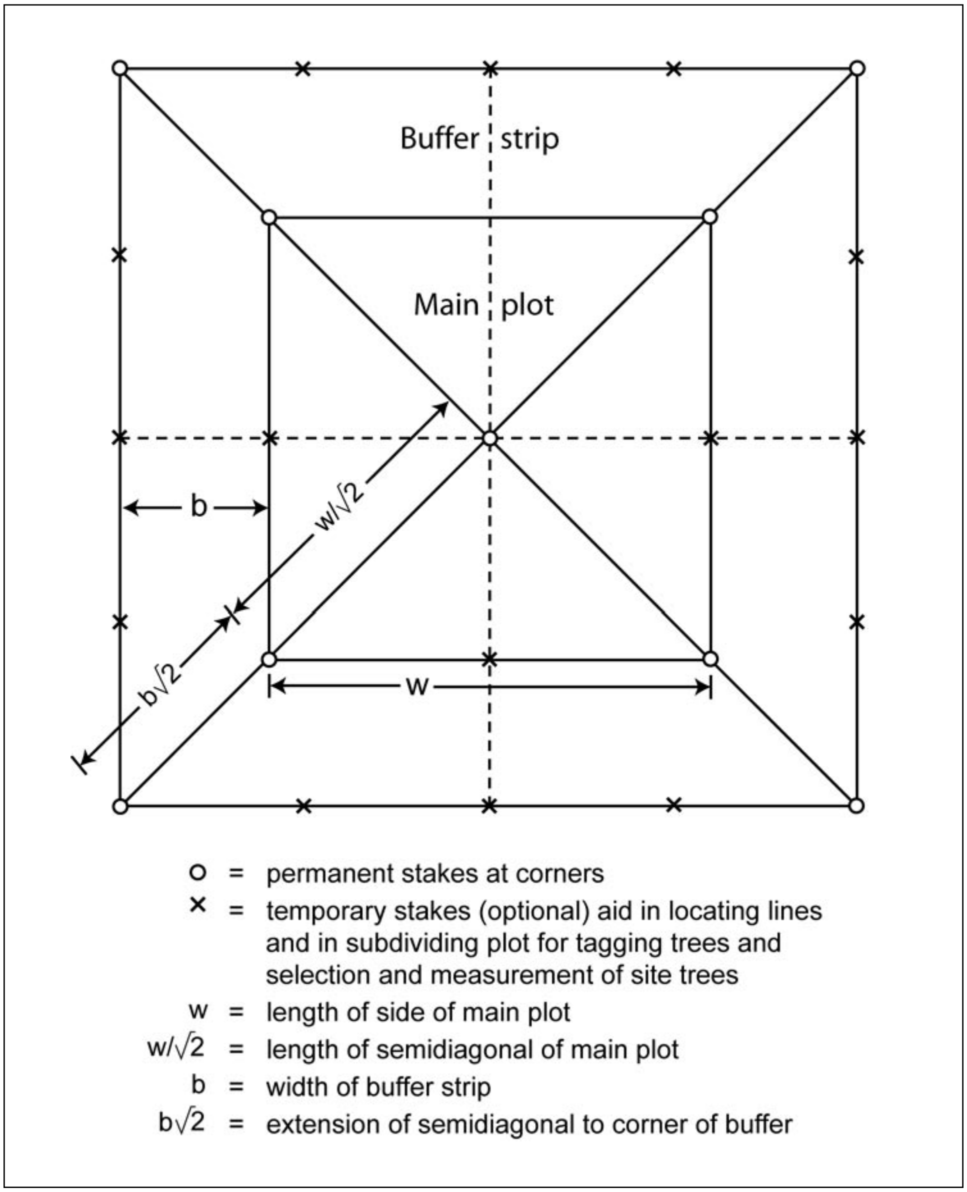

Figure 1—Typical layout of a square plot.

Fieldwork is simplified and mistakes are reduced if a standard plot shape and layout procedure are used.

and tape or laser rangefinder by measuring diagonals from an initial plot center (fig. 1); subsequent measurement of boundaries provides a check on errors. Rectangles are sometimes advantageous where there is a pronounced site gradient (as on steep slopes) and the long axis of the rectangle can be oriented at right angles to the gradient to reduce variation within the plot. Rectangles may also be advantageous in riparian studies.

Fieldwork is simplified and mistakes are reduced if a standard plot shape and layout procedure are adopted and used whenever the situation permits.

Plot radii or plot sides must be specified as horizontal dimensions, and field plot layout procedures must provide for slope corrections (automatic with some laser instruments).

Recommendation: The square plot is generally the most useful and convenient for research studies.

Some special considerations arise in regularly spaced plantations, which sometimes influence positioning, orientation, and exact size of plots.

In some research plantations established with very close control of spacing, it is feasible to use a square or rectangular plot positioned so that its sides lie midway between rows, thereby insuring that plot area is identical with the growing space available to the trees on the plot. This is desirable when feasible and will produce plots with areas that differ slightly from the simple fractional acres or fractional hectares generally used. A more common situation is that in which spacing of an existing plantation is not sufficiently regular to allow positioning the plot with sides midway between rows, but is still sufficiently regular that position and orientation of the plot can result in a plot area that differs appreciably from the total growing space available to the trees on the plot. This in turn will bias all growth computations. One means of reducing such bias is to orient the plot so that its sides intersect the planting rows at an angle.

Variable-radius plots (points) may also be used for permanent plots. Single points are not a suitable sampling unit for research purposes, as they include too few trees to provide satisfactory estimates either of growth rate or of the stand attributes used as predictors of growth. A systematic or clustered arrangement of 5 to 10 or more points within a stand can be used, however. Variable-radius plots are more consistent with commonly used inventory procedures than are fixed-area plots, and they have the well-known advantage for some purposes that sampling proportional to basal area concentrates the measurements on the trees of larger size and value and (usually) higher growth rates. In mixed-species stands, they also select species in proportion to the basal area they represent.

Variable-radius plot (point) clusters and fixed-area plot clusters are best suited to studies that sample pre-existing stand conditions, studies where treatments are to be applied to relatively large areas, and to monitoring silvicultural treatments, rather than to the type of silvicultural experiments most common in the past in which treatments are applied to small areas.

Because variable-radius plots include few trees from the smaller diameter classes and information is generally also needed for these, it is usually necessary to combine the variable-radius plot with a concentric fixed-area plot on which all trees below a specified limiting diameter are recorded. The radius of the fixed-area plot should equal the limiting distance as determined for that specified limiting diameter (Bell and Dilworth 1997, table 16). For example, if using a 20 basal area factor (BAF) angle gauge to select trees larger than 8.0 in and a fixed plot for trees 8.0 in and smaller, the radius of the fixed plot would be 15.56 ft (1/57.3 acre), which is the limiting distance for an 8.0-in tree, the largest to be measured on the fixed plot.

The fact that trees initially outside the variable-radius plot grow "onto" the plot as they increase in size ("ongrowth" trees, also referred to as ingrowth) complicates computations and introduces irregularities in growth estimates for successive periods (Gregoire 1993 [which contains an extensive list of references], Martin 1982, Myers and Beers 1968). Such trees are often missed in subsequent plot remeasurements, and this is a frequent source of error. (Similar problems occur with nested fixed-area plots, which are often used to avoid measuring very large numbers of small trees.)

Such a cluster of points usually extends over more physical area than a typical fixed-area plot serving a similar purpose. This may be an advantage or a disadvantage, depending on the nature and purpose of the study. It may be difficult to provide the buffers and replication needed when several treatments are to be applied within a limited area in a silvicultural experiment. Over an extended observation period, an initially reasonable spacing of points can lead to variable plots that overlap or extend into adjacent dissimilar treated areas, and to inconsistencies in tree numbering. Because the point cluster extends over a greater area, however, it may be more representative of conditions existing on a stand basis and may be more consistent with data arising from typical stand examination procedures.

Plot Size

Plot size is influenced by intended purpose, by stand conditions and variability, by expected duration of the study, and by cost considerations.

The criteria for suitable plot size in a research study are not the same as in an inventory. Frequently, an inventory aims to determine average values or totals of certain variables (for example, volume) for given strata or physical areas, based on plots falling in those strata or areas. Increased plot numbers can compensate for increased variability associated with smaller plots, and estimated means are unbiased regardless of plot size if properly installed. Some recent inventories use plot clusters with a greater aggregate area than the single plots often used in the past, and include measurements of many associated quantities in addition to timber (Max et al. 1996). Remeasurement data from a subset of such plots may be more compatible with typical research data and objectives than are data from many past inventories.

In discussing research plot size, it is useful to distinguish two categories of studies: (1) those in which the individual, relatively small plot is the basic experimental and analysis unit and (2) large-scale experiments in which the basic unit is a treatment unit of considerable size.

Small-plot experiments—Most past silvicultural research has used individual, relatively small plots, both because of cost considerations and because it is much easier to secure comparability in initial conditions and in treatment applications on small plots than on large areas.

Many research studies use regression equations to estimate individual tree or plot growth as functions of current stand values on individual plots. Very small plots will produce highly variable estimates and can lead to biased estimates of regression coefficients as a result of edge effects and bias in subjective location of plots. Variability increases with decreasing plot size, and plots that are excessively small relative to the pattern of within-stand variation will produce a considerable range of values for variables such as density and volume (Smith 1975). If such plots are then subjectively located for apparent uniformity and full stocking (a common procedure in field experiments), the resulting values may be higher than are realistically attainable on a stand basis. If plots are systematically or randomly located, observed growth on the plot will represent in part an effect of adjacent, unmeasured, differing stand conditions. High-density plots may grow well because they are using adjacent growing space. Low-density plots may grow relatively poorly because of the competition of adjacent dense groups of trees.

Small plots may give inaccurate and often biased estimates of mortality and damage. In many studies, plots that lose a substantial part of their stocking between two successive measurements are assumed to represent instances of "catastrophic mortality" and are discarded. On small plots, however, death of even a few trees in a given period can result in large negative increments. The analyst cannot tell whether this represents merely a few trees whose loss is insignificant in overall stand development, or a major disaster. The variation so introduced can totally obscure any relationship between growth response and stand treatment. The plot must therefore be discarded. The result is not merely highly variable estimates of mortality and damage, but estimates that are biased by the plot selection process. Estimates of some other stand attributes are likewise very sensitive to plot size (Gray 2003).

Plot size can also affect estimates of top height and corresponding estimates of site index (Garcia 1998, Magnussen 1999).

Excessively small plots can be expected to give erratic values for stand statistics and poor correlations of increment with site and stand attributes. They may also bias estimates of coefficients in equations expressing increment-stand density relationships (Hynynen and Ojansuu 2003, Jaakola 1967) if plot size is too small relative to the pattern of variation in within-stand density, so that increment is materially influenced by edge effects. Such effects will generally be more serious in mechanically located plots (as in inventories) than in research plots established in selected stand conditions, which are usually chosen for homogeneity and provided with suitable buffers to reduce possible edge effects.

Although the effects of plot size on yield analyses have not been thoroughly investigated, a number of rules of thumb for desirable size of fixed-area plots are given in the literature.

Early U.S. investigators commonly recommended plot sizes that would include at least 100 stems exclusive of understory at the end of the experiment (Bruce 1926, Marckworth and others 1950, Osborne and Schumacher 1935, USDA Forest Service 1935—still an excellent reference on many aspects of plot installation and measurement). Because much of this work was in untreated stands, presumably a somewhat smaller number would be acceptable in the more uniform stand conditions expected in plantations and consistently thinned stands.

Fabricius and others (1936) recommended plots of at least 0.6 acre (0.25 ha), larger in irregular stands. Robertson and Mulloy (1944, 1946) recommended 0.5- to 1.0-acre (0.2- to 0.4-ha) plots. Hummel and others (1959) recommended plot sizes of 0.3 to 0.5 acre (0.12 to 0.20 ha) for pure conifers and 0.5 to 1.0 acre (0.2 to 0.4 ha) for mixed stands. The Forestry Commission (1979) recommended plot sizes of 0.25 to 0.5 acre (0.1 to 0.2 ha) for general use, with a minimum of 0.2 acre (0.08 ha) for single plots in conifer plantations, 0.3 acre (0.125 ha) for hardwoods, and 0.1 acre (0.04 ha) in replicated treatment experiments (excluding buffers).

Vuokila (1965) compared coefficients of variation for alternate plot sizes and recommended a size in hectares equal to 0.01 x (dominant height in meters), which corresponds to a plot size in acres of 0.0075 x (dominant height in feet). Decourt (1973) recommended the same standard, with the restrictions that minimum plot size should not be less than 0.25 acre (0.1 ha) and that the plot should contain 100 to 200 stems. Hegyi (1973) made a somewhat similar analysis of plot size in three untreated jack pine (*Pinus banksiana* Lamb.) stands. His coefficient of variation curves suggest minimums of 50 to 75 stems per plot and areas of about 0.1 acre (0.05 ha) for these small-diameter stands. Note that these comparisons of coefficients of variation all deal with live stand volumes and basal areas, rather than with increment rates—which are frequently the values of primary interest.

Plot sizes in the general range of 0.25 to 0.5 acre (0.1 to 0.2 ha) have been used in several U.S. and foreign thinning and fertilization studies (Carbonnier and Fries

1976, Clutter and Jones 1980, Hamilton 1976, McEwen 1979). In 1969, the University of Washington Regional Forest Nutrition Program (RFNRP) adopted a minimum plot size of not less than 0.1 acre (0.04 ha) (Hazard and Peterson 1984). The British Columbia Forest Productivity Committee specified a minimum of 0.12 to 0.25 acre (0.05 to 0.1 ha) according to number of stems, but not less than 60 stems, plus buffer.[1] Some studies in the Pacific Northwest have used quite small plots—sometimes as small as one-twentieth acre (0.02 ha)—because of difficulty in finding fully comparable stand conditions over an area large enough to allow replication of a series of treatments at a single location. Unsatisfactory experience with the 0.1-acre plots used in the RFNRP led the Stand Management Cooperative to adopt a basic plot size of 0.5 acre, plus a 30.5-ft buffer.[2]

Desirable plot size depends on the research objective as well as the nature of the stands involved.

Note that all the rules of thumb given above lead to plot sizes considerably larger than those used in many inventories, even though stands are selected for uniformity. Plots smaller than those used in the University of Washington RFNRP and British Columbia Forest Service studies cited are clearly undesirable as sources of growth and yield data, and even these have severe limitations in the study of diameter distributions, mortality, and damage. But, desirable plot size depends on the research objective as well as the nature of the stands involved.

Consistency among plot sizes in different stand conditions may be obtained by relating a standard number of stems to average diameter or to stand height. Figure 2 gives an example of such a guide, indicating the plot sizes required to include 50 stems in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands of a given average diameter and percentage of normal stand density. (Many thinned stands, for example, would fall between the 50- and 75-percent curves indicated in early thinnings, and near the 75-percent curve at older ages.) Similar guides can also be derived from the relation of number of trees and dominant height, or from the crown area-diameter relation of open-grown trees. Such guides should be qualified by a minimum number of trees acceptable in the most open stands (minimum of 50 suggested). Generally, it is most convenient to use a single plot size determined by the most extreme treatment within an installation.

The preceding discussion applies to relatively uniform even-aged stands of a single species and, in many cases cited, to plantations. Mixed-species stands and uneven-aged stands will be inherently more variable and will require larger plots—

[1] Forest Productivity Committee. 1974. Field manual, balanced installation field programme. 63 p. + appendices. Unpublished report. On file with: British Columbia Ministry of Forests, P.O. Box 9049, Prov. Government, Victoria, BC V8W 9E2.

[2] Rinehart, M.L. 1986. Stand Management Cooperative—standardized field manual. Seattle, WA. 34 p. + appendices. Unpublished report. On file with: University of Washington, College of Forest Resources, Box 352100, Seattle, WA 98195-2100.

