Postprint of: Vanclay, J.K., 1991. Data requirements for developing growth models for tropical moist forests. *Commonwealth Forestry Review* **70**(4):248-271.

REVIEW: DATA REQUIREMENTS FOR DEVELOPING GROWTH MODELS FOR TROPICAL MOIST FORESTS

*Jerome K. Vanclay**

Department of Economics and Natural Resources, Royal Veterinary and Agricultural University, Thorvaldsensvej 57, DK-1871 Frederiksberg C, Denmark.

Summary

> Permanent sample plots provide the basis for growth modelling, yield prediction and sustained yield management, and the reliability of the data is crucial to these and many other aspects of forest management. To obtain reliable data, it is necessary to ensure consistent standards and that a wide range of stand and site conditions are sampled using both passive monitoring and experimental plots. Individual trees should be numbered, marked and mapped. Remeasurement frequency should be determined to facilitate plot relocation and ensure that growth is greater than measurement errors. Measurement records should be unambiguous and secure.

Introduction

One way to assist the continued survival of the tropical moist forest is to manage it for commercial production of timber and other forest products, so that it becomes valuable in the eyes of local communities. Two conditions are essential, but not sufficient for its survival. Firstly to ensure that harvesting leaves the forest in an ecologically and silviculturally "good" condition (VANCLAY, 1990b). Secondly, to eke out the resource so that harvesting provides a continuing supply of timber and other benefits (VANCLAY, 1991a). Growth models, when combined with inventory, provide a reliable way to examine harvesting options, to determine the sustainable timber yield, and to examine the impacts on other values of the forest.

The first step in constructing a growth model is to obtain suitable data. All too often, the modelling approach is dictated by limitations of the data. Data requirements of many modelling approaches are similar and allow a set of minimum procedures to be established. The procedures discussed here relate to the requirements for development of growth and yield models. Additional details may be necessary if plots are to serve other uses such as ecological studies.

Although directed at tropical moist forests, this review is applicable to data requirements of growth models generally. Stem analyses do not provide reliable growth data for many tree species in the tropical moist forest, so data must be obtained from remeasurements on permanent sample plots (PSPs). KRAMER and KOZLOWSKI (1979:27) reported some of the anomalies of growth rings in tropical tree species. Some evergreen trees (e.g. *Swietenia* spp.) may form rings while deciduous trees (e.g. some *Ficus* spp.) may not. Some species (e.g. *Hevea braziliensis)* may form several growth rings each year, while other species (e.g. *Shorea robusta)* may form only one ring but not necessarily in the same month each year. MARIAUX (1981) presented a detailed review of the possibilities and problems of stem analysis in tropical tree species.

Permanent plots can never be completely replaced by temporary plots even for species amenable to stem analysis, because only PSPs allow satisfactory statistical comparisons within and between plots to check the adequacy of models (STRAND, 1970), and only PSPs can provide reliable and consistent data on mortality, crown dynamics and stand level variables (MCQUILLAN, 1984).

DEADMAN (1979) recorded a number of observations concerning data for growth modelling: permanent plots must cover extremes of site and treatment; periodic reviews of data collection policy are necessary;

quality of data collected is of extreme importance; and documentation should be complete, consistent and accurate. ADLARD (1990) emphasized three factors: relevance, reliability and relationships. VANCLAY (1990a) stressed standardization of procedures, accurate measurements, specific location (description and map coordinates), clear objectives and sufficient resources (funds and trained staff). CURTIS (1983) provided a comprehensive reference manual for PSP establishment and maintenance in temperate regions, most of which is relevant to the tropical moist forest.

Data used for growth research must be of a higher quality than that used for point-in-time inventories. For example, a diameter measurement of 50 ± 0.5 cm may seem precise, but if a remeasure indicates 51 ± 0.5 cm, the growth estimate will be 1 ±0.7 cm which is not very precise.

Differing Data Needs

Sample plots serve many purposes, but different procedures are required to satisfy efficiently various needs of resource managers. Some information needs and corresponding sample plot procedures include:

- *Resource Inventory* ("What is the present nature and extent of the resource?"): Typically a large number of plots (or point samples) will be required to achieve the desired precision. Precision can be gained by orienting plots across environmental gradients to maximize within plot variation and thus reduce between plot variance. Cost considerations usually dictate that temporary inventory plots (or point samples) are most efficient for resource inventory (e.g. MATIs *et al.* 1984, SCHREUDER *et al.* 1987). Specialized techniques for timber cruising offer great efficiencies (e.g. 3-P sampling), but may not provide data suitable for input to yield forecasting systems.

- *Continuous Forest Inventory for yield control:* If yield regulation is by volume control, it is important that permanent plots be representative and established in various forest types and stand conditions in proportion to their area (this system is often called Continuous Forest Inventory). As with resource inventory, precision is gained by minimising between plot variance. Plots should be marked so that they can be relocated for remeasurement, but should remain inconspicuous so that they receive unbiased management.

- *Growth Modelling:* The development of growth models requires data obtained from the remeasurement of PSPs. The most reliable and flexible modelling techniques require data in which the individual trees are identified. This requires that all trees on the PSP are permanently tagged and uniquely numbered. Irrespective of the modelling approach, unique numbering and tagging of trees is the only sure way of detecting measurement errors. Growth modelling also requires homogeneous plots, and this means minimising within plot variance: the ability of the PSPs to quantify the present resource is irrelevant. Thus the same plot series cannot be efficiently used for both resource inventory and growth model development. If the growth model is to be used to investigate silvicultural and management alternatives, the database must include experimental data with paired treatment and control plots, both with adequate isolation. In contrast to continuous forest inventory plots, it is not necessary for PSPs to be representative or numerically proportional to forest type areas, but it is essential that they sample the full range of stand conditions.

- *Long Term Monitoring of Environmental Change:* DAWKINS and FIELD (1978) describe a series of plots to monitor subtle long term changes in a forest. Whilst such studies are desirable, few organizations have the resources or need to establish such plots on the same scale as required for growth studies. Such detailed plots should be reserved for special studies. For growth modelling, it is better to sample the full range with conventional PSPs than to have a few detailed "Dawkins" plots. However, quantity is no substitute for quality.

Permanent sample plots established to provide data for growth modelling should be designed to satisfy this primary need, and should not be compromised in order to satisfy secondary needs. They need not provide efficient resource inventory data, as alternative sampling procedures can better fulfill that need.

Model Development

The initial and most obvious requirement for data is during model development when they are required for the construction of the basic functions comprising the model.

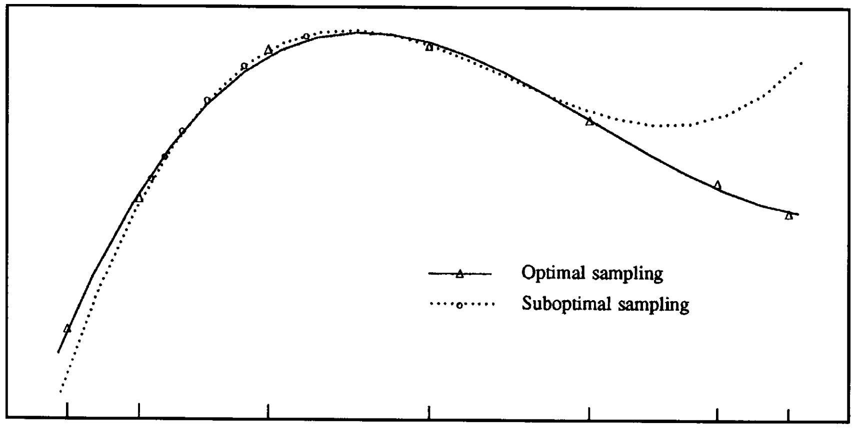

FIG 1: Polynomial approximation of a function with optimal and sub-optimal sampling

It can be shown mathematically, that the relationship between two variables given by a series of points known without error, can be described by polynomials most accurately if the sample points are located along the trend line with intensity increasing towards the limits of the region of interest. Figure 1 illustrates a cubic polynomial fitted to seven points selected from a diameter increment function (VANCLAY, 1991b, species group 1). The ticks on the horizontal axis indicate a near optimal sampling (Δ) which produced a very good approximation (solid line) to the original function. A more arbitrary sampling (○) resulted in a poor approximation (dotted line in Figure 1). In establishing a statistical relationship, these points are not known with certainty, but with some error, and the sampling intensity should reflect the variance. Extending this concept to a multi-dimensional space, it can be seen that sampling should be carried out across the entire response surface, with a greater intensity at the extremities, and in accordance with the variance. Limited but reliable data at each extreme and at the mean are more useful than copious data clustered about the mean (KIRKLAND, 1985).

Such data should not only sample a range of stand and tree conditions, but must also include remeasurements to enable detection of change, and must include a sufficient time period to average any climatic variations, and to ensure that growth patterns are not obscured by measurement error.

Validation and Monitoring

To provide a convincing demonstration, data used to validate a model should be excluded from its development and may comprise data drawn from a different population. This ideal is not always attainable, and it is common to partition the available data into two subsets, one to be used for development and the other for validation. It is important that the subset used for validation should contain at least some data collected over very long periods to allow detection of possible subtle but cumulative errors in the model. Where the model is used to estimate some optimum stand condition, it is advisable to obtain data to ascertain the production from this estimated optimum condition.

Monitoring may be viewed as continuing validation of a model by checking its operational predictions. It involves comparing projected and realised yields to identify any discrepancies. Such discrepancies may arise due to changes in management regime (especially logging practices), decline in site productivity, inaccurate resource data, or corruption of the validated growth model. Monitoring the performance of models is often neglected, but is necessary to ensure reliable forecasts.