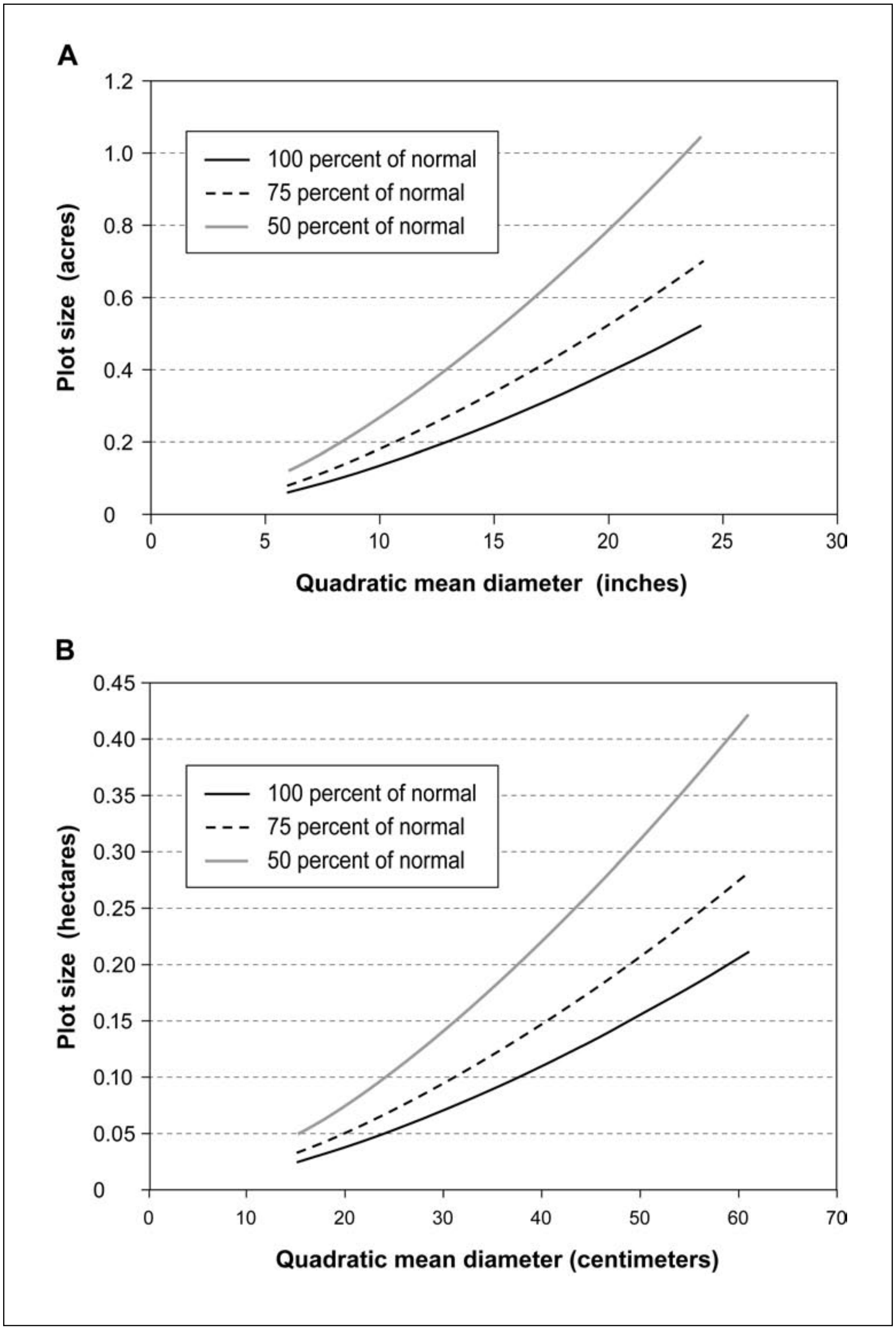

Figure 2—Plot sizes required to include 50 trees in Douglas-fir stands of given quadratic mean diameter and density expressed as percentage of normal (with normal defined as number of trees relative to that in table 25 of McArdle and others [1961]) in English (A) and metric (B) units.

sometimes much larger—to characterize stand structure and growth. (For example, Synnott (1979) recommends 2.47-acre (1.0-ha) plots for mixed tropical forest.) The same is true of studies that attempt to measure mortality and impacts of wind, disease, and insects.

Although the above discussion applies directly only to fixed-area plots, similar considerations apply to variable-radius plots. The basal area factor, number of points, and limiting diameter and radius of the concentric fixed-area plot should be chosen to include a sufficient number of trees to provide a reasonably smooth diameter distribution and the ability to distinguish "catastrophic" from "regular" mortality. The decision on arrangement and spacing of points should take into account future growth, so that with increase in tree size, the variable-radius plots will not overlap each other or adjacent dissimilar treatments or conditions, within the anticipated life of the study.

Plots composed of single trees or small groups of trees have their uses for such purposes as determining presence or absence of response, relation of response to individual tree characteristics, and pruning studies. Fully satisfactory and generally accepted techniques for expanding such results to a unit area basis are not now available, however.

> ***Recommendation***: Experimental designs that involve a large number of treatments assigned to plots within a single homogeneous stand condition—forcing use of very small plots because of the limited size of suitable areas—are not generally feasible for silvicultural and yield research and should be avoided.

Plot size should be selected in relation to the stand conditions expected at the end of the planned period of observation, rather than to initial conditions only.

Although no fixed universal standards can be given, required size of plot (or plot cluster) will increase with (1) average tree size and (2) within-stand heterogeneity. Plot size should be selected in relation to the stand conditions expected at the end of the planned period of observation, rather than to initial conditions only. Plot size should be large enough in relation to stem size, number of stems, and pattern of stem distribution to meet the following criteria:

- The plot can be regarded as representative of a condition that exists, or could exist, on a stand basis (that is, minor shifts in plot location would not materially alter the plot statistics).
- Growth of trees on most of the plot area is little affected by surrounding, possibly unlike, stand conditions.
- Sufficient stems are included to provide a reasonably smooth diameter distribution.
- "Catastrophic" mortality can be distinguished from "regular" mortality composed of suppression losses plus occasional death of scattered larger trees.

Experiments using relatively large treatment areas—Historically, most (though not all) past silvicultural and yield research has used the individual, relatively small plot as the experimental and analysis unit, and the preceding discussion relates primarily to such studies. In recent years, there has been an increasing number of large-scale experiments in which the experimental unit (treatment unit) is much larger—often on the order of 20 to 60 acres or so (Monserud 2002). These have been undertaken because of the increased interest in the relations between silvicultural treatments and silvicultural regimes on the one hand, and visual effects, wildlife effects, harvesting and management costs, mortality, and other response variables that cannot be effectively evaluated on the traditional small plots. They also permit comparisons among treatments or regimes involving uneven-age management or mixed-species management that cannot be satisfactorily represented by individual small plots. Compared to typical small-plot experiments, such experiments have the advantage that responses will be closely comparable to those obtainable in operational applications of similar treatments or silvicultural regimes. They have the disadvantage that the degree of homogeneity obtainable in initial site and stand conditions is necessarily less than in small-plot experiments, and the power of statistical tests is therefore likely to be less.

In such experiments, the relevant descriptive and response variables are the means of a series of small plots that sample conditions within the larger treatment unit. Plot distribution within the unit may be either random or systematic, but a systematic distribution is usually used because it simplifies plot location and later relocation. Size of such plots is largely a matter of convenience, provided that the number of plots within the treatment unit is adequate to provide estimates of unit stand conditions, stand increment, and mortality of satisfactory precision. When multiple plots are combined in the analysis, the irregularities introduced by ingrowth on either variable-radius or nested fixed-area plots tend to average out and can often be ignored.

Appendix C describes (in somewhat abbreviated form) sampling procedures now in use in such a large silvicultural experiment (Curtis and others 2004) for measurement of overstory and regeneration, and limited understory measurements that provide some information at low cost. We do not claim that these are necessarily "best" procedures, but they may be helpful as guides to be modified as needed.

Plot Buffers

In experiments in which the individual, relatively small plot is the basic analysis unit (as opposed to unit values determined as means of multiple plots within a unit), plots should be surrounded by a buffer strip of comparable initial conditions that receives identical treatment. This insures that growth of the plot is not influenced by adjacent, unlike stand conditions and treatments. It also provides for the possibility of future destructive sampling of individual trees for such purposes as determination of past height growth patterns and wood quality studies, without destruction of the plot proper.

Adjacent stand density differences have an effect on microclimate on the plot. It is well known that root systems extend for considerable distances and that root grafting and physiological linkage with nearby trees are common in some species. Root systems of trees on the plot will exploit water and nutrients available adjacent to the plot, and vice versa. Therefore, growth on the plot is likely to be influenced by adjacent changes in site conditions and stand density. Adjacent fertilizer treatments may affect growth of unfertilized plots through root systems that extend across plot boundaries, through downslope movement of soil water (requiring a further increase in buffer width), and through litter fall from fertilized trees onto unfertilized areas.

Width of the buffer should be at least equal to the expected crown width of dominant trees at the end of the planned period of observation.

Failure to provide adequate buffers will tend to produce underestimates of differences in response to treatment. Provision of adequate buffers is most critical on small plots, because small plots have a greater proportion of edge to total area than do large plots.

A frequently quoted rule of thumb is that width of buffer should equal stand height (Fabricius and others 1936, USDA Forest Service 1935). In the tall stands of the Pacific Northwest, however, this rule often gives values that seem unreasonable and impractical in application. Buffer size is sometimes specified as a proportion of plot area, but any single fixed proportion will give unreasonable values when applied to extremes of plot size.

If future destructive sampling of individual trees in the buffer is anticipated, width of the buffer may need to be increased to allow for this and to insure that the sample trees can be considered representative of conditions on the measured plot proper. An additional isolation strip outside the treated buffer may be needed if there is an adjacent drastically different stand condition (for example, a clearcut), an abrupt site change, or concern over possible movement of fertilizer.

> ***Recommendation***: A rule that is probably adequate for most situations, provided adjacent conditions are not drastically different, is that width of the buffer should be at least equal to the expected crown width (which can be calculated from expected diameter at breast height [d.b.h.]) of dominant trees at the end of the planned period of observation. The Forestry Commission (1979) recommendation of 33 ft (10 m) seems reasonable as a general guide for stands of moderate diameter.

Surveying and Marking Plots

Much time is lost relocating inadequately monumented plots. Lost corners and carelessly surveyed plots are frequent sources of error in plot areas and in corresponding values of stand statistics.

Plot locations should be referenced to some easily relocatable point and well documented with a map and GPS coordinates.

The plot center or a plot corner should be referenced to some easily relocatable point along a road or other access route, by compass bearing and measured distances. Other plots in the installation should be referenced to this by bearings and distances, and a careful sketch map should be prepared that is adequate for later relocation of the plots by someone unfamiliar with them. Declination used should be recorded. The map should include approximate location in relation to the public lands survey system and the latitude and longitude. Plot corners or centers and the starting point along the access route should also be identified by global positioning system (GPS) coordinates, when feasible. If overstory trees or topography make accurate GPS coordinates unobtainable, a GPS reading may be obtained at a nearby point, with an azimuth and distance to the point of interest, allowing computation of coordinates.

Plot centers and corners must be marked by stakes of some permanent material, such as metal, polyvinyl chloride (PVC) pipe, or substantial stakes of preservative-treated wood. Some have used short lengths of steel rebar inside PVC pipe, which can still be relocated with metal detectors if buried by harvesting operations. Stakes should be marked in a way that positively identifies the plot and the particular corner and should be witnessed by appropriate paint blazes, and tags on several adjacent trees. Tags should be positioned well below stump height so that they will not be destroyed if the trees are cut. Tags should be attached by plastic "barlock" connectors (thin-barked trees), staples (thick-barked trees), or long protruding nails so that tags will not soon be overgrown (fig. 3). Distance and azimuth from stake to witness trees should be recorded. Azimuths and horizontal distances between corners or centers must be carefully measured and recorded. The sketch map should show all azimuths and distances needed to relocate plot centers and corners.

Large plots, elaborate installations, or difficult terrain may warrant highly precise surveys. In most situations, satisfactory results can be obtained by careful work with staff compass and tape or (better) by the recently introduced staff-mounted laser instruments. Lasers can penetrate considerable foliage when used with a suitable reflector, and markedly improve both accuracy and speed of the distance measurements in steep terrain. To insure against blunders, boundaries should be run twice in opposite directions, or error of closure calculated and found to be acceptable. All dimensions and areas should be expressed on a horizontal basis.

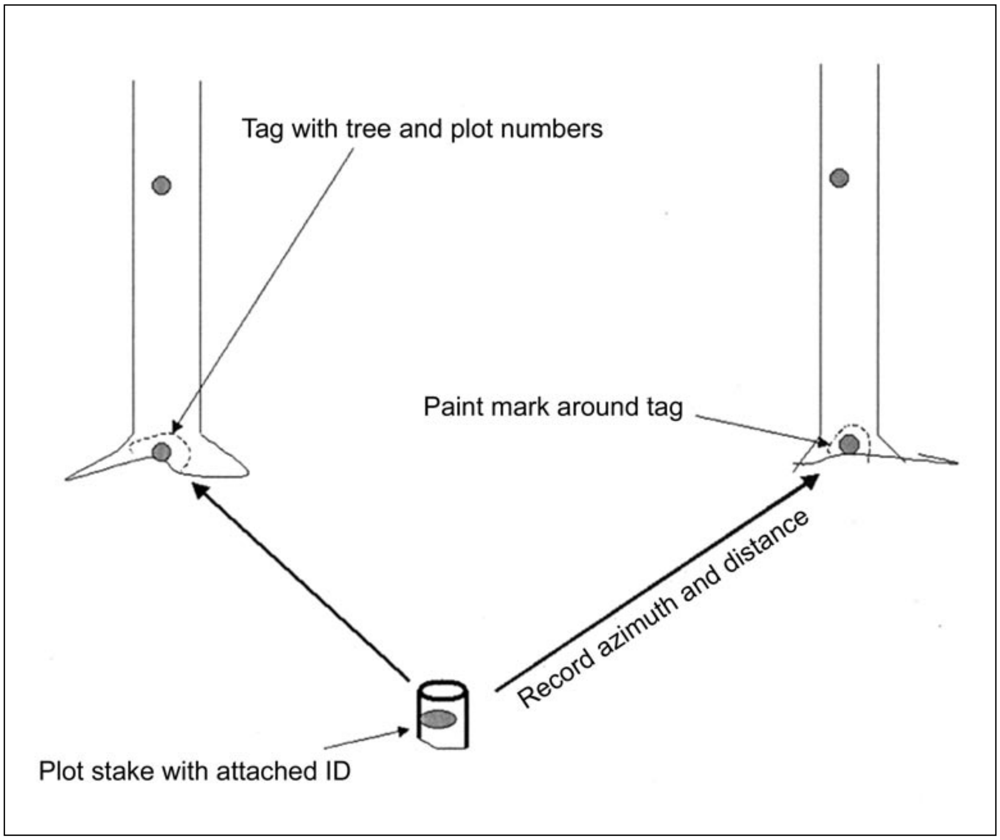

Figure 3—Method of witnessing plot center or corner stakes.

A commercially available aid (Haglof DME 201[3]) useful in establishing small circular plots (about 0.2 acre or less) consists of a staff-mounted transponder at plot center and a receiver that provides the user with the slope distance from the transponder, thereby eliminating the need for tape measurement (although correction for slope is still needed).

Plot borders should be marked with paint blazes or signs (except where public attention is undesirable) or standard scribe marks on adjacent trees facing the plot border. In dense stands they should be carefully delimited with string before the trees are initially tagged and measured.

A standard record form should be used and checked to insure that all specified items are recorded.

[3] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

Plot Protection

There must be an agreement with the organization administratively responsible for the area to protect the installation from disturbance for the planned period of observation. The land manager must be informed of the exact location and nature of research plots, and the installation should be entered in the manager's geographic information system (GIS) database. Organizations should have a standard procedure for insuring that managers have an up-to-date record of research installations on their lands, and that these are not disrupted by forest operations without prior consultation and agreement with the research organization. Plot boundaries should be painted or otherwise marked, and exterior boundaries should be conspicuously signed (with contact information) so that management personnel will recognize the area as a research installation when encountered in the field and know the office to contact for information.

Common hazards include road construction, thinning and harvest operations, aerial application of fertilizers or herbicides, vandalism, and land ownership changes. Any of these can quickly destroy the usefulness of a research installation. In the absence of strong overall direction, local land managers often do not realize the value of existing research installations, and may give their protection lower priority than facilitation of their immediate administrative operations.

Plot Measurement

All measurements and records on a given installation should be either in metric or in English units. The two should not be mixed. Tapes and instruments graduated in both systems invite errors and should be avoided where possible. In general, metric units are preferable for new installations. Measurement of old installations should continue in English units until such time as the entire system of records is converted to metric.

Record of Initial Conditions

General characteristics and past history of the stand and plot, so far as these are known, should be recorded at the time of the initial measurement according to a standard procedure and specifications. This includes such items as location (public land survey, map coordinates, political subdivision); ownership; administrative responsibility for the area; elevation; aspect; percentage of slope, stand origin (natural, planted, seeded, planted with natural fill-in); seed source and stock type for planted stands (if known); forest type; age at time of first measurement (even-aged stands); known past treatments (site preparation, vegetation control, thinning, fertilization, etc.) or injury; estimated site index (specify system); soils classification and habitat type, when available. Quantitative items such as elevation, aspect, and age should be recorded as numerical values rather than classes, to provide flexibility in later use. (For example, the practice of recording aspect as cardinal direction only—instead of azimuth—prevents use of the trigonometric functions in later analyses to describe the location of maximum and minimum growth.) It is helpful to have a standard form to be completed for all new studies, to insure that important items are not missed.

There should be a complete record of stand conditions at the time of plot establishment and immediately before any treatment. All stems removed from a plot should be recorded by species and d.b.h., and any treatment should be completely described. If d.b.h. is not directly available for cut trees, it should be estimated from measured stump diameters and stump heights (Alemdag and Honer 1973, Beck and others 1966, Chambers 1978, Curtis and Arney 1977, McClure 1968). When plots are established in stands that have had cutting prior to plot establishment, date of cut should be ascertained, and the numbers and dimensions of trees removed from the plot should be estimated by stump measurements or otherwise insofar as possible.

Although diameters can be estimated from stump measurements with reasonable accuracy under favorable conditions, the procedure becomes unreliable when trees are small, if stumps are not recent, or if portions of the plot are covered with slash or brush or have been disturbed by logging equipment. Direct measurement before trees are cut is preferable.

Tree Numbering

Each live tree of measurable size within the plot should be assigned a unique permanent identification number. This is necessary for later separation and summarization of the components of forest growth; namely, survivor growth, mortality, cut, and ingrowth (Beers 1962).