Applications Data

Applications data may comprise basic resource information used in conjunction with the growth model to estimate future yields. Most operational resource inventory provides suitable data. Such data should detail areas of each homogeneous forest unit, the species composition, stand condition, and the site productivity of each unit. MEAD (1982) discussed how to gauge the value of data of this type. VANCLAY and PRESTON (1989) gave an example of the integration of inventory data and a growth model to predict yields in tropical moist forest in north Queensland. Resource data have been integrated since inventories began, but recently attempts have been made to define principles and procedures for efficient integration (e.g. LUND, 1986). Integration simply implies combining data obtained in different places, for different reasons, by different agencies or at different times (VANCLAY, 1990a). This may involve combining regional inventories to provide national or global statistics, finding correlations between timber inventory and soil or fauna survey data, or using growth models derived from PSP data to extrapolate data from temporary inventory plots to estimate sustainable yields (e.g. VANCLAY and PRESTON, 1989).

Integrated inventory designs enable data from different inventories to be meaningfully combined. This does not necessarily mean that everything in every inventory must be measured. On the contrary, it is better to do a few things well than to do a lot inadequately (VANCLAY, 1990a). However, in designing a PSP system, it is necessary to be aware of the information requirements of other researchers and other disciplines, and to consider how these requirements can be efficiently accommodated in PSP design. It is not necessary that all these requirements be satisfied immediately, but rather that the design accommodates these needs so that they can be phased in as required and when feasible.

Plot Selection and Establishment

Ideally, PSPs should sample the geographic range of the forest, and encompass a broad range of forest types, site quality and topography. A broad range of stand basal area and tree sizes should be sampled for each tree species. Plots should include stands which have been subjected to a range of silvicultural management, including extremes of logging and treatment.

Growth of forests varies from year to year, fluctuations can be extreme, and mortality tends to be clustered in both time and space (CURTIS, 1983). Thus short time periods can give rise to biased growth estimates. Reliable growth models require PSPs with long measurement histories and adequate geographical distributions. Some of the plots should be left unlogged over long periods to ensure the most exacting validation.

CURTIS and HYINK (1984) recommended that new PSP installations should be established only as part of a carefully planned series designed to give reasonable coverage of some defined range of site, geography, stand condition and treatment. The primary objective should be to provide data for defining response surfaces; thus studies should involve many locations with minimal replication at each location. Satisfactory growth models are dependent upon the availability of high-quality data from a wide range of stand conditions and treatments. Both "passive monitoring" data (i.e. survey data in undisturbed forest) and "treatment response" data (i.e. from paired treatment and control plots) from designed experiments are necessary.

Subjective location of PSPs may give rise to bias in the database if the environment cannot be completely quantified. It is preferable to locate PSPs randomly within a defined stratum of interest. This stratum may be defined on the basis of standing volume, species composition, soil type or any other objective means. Care needs to be taken when establishing plots at the forest edge or along roads and firebreaks, to avoid bias (RENNOLLS, 1978; FOWLER and ARVANITIS, 1979). BRUCE (1977) gave a number of reasons why research plots may give higher yields than managed forests. Although some bias may be due to plot demarcation and management, much of this bias arises from subjective location of plots. The need for random location based on a thoughtful stratification cannot be overemphasized.

There is some evidence that gains in precision can be achieved by sampling more large trees (e.g. GERTNER, 1987), and it may be desirable to establish some plots around subjectively selected large trees.

Such subjective selection of plots may introduce bias, but this may be an acceptable trade-off to reduce the variance associated with growth predictions from large trees. To minimize bias, these plots should constitute a small proportion of the total, and should be selected within strata based on site quality and stand density (e.g. stand basal area).

Plots which are intended to be left unmanaged, for example to allow expression of density-dependent mortality and natural basal area in dense stands, should be clearly marked and excluded from any logging operations. Such plots which receive special management (no logging or more intensive treatment), should have adequate buffers to eliminate edge effects. The appropriate size of the buffer depends on tree size, but should be wider than the mature tree height. Other plots intended to receive routine management, should be marked in such a way as to be invisible to forest workers so as to ensure representative treatment. SYNNOTT (1979) argued that a plot should be "difficult to recognize for those who do not know where it is, and easy to recognise for those who do and are looking for it". Plots must have unambiguous addresses (DAWKINS arid FIELD, 1978). In some areas, plots may suffer excessive trampling through high visitation. DAWKINS and FIELD (1978) marked plot locations clearly, but 50 m away from the plot, and used invisible steel markers at all four plot corners.

Experiments

Although experimental data are extensively used in developing plantation growth models, it is more common to develop growth models for mixed forests solely from passive monitoring data. Although logging and treatment of these forest stands is likely to influence stand density, other unknown factors may also determine stand density and composition in these plots.

There is a very real danger that attempts to describe the behaviour of the stand as a function of stand density, for instance, will be confounded by the effects of site, pest and disease occurrence, and past history. BOX (1966) warned that to find out what happens to a system when you interfere with it, you have to interfere with it, not just passively observe it. SNEDECOR and COCHRAN (1980:356) discussed a study in which a survey revealed the unexpected result that the application of farmyard manure reduced the yield of potatoes by half a tonne per hectare. In contrast, in controlled, randomized experiments, manure increased the yield by three to six tonnes per hectare. The difference may be due to the fact that those who had manure were livestock farmers with little interest in growing potatoes, and those who were most skilful at growing potatoes had no manure. Can we be sure that a similar problem in our PSP data is not troubling our attempts to develop growth models (e.g. stand density and site quality interaction)?

Passive monitoring data may indicate greatest growth on the best sites with high standing basal areas, and little growth on poorer sites with little basal area. A growth model constructed from such data could suggest that greater increments accrue in stands with greater competition, as the effects of site quality and stand density would be confounded. Thus a model constructed from such passive monitoring data would predict a reduction in diameter increments following thinning, whilst a model from experimental data (e.g. thinning studies) would show an increase in diameter increment. Consideration should be given to establishing a series of plots in homogeneous tracts of each forest type. Some should be left at maximum stocking to allow expression of density-dependent mortality and natural basal area, some should be logged and treated as a managed stand, and others should be heavily thinned to allow expression of open-grown development and regeneration. It does not matter that extreme treatments may never be applied in practice; they remain essential to define properly the response surface for growth models.

Number of Plots

The number of plots is usually determined by available resources. There is little point establishing more plots than can be maintained. It is better to have few plots providing reliable data, than many plots with inadequate management. The number of plots will also be determined by the variability of the forest estate, and the need to sample the full range of forest conditions. SYNNOTT (1979) recommended 50 to 100 randomly located plots for each forest type.

A database comprising a few plots each with many remeasurements violates statistical assumptions of independence, and may require special analysis techniques (WEST *et al.* 1984, 1986). This violation becomes significant when the number of remeasures is large relative to the number of plots. An alternative is to use partial replacement, abandoning plots after several remeasures and establishing new ones (TENNENT 1988). However, some plots must be retained for long periods with many remeasures to allow convincing validation.

Size and Shape of Plots

A general guide to the choice of plot shape is to minimize the plot edge to area ratio, and the number of corners. This leads to the choice of point samples, or circular, triangular, or four-sided plots according to the emphasis attached to corners and edges. Triangular plots are rarely used, perhaps because of the high edge to area ratio, and four-sided plots are generally rectangular (or square) to facilitate relocation of corners and boundaries. Point samples (BEERS and MILLER, 1964) have an advantage in being defined by a single point and a basal area factor (BAF), but they are inconvenient when dealing with recruitment, and create difficulties for the development of distance-dependent models. Circular plots are also defined by a single point and a radius, but the plot boundary becomes more difficult to define as the plot becomes large, as unlike polygonal plots, sight lines cannot be established along boundaries. As these plots are defined by a single marker (the centre), they may be more difficult to relocate if the marker is damaged or removed. Rectangular plots are more versatile. Plots marked by four corner pegs may be less likely to be lost than circular plots marked by only one peg. However, a more important reason for the choice of rectangular plots is their straight edges, few corners, and convenience. Square plots offer a theoretical advantage of minimum edge to area ratio.

Ideally, the plot size should be sufficiently small for the plot to be homogeneous, at least with respect to forest type and site productivity, and sufficiently large to provide a representative sample of the forest stand. If a distance-dependent model is contemplated, the plot should be sufficiently large to allow estimates of competition to be determined for several trees on the plot. This leads to the conclusion that larger plots offer greater flexibility, and the author's experience suggests that plots up to one hectare should be considered for growth modelling studies in the tropical moist forest. Ecological studies may warrant even larger plots.

CURTIS and POPE (1972) suggested that small plots may result in erratic estimates of stand attributes because of within stand clumping, and recommended the use of large plots. PAYANDEH (1974) examined the distribution of trees within north American forests, and reported that unlike plantations, natural forests rarely exhibit a regular spacing, but tend to have a random (in hardwoods) or slightly clustered (conifers) spatial distribution. HANN (1980) used plots varying in size from 0.3 to 0.5 hectares in even-aged stands, and 0.8 to 1.2 hectares in uneven-aged stands. Plots smaller than 0.8 hectares were available for the unevenaged stands, but were discarded by HANN (1980) to avoid problems arising from within stand clumping. SYNNOTT (1979) recommended square plots one hectare in area, subdivided into 25 subplots. WEST *et al.* (1988) found that 0.5 ha was the practical upper limit in tropical moist forest for homogeneous plots, as physical and floristic discontinuities hampered the establishment of larger plots.

Unless circular plots or point samples are adopted, the orientation of the plots needs to be considered. This may be inconsequential for square plots, but may be significant with elongated rectangular plots. Three possibilities exist. The plots may be randomly oriented, may be oriented according to the cardinal direction (e.g. long axis north-south), or may be oriented according to topography. In view of the need for plots which are homogeneous with regard to site productivity, the last of these is likely to be preferable. It is suggested that wherever possible, plots should be oriented with their long axis perpendicular to the slope, or any other perceived gradient of site productivity to minimize within plot variation. In contrast, for temporary inventory plots, it is desirable to maximize within plot variation so as to reduce the between plot variation and thus the sampling error. PSPs for growth model development have a different goal, and thus within plot variation should be minimized.