For some objectives, removal of potential ingrowth trees at the time of study establishment simplifies later measurements. But, ingrowth is a part of normal stand development, accepted as such in most studies and often of interest in itself. In most studies, ingrowth should be identified and tagged as it appears. In those cases where there are very large numbers of potential ingrowth trees, it may be necessary to resort to subsampling (discussed in a later section).

Live trees that are below minimum measurable size at the time of initial plot establishment but appear likely to grow to measurable size later may also be assigned numbers and tagged at the time of establishment, even though d.b.h. is not measured. Although initially time consuming, this insures that numbers will be in sequence—thereby simplifying relocation of trees and handling of records at subsequent measurements. This practice is desirable in plantations and similar situations where the number of such stems is limited and most will later reach measurable size.

Individual trees should be tagged by means that will not harm the tree and will persist through time.

As one alternative procedure for insuring that ingrowth trees will be numbered in sequence with adjacent trees, tree numbers assigned at time of plot establishment can be multiples of 10. When an ingrowth tree is later found, it is then assigned the number of the nearest initially numbered tree, plus 1, 2 … 9 as the case may be. For example, if a tree was initially assigned the number 1120 or 112, numbers 1121 through 1129 are then available for subsequent assignment to nearby ingrowth trees. Alternatively, if a tree was initially assigned the number 112, nearby ingrowth trees can be numbered as 112.1, 112.2, … etc. This system can be used when the number of very small trees makes initial tagging of all trees impractical.

The method used for numbering or tagging trees will depend in part on size and characteristics of the trees. A number of methods have been used:

(a) The most common method in the past has been the use of metal tags attached with aluminum nails at breast height (b.h.) (fig. 4a). This is convenient for large thick-barked trees. Nails should be driven no farther than necessary to stay in place, slanting slightly upward and with the tag placed at the nail head so that it does not quickly become overgrown. On small trees and thin-barked species, nails may cause swellings that interfere with measurement; where this is a problem, either tags can be attached at a lower or higher point (with b.h. a fixed distance from the nail, preferably indicated by a paint mark), or painted numbers can be used instead. If nails are used, they must be pulled as needed at each measurement to prevent overgrowth of the tags. (Except, on very thick-barked trees where the nails do not penetrate the wood, they will gradually move outward along with the bark plate). Nails should be removed and the tag nailed to a root or below stump height before trees are cut. This prevents damage to saws and allows identification of cut trees. Major disadvantages of nailed tags are the risk of future damage to saws and mill equipment if tags are not removed prior to cutting (aluminum rather than steel nails may reduce but do not eliminate the problem) and the continuing need for periodic nail-pulling to prevent overgrowth of tags.

(b) One alternative is painted numbers (fig. 4b), with a supplementary paint mark at the b.h. measurement point. This prevents damage to saws, but painting is not feasible during wet weather, and there will be a need for repainting at subsequent measurements for numbers to remain legible. Rough-barked trees will require smoothing of bark before painting; this must be done above or below, not at the b.h. point.

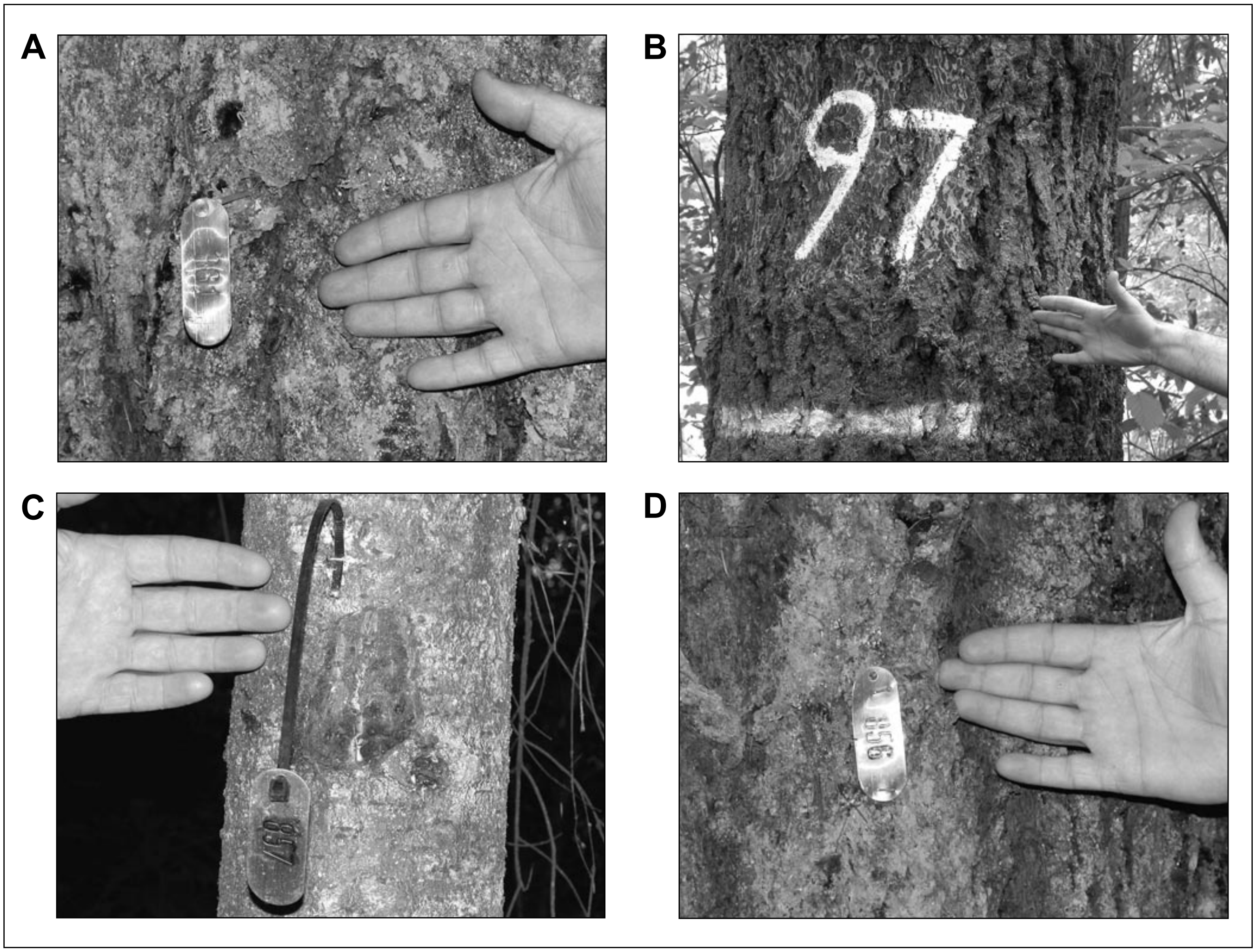

Figure 4—Methods of attaching tree tags: (a) nails, (b) painted numbers after smoothing bark, (c) plastic barlocks stapled to tree, (d) tags stapled directly to thick bark plates.

(c) An alternative that eliminates damage to saws and frequent need to pull nails to avoid overgrown tags, and can be used in any weather, is the use of plastic barlocks stapled to the tree (fig. 4c) by using a squeeze-type stapler and 9/16-in staples. Use a single staple applied horizontally for best results. This works well on small thin-barked trees where the staples can penetrate into the wood; the point of attachment is then soon overgrown and the length of the barlock is sufficient to allow considerable growth without overgrowing the tag. It is not satisfactory for older thick-barked trees unless one gouges the bark sufficiently to allow stapling into wood. Barlocks used should be resistant to ultraviolet light. Unfortunately, they may sometimes attract attention and may be ripped off by vandals or large wildlife.

(d) Another alternative applicable to older thick-barked trees is to staple the metal tag directly to bark plates (fig. 4d). Although we have used this method for only a limited time, it appears to be fairly long-lasting and avoids the overgrowth and saw damage problems.

(e) For very small trees, tags can be attached to a branch near b.h. with wire or barlocks. (Tags should **never** be wired around the stem; this can cause deformities or death of the tree.) Seedlings can be identified with tags attached to wire pins adjacent to the seedling. When regeneration is sampled with very small subplots, planted seedlings can be identified by distance and azimuth from the subplot center marker.

For some specialized purposes, UPC (bar code) tags are an alternative to the usual metal tags.

Research is currently in progress at the University of Washington on embedded machine-readable chips for permanent tree identification, analogous to procedures now used with livestock. These are not currently available, but if successful and available at reasonable cost, they would eliminate the problems of saw damage, tag overgrowth, and tag removal by vandals.

Opinion: The most generally satisfactory methods are barlocks (fig. 4c) for thin-barked trees, and direct stapling of tags to bark plates (fig. 4d) for thick-barked trees.

When plots are established, the field crew should be provided with sets of tags prenumbered in sequence. They should also have a label maker and metal label tape, or write-on aluminum labels, to supply tags as needed if the sequence provided is exceeded. (Duplication of tag numbers on the same plot **must** be avoided). Likewise, remeasurement crews should make new tags as needed to replace lost tags and for tagging ingrowth.

It is sometimes desirable to use a distinctive paint marking on site trees or height-sample trees. It is often convenient to divide the plot into strips or sectors with string to insure that no trees are missed and that tags are arranged in a systematic manner (fig. 5), which will facilitate later relocation of trees. It may sometimes be desirable to divide the plot into numbered subplots so that trees can later be sorted by subplots as an aid to relocation. Relocation of trees during plot remeasurements will be facilitated if all numbers are placed on the same side of the trees within strips or subdivisions of the plot, arranged so that tags face the crew as they travel across the plot in a systematic sequence. If on remeasurement a tree is found to be out of sequence, the number of the nearest properly tagged tree should be recorded.

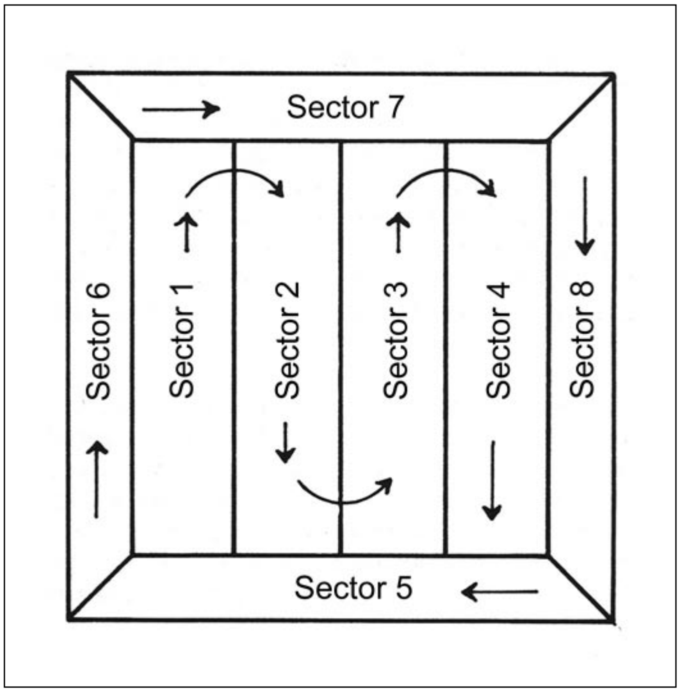

Figure 5—Plot divided into sectors: arrows show sequence of tree tagging and measurement. Tags should be positioned to face the crew as they travel through the plot. Subdivision lines are best oriented in the direction most nearly parallel to the contour, to minimize effort in traveling between trees and to facilitate use of subdivisions in distributing site trees across any site gradient.

A consistent procedure must be used with "line trees" in determining whether or not to consider them on the plot and tag them. The decision is best based on location of the center of the tree at stump height. Trees exactly on line by this standard can be classified as "in" or "out" according to the direction of lean, if any. Borderline cases can be classified as "in" or "out" alternately or by coin toss. "Out" trees should be identified by paint blaze or standard scribe mark facing the plot, to prevent later confusion.

Depending on stand conditions and stage of development, dead limbs may be pruned to a height of 6 or 7 ft to facilitate numbering and later remeasurements. Removal of live limbs should normally be avoided except as necessary to allow access to the tag and d.b.h. measurement point. Any such pruning should be done with handsaws or loppers, to avoid stem injuries.

At each remeasurement, a search should be made for additional unnumbered trees (ingrowth, previously missed trees, trees with lost tags). Lost tags can often be recovered from the duff; if not, the tree number may be identifiable from its position and the same number then replaced. New numbers should be assigned to any ingrowth or previously missed trees (by using the xxx.x or similar convention that maintains the number sequence to facilitate relocation). If this is neglected, impossibly large "ingrowth" trees will later appear in the record. Such impossible "ingrowth" introduces abrupt changes in calculated periodic growth values, and the missing values must then be supplied by borings or by estimating past unmeasured diameters, heights, and other characteristics of these trees.

When tagging new trees, never reuse an old number from dead or harvested trees.

Note that when tagging such new trees in the field, one should **never** transfer to them numbers previously used on trees that have died or been cut. This practice, though convenient in the field, causes endless confusion. Tags should be made as needed for newly assigned numbers. The number of the nearest previously numbered tree should be noted as an aid to later relocation.

Determination of Breast Height

For consistency in successive d.b.h. measurements on the same tree, all measurements must be made at the same point on the tree bole. The system used must include a mark at the b.h. point on all numbered trees. This mark may be a painted band or the location of the tag. There are, however, some unresolved inconsistencies in definition of b.h. that require a choice.

In the United States, b.h. has in the past been defined both as 4.5 ft above mean ground level (common practice in many past research studies) and as 4.5 ft above ground level on the high side (common inventory practice). The former definition sometimes gives unreasonably low points for large trees on steep slopes; the latter definition gives a point that, for trees on steep slopes, rises as the tree increases in size (Bruce 1980). A further source of uncertainty is that in many cases, the standard used in in the past in collecting the data used to construct existing volume and taper equations and tables is unknown. On gentle slopes, the difference between the two procedures is slight.

A second inconsistency arises in the shift from English to metric measurements. Traditionally, b.h. has been defined in the United States as 4.5 ft above ground, however "ground" is defined. Some people in the United States and other English-speaking countries have used the equivalent metric value of 1.37 m; however, the international standard is 1.3 m, and this will probably eventually become standard in the United States as it is now in Canada (Bruce 1976, Demaerschalk and Kozak 1982).

Recommendation: When new plots are installed, it is best to establish and mark (by tag or paint) the b.h. point measured from ground level on the high side, thereby at least partially avoiding the unreasonable heights that sometimes arise from use of average ground level on steep slopes. All subsequent measurements should be made at this same marked point on the tree.

A consistent procedure should be used for forked trees and trees with abnormal swellings at the b.h. point. Suggested conventions are (fig. 6):

- If a tree forks above b.h., treat it as a single tree, with the tag and diameter measurement below the swelling caused by the fork but as close to normal b.h. height as feasible.
- If a tree forks below b.h., treat it as two trees, with the tag and diameter measurement located at (1) 2.0 ft (0.6 m) above fork at the initial measurement or (2) 4.5 ft (1.3 m) above ground, whichever is higher.
- If the tree has an abnormal swelling at the normal b.h. point, tag and measure it immediately above the irregularity at the point where it ceases to affect stem form.

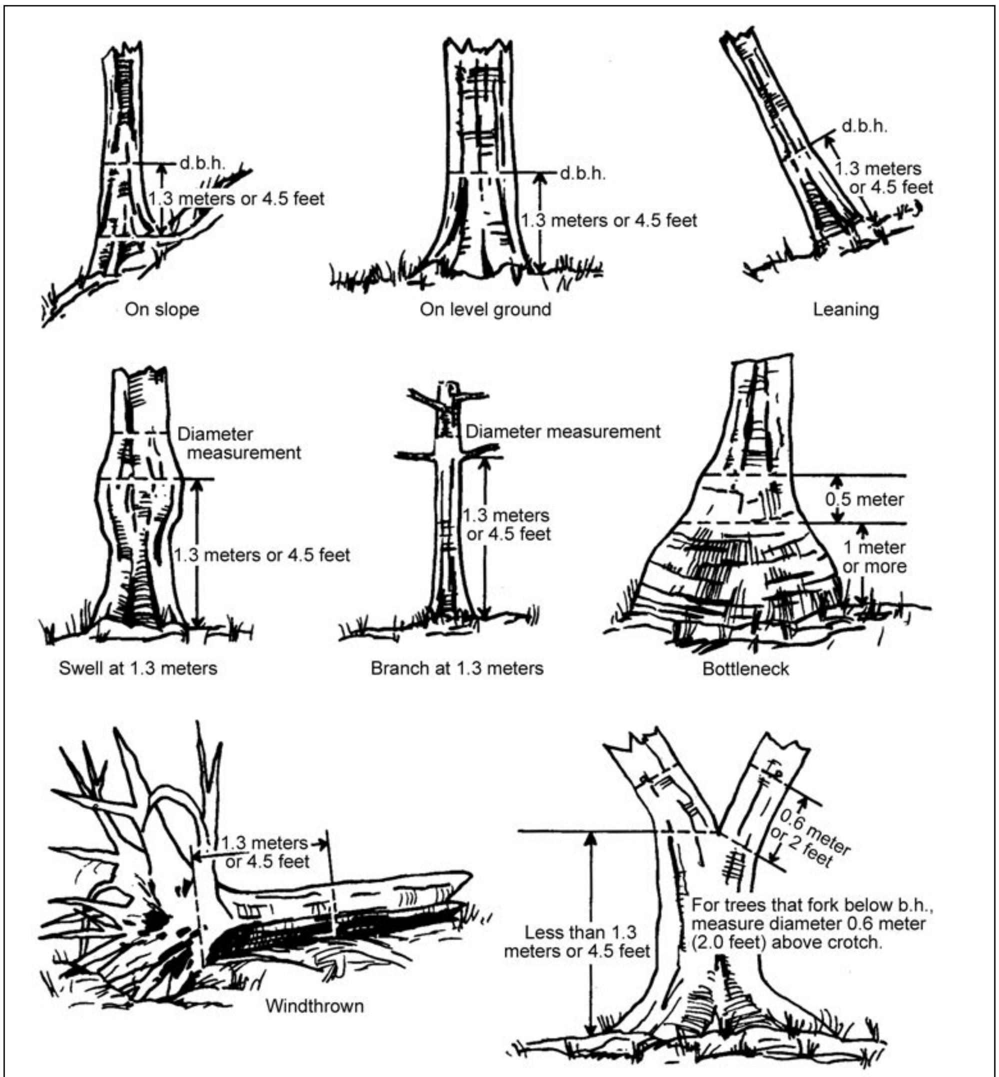

Figure 6—Measurement points for measuring diameter at breast height (d.b.h.) of trees in various situations.