Measurement Procedures

Providing that PSPs continue to provide useful information, existing standards and procedure should be maintained to ensure uniformity. The continuity of standards is critical. However, when new plots are established or procedures for existing plots are revised, the following requirements should be accommodated (WHITMORE, 1989):

1. Divide each plot into subplots of maximum size 20 x 20 m. Mark corners permanently. Brightly coloured plastic pipe makes good rot-resistant pickets, but where elephants or primates are likely to destroy these, trenches may have to be dug instead. Since logging can completely destroy all plot marks, buried steel markers may be used in conjunction with these.

2. Trees must be numbered and permanently marked. Never use the same number twice. Do not re-use the number of a tree which dies but give ingrowth trees new numbers. Use an embossed aluminium tag fastened with an aluminium nail half driven home (to allow for growth). These nails need renewing about once every five years. Nails should be below the merchantable section, and should always be on the same side of the tree (e.g. northern or uphill) for ease of relocation.

3. Make a map to show the position of every tree to the nearest 1 m or better. Work one subplot at a time. A maximum subplot size of 20 x 20 m makes mapping easy. Without a map confusions always occur because of death, ingrowth or lost number tags. Place measuring tapes along two adjacent sides of the subplot, and estimate and map coordinates of each tree while in the forest. REED *et al.* (1989) suggested an alternative using pentaprisms.

4. Specify the minimum girth for the smallest tree to be included. This becomes important later when ingrowths occur. For the sake of clarity, note when surveys originally using imperial measure have been converted to metric measure. For example, 12 inches girth = 9.7 cm diameter, but the metric minimum is commonly 10 cm.

5. Since girth can be measured sufficiently accurately only if always done at the same place, it is best to paint a ring on each tree with one straight edge. Painted rings need renewing every 3-4 years. In wet weather emulsion paint is easier to apply than oil-based paint. Some paints (especially oil-based paints) may cause abnormal bark shed and callus growth (e.g. *Eucalyptus maculata* and *Flindersia pimenteliana* in Queensland), so paints should be tested before general use. A less accurate alternative is always to measure girth a fixed distance above or below the number-tag nail. If a nail is used as the reference point the girth should be measured a standard distance away from it (e.g. 20-50 cm) because some species develop swollen callus tissue around the nail itself. Make sure the girth measurement point is well above all buttresses, for these may grow upwards.

6. The measuring tape must be of metal or fibreglass because cloth tapes stretch when wet. All measuring tapes should periodically be checked against a reliable standard.

7. Since errors occur in recording girths, measure every tree twice independently. If the second reading differs, make a third one. Loose bark (except on species with corky or flaky bark), epiphytes and climbers must be removed from the line of measurement. The booker should always repeat the measurement for the measurer to confirm.

8. If, despite precautions at initial survey, a buttress grows up into the line of measurement, the line (and preferably the reference nail if any) will need to be moved further up the bole although this is clearly not satisfactory, because it alters the girth measurement base for that tree. Measure at both the old and new heights, and record that a change in measurement height has occurred.

9. For trees with more than one trunk at the height of measurement decide the purpose of survey and, if necessary, create separate tree number and girth records.

What to Measure

Plot location should be described and its coordinates (latitude and longitude or other grid coordinates of the south-west corner, correct to the nearest second or better) and orientation (direction of long axis) should be recorded. Topographic features (altitude, slope, aspect, distance to ridge), climate (rainfall amount and distribution), indicator plants, and soil physical characteristics (depth, texture) should also be recorded. Uniformity of site should also be assessed. These variables need only be recorded at plot establishment, and at occasional remeasures. Factors which may cause fluctuations in the observed growth include drought, heavy seed crops, pest populations, disease outbreaks and fire damage. Such information may assist the validation of models and guide the interpretation of outliers in regression analysis. Thus the occurrence of such events should be recorded on the plot measure record.

SYNNOTT (1979) observed that it is impossible to measure all sizes and species, and is irrelevant to measure all seedlings and saplings since most will die. He recommended that all trees (of all species including useless stems) exceeding 10 cm d.b.h. (diameter breast high over bark) be measured. This is necessary to enable estimates of stand basal area, an important variable in predicting tree growth and stand dynamics. Limits as small as 3 cm have been adopted in natural coniferous forests (e.g. ARNEY, 1985; VANCLAY, 1988), but may be impractical in tropical moist forests. Reliable ingrowth data require that the measurement limit is less than the desired ingrowth size (e.g. for recruitment at 10 cm d.b.h., measure all trees exceeding 7 cm). Subplots within the main plot may be used to record data on stems smaller than this measurement limit.

Tree diameter and status (alive/dead/felled and cause) should be recorded at every measure. Every tree present at the previous measure should be accounted for. Height, crown parameters and estimated defect should be recorded at establishment, and periodically at remeasurements. Diameters should be measured at 1.3 metres (from the ground on the uphill side of the tree) or above buttress, and should be measured perpendicular to the axis of the tree (CARRON, 1968:17). The vantage point for height measurement should be carefully chosen to allow good visibility and a sighting angle of around 45 degrees (ROMESBURG and MOHAI, 1990). Natural mortality should be clearly distinguished from logging, treatment and other removals. Trees which appear lost should be marked as such, and should not be attributed to death unless there is evidence to support this.

The measure crew must check doubtful items and make sure that the current measurements are correct. They should record that such checks have been made. Decrements and other anomalies in the data should not be altered once the measure crew has departed the plot. Although these data may at times look unrealistic, "massaging" the database to alter these data may cause significant loss of information. At best, this practice may result in unrealistically low estimates of standard error associated with any functions developed. At worst, it may exclude the opportunity to investigate some originally unsuspected event (e.g. weather patterns and climate change) or unforeseen topic. There may be good reasons to "massage" or omit data from some specific analysis, but the main database should never be altered.

The quality and cost of data available for analysis may be improved substantially through the use of electronic data recorders (BELTZ and KEITH, 1980; FINS and RUST, 1987; LEECH *et al.* 1989; WOOD, 1990). Electronic hand-held devices enable basic checks of the input data to eliminate simple errors (e.g. transposition) at their source, instant validation, comparisons with previous measure, and speedy transfer of data to database. They can ensure that the measurer does not progress to the next tree or plot until all necessary variables have been recorded.

In summary, the following variables should be measured:

- At the initial enumeration (and occasionally remeasured as new technology improves the precision that can be attained):

  - plot location, dimensions and area,
  - tree species and coordinates,
  - topography (altitude, aspect, slope, relative position on slope),

- forest type,
- floristics (all species on plot and relative abundance),
- physical soil characteristics (depth, texture, colour, parent material), and an
- indication of the uniformity of the site;

- At the first measure, immediately after logging, and periodically (e.g. every second or third measure):

  - sufficient tree heights for the determination of site productivity (or data necessary for alternative estimates of site productivity),
  - merchantable heights and defect assessments of all stems (including non-commercial species, as utilization standards may change with time),
  - crown characteristics (dominance, size, density, position, etc.), and
  - basal area counts at each tree (unnecessary if tree coordinates are recorded);

- At every measure, assess all stems (including non-commercial, every stem from previous measure must be reconciled) for:

  - diameter (over bark, breast high or above buttress) and height to measure point,
  - validity (to indicate defects at measure point and anomalous but correct increments),
  - status (alive, dead, logged, treated), and
  - tree coordinates (recruits only);

- As necessary, record the occurrence of:

  - logging, treatment and other management activities, and the prescription used,
  - scars and other damage which may affect measurements or growth,
  - meteorological phenomena (drought, flood, etc.), - mast years (heavy seed crops),
  - pests, diseases, fire, or
  - any other aspect which may affect growth.

When to Remeasure

Theoretically, the frequency with which plots should be remeasured is influenced by two factors: ease of re-locating and identifying trees, and the rate of growth or change relative to the measurement error. Remeasurements must be sufficiently frequent to ensure that the location of the plot and/or identities of stems are not lost; in some forest types this may be as frequent as every two years. Conversely, cost efficiencies demand that remeasurements should not be unnecessarily frequent. The increment of stems should be substantially greater than the error associated with the measurement if the remeasure is to be useful; shorter intervals lead to excessive variance in regression functions. ARNEY'S (1985) model of temperate coniferous forest used only data from measure intervals of 4 years or more, and VANCLAY'S (1991b) growth model for tropical moist forest used data spanning approximately 5 years. In the tropics, an interval of two to five years may be appropriate for the remeasurement of PSPs.

As annual increments are generally required, measurements should be taken on the anniversary of the previous measure whenever possible, especially for annual or biennial measurements. Always try to measure during the same season, as trees in the seasonal tropics may exhibit marked seasonal fluctuations in girth due to changes in xylem water tension (LIEBERMAN, 1982). Remeasurements should avoid periods of rapid change (e.g. bark shed, rapid growth), should aim to measure during dormancy where it occurs, and should try to replicate environmental conditions at the previous measure (e.g. avoid remeasuring immediately after rain if the previous measure was after a long dry spell). Remeasurements should also be taken at the time of (preferably both before and after) logging (or silvicultural treatment), and as soon as possible after wildfire, cyclone or other disturbance. Knowledge of impending logging or treatment is required, particularly if plot boundaries are concealed, so that the necessary measures can be arranged. It may be desirable to mark plots with buried steel pegs prior to logging to insure against the loss of plot markers.

Administration

Administrative and office procedures associated with maintaining PSP measurement records are often neglected and can be a major cause of loss of information. Aspects to consider include the design of field forms, copying and storing the completed forms, and transferring the data to computer.

Forms should be designed specifically for the purpose of PSP measurement, and every column should be clearly marked with the data to be recorded. The form should have no redundant fields, and staff should become accustomed to completing every field. Every form should indicate plot identity, date, page number (e.g. page 1 of 3) and the name of the assessing officer, and this should be completed before departing the plot. Forms should be completed using a sharp dark pencil (e.g. a 0.5 mm clutch pencil with 2B lead), and no alterations should be made after departing the plot. Forms should not be transcribed, as this invites transposition and other errors. Any duplicate copies required should be photocopied (where photocopiers are not available, transcriptions should be clearly marked as such, and should be carefully checked by a third person). Forms should be filed securely and unambiguously, preferably with one plot per folder, with the forms arranged in chronological order. It is a wise precaution to have a copy of the data stored in a remote location (e.g. district and head office).