Stand Age

Stand age must be determined for all even-aged stands. This is best done at the time of first plot measurement.

Tree ages are normally determined by boring at b.h., by counting rings on stumps, or from known planting dates. Some estimate of intervening years is necessary to convert age determinations to corresponding total age from seed. The record may show age as total age from seed, years from planting date + stock type (if known), or age at b.h. but must clearly specify which and should indicate the basis for conversion from actual measurements to the ages given and the best available estimate of conversions from age at b.h. to total age or vice versa. In young plantations of conifers with clearly defined internodes, age at b.h. can be readily determined by counting internodes from tip to b.h. point.

A stand age at b.h. based on borings or internode counts is highly desirable in plantations as well as in natural stands, even though year of planting may be known. Time required to grow to the b.h. point varies with site quality, weather, site preparation, brush control, and other factors and is often considerably shorter in plantations than in natural stands. Hence, inconsistencies in method of determining age can introduce apparent differences among stands that have little meaning for long-term development. Use of measured age at b.h. in site estimation and growth relationships avoids at least part of this variation.

Stand age is meaningful only for even-aged stands. It should be defined as average age of dominant or crop trees or of trees selected by some nearly equivalent numerical rule, such as the 40 largest per acre (100 per ha). Occasional large residuals, lower crown classes, and trees unlikely to reach rotation age should be excluded. The sample should normally include designated site trees, if any, plus additional trees selected from the stand tally on the basis of dominant or crop tree classification or the 40 largest trees per acre.

The sample should be large enough to determine the mean age of dominant (crop) trees on the plot to a prespecified standard of precision. Staebler (1954) suggests a standard error of the mean of 1.0 year or less, after elimination of obvious outliers.

Individual tree ages used in calculating the plot mean should be retained in the record, with identifying tree numbers. The plot age carried in the record should be the mean calculated to the nearest year, **not** a broad age-class category.

In mixed-species stands, sufficient samples of each major species should be taken to determine whether or not age differences exist among species.

Tree Dimensions

Standard procedure at each scheduled plot measurement must provide for:

- D.b.h. measurement of all trees above the lower limit of measurement.
- Classification of measured stems by crown class, tree status, condition, and nature of any injury or death, in accordance with a standard coding system. The system must also recognize the categories: survivors, ingrowth, mortality, cut, intentionally killed trees, previously missed trees, and understory, as applicable. Understory stems (those clearly of an age class younger than the main stand) should be recognized as a separate crown class or cohort, when present.
- Measurement of heights of a sample of trees sufficient to provide a reliable height-diameter curve and estimates of stand average height, top or dominant height, and site index.
- Measurement of heights to live crown (and crown width, if measured) on the same trees at successive measurements is highly desirable.
- An estimate of tree form. This is most commonly made indirectly by means of standard volume tables or taper functions based on diameter and height but may be done by direct measurement of a sample of trees.

When plots are remeasured, it is advantageous to use a standard tally sheet format (fig. 7) or recording device display containing the previous measurements on each tree. New and old measurements should be checked for reasonable agreement, and major discrepancies should be checked by remeasurement of the tree. (Electronic recording devices can be programmed to "beep" when a measurement differs by

Study: LOGS	Location: sec 27, T10S, R7E	
Inst: Hoskins	Plot area: 0.20 ac	Measurement date: Crew:__________
Plot: 3	Initial msmt date: 1963	Month Day Year English x or metric___
Suplot: none	Quadrant: NA	

Tree #		Species	Age bh	Tree	Crown	DBH		Height		HLC		Damage			Damage			Dead	Cause	Coordinates		Notes
	new			class	class	1998	2004	1998	2004	1998	2004	Kind	Sev	Rec	Kind	Sev	Rec	class		X	Y	
1	0	PSME				21.1		125		60												
2	0	PSME				18.3		120		58												
3	0	PSME				16.8		118		49												
4	0	PSME				12.7		99		50												
5	0	PSME				19.2		115		51												
6	0	PSME				18.5		112		55												
7	0	PSME				16.1		110		56												
8	0	PSME				16.9		110		51												
9	0	PSME				22.1		130		60												
10	0	PSME				10.3		82		61												
5	1	TSHE				4.1		23		10												

NOTE: "Cause" applies to "recent" damage and to "recent" dead trees (Tree classes 21,22). Leave blank if not clearly evident.
" Age bh" as of date of measurement, enter only for trees bored at this measurement date.

Figure 7—A plot measurement field form or recorder screen.

more than a specified amount from the previous measurement). This will frequently avoid gross blunders and recording errors, which are easily corrected in the field but which become a major nuisance if not caught until the compilation stage.

The initial measurement is particularly prone to blunders and recording errors, as no check is available. One method of avoiding troublesome errors in the initial measurement is to make two successive measurements at the time of plot establishment, exchanging the measurement and tally roles among the crew. Measurements that do not agree within reasonable limits are repeated and corrected on the spot. The time required for such a second measurement, although considerable, is usually a relatively small fraction of the total time required for initial plot installation and measurement.

Diameter measurements—D.b.h. of each tagged tree should be measured at the marked b.h. point (usually indicated by tag position, or by a paint mark) at each plot remeasurement, normally to the nearest 0.1 in or 1.0 mm. Except in stands with many very small stems (where a "go-no-go" gauge or fork caliper is useful), this is best done with a diameter tape.

When a tree that died since the previous measurement is encountered, its diameter is recorded, together with a mortality code indicating that it was found dead at this measurement and the cause of death (if evident). It will save time in future remeasurements if such trees are blazed or painted and the tag removed and nailed at a point below any possible stump height (to avoid damage to equipment in the event of any salvage). Nailing the tag below stump height makes the tree easily identifiable as previously recorded mortality with a known approximate year of death.

It was a common practice in the past to measure only trees above an arbitrary d.b.h. limit, more or less corresponding to some merchantability standard. This was usually done to simplify fieldwork, but it has been the source of numerous difficulties in analysis. Such truncation of diameters distorts the statistics of stand average diameter and number of trees, hampers or prevents fitting of diameter distribution functions, and often makes different data sets completely incompatible. It should be avoided.

In principle, it is desirable to tally all stems taller than b.h.; however, very small stems are difficult to tag and measure and may be numerous. As a practical matter, it is usually necessary to adopt some lower limit of measurement such as 0.5 in or 1.5 in or 2.5 cm. Higher limits should not be used. Where it is not feasible to measure all trees on the plot above such a limit, a subsampling scheme can be adopted.

When fixed-area plots are established in very young stands and are to be observed over an extended period, a plot size adequate for the initial condition is much too small for the stand condition expected at the end of the observation period.

Conversely, a plot size suitable for the final stand condition may initially involve tagging and measuring a prohibitive number of small stems.

A procedure sometimes used in this situation is to tag and measure all stems on subplots within the main plot, but only stems over a specified larger d.b.h. (no larger than absolutely necessary) on the remainder of the plot. The sample of small trees must be large enough to provide stable estimates and must be representative of trees on the main plot area. Because small stems are frequently clumped, several systematically located subplots within the main plot may be preferable to the single concentric plot often used. A common mistake is insufficient sampling of the small stems. Particular care must be taken that the ingrowth bigger than the larger d.b.h. limit is found, numbered, tagged, and measured at each remeasurement.

Note that increment values for each successive period will be based on a slightly different tree sample (because of ingrowth into the main plot), that this design complicates computation of plot summaries, and that it involves a continuing need to search for and tag numerous new ingrowth stems at each subsequent measurement.

When variable-radius plot (point) sampling is used, the tree population must be subdivided by a limiting d.b.h. below which trees are recorded on a circular fixed-area plot and above which trees are recorded if their diameter subtends an angle larger than the critical angle for the basal area factor selected for the larger trees. Size of the fixed-area plot for small trees should match the size of the variable-radius plot for the larger trees. A suitable choice of limiting d.b.h. and associated size of the fixed-area plot can reduce the problem of measuring very large numbers of small trees, while including enough such trees to define the diameter distribution.

Because measurement of heights is time consuming and frequently inaccurate, height and crown length sampling and measurement are the weakest points in much existing data.

Height measurements—Stand height is (with age, number of trees, and quadratic mean diameter [Curtis and Marshall 2000]) one of the basic descriptors of a stand. It is **essential** to most analyses of growth and yield. Heights are necessary for computation of volume and volume increment, accurate estimates of bole biomass, estimation of site index, and characterization of stand conditions and stand development. Crown length (or equivalently, height to live crown or crown ratio) is now used in many tree and stand simulators, and it is therefore highly desirable that this also be measured. Because measurement of heights is time consuming and frequently inaccurate, height and crown length sampling and measurement are the weakest points in much existing data.

For species in which the limit of merchantability is generally determined by bole diameter, as in most conifers, only total height rather than merchantable height need be measured. Merchantable heights, if wanted, are better determined from taper curves. In species where the limit of merchantability is frequently determined by "breakup" of the main stem rather than by diameter (for example, many hardwoods), it may be desirable to measure merchantable height in addition to (but not instead of) total height.

It is often impractical to measure heights of all trees on the plot, and one must then resort to subsampling. A suitable sample of trees should be measured for heights when the plot is established and at each remeasurement.[4] This requires (1) adequate sample size, (2) efficient distribution of the sample, and (3) careful height measurement. Measurement of only a few heights at a given date, insufficient for construction of a height-diameter or volume-diameter curve, serves no useful purpose.

Recommendations:

- Each plot or plot cluster should be sampled independently. Samples generally cannot be combined across plots or treatments without biasing analyses.
- Height-sample trees are best drawn initially from the plot tally, rather than selected visually. After the initial sample is drawn, trees with broken tops, pronounced lean (over 10°), severe malformations, or disease should be rejected or coded as unsuitable for developing height-diameter curves or for site index estimates. Sample trees should be reasonably well distributed across the plot area.
- The sample should include trees from the full range of diameters present, and should specifically include the largest and smallest diameter classes. A common and serious mistake is omission of small d.b.h. classes, which leaves the curve shape undefined. The sample should **not** be confined to dominants and codominants only.
- Large d.b.h. classes should generally be sampled more heavily than small d.b.h. classes, because they contribute more to volume, volume growth, and value. The small trees must also be sampled in a manner adequate to characterize that portion of the height-diameter curve and provide information on vertical structure of the stand.
- When designated site trees are used, these should routinely be included in the height sample, with additional sample trees selected as needed to provide a satisfactory distribution across the range of diameters.

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[4] Given several well-distributed height samples, curves for intermediate dates can often be obtained by interpolation or by fitting a system of height-diameter-age curves. This, however, is computationally bothersome, may obscure real differences in growth among periods, and is usually a makeshift solution made necessary by past omissions. It is better to avoid the need.

- Normally, except where new trees are needed to replace trees lost by cutting, mortality, or severe top breakage, the same height-sample trees should be used at each successive measurement. This provides better estimates of height increment than independent sampling at each measurement (even though it may perpetuate peculiarities of the initial sample). It may be convenient to mark height trees with paint for easy subsequent recognition. Height trees lost through cutting or mortality should be replaced by other trees of similar diameter and crown position. Over long periods or in plots established at an early stage of stand development, it will become necessary to delete some trees and add others to maintain a satisfactory distribution across the range of diameters.

The Stand Management Cooperative (Maguire and others 1992) and the Hardwood Silviculture Cooperative (Bluhm and others 2003) currently require 40 height-sample trees for each single-species, homogeneous research plot. A general rule of thumb would be for two-thirds of the trees to be distributed across the d.b.h. classes larger than the average stand d.b.h. and one-third across the smaller d.b.h. classes. This should be considered a minimum number of acceptable height-sample trees for a single-species, homogeneous plot with well-established crown differentiation. If plots at a given location receiving the same treatment are similar in structure and productivity, height-sample trees may be pooled for a common height-diameter curve. In this case fewer trees per plot could be sampled as long as the total sample is at least 40 and the trees are distributed across the plots and the range of diameters. More trees will be required in plots with a wide range in diameters and in mixed-species stands. Some types of studies, such as genetics trials, will require heights of all trees. The recent introduction of much-improved height measurement instruments (discussed below) has greatly improved the ease and accuracy of height measurements, and larger samples than commonly used in the past are now feasible. On small plots with relatively few trees, measurement of heights of all trees is desirable.

Data should be compared to previous data before leaving the field to help identify errors and make corrections.

Height estimates should be compared with previous measurements (ocularly, or automatically by electronic recorder) before the field crew leaves the plot. If obvious discrepancies are found, the measurement should be repeated to determine whether the present or previous measurement is in error, and corrections made accordingly. Where conditions allow, height growth since the previous measurement can also be estimated from internodal distance, as a check in doubtful cases.

If more than one species is present, a decision must be made on sampling the associated species. Options are:

- If the secondary species represents a minor component of the plot, and particularly if it is not greatly different in characteristics from the primary species, then the simplest course may be to ignore height differences and sample the primary species only—accepting any errors that may arise from use of heights of the primary species for the secondary species.
- If the secondary species is few in number but includes a few large trees with a substantial contribution to plot volume, the best course will be to measure heights of all such trees and use these heights in computation of their volumes.
- If the secondary species represents a substantial portion of both plot volume and numbers of trees or is otherwise important to study objectives, then a height sample should be drawn and measured the same as for the primary species.

Similar considerations apply in situations where two clearly distinguishable and important cohorts (age classes) are present.

A number of instruments are available for height measurements (Williams and others 1994, Wing and others 2004). Choice of instruments and procedures for measurement of heights is influenced by expected tree size, terrain, and brush and understory conditions.

In very young stands, height poles are fast and accurate. Commercially available telescoping poles provide measurements to 30 to 40 ft (9 to 12 m) in height, depending on the model. Sectional poles have been constructed that can be used (with considerable difficulty) for heights up to 50 to 60 ft (15 to 18 m) or more. Care must be taken that the pole is kept close to the tree and that the pole tip is at the same distance from the observer as the tree bole. The observer should stand as far away as possible, and at a point higher than the base of the tree if such is available.

The most common procedure in the past has been to measure slope distance from observer to the tree with tape, and angles to tip and base of tree with a handheld clinometer. Then (1) calculate corresponding horizontal distance by using slope correction factors given in table 3 in appendix E or equivalently as (slope distance) x (cosine of angle in degrees), and (2) calculate tree height as:

$$H = [(\text{horizontal distance}) \times (\text{slope to tip in percent})] - [(\text{horizontal distance}) \times (\text{slope to base in percent})]$$

where slope to base is negative if below horizontal, positive if above.

This procedure is adequate for moderate-size trees on moderate slopes, without heavy brush. Special circular slide rules were used in the past to simplify field computation of heights, but these have been replaced by the programmable pocket calculator. With such a calculator and a clinometer graduated in degrees, cumbersome tables and calculation of horizontal distance as a separate step can be eliminated by using the procedure shown in figure 8. Angles should be read to the nearest one-fourth degree (or 1 percent).

It is often convenient to adopt a standard procedure of sighting on the b.h. mark rather than the base of the tree (often obscured by brush), and then adding the value of b.h. (4.5 ft or 1.3 m) to the calculated height. A flashlight is useful to provide a sighting point in heavy brush or shade.

On steep terrain or if heavy brush is present, distance measurement by tape becomes laborious and inaccurate, resulting in poor height measurements. Procedures not requiring tape measurement of distance are advantageous.