Details from the previous measure should be available during plot remeasures. This can be achieved by printing remeasure forms by computer and including details of previous measurements. Alternatively, this can be achieved by photocopying parts of the previous measure onto the new measure sheet, or by downloading previous data onto an electronic data recorder.

As data entry detects many illegible characters, errors and omissions, data should be entered onto computer as soon as practicable after collection, whilst the measure crew still recall some details of the plot. Data should be verified (i.e. re-entered and compared) by a different operator to detect any errors in data entry. Electronic data recorders offer several advantages, including such validation at the point of data collection, where checks can be made. Validation programs should check the data for further errors arid omissions, and summary reports should be produced for the information of assessing officers and forest managers. Copies of the data should be made and stored in secure remote locations.

Obvious errors and omissions in the computer data file should be amended, but the temptation to "massage" the data so that it all looks consistent should be avoided. The data on the computer must accurately reflect the field measurements. An anomalous measurement may or may not be due to measurement error in the field, and the database administrator's adjustment remains a guess rather than a fact. Any alteration inserted by the database administrator should be clearly indicated as such (in the "validity" field), and these alterations should be kept to a minimum. It is much safer to let users edit their own copy of the data as necessary for their own analyses, than to alter the master copy.

An effective system requires a considerable commitment in staff and resources to initiate and maintain the PSPs, and this commitment must be on-going. Sufficient resources and trained staff are essential, or the quality and utility of data will deteriorate.

Reappraisal

Periodic reappraisal of data collection policy and practice is necessary to ensure that the data being collected are fulfilling current and perceived future needs. "The quality of data is of extreme importance. Competent, well motivated and supervised field crews are needed for measurement, and the control of all research plots should be vested in a single high level authority" (DEADMAN, 1979). Reappraisals should address specifically two questions concerning data quality: "Is the specified quality adequate for current and perceived future needs?" and "Is the specified quality being attained?"

The need to sample extremes of forest condition has already been discussed. However, the concept of what is extreme changes over time. Thus it is necessary to consider if the extremes being sampled are sufficient, and if not, new plots should be established. The cost of data collection and handling is high, so plots should be abandoned when no longer useful. The decision to terminate a plot with a long measurement history should not be taken lightly, as these plots will be most valuable for validation. However, it is inevitable that natural (and human) perturbations (e.g. lightning strike, landslip, insect or fungal attack) will extensively modify some plots. Such plots may no longer provide useful tree growth data, but may provide useful recruitment and other ecological data.

Perception of future requirements will change over time, so the data collection policy should be periodically amended to conform with these perceived needs. These amendments may require the termination of some plots, establishment of others, addition of new variables to be measured, or the deletion of others. However, changes in measurement procedures (especially deletion of variables) should not be undertaken lightly; stable, consistent measurement procedures are essential for growth research. There should be substantial and continued resistance to changing the plot measurement system (MCQUILLAN, 1984).

Permanent sample plots should satisfy the data requirements for growth models ten and more years hence. In order to provide for this next generation of growth models, it is appropriate to appraise critically the utility of the present PSPs, and to establish new plots specifically directed at collecting data for such future growth models. Such a series of "elite" plots should sample the range of forest conditions (and include thinning studies), but should be established in limited numbers so that appropriate care and attention can be given to detail and accuracy. The emphasis with these plots must be quality, not quantity.

Problems with Existing Data

The greatest problem facing many agencies is that the data necessary for growth model development are not available. Plots may not have been established, may have been neglected or abandoned, and measure records may have been lost. As there is little that can be done to salvage such lost data, it is imperative that care and attention are devoted to existing PSPs and their measure records. Other problems which severely restrict the utility of data include unreliable measurements, changes to procedures, and mistaken or undetermined species identities.

Data for the development of growth models may be derived from PSPs which were established for purposes other than growth modelling. Such plots may sample a restricted range of stand conditions, omitting very poor and exceptionally productive sites, and avoiding extremes of stocking. Thus these data may not provide an efficient means to estimate response surfaces by regression equations to predict the behaviour of the forest under various conditions. Records concerning the establishment of many PSPs are sketchy or unavailable, and the reasons for the placement of these plots are frequently not clear. Some plots may have been randomly or haphazardly located in defined strata, but others may have been subjectively located. Any departure from a stratified random approach in establishing these plots requires some soul-searching on the part of the modeller, in considering the possible effects of personal bias in choosing plot locations, particularly where site quality cannot be reliably quantified.