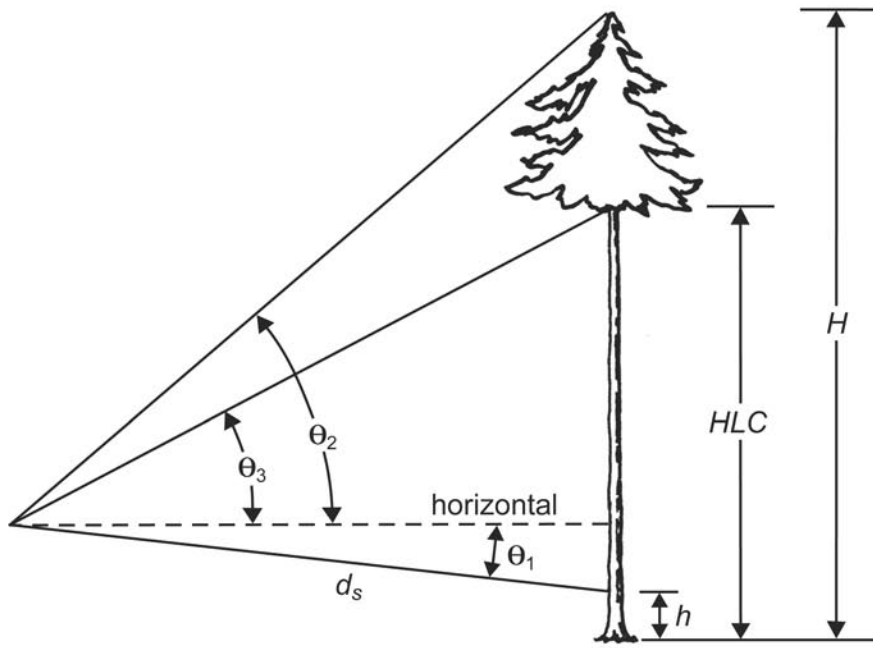
A useful procedure for estimating tree height requires only a height pole and a clinometer.

Several optical rangefinders have been marketed but are not generally satisfactory. The simpler types lack the precision needed for research work. Some limit the user to a fixed distance, which is impractical in dense stands where trees are often visible from only a few points. The more precise instruments are expensive and often cumbersome and difficult to use with poor lighting and visibility.

A useful procedure, requiring only a height pole and a clinometer, that provides satisfactory precision for moderate-size trees while eliminating tape measurement of distance, is illustrated in figure 9 (Curtis and Bruce 1968, Bell and Gourley 1980). This procedure does not require measurement of distance to the tree and allows for greater ease of movement by the observer to get the best view of the point on the tree to be measured.

Tall trees (over 100 ft or 30 m) tax the accuracy of simple clinometers. Sighting angles over 45° should be avoided. Precision of handheld instruments can often be improved by resting the instrument hand on a staff as support. This reduces hand tremor and provides a constant instrument height for all angles measured from a given point. It is often advisable to make two height estimates from different positions and average the results, as errors are the combined result of errors in clinometer reading and in measurement of distance, and of any lean in the tree. An alternative procedure, sometimes useful in improving height growth estimates in relatively open stands in which the tree tip is easily visible, is to record bearing and slope distance from tree to observer at the initial measurement and then take subsequent height measurements from the same position.

A tripod- or staff-mounted optical instrument such as the Bitterlich Telerelaskop will improve accuracy.



Formulas:

(1) $H = d_s \times \cos \Theta_1 \times (\tan \Theta_2 - \tan \Theta_1) + h;$

(2) $H = d_s \times \dfrac{(\sin \Theta_2 - \Theta_1)}{\sin (90^\circ - \Theta_2)} + h;$

$$\tan \Theta = \frac{(\text{slope } \Theta \text{ in percent})}{100},$$

so

(3) $H = d_s \times \cos \Theta_1 \times \dfrac{(\text{slope } \Theta_2 - \text{slope } \Theta_1)}{100} + h.$

Figure 8—Estimation of tree height with clinometer and tape measurement of slope distance.

Θ is angle in degrees.

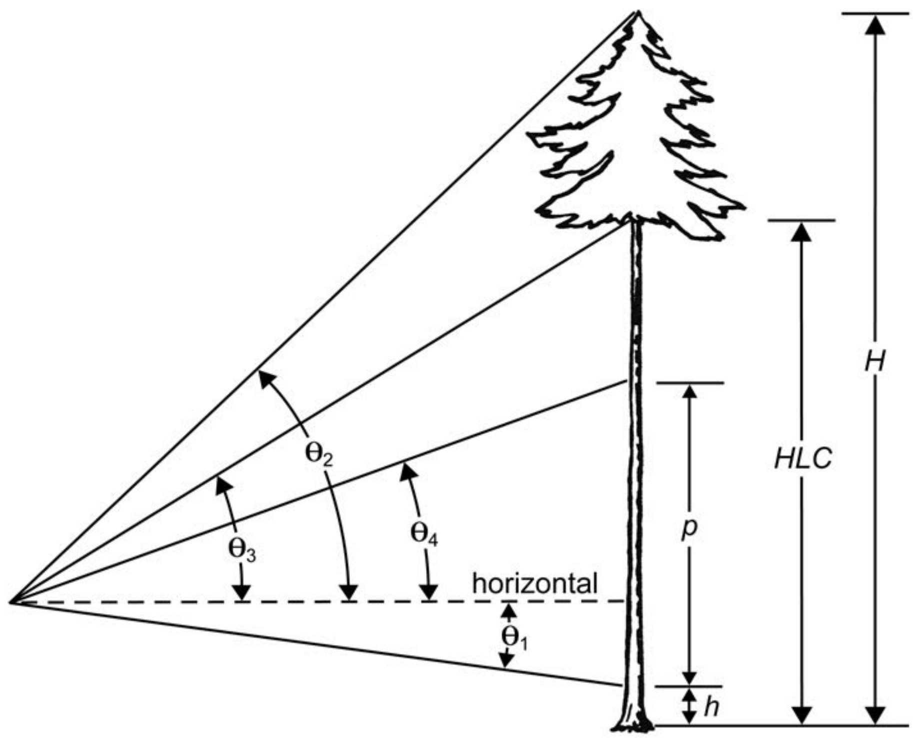
H is total tree height.

HLC is height to live crown.

h is height to lower aim point (usually, breast height).

d_s is slope distance, measured parallel to line of sight from observer to center of tree at lower aim point.

Angles should be measured to nearest one-fourth degree or 1 percent. Formulas for *HLC* are as shown for *H*, but with Θ_3 replacing Θ_2.



Formulas:

$$H = \frac{p \times (\tan \Theta_2 - \tan \Theta_1)}{(\tan \Theta_4 - \tan \Theta_1)} + h;$$

$$HLC = \frac{p \times (\tan \Theta_3 - \tan \Theta_1)}{(\tan \Theta_4 - \tan \Theta_1)} + h.$$

Figure 9—Estimation of tree height by the pole and clinometer method. Θ is angle in degrees. Because tan Θ = 0.01 slope Θ in percent, substituting 0.01 slope Θ in the equation causes the 0.01 factors to cancel out. Thus the equation can use either tangent of the angle (in degrees) or percentage of slope.

H is total tree height,

HLC is height to base of live crown,

h is height of lower aim point (usually breast height),

p is length of portion of pole above lower aim point. Length of pole should be at least one-fourth of total tree height, more when feasible.

Care must be taken that base and tip of pole are against the tree bole, or beside the tree at the same distance from the observer as the tree bole. Measurements should be taken perpendicular to direction of any tree lean.

Figure 10—Recently introduced laser instruments greatly improve speed and accuracy of height measurements and, with compass and staff attachments, are suitable for rapid surveys of moderate precision.

New instruments have greatly improved the speed and precision of height and distance measurements.

The introduction of instruments such as the "Impulse "(Laser Technology Inc.) and "Forest Ace" (Measurement Devices Ltd.) laser instruments (fig. 10) (Wing and others 2004) for measuring heights and distances has greatly improved the speed and precision of height and distance measurements. When used in conjunction with a reflecting prism placed at the base of the tree at a known height such as b.h., these can provide readings through a considerable amount of foliage and give horizontal distances and heights without tape measurement of distances or manual slope corrections. The principle is the same as the old tape and clinometer method (fig. 8) but the computations are done automatically, the optical sight improves accuracy of angle determinations, and distance measurements are faster and more accurate than tape measurements. Another instrument serving the same purpose and having similar advantages for moderate-size trees is the Haglof "VERTEX III," which uses sound and a transponder attached to the tree bole (note: heavy rain or a nearby stream can affect signal transmission).

These or similar instruments have become indispensable to anyone needing to measure large numbers of heights. Whichever instrument is used, the observer should have a good view of the sighting point on the tree, and measured angles should generally be kept below 45°.

> ***Recommendations:*** Height poles are fast and accurate for short trees. For trees too tall for easy use of height poles, the new laser or sonic instruments are far superior to the older methods in speed and accuracy. However, if such instruments are not readily available, the older tape and clinometer and pole and clinometer methods are still useful and will give results of acceptable accuracy for trees of moderate height.

Crown measurements—Crown dimensions were only rarely measured in older studies. Yet, crown development reflects the past history of trees and stands and is closely related to competitive status and growth rate and to growth potential.

Height-to-live-crown (HLC) is the most easily determined crown dimension. In combination with total height, this gives crown length and live crown ratio (crown length/total height). These are associated with tree competitive status and potential response to treatment and have been useful predictors of growth in growth and yield models (Hahn and Leary 1979, Hann and others 1997, Holdaway and others 1979, Krumland and Wensel 1980, Stage 1973). Hence, measurements of height to live crown should be made for all trees in the height sample.

Some care is needed in defining base of live crown for consistency among different installations and measurements made by different individuals. Different observers will not be entirely consistent in judging the location of the base of live crown, and therefore measurements of height to live crown are inherently less precise than those for total tree height.

A suggested definition for conifers is "lowest whorl with live branches in at least three quadrants, exclusive of epicormic branches and whorls not continuous with the main crown. Irregular and one-sided crowns must be ocularly "adjusted" to estimate the corresponding position of the base of a normally formed crown of the same volume. Some hardwoods typically have highly irregular crowns, and in such cases, "lowest live branch" may be the only feasible definition. In some species, the lower crown may droop far below the base of the lowest live branch, and an additional height to live foliage may be useful.

Crown widths are also frequently of interest in studies of tree and stand growth and response to treatment. These are best made as an average of measurements along the long and short axes.

If stands are not excessively dense, crown widths can be readily measured on large-scale aerial photographs. Ground measurements require vertical projection of crown margins, which can be done with such simple instruments as the Suunto clinometer, a pole with rod level, by ocular estimation (small trees); or with any of a variety of instruments constructed especially for the purpose.

Ground measurements of crown width are easily obtained for short trees with crowns extending nearly to the ground and in very open stands, but become difficult and inaccurate with increasing height and stand density. Ground measurement of crown widths is considerably more difficult and time consuming than measurement of height to live crown.

Recommendations: Height to live crown should be routinely measured on all new research installations and on the more valuable older installations. Crown width should be measured only on selected installations where there is a clear and specific purpose for such measurements.

Upper-stem diameters and tree form measurement—There may be need to measure upper-stem diameters on a sample of trees for either of two reasons:

- The form estimate implicit in conventional double-entry volume equations may not adequately account for a change after treatment; hence, estimates may be needed for individual plots or treatments.
- Information on stem taper and size assortments may be needed as a basis for subdivision of tree and stand volume into size, product, or value classes.

The question of possible effects of stand treatment on standard volume equation and taper function estimates has not been entirely resolved. Direct estimation of individual tree and plot volumes is laborious and expensive. Most researchers have preferred to assume that treatment effects on form, beyond those incorporated in standard volume and taper equations including height, diameter, and—sometimes—crown ratio as predictors, can be ignored. Hence, upper-stem measurements specifically for this purpose are probably not needed. This is a convenient assumption rather than a clearly demonstrated fact.

There is generally a need for estimates of volume to different merchantability limits, and by size, product, or value classes. Some information is easily obtainable from the tarif system (Brackett 1973, Chambers and Foltz 1980); more complete information is given by stem taper curves.

Suitable taper curves are often available from other sources (Hann 1994). If not, it may be desirable to include upper-stem measurements on a sample of trees to provide the basis for developing such curves and associated assortment tables. Needs for such information and existing sources should be considered as part of the study planning process.

If there is need for upper-stem measurements, these can be obtained either by measurement of felled trees on the plot or on the adjacent buffer strip, or by dendrometry. Commercially produced instruments suitable for measuring upper-stem diameters in the standing tree include the Wheeler pentaprism caliper (Wheeler 1962) the Bitterlich relaskop, the Bitterlich tele-relaskop, and some of the new laser instruments (Garrett and others 1997, Parker 1997, Parker and Matney 1999, Williams and others 1999.) The old Barr and Stroud dendrometer was precise, but is no longer manufactured.

Some taper equations allow for calibration by using one or more upper-stem diameters (Flewelling 1993, Kozak 1998). In contrast, direct estimation of tree volume requires measurements of stump height, d.b.h., total height, and diameters inside bark at a series of relative height intervals such as 0.05, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, and 0.95 of total height (or alternatively, at fixed height intervals) and total height. Diameter inside bark can be directly measured for upper-stem positions on felled trees but must be estimated for measurements on standing trees (Mesavage 1969). Height to base of live crown is a highly desirable additional measurement, and some studies require stem diameter at this point (which is related to leaf area). Detailed procedures and various taper and volume equations are given by Bitterlich (1981), Bruce (1972), Bruce and others (1968), Cao and others (1980), Flewelling and Raynes (1993), Gray (1956), Grosenbaugh (1963), Kozak (1988), Martin (1981), Max and Burkhart (1976), and Walters and Hann (1986).

The time and cost of such data collection and analyses are substantial and should be carefully evaluated in relation to needs before such work is undertaken.

Site Index Estimates

Even-aged stands are commonly classified by site index, the expected height of a specified portion of the stand at a specified reference age, as an index of productivity. Details of definition of the stand component used and the estimation techniques differ among species and regions because of the evolution of techniques over time and the vagaries of different authors (see Hann 1995 for a list of available site equations for the Pacific Northwest and California). Normally, classification is based on the principal species present, although approximate conversions are possible for species having similar site requirements.

Established procedures often involve subjective choice of site trees on the basis of crown class or other descriptive criteria. Newer procedures define site trees by position within the diameter frequency distribution. Where a procedure is well established, plot measurement procedures should provide for its use. Procedures continue to evolve, however, and a procedure in general use at the start of an experiment is not necessarily that which will be used at its conclusion.

Trees with damage affecting height and height growth should be excluded from site index estimates. If all site trees were not measured, height estimates for the specified stand component may be obtained as values read from the height-diameter curve for the mean diameter of the specified component, or as a mean of measured heights of sample trees drawn from that component. If the latter procedure is followed, guidelines will be needed for the required number of sample trees, based on the variability of site index estimates. In general, the required number will increase

Site index estimates and the population of qualified site trees often change over time, and the record should be updated as this occurs.

as plot size increases and also as the difference between plot age and index age increases, but the number cannot exceed the number of qualifying trees present on the plot and, if necessary, its buffer strip. A site index estimate should not be based on fewer than four trees per plot (authors' opinion), and more are highly desirable when allowed by plot size and component specifications. Site trees should be identified on the plot record and remeasured at successive plot remeasurements as long as they meet the specifications for qualified site trees. Age of site trees should be determined by boring at b.h., when feasible. Ages and heights of individual trees should be retained in the record, to allow for possible future recomputation with alternative procedures.

Site index estimates will improve as stand age approaches the reference age. Therefore, a new estimate should be made for each measurement date. Actual shape of the height growth curve differs among stands. As young stands develop, later estimates of site index will more accurately represent the growth potential of the site. Site index estimates and the population of qualified site trees often change over time, and the record should be updated as this occurs.

> ***Recommendation:*** In general, it is best to base site index estimates on a stand component defined in terms of the d.b.h. frequency distribution rather than subjective crown classes. The preferred basis is a specified number of the largest diameter stems per unit area, such as the 40 largest per acre (100 largest per hectare).

Application of any selection rule should include a "well-distributed stems" requirement to insure that the average represents the entire plot area and is not materially influenced by any site gradient across the plot. (For example, on steep slopes the tallest trees may be located along the lower edge of the plot.) One means of insuring this is to divide the plot into subplots or strips parallel to the contour and of approximately equal area, and then apply the site tree selection rule separately within each subplot. The preferred method is to divide the plot into 1/40-acre (0.01 ha) subplots and select site trees as the largest otherwise suitable tree within each subplot (Forest Productivity Council of British Columbia 1998).

Stem Maps

Consideration should be given to stem mapping selected installations expected to be major sources of long-term growth data. Stem maps can provide:

- Easy relocation of missing trees and of sample trees drawn from the plot record.
- Description of spatial distribution of stems.
- Description of spatial distribution of mortality and injury.

- Information needed for development of distance-dependent simulation models, which use measures of inter-tree competition based on individual tree dimensions and inter-tree distances.

Stem mapping can be done rapidly in stands with moderate numbers of stems, good visibility, and easy terrain. It becomes laborious, expensive, and error prone when there are large numbers of small stems, difficult terrain, or dense brush; it should not be undertaken lightly under such conditions.

A common procedure uses angles and distances from plot center or plot corners, a procedure that has been greatly improved in speed and accuracy by the new staff-mounted laser instruments with compass attachment (Moeur 1993). An alternative procedure that takes advantage of the newer distance-measurement instruments uses triangulation of distances measured to each tree from two known points such as plot corners (Quigley and Slater 1994). An older procedure suitable for small plots determines coordinates by reference to two tapes stretched at right angles and using right-angle prisms (Reed and others 1989). Digitized aerial photography is highly efficient for open stands.

Stem mapping need be done only once on an installation. Once coordinates for each tree are available, actual stem maps for the first or any subsequent measurement can be produced by computer.

Regeneration and Understory Vegetation

Much past work has been concerned primarily with development of the trees composing the present or expected future merchantable volume of a stand, and has often paid relatively little attention to development of understory trees and secondary vegetation. Planned regeneration has generally been measured and documented; not so the establishment of tree species in the understory that do not constitute part of the planned future crop. And, establishment and development of nontree species in the understory have generally been ignored unless they constitute a threat to planned regeneration. Although often described in very general terms, quantitative information has generally been lacking.

With the current emphasis on wildlife habitat, biodiversity, stand structures, and silvicultural systems that are alternatives to the long-established clearcutting system, and recognition that competing vegetation can have major influences on crop-tree growth, there is a new interest in characterizing the composition and growth of the understory that develops under various stand treatment regimes. And, its composition is often the basis for classification of plant communities that are related to other ecological and management concerns.

There is a new interest in characterizing the composition and growth of the understory that develops under various stand treatment regimes.

Regeneration—Information is commonly wanted on the number, species, dimensions, spatial distribution, and survival of tree regeneration. By definition, this refers to trees smaller than the minimum diameter (or height) included in the main plot measurements discussed earlier. When the experimental units are relatively small plots, this will require subsampling by subplots or by transects within the main plot. When the experimental units are relatively large treatment areas, they can be sampled either by a grid of small plots independent of the plots used to characterize the treatment area, or (more efficiently) by a series of small subplots superimposed on the larger plots used for the main tree measurements.

One often wishes to trace the development and survival of planted trees, as opposed to natural seedlings. For this purpose, planted trees must be identified so that development and survival of individual seedlings can be followed through time. This can be done either by tagging planted seedlings or by recording azimuth and distance of each seedling from the center or corner of the regeneration subplot.

The number, size, and condition of snags and the amount, dimensions, and condition of down material are frequently of interest from the standpoints of wildlife habitat, carbon sequestration, and fuel loading.

Secondary species—A complete inventory and description of all the secondary (nontree) species on an area is an extremely time-consuming, laborious, and expensive undertaking. And, it requires a degree of botanical expertise usually lacking in field crews. From a silvicultural standpoint, one does not usually need a complete enumeration and description (although these might be required for modeling or computing abundance and diversity indices for ecological studies). Primary interest is usually in those species that are serious competitors of tree species and in those that are of value for wildlife or for specialized products such as floral greens. The number of species that are of major importance from these standpoints within a given area is usually fairly small. It may often be sufficient to describe conditions in terms of percentage of cover and average height of a small number of species or species groups. Frequently, ocular estimates of these values on small subplots or transects, made at successive measurements, will suffice to identify trends in understory development under different stand treatment regimes.

Snags and Coarse Woody Debris

The number, size, and condition of snags and the amount, dimensions, and condition of down material are frequently of interest from the standpoints of wildlife habitat, carbon sequestration, and fuel loading. Therefore, consideration should be given to securing and maintaining a record of snags and down material.

Tagged trees that have been found dead can be reexamined at subsequent measurements to determine rate of deterioration. Snags existing at the time of plot establishment can be tagged, recorded as snags, and reexamined at subsequent measurements. The number of snags on small plots is often small and highly variable, and estimates based on individual small plots therefore have inherently high variance. In large-scale experiments where relatively large treatment units are sampled by a series of small plots, it may be desirable to overlay a larger plot size for snags.

Quantity and dimensions of down material present at each measurement can be estimated on the basis of subplot or transect samples. On very small plots, complete enumeration and measurement of all qualifying pieces is possible. With larger plots or large treatment units, this becomes impractical and sampling is necessary. A variety of methods have been used (Stahl and others 2001). The most widely used technique is line intersect sampling. In simplest form this consists of recording piece diameter at the point of intersection of the piece with one or more randomly oriented lines. Elaborations can provide estimates by piece size and decay class. Excellent discussions of field techniques are given by Iles (2003, chapter 10—very readable), Marshall and others (2000), and Waddell (2002).

Several generally similar but not identical systems exist for describing characteristics of snags and down material (Bull and others 1997, Cline and others 1980, Maser and others 1979).

A systematic procedure must be used for identifying and filing photographs to insure that the needed information is recorded.

Photographs

A sequence of photographs showing stand development over time is useful for both oral presentation of research results and illustration of publications. The need for photographs should be considered and procedures specified at the time a study is established. Usually, a sequence of photographs beginning with the initial plot measurement date should be obtained for at least a sample of plots, sufficient to illustrate the stand conditions and treatments involved.

Photos are most useful when they show the same scene at successive points in time (Hall 2002). So far as is feasible with changing stand conditions, photos should be taken in the same direction from the same points at successive dates. Vegetation development will often make this unfeasible, in which case, one should seek nearby points that illustrate representative conditions. Photopoints can be identified either by distinctively marked stakes or by distance and bearing from plot corners or plot centers, and should be documented and permanently stored with other information about the plot. A person or some object of easily recognized dimensions should be included in photos to provide a size scale meaningful to the viewer.

Photos are worthless unless they are carefully and completely identified by study, installation, plot, location, date, photographer, and any special points illustrated. A systematic procedure must be used for identifying and filing photographs to insure that the needed information is recorded; that each photo can be associated with other records for a particular study, installation, and plot; and that negatives and transparencies are protected from damage.

Remeasurement Schedule

A plot remeasurement schedule should be specified and adhered to as closely as possible. A standard planning procedure should be provided to insure that scheduled remeasurements are not missed.

The interval between measurements depends on stand conditions and on the purpose of the installation. In general, measurements at relatively short intervals are needed for rapidly growing stands (young stands, good sites) or where there is major interest in short-term changes in growth in response to treatment. Longer intervals suffice in slower growing stands. Except where there is a specific need, measurements at very short intervals (say, under 3 years) are not generally useful because of the irregularities introduced by year-to-year variations in growth and the difficulty of accurately measuring small growth changes.[5] With longer intervals and slower growing stands, limited deviations from the planned measurement schedule may be allowable, depending on the nature of the study; but measurements must not be missed or postponed when an associated treatment is applied. A complete stand measurement should be made whenever a thinning, fertilization, or other stand treatment is carried out.

Research studies most commonly use a fixed interval for all plots in a given installation or study. This is usually specified in calendar years but may be defined by amount of height growth or other measure of stand development, as a means of allowing for differences from expected growth rates and obtaining closer comparability among installations.

Measurements should be made during the dormant season if at all possible. Although fractional years arising from measurement during the growing season can be used in analyses, they are a complication and a source of errors (which may be large for short growth periods). Changes in bole moisture content and the attendant shrinkage and swelling have measurable effects on diameters and estimated diameter increments; to a considerable degree, these effects are associated with season and are reduced by dormant season measurement. If measurements must be done outside the dormant season, these should be on as nearly as possible the same date on each occasion.

[5] A first remeasurement soon after establishment will, however, serve to correct measurement and recording errors made at the time of measurement.

Control of Treatments

Thinning or Other Partial Cuts

Type, severity, and frequency of thinning or other operations in silvicultural research studies are normally specified in the study plan. Procedures for applying and controlling operations on the ground to meet these specifications and needs for pretreatment information will vary with study objectives and the required degree of control over silvicultural operations.

In precommercial thinning, the objective is generally some specified number of well-spaced best trees, compatible with some target diameter for first commercial thinning. Detailed knowledge of present stand statistics is usually not necessary to apply the initial thinning, although knowledge of initial stand statistics may be needed in later analyses. For subsequent thinnings, knowledge of pretreatment stand statistics and growth may or may not be necessary to carry out the thinning, depending on study objectives and specifications.

In stands that have been previously spaced some time before study installation, the objective may also be to leave a specified number of well-spaced best trees. This can often be achieved without prior knowledge of stand statistics and growth. In some studies, however, knowledge of individual tree growth obtained by measurement may be the primary basis for deciding which trees to remove.

If study specifications call for retention or removal of some specified fraction of growth or growing stock, then the stand must be measured and stand statistics calculated before the marking is done, as the approximate volume and size distribution of trees are necessary as a guide to the marking operation.

The close control of residual numbers, size, and spatial distribution of trees needed in many silvicultural studies often requires subdivision of the plot and plot record into subplots for marking purposes. Where very close control of residual spacing is wanted, the area may be gridded with string or otherwise at the desired spacing and a suitable tree nearest to each grid point designated as a leave tree. More commonly, it will suffice if the required number of reasonably well-spaced best trees is left on each subplot or other subdivision of the plot.

Fertilization

Although operational forest fertilization is generally done by aerial application, most research studies use carefully controlled hand application. The plot is subdivided with string or otherwise into relatively small segments or squares, and measured amounts of fertilizer are applied to each subdivision. Although this uniformity of application is not consistent with the variability encountered in operational fertilization, it is necessary if the objective is to relate growth response to fertilizer dosage and is often the only way to apply fertilizer to small areas with adjacent unfertilized plots.

Plots are sometimes installed in operationally fertilized areas in an attempt to estimate the gain in yield from fertilization. For meaningful results, one or both of two procedures must be followed: (1) the fertilizer dosage actually reaching each plot must be estimated by sampling with an adequate number of fertilizer traps on each plot, or (2) clustered subplots may be distributed within portions of the treated area that are comparable in other respects, in a manner that insures that the average amount of fertilizer received by the cluster will approximate the nominal area dosage.

The gain in yield from fertilization is estimated by comparing growth on the fertilized plots with that on comparable unfertilized plots, or with some other estimate of expected untreated growth. Because of the relatively large treatment areas necessary with aerial application, it is difficult to provide comparable control plots and adequate replication. This fact, plus the high variability in actual dosage and in stand conditions within operational areas, makes direct quantitative measurement of treatment response to aerial applications difficult, inaccurate, and often impossible; hence the researcher's preference for uniform ground application in fertilizer studies (Bruce 1977).

Pretreatment statistics are helpful to describe initial conditions even when control plots are used.

Timing of Measurements in Relation to Treatment

Main Plot

A complete stand measurement is needed whenever a thinning, harvest, or fertilization treatment is applied to an installation. For plots that are fertilized only, a single measurement suffices. For plots that are thinned, information is needed for the live stand before thinning and after thinning, for trees cut, and for damage occurring during the thinning operation. Pretreatment statistics may or may not be used as a basis for controlling the silvicultural operation, but they are always needed in analyses to describe the initial conditions. Associated control plots are sometimes used but often are not sufficiently comparable to provide satisfactory information. Posttreatment stump measurements, although possible, are often inaccurate and are an undesirable substitute for adequate pretreatment measurements.

When possible, a pretreatment measurement and the actual treatment should be done during the same dormant season. At a minimum, diameters of all trees should be measured before a thinning or harvest operation. A posttreatment remeasurement is then needed as soon as possible after completion of the operation, to identify trees cut, destroyed, or damaged during the thinning or partial harvest operation.

When a thinning or other partial cut is done at the time of plot establishment, alternative procedures may be used, depending on stand conditions and the expected numbers of cut and leave trees:

1. Preliminary tally followed by postcut measurements. A preliminary dot tally (by 1-in or 1-cm classes) can be made to guide treatment and provide precut stand statistics, followed by numbering, tagging, and complete measurement of leave trees after treatment.
2. Pre-identify leave trees. If leave or cut trees can be identified before measurements are made, it may suffice to measure and record other (cut) trees by 1-in or 2-cm classes only. If numbers are assigned to the leave trees, they can be recorded in the order encountered, which provides an indication of spatial position. All designated leave trees must be measured to 0.1 in or 0.1 cm, numbered, and tagged or painted. A postthinning check is made to identify trees destroyed, missed, or damaged.
3. Permanently number all trees at the start. Tag or paint all trees with tree number and a clear identification of the height at which d.b.h. is to be measured. Measure all trees for exact d.b.h. (nearest 0.1 in or 0.1 cm). Then make a postthinning check to identify trees that were cut, destroyed, missed, or damaged.
4. Temporarily tag all trees. To avoid permanent tagging of trees that are measured only once and then cut, temporary numbered cards can be stapled to the trees. Numbers should be in the sequence in which trees are encountered and positioned so that the top edge of the tag denotes the height at measurement. Measure all trees and make the postthinning check as in (1). Permanently number the leave trees with tags or paint at the time of the postthinning check.

If pretreatment stand statistics are needed to guide treatment and methods, a dot tally of all trees by size classes may provide all that is needed. Leave (or cut) trees are then selected, marked, and tallied before the cut. In some operational-scale studies, precut marking of individual trees may not be feasible; tree selection is then done by the operator, subject to periodic check for compliance with specifications. Numbering, tagging, and accurate measurement of the leave trees can be deferred until after the thinning or harvest operation.

When thinning is done at the time of plot establishment, it may be desirable to measure heights at the time of the postthinning check, rather than at the prethinning measurement. This avoids one-time height measurements on trees that are then immediately cut, confines the sample to trees likely to be present at the next measurement, and provides better visibility of tree tops. If, however, prethinning heights (especially for small trees that may be removed in thinning) or volumes are needed as a basis for controlling treatment, heights must be measured before thinning. Substitutes for any trees cut can be remeasured at the postthinning check, which is often not made until the next growing season. In such cases, recorded height should be the estimated height at the end of the previous growing season.

On previously measured plots, trees having prior height measurements should be remeasured at the time of the prethinning measurement. If any of these trees are cut or if additional trees are needed to maintain a desirable distribution of the height sample, additional trees should be added at the time of the postthinning check. Growth estimates for the subsequent period can then be based on the same sample trees.

Buffer

Although all residual trees on the main plot must be assigned permanent numbers, tagged, and measured at the time of plot establishment, the procedure to be followed with trees on the buffer may differ according to the nature of the study and the treatments applied.

There is normally no need to tag or measure trees on the buffer surrounding an untreated control plot or any plot that is not thinned. There may or may not be a need to measure buffer trees on plots to be thinned, as a basis for controlling thinning. If needed, a dot tally by diameter classes usually suffices.

Studies of individual tree competition that require information on diameter and location of competing trees may require numbering, measurement, and stem mapping of trees in the buffer strip, in the same manner as on the main plot. This situation arises when very small plots are used for such studies, in which it is not possible to designate a central subplot that is not influenced by trees in the buffer strip.

Operations Log

There should be a systematic procedure for recording the date and nature of any measurements made or treatments applied.

There should be a systematic procedure for recording the date and nature of any measurements made or treatments applied. It should be standard practice for the field crew leader to prepare a file memorandum or report recording what was done, when it was done, who did it, costs in person-hours or dollars, and any incidental observations made while on the plot(s).

Any damage or untoward events affecting the plot or overall study should be recorded when discovered and fully described in the record. This includes such things as major wind, snow, or ice damage; major insect or disease injury; and human activities not planned as part of the study (road relocations, failure to protect plots from operations on adjacent land, vandalism, trespass, ownership change).

Data Recording

Obtaining quality data requires well-trained crews following established procedures for handling data in the field and office, using well-maintained equipment appropriate for the job. Recording of measurements in the field should be done neatly (if written) and carefully with the recorder orally confirming observations made by the measurer. If available, relevant prior measurement data should be easily available for the recorder to compare for reasonableness in order to catch current or past measurement errors. For each current measurement made that has a past measurement available, the recorder should check whether the increase in diameter or height is reasonable and if the height increase is consistent with internodal length (if visible).

If done as soon as possible after the measurements are completed, a preliminary data edit can catch gross errors while they can still be readily corrected.

Figure 7 is an example of a field sheet that can be produced by computer with the relevant prior measurements, and printed or copied on waterproof paper. Although paper field sheets are still useful for small-scale and specialized tasks, they are being replaced by electronic data recorders. A screen set-up similar to figure 7 can be used with these.

Small, field-rugged computers are now commonly used for data collection. Electronic data recorders eliminate manual data transfer (keypunching) from field sheets to computer, a time-consuming and error-prone task. They can also allow for the automation of onsite editing and data-checking tasks, such as checking that all required fields have been entered with an appropriate code and that measurements fall within reasonable limits. Until recently, the software required for data entry required custom programming. Now most computers have spreadsheet applications available that are adequate for many small jobs. For more complex data collection efforts, programs like DataPlus (Field Data Solutions, Inc.) can be used to create custom data entry applications quickly and with no programming experience.

Preliminary Data Editing

As soon as possible after the measurements are completed (and the data entered, if field sheets were used) there should be a preliminary data edit designed to catch gross errors while they can still be readily corrected. These edit checks may start by simply computing the minimum and maximum values of the various measurements (for example, d.b.h and height) to identify unreasonable values. A simple tally of numbers of trees by species or other codes can identify unknown codes. Computing the number of live and dead trees and comparing this with the number of live trees at the prior measurement provides a quick check that all trees have been accounted for. In addition to these tallies, simple graphical checks, such as scatter plots of heights over diameter, or more elaborate plots of the change in individual tree measurements (for example, diameter, height, and height to live crown) over their current measurement can reveal potential errors and outliers in tree measurements (see Karsh and Lavigne 1993 for more elaborate editing guidelines). Such procedures can be done in spreadsheets or with more sophisticated statistical software packages and can often catch gross errors that would waste much time and effort if left until the analysis stage.

Data Management

In the past, plot procedures, measurements standards, data recording codes and formats, and computational procedures have often been developed more or less independently for each study by the individual researcher or organizational unit involved. These have been shaped by the investigator's immediate needs and interests, experience, and limitations, and are often inadequately documented.

Standardizing data standards, codes, and documentation for a minimum variable set facilitates use of data beyond the original planned use.