PSPs should receive representative management (logging, treatment, etc.), except for experiments which sample extreme stand conditions. This may be assured where plots are marked with subterranean or other invisible markers, but intentional or unintentional bias in logging, treatment and other management may become significant when the plot is visible. Such management bias may not be a problem where it is reflected in the stand structure (e.g. removal of trees), but the effects of differences in logging damage and climber cutting may be more insidious. However, such differences are likely to be greater for research plots than for passive monitoring plots. Differential management should be reflected in stand structure, but tests of some PSPs established for 50 years in Queensland failed to detect differences between PSPs and temporary plots established adjacent to them.

Growth in tropical forests is often highly variable, and this variation may be attributed, at least in part, to factors such as weather, seed years, pest populations, disease outbreaks, fire damage, etc. Such information may be useful for interpreting apparently anomalous data detected during analyses, but is infrequently recorded and rarely transferred to the database. Evaluation of site productivity is a major obstacle in predicting yields from tropical moist forest, and development of a method for reliable site evaluation, and acquisition of the necessary data, should be a priority.

How serious are these deficiencies so often present in data available for growth modelling? It is impossible to predict what difficulties these and other deficiencies may introduce, until the data are actually used in earnest. No data set can be perfect, but many will be found to contain deficiencies that will frustrate future analyses. Although plot remeasurement may appear to the measure crew to be unrewarding, collection and management of PSP data is vital to for informed forest management.

Conclusion

PSPs provide the basis for growth modelling, yield prediction and sustained yield management, and the reliability of the data is crucial to these and many other aspects of forest management. To obtain reliable data, it is necessary to ensure that

- standards are consistent,
- a wide range of stand and site conditions are sampled,
- both passive monitoring and experimental plots are used,
- trees are numbered, marked and mapped,
- remeasurement frequency enables plot relocation and growth greater than measurement error, and
- measurement records are unambiguous and secure.

Acknowledgements

Part of this work was researched while the author was a visiting academic at the Oxford Forestry Institute. The author wishes to thank the OFI and the Queensland Forest Service for providing this opportunity. Philip Adlard of the OFI, Niel Henry and John Rudder of the QFS, Jerry Leech of the South Australian Woods and Forests Department, and Geoff Wood of the Australian National University provided helpful comment on the draft manuscript.

References

ADLARD, P. G. (1990). Easing the pathway between field and file. *Bull. Rech. Agron. Gembloux 25, 2.*

ARNEY, J. D. (1985). A modeling strategy for the growth projection of managed stands. *Can. J. For. Res.* ***15,*** 511-518.

BEERS, T. W. and MILLER, C. L(1964). Point sampling: research results, theory and application. Purdue Univ., Research Bull. No. 786.

BELTZ, R. C. and KEITH, G. C. (1980). Electronic technology speeds forest survey. *South. J. Appl. For. 4, 3,* 115-118.

Box, G. E. P. (1966). Use and abuse of regression. *Technometrics 8, 4,* 625-629.

BRUCE, D. (1977). Yield differences between research plots and managed forests. *J. For.* ***75,*** *1,* 14-17.

CARRON, L. T. (1968). An Outline of Forest Mensuration with Special Reference to Australia. A.N.U. Press, Canberra. CURTIS, R. O. (1983). Procedures for establishing and maintaining permanent plots for silvicultural and yield research. USDA For. Serv. Gen. Tech. Rep. PNW-155.

CURTIS, R. O. and HYINK, D. M. (1984). Data for growth and yield models. In **D. D.** van Hooser and N. van Pelt (Compilers), Proceedings - Growth and yield and other mensurational tricks: A regional technical conference. Logan, Utah, Nov 6-7 1984. USDA For. Serv. Gen. Tech. Rep. INT-193.

CURTIS, R. O. and POPE, **R. B.** (1972). Some considerations in design of growth studies and associated inventories of the Western National Forests. Draft of Internal Report, USDA For. Serv. Pac. Northwest. For. and Range Exp. Sta., Portland, Oreg.

DAWKINS, H. C. and FIELD, **D. R. B.** (1978). A long term surveillance system for British woodland vegetation. *Commonw. For. Instit., Occas. Pap. 1.,* Oxford.

DEADMAN, M. W. (recorder), (1979). Session 2 on Growth and Yield Prediction. In D. A. Elliott (ed.) Technical Working Group Meeting on Mensuration for Management Planning of Exotic Forest Plantations, 2-6 Oct 1978, N.Z. For. Serv. For. Res. Instit., F.R.I. Symp. No. 20. FINS, L. and RUST, M. (1987). Comparative cost of using an electronic data recorder and field forms. *West. J. Appl. For. 2,1,* 28-30.

FOWLER, G. W. and ARVANITIS, L. G. (1979). Aspects of statistical bias due to the forest edge: fixed area circular plots. *Can. J. For. Res. 9,* 383-389.

GERTNER, G. (1987). A procedure to evaluate sampling schemes for improving already calibrated models. *Forest Sci.* ***33,*** *3,* 632-643. HANN, D. W. (1980). Development and evaluation of an even- and uneven-aged ponderosa pine/Arizone fescue stand simulator. USDA For. Serv. Res. Pap. INT-267.

KIRKLAND, A. (1985). Data needs and recent developments in resource management and planning. Theme