Good-quality data often have a life that goes beyond a specific research project or even beyond the career of the researcher responsible for collecting them. Old data sets can often provide answers to new research questions without a new data collection effort. In addition, some research requires drawing together individual data sets from different sources to develop regional or more generally applicable estimates of treatment responses and potential yields. In some cases, there is a need to secure new data to supplement those now existing and to extend work to less studied species or conditions. The magnitude of work and costs involved in the establishment, maintenance, and measurements of research plots and management of the data produced has led to more extensive use of cooperative data collection efforts, now facilitated by computer technology. In the past, cooperation and exchange of data has often been severely hampered by the general absence of uniform procedures for collecting, coding, recording, documenting, and summarizing data.

It is often a major task merely to discover what information exists. Once data are located, much information is then lost in attempting to reconcile inconsistent measurements and coding systems. Individual data sets frequently require their own tailor-made computer programs. Conversion to a common format and codes, essential for analysis by a single set of programs, is costly and prone to error.

Standardization is clearly important. It is impractical to expect that detailed specifications could be written that would meet the data collection needs of all organizations and all research objectives. However, research workers and cooperating organizations concerned with particular species or types of major importance should jointly prepare and adopt specifications for collecting and recording permanent plot data. These should provide for a minimum set of required measurements, standards, information codes, and documentation.

The elements involved are:

- An individual(s) in each organization responsible for permanent plots. They should establish and maintain a database of plot data relevant to specified objectives that can be continually updated. This would provide specified information on the nature of the installation, treatments applied, and the status of existing data.
- Agreement on minimum specifications for the basic design standards and measurements to be made on all permanent plots. This manual and field manuals from regional cooperatives should provide a basis for this process.
- Individual organizations should maintain up-to-date documentation on the data format and coding system used. Standard data formats and coding system would be desirable. However, many organizations have existing legacies and it is impossible to anticipate the special interests and objectives of individual studies. For cooperative data collection efforts, data formats and codes should be designed so that the user has latitude to subdivide codes or add additional special-purpose codes, while retaining certain mandatory categories and codes common to all data in the system and necessary for compatibility with associated computational programs.

Examples of codes and the types of information typically needed are given in "Tree Classification Codes" in Appendix A. The Silviculture and Modeling Team at the Pacific Northwest Research Station's Olympia Forestry Sciences Laboratory currently uses these codes. Although there is no implication intended that others should adopt these as given, they do illustrate the types of information that must be provided in such a system.

Each organization will likely use its own computer programs designed to operate on their data sets for the format and specific codes used. For cooperative studies, common applications should be available. These should be well documented and perform the following tasks:

- Maintaining and updating information describing installation and plot status.
- Updating plot and tree data.
- Editing and correcting new plot and tree data.
- Calculating standard summaries of plot and tree data.

Efforts to encourage standardization and develop data management systems are not new. The Western Forestry and Conservation Association (1977) gave a list of

A critical component to data management is data storage.

recommended items to be included in plot records. Arney and Curtis (1977) gave specifications for a plot index system and a detailed tree record format and coding system used in a large regional yield study in Douglas-fir. These codes and formats have since evolved considerably and have been incorporated in many systems (for example, Sweet and Byrne 1990), often in the context of commercially available relational database programs. Such systems or portions of them exist in some organizations, including regional research cooperatives and some industrial organizations. Most are either not publicly available or are incomplete or inadequately documented.

A critical component to data management is data storage. Although data sets need to be accessible and updateable, they also need to be protected. Paper records (documentation, maps, and field sheets) should be stored in a fireproof cabinet. Computer files and programs should be backed up and archived offsite on a durable medium and in a format that is likely to be readable in the future despite changes in software and operating systems. A scheme to periodically verify and refresh electronic data storage systems will be required.

Maintenance and operation of a data management system are not simple tasks that can be delegated to anyone with some acquaintance with computers and data processing. It requires both abilities in programming and operation of database programs, and a considerable knowledge of related aspects of forest mensuration and silviculture. Without the latter, nonsense may not be recognized until it is too late to do anything about it.

Metric Equivalents

When you know:	Multiply by:	To find:
Inches (in)	25.4	Millimeters (mm)
Inches (in)	2.54	Centimeters (cm)
Feet (ft)	.3048	Meters (m)
Square feet (ft^2)	.0929	Square meters (m^2)
Cubic feet (ft^3)	.028	Cubic meters (m^3)
Acres (ac)	.4047	Hectares (ha)
Milacres	.0004047	Hectares (ha)
Square feet per acre (ft^2/ac)	.2296	Square meters per hectare (m^2/ha)
Cubic feet per acre (ft^3/ac)	.06997	Cubic meters per hectare (m^3/ha)
Miles per hour (mph)	1.609	Kilometers per hour (kph)
Fluid ounces (oz)	.0296	Liters (L)
Gallons (gal)	3.78	Liters (L)
Tons	.907	Megagrams (Mg)
Degrees Fahrenheit (°F)	(°F – 32) × 0.556	Degrees Celsius (°C)

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Appendix A: Checklist of Needed Plot and Tree Measurement Information

Plot description

The following indicates plot description items that should be recorded in some standard format:

- Installation number
- Plot number
- Location: forty, section, township, range, state, GPS coordinates
- Local name of installation
- Organization responsible
- Contact person
- Status: active, abandoned, destroyed
- Plot age b.h. (or from seed—specify), at first measurement
- Site index
- Site index system used
- Plot area
- Plot shape
- Stem mapped: yes or no
- Primary species
- Secondary species
- Elevation
- Aspect, azimuth (N = 360)
- Slope percent
- Slope position
- Measurement units: English or metric
- Stand origin: natural, planted, seeded (if known, note spacing, seed source, site preparation, etc. under general comments)
- Project identification
    - Date of first measurement: month, day, year
      (repeat for each successive measurement)
    - Date of first thinning, if any: month, day, year
      (repeat for each successive thinning)

Date of first fertilization, if any: month, day, year
(repeat for each successive fertilization)

- Fertilization treatments: (enter successively for repeated treatments)
- Method of fertilizer application (hand, fixed-wing aircraft, helicopter)
- Nutrient element, application rate per unit area

- Physical soil description (if available)
- Analytical soil characteristics (if available)
- Area environmental characteristics (if available)
- Vegetation control, if any
- General comments: descriptive notations on any special characteristics of the area, plot, or treatment history not adequately described.

Tree Description Record

Installation number
Plot number
Tree number
Species
Age b.h. as of this plot measurement (ring counts made at this measurement)
Stem map coordinates (stem-mapped plots only)
Tree measurement information to be recorded for each successive measurement:

- Diameter b.h.
- Height (height-sample trees only)
- Height to live crown (height-sample trees only)
- Crown width (height-sample trees only, optional)
- Crown class code
- Tree class code
- Tree damage, nature/cause
- Tree damage, severity

Current Forest Service species codes for both tree species and secondary vegetation consist of four alpha characters, of which the first two are the first two letters of the genus and the second two are the first two letters of the species name. In cases where this leads to duplication, a fifth numerical character is added. Thus, the species code for Douglas-fir (*Pseudotsuga menziesii*) becomes PSME. A list of species codes for the coastal Douglas-fir region is given in table 164 of Henderson and others (1989). A more complete and up-to-date nationwide list is given in the national plants database (http://plants.usda.gov).

Tree Classification Codes

The following system of tree classification codes is currently used in silvicultural studies at the Olympia Forestry Sciences Laboratory, and will serve to illustrate the types of information needed. This illustrates characteristics needed in any system. With modifications or additions it should meet most needs. Thus, some users may want additional codes relating to fire (such as percentage of crown scorch, height of bole charring) or to other specific diseases and pests.

Species

Code	Common name	Scientific name
ABAM	Pacific silver fir	*Abies amabilis* Dougl. ex Forbes
ABGR	Grand fir	*Abies grandis* (Dougl. ex D. Don) Lindl.
ABLA2	Subalpine fir	*Abies lasiocarpa* (Hook.) Nutt.
ACCI	Vine maple	*Acer circinatum* Pursh
ACMA	Bigleaf maple	*Acer macrophyllum* Pursh
ARME	Pacific madrone	*Arbutus menziesii* Pursh
ALRU	Red alder	*Alnus rubra* Bong.
CHNO	Alaska yellow-cedar	*Chamaecyparis nootkatensis* (D. Don) Spach
PICO	Lodgepole pine	*Pinus contorta* Dougl. ex Loud.
PIMO	Western white pine	*Pinus monticola* Dougl. ex D. Don
PISI	Sitka spruce	*Picea sitchensis* (Bong.) Carr.
PREM	Bitter cherry	*Prunus emarginata* Dougl. ex Eaton
PSME	Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
RHPU	Cascara	*Rhamnus purshiana* DC.
SASP	Willow species	*Salix* species
THPL	Western redcedar	*Thuja plicata* Donn ex D. Don
TSHE	Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
UNCLH	Unclassified hardwood	(species unidentified)
UNCLS	Unclassified softwood	(species unidentified)

For species not listed above, use the first two letters of the genus and first two letters of the species scientific names for the code.

Tree Class

Code	Tree class (all trees)
10	Live tree (leave tree)
11	Ingrowth tree
12	New tree, missed at previous measurement(s)
13	Live tree not suitable for height/diameter curves or height growth
21	Standing dead (snag)
22	Down dead
23	Dead cut tree
24	Presumed dead; could not relocate
30	Live cut tree (marked to be cut)
31	Live tree cut, not planned at time of treatment
40	Off-plot tree

Crown Class

Code	Crown class (live trees only)
1	Dominant
2	Codominant
3	Intermediate
4	Suppressed
5	Understory
6	Overstory (usually from an older age class; sometimes called superdominant)
7	Open grown
8	Shrub (single stem origin)
9	Shrub clump (multiple stem origin)

Dead Tree Class

Code	Snags
1	Bark present; limbs and branches present; top usually pointed; sapwood intact, sound, incipient decay, hard, original color; heartwood sound, hard, original color.
2	Bark beginning to slough; few limbs and no fine branches remaining; top may be out; sapwood sloughing, advanced decay, fibrous, firm to soft; heartwood sound at base, incipient decay in outer edge of upper bole, hard.
3	Bark sloughing; limb stubs only; top broken; sapwood sloughing, fibrous, soft; heartwood incipient decay at base, advanced decay throughout upper bole, fibrous, hard to firm.
4	Bark sloughing; few to no branch stubs; top broken; sapwood sloughing, cubical, soft; heartwood advanced decay at base, sloughing from upper bole, fibrous to cubical, soft.
5	Bark mostly gone; no branches or stubs; top broken; sapwood gone; heartwood sloughing, cubical, soft, or fibrous, very soft, conifers frequently encased in hardened shell.

Code	Down dead
1	Bark intact and tight; branches, twigs, and fines present; shape round; wood hard; log elevated above ground on support points.
2	Bark mostly present but may be loose; branches present but twigs and fines generally absent; shape round; wood hard to partly soft; log elevated above ground but slightly sagging.

3	Bark loose and missing in places; twigs and fines absent; wood hard and in large pieces with some decay; shape round to oval; all of log on ground.
4	Bark generally absent; small branches, twigs, and fines absent; wood soft and in blocky pieces; shape round to oval; all of log on ground.
5	Bark entirely absent; branches, twigs, and fines absent; wood soft and powdery; shape oval; all of log always on ground.

Damage Codes

Damage is coded as a five-character code as follows: XXSSR where XX is two-character damage code, SS is two-character (or digit) severity code, and R is one-character recency code. Up to three sets of codes can be used. If damage does not fit one of the defined severity codes, then do not code the damage.

Code	**Logging damage**
LB	Live branch breakage (felling damage to major branches)

Code	**Severity**
1	One to five major branches broken
2	More than five major branches broken

RD	Root damage (usually caused by skidding)

Code	**Severity**
1	Support roots damaged on one side of tree
2	Support roots damaged on two sides of tree
3	Support roots damaged on three sides of tree
4	Support roots damaged on four sides of tree

SB	Basal bark removal—debarking within first 1.3 m above ground on bole, usually caused by skidding, and can extend into bole section above 1.3 m. Used only for wounds occurring within the first 1.3 m. If wound does not extend into the lower 1.3 m, then code as upper bole damage, UB. Basal bark removal severity is divided into two single numeric fields, one for the width dimension (circumference class), and one for the vertical dimension (length class); both fields must be completed for basal bark removal.

Code	**Circumference class (width dimension)**
1	Bark missing on <10 percent of circumference
2	Bark missing on 10 to 25 percent of circumference
3	Bark missing on 26 to 50 percent of circumference
4	Bark missing on 51 to 75 percent of circumference

5	Bark missing on 76 to 95 percent of circumference
6	Bark missing on more than 95 percent of circumference

Code	Length class (vertical dimension)
1	<0.5 m (<1.5 ft)
2	0.5 to 0.9 m (1.5 to 2.9 ft)
3	1.0 to 1.4 m (3.0 to 4.4 ft)
4	1.5 to 1.9 m (4.5 to 6.0 ft)
5	2.0 m + (6.0 ft +)

UB Upper bole damage—usually felling damage to bole above 1.3 m. Not used for wounds extending into the lower 1.3 m of the bole. For wounds extending into the lower 1.3 m of the bole, use basal bark removal damage code, SB.

Code	Severity
1	2 to 3 m vertical stripe, one side only
2	3+ m vertical stripe, one side only
3	Vertical stripe(s) on two or more sides

LT Broken top **caused by logging**

Code	Severity
1	Leader or tip missing (top one to three internodes missing)
2	25 percent or less of crown missing, but more than three internodes missing
3	26 to 50 percent of crown missing
4	More than 50 percent of crown missing
5	Leader or stem broken, but still attached and alive

LL Excessive lean (includes bent; excludes down) **caused by logging**

LR Uprooted, down but alive **caused by logging**

LM Recently dead, **caused by logging**

Code	Crown appearance, disease, and insects
AP	Aphids
CH	Chlorotic (yellowish needles, may be a symptom of root rot)
DI	Diseased/sick/dying (declining vigor, short, sparse needles sometimes accompanied by chlorotic appearance)
LA	Leaf abnormalities (rusts, blisters, curling)
LE	Leaf-eating insects
MI	Mistletoe

RU	Blister rust (on white pine)
TA	Limb and twig abnormalities (galls, cankers, lesions, witches' brooms, etc.; not blister rust)

Code	Stem diseases and insects
BE	Bark beetles
SD	Decay
SC	Cankers, galls, and lesions
SR	Rusts
WB	Wood borers (primarily in hardwoods)

Code	Animal damage
AD	Animal damage (other than listed below)
AR	Antler rub
BD	Bear bark removal
BR	Deer or elk browse
BV	Beaver
PD	Porcupine
SH	Sapsucker or woodpecker feeding holes (typically ring(s) of small-diameter, pencil-sized holes around stem)
WC	Woodpecker cavities (usually found in dead portions, but occasionally found in live stems)

Code	Weather
DE	Desiccation
LG	Lightning
SS	Sunscald
TD	Tip dieback (frost damage)
UR	Uprooted, down (alive)
WS	Wind, snow, ice

Code	Stem physical defects (stem form)
BS	Basal scar (origin unknown)
BT	Broken top

Code	Severity
1	Leader or tip missing (top one to three internodes missing)
2	25 percent or less of crown missing, but more than three internodes missing
3	26 to 50 percent of crown missing

	4	More than 50 percent of crown missing
	5	Leader or stem broken, but still attached and alive
CK	Cracks	
CR	Crook	
DT	Dead top	

Code	Severity
1	Leader or tip dead (top one to three internodes dead)
2	25 percent or less of crown dead, but more than three internodes dead
3	26 to 50 percent of crown dead
4	More than 50 percent of crown dead
5	Leader or stem broken, but still attached and dead

EB	Epicormic branching
EL	Excessively limby (wolf tree or grouse ladder)
FT	Forked top or stem

Code	Severity
1	Leader or tip forked (within top one to three internodes)
2	Within crown, but below top three internodes
3	Above b.h. but below crown
4	At or below b.h.

FU	Fluting
MT	Multiple top or stem (more than two above b.h.)

Code	Severity
1	Leader or tip forked (within top one to three internodes)
2	Within crown, but below top three internodes
3	Above b.h. but below crown
4	At or below b.h.

RB	Ramicorn branch(es)
SI	Sinuosity
SG	Stems grown together (cannot measure separately)
SW	Sweep
SP	Sprout (origin of stem)
WP	Whip
XL	Excessive lean (includes bent, excludes down)

Code	Damage—Other (use for all damage not already defined above)
M	Damage likely to reduce monetary value or vigor substantially
S	Damage likely to render tree monetarily worthless or likely to eventually result in tree death
N	Minimal or no economic damage

Code	Damage Recency
N	New; since last measurement
O	Old; before last measurement

Code	Mortality (since prior measurement)
RD	Root disease
WS	Wind, snow, ice
Blank	Unknown or other

Comment Codes

Code	Meaning
01	See field sheets
02	No tag
03	Tag hung on branch
04	Tag on barlock circling stem
05	Tag too high
06	Tag too low
07	Height measurement verified
08	Diameter measurement verified
09	Previous height changed
10	Previous d.b.h. changed
11	Change in terminal
12	Replacement tree
13	Cut tree
14	On skid road/landing
15	Height not measured
16	Verified cut
17	Marked as cut tree but not cut
18	Height to live crown measurement verified
19	Uneven crown—average height to live crown
20	<15 cm recent colluvium
21	15 to 50 cm recent colluvium
22	50 to 100 cm recent colluvium

23	>100 cm recent colluvium
24	High d.b.h.
25	Low d.b.h.
26	Broken below b.h.
27	Origin from rooted branch
28	Moved diameter to b.h. location
29	Pruned

Appendix B: Field Tree Measurement Procedures

Plot measurement record

A standard form, which can also serve as a data entry document, (or an equivalent recorder screen) should be used for field measurements. For remeasurements, the information needed for tree identification plus previous measurement values needed to provide a check against measurement errors must be entered before fieldwork.

Figure 7 is a computer-produced form (or equivalent recorder screen) with the following fields:

Tree #: tree identification number, preprinted for all trees recorded at the previous measurement. Final digit is "0" for trees present at initial measurement (can be left blank on field form, if preferred); subsequent ingrowth trees are assigned a number determined as that of the nearest initial tree + a nonzero integer from 1 to 9.

Species: tree species, preprinted.

Age BH: tree age at breast height, as of the year of plot establishment. Preprinted if determined at the date of a previous measurement.

Tree class: codes representing live, ingrowth, etc., this measurement.

Crown class: this measurement.

DBH:
- (1) previous measurement (1998 in this case), to nearest 0.1 inch.
- (2) this measurement, to nearest 0.1 in.

Height:
- (1) previous measurement (1998 in this case), to nearest foot.
- (2) this measurement (1998 in this case), to nearest foot. Entered directly if measured by height pole or laser; if by clinometer and tape or clinometer and pole methods, transcribed from the height measurement field sheet (fig. 11) before leaving the area.

HLC: height to live crown.
- (1) previous measurement (1998 in this case) to nearest foot.
- (2) New measurement (2004) to nearest foot. Entered directly if measured by height pole or laser; if by clinometer and tape or clinometer and pole methods, transcribed from the height measurement field sheet (fig. 11) before leaving the area.

Damage: kind, severity, and recency as determined at current measurement and recorded with the appropriate codes.

Dead class: dead trees only, condition code.

Cause: current measurement, appropriate code.

Coordinates: tree coordinates on stem-mapped plots.

Notes: comments.

Other items can be added as needed for a particular study.

Installation___________ Location____________ Date_____________
Plot_____________ Study______________ Measured by____________
Subplot__________ English___ /metric___ Recorded by____________

Tree #		DBH		Previous 19__		Slope Dist ds	∠ tip $\theta 2$	∠ HLC $\theta 3$	∠ pole $\theta 4$	Pole lgth p	∠ base $\theta 1$	Add h		Calc H	Calc HLC	Notes
				H	HLC											

Calculation checked by____________ on ______________
Transcribed to permanent record by_____________ on______________

Figure 11—A field form for height measurement, for use with either tape and clinometer or pole and clinometer methods.

Height measurement form and measurement procedures

Sample-tree height measurements are normally obtained as a separate operation after measurement of diameters of all trees on the plot. The diameter record is used as the basis for selecting or modifying the sample of trees to be measured for heights.

If heights are measured with a height pole or laser, values are entered directly on the plot measurement form (fig. 7). If heights are measured with tape and clinometer or tape and pole methods, the field form shown in fig. 11 can be used. Columns on the form represent the following:

- Tree identification number for each tree in the height sample.
- D.b.h. of each tree.
- Recorded height (H) at last measurement, if any.
- Recorded height to live crown (HLC) at last measurement, if any.
  (Note: First four items may be either preprinted on the form or transcribed from a computer-generated list of trees measured for heights at the last measurement. This initial list must then be modified by any deletions and additions needed to obtain a satisfactory height sample for the current measurement.)
- Slope distance from instrument to tree.
- Angle to tip of tree.

- A blank column may be inserted to allow for measurements to some other point, if wanted; for example, if height of the n^{th} node from tip is wanted to provide an estimate of height growth in the last *n* years.
- Angle to base of live crown.
- Angle to tip of measurement pole (if using tape and clinometer method).
- Length of measurement pole used.
- Angle to lower aim point.
- Height of lower aim point above ground.
- Blank column provided for miscellaneous notes.
- Total height of tree calculated from above values.
- Height to base of live crown calculated from above values.

Heights should be calculated in the field and checked for reasonableness against the previous measurement (if any).

Appendix C: Sampling and Plot Measurement Scheme for a Large-Scale Management Experiment

A number of large-scale management experiments have been initiated in the Northwest in the past decade (Monserud 2002) to evaluate silvicultural regimes that attempt to integrate production of timber, wildlife, biodiversity, and scenic values. The regimes cannot be realistically evaluated on the small plots that have been common in silvicultural research. Therefore the experimental units become treatment areas on the order of 20 to 60+ acres. This necessarily introduces considerably more uncontrolled variation than in typical small-plot experiments, but provides results that are operationally realistic and allows evaluation of scenic and wildlife effects that are not possible on individual small plots.

The meaningful analysis unit is the treatment unit. The primary values being compared are mean values for the units estimated from a series of small permanent plots within each unit. From this standpoint, size of the individual plot is not critical provided the number of such plots is sufficient to provide good estimates of mean unit characteristics, including both stand condition and growth rates.

In this section we describe one scheme now in use for sampling treatment units in such an experiment (Curtis and others 2004). We do not present this as the only or the best method, but it may be helpful for others with similar problems.

Each treatment unit is sampled with a series of small plots arranged on a systematic grid, with spacing selected to yield some desired number of such plots within each treatment.

The individual tree measurement plot is a 1/5-acre circular plot, with center marked by a white polyvinyl chloride (PVC) pipe driven in the ground and referenced by azimuth and distance to three tagged witness trees (fig. 12).

Prior to the initial stand treatment, all trees 9.6 in and larger are measured on the 1/5-acre plot (fig. 12). Trees 5.6 in and larger are measured on a 1/10-acre concentric plot. Trees 1.6 to 5.5 in are measured on a 0.025-acre concentric plot. Pretreatment d.b.h. measurements are recorded to nearest inch or centimeter (fig. 13). This provides the stand table that serves as the basis for preparing treatment specifications. Height measurements on a sample of trees may or may not be wanted as a basis for preliminary volume computations.

After the initial stand treatment, all trees are tagged, detailed individual tree measurements are made, and descriptive information is recorded as shown in figure 7 or an equivalent form.

Four supplementary subplot centers are located at the intersection of the 1/5-acre plot boundary and N-S and E-W lines through the plot center. These are marked with PVC pipe of smaller diameter, and serve as centers of two types of subplot:

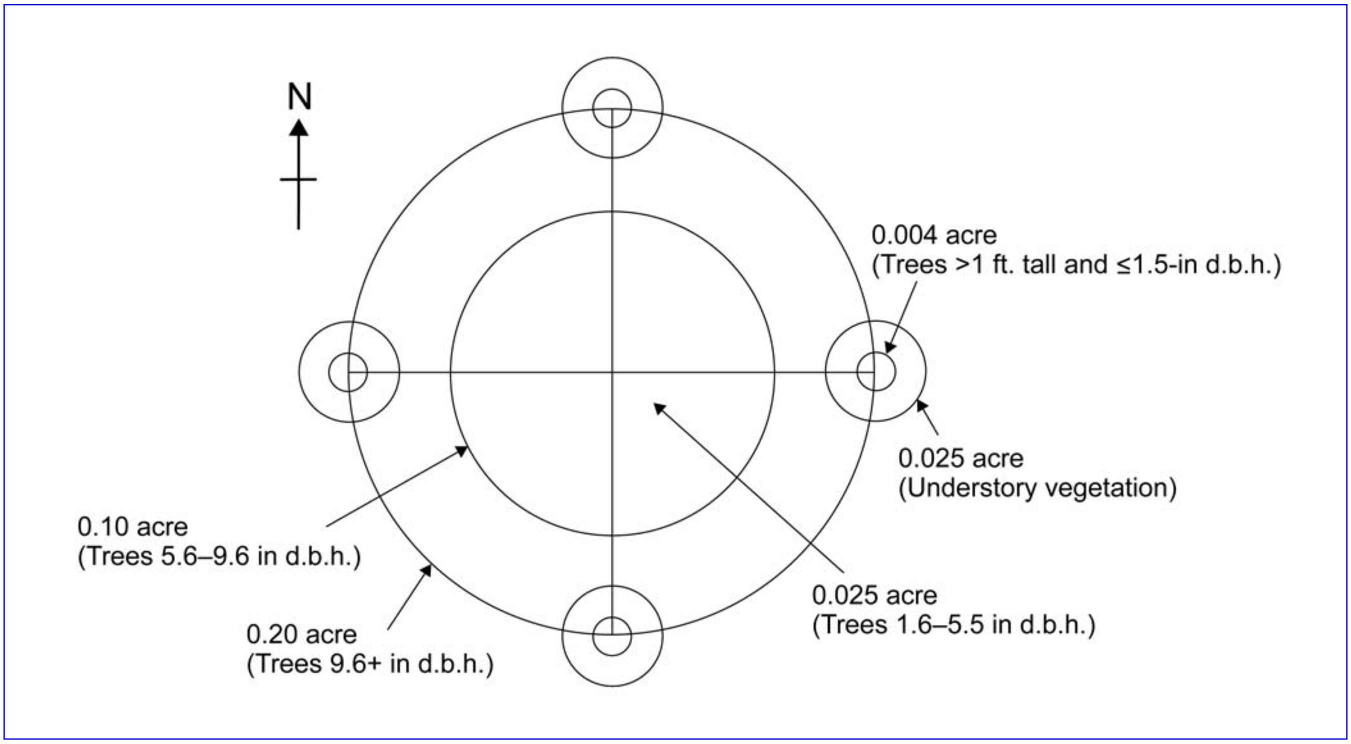

Figure 12—Permanent plot design, with associated subplots.

Installation___________ Treatment___________ Plot No.______________

Location: Legal Description____________________ GPS________________

Crew_________________________ Date___________

Reference trees: R1: species__________ DBH_____ Azimuth_____ Distance

R2: species__________ DBH_____ Azimuth_____ Distance

R3: species__________ DBH_____ Azimuth_____ Distance

Grid azimuth__________________ Distance between plots_______________

Trees 1.6–5.5 in d.b.h. on 0.025 acre, plot radius 18.6 ft No pretreatment measures on control (untreated) plots

Trees 5.6–9.5 in d.b.h. on 0.10 acre, plot radius 37.2 ft

Trees 1.6–5.5 in d.b.h. on 0.20 acre, plot radius 52.7 ft

Species	DBH	HT		Species	DBH	HT		Species	DBH	HT	

Figure 13—A field form for pretreatment tree measurements with the plot design of figure 12.

- Trees >1 ft in height and ≤ 1.5 in d.b.h. are recorded (but not tagged) on 0.004 acre. Planted trees, if any, are identified by distance and azimuth from the subplot center.
- An ocular estimate of percentage of cover and average height of each major nontree species present is made on a concentric 0.025-acre circular plot.

Data sheets for recording subplot data are illustrated in figures 13 and 14. A supplementary record, not shown, identifies each planted seedling on the subplot by species, height, and azimuth and distance from the subplot stake. This makes it possible to follow mortality and growth of individual seedlings until they reach a size suitable for permanent tagging.

This scheme provides comparable estimates of unit means at successive remeasurements at minimal cost. It can be supplemented as needed by subdivision and classification by quadrants within the plots, by transects measuring such things as regeneration development in openings of different sizes, by more elaborate enumeration of minor shrub and herbaceous species present, or additional measurements of such things as coarse woody debris.

REGENERATION AND UNDERSTORY INVENTORY

Installation___________________ Plot__________ Subplot____________

Measured by_______________________ Date__________

Established regeneration, 4-mil-acre subplot radius (7.45 ft)

Established acceptable stems (H >1 and DBH <1.6 in)	Species	DBH	Height	Origin (P or N)
Largest stem				
Second largest				
Additional planted				

	PSME	TSHE	THPL	ALRU		
Number on plot						

Ground vegetation, 1/40-acre subplot (radius 18.6 ft)

Plant group	Shrubs	Ferns	Herbs/Forbs	Grasses	Mosses
Percentage cover					

Common name	Scientific name	Code	Percentage cover	Average height (ft)

Figure 14—A field form for recording regeneration and understory with the plot design of figure 12.

Appendix D: Checklist of Items Likely To Be Needed

Copy of study plan, any establishment report

Manual or specifications with applicable measurement instructions and recording codes

Maps

Aerial photos

GPS equipment

Tatum holder

Pocket calculator

Field tally sheets or recording device, containing previous measurements, if any

Coordinate paper or standard form for sketch maps

Protractor

Engineer's pocket scale

Pocket stereoscope

String, large cones (for delimiting plot boundaries and strips within plot)

Paint gun, pressurized paint cans or tube paint for marking boundaries, numbering trees, marking b.h. point

Lumber crayons, yellow

Lumber crayon holders

Nails, aluminum (for tags)

Plastic barlocks

Staple gun, staples (9/16 in), cards (if there may be a need to tag trees temporarily)

Prenumbered metal tags, in sequence (if tagging new plot)

Label maker with metal tape, or write-on metal tags

Claw hammer

Wire (for tagging small trees, corner stakes)

Side-cutting pliers

Flagging, assorted colors

Bark scribe

Hatchet

Machete or brush axe

Small maul (for driving stakes)

Stakes (metal, plastic, or other permanent material) for plot corners and centers

Pruning saws, with sheath

Pocket compass

Staff compass with staff

Fiberglass tape, 100 to 150 ft or 60 m, with reel (for laying out plot boundaries and measuring base lines)

Spare tape
Pocket cloth tape, 75 ft or 30 m
Range poles
Height pole, rod level
Clinometers of type appropriate for expected tree size
Laser, with staff mount and extra batteries
Prism reflector for use with laser
Diameter tapes, with spares
Increment borers with extra bits
Increment core holders (plastic drinking straws or the equivalent)
Bark gauge
Signs for plot boundaries
Hand lens
Flashlight with extra batteries
Flagged pins (initial plot layout)
First-aid kit
Packs for carrying equipment
Safety goggles, hard hats, high-visibility vests, footgear as appropriate for working conditions
Bow saw
Chainsaw and associated equipment (if trail and boundary clearance is needed)

Appendix E: Plot Dimensions

Commonly used plot dimensions and slope correction factors are given in tables 1 through 3.

Table 1—Dimensions of square plots of specified area

English units				Metric units			
Area	**Side**	**Diagonal**	**Semidiagonal**	**Area**	**Side**	**Diagonal**	**Semidiagonal**
Acres	- - - - - - - - - -*Feet* - - - - - - - - - -			*Hectares*	- - - - - - - - - *Meters* - - - - - - - -		
0.001	6.60	9.33	4.67	0.001	3.16	4.47	2.24
.01	20.87	29.52	14.76	.01	10.00	14.14	7.07
.05	46.67	66.00	33.00	.05	22.36	31.62	15.81
.10	66.00	93.34	46.67	.10	31.62	44.72	22.36
.15	80.83	114.32	57.16	.15	38.73	54.77	27.39
.20	93.34	132.00	66.00	.20	44.72	63.25	31.62
.25	104.36	147.58	73.79	.25	50.00	70.71	35.36
.30	114.32	161.67	80.83	.30	54.77	77.46	38.73
.40	132.00	186.68	93.34	.40	63.25	89.44	44.72
.50	147.58	208.71	104.36	.50	70.71	100.00	50.00

Table 2—Dimensions of circular plots of specified area

English		Metric	
Area	**Radius**	**Area**	**Radius**
Acres	*Feet*	*Hectares*	*Meters*
0.001	3.72	0.001	1.784
.01	11.78	.01	5.64
.05	26.33	.05	12.62
.10	37.24	.10	17.84
.15	45.60	.15	21.83
.20	52.66	.20	25.23
.25	58.88	.25	28.21
.30	64.50		
.40	74.47		
.50	83.26		

Table 3—Multipliers to convert slope distance to horizontal distance and horizontal distance to slope distance

Slope	cos θ	1/cos θ	Slope	cos θ	1/cos θ
Percent			*Percent*		
0	1.0	1.0	62	0.850	1.177
5	.999	1.001	64	.842	1.187
10	.995	1.005	66	.835	1.198
15	.989	1.011	68	.827	1.209
20	.981	1.020	70	.819	1.221
22	.977	1.024	72	.812	1.232
24	.972	1.028	74	.804	1.244
26	.968	1.033	76	.796	1.256
28	.963	1.038	78	.788	1.268
30	.958	1.044	80	.781	1.281
32	.952	1.050	82	.773	1.293
34	.947	1.056	84	.766	1.306
36	.941	1.063	86	.758	1.319
38	.935	1.070	88	.751	1.332
40	.928	1.077	90	.743	1.345
42	.922	1.085	92	.736	1.359
44	.915	1.092	94	.729	1.372
46	.908	1.101	96	.721	1.386
48	.902	1.109	98	.714	1.400
50	.894	1.118	100	.707	1.414
52	.887	1.127			
54	.880	1.136			
56	.872	1.146			
58	.865	1.156			
60	.857	1.166			

Note: d = horizontal distance
ds = slope distance
θ = slope angle in degrees
$d = ds \times \cos\theta$
$ds = d / \cos\theta$

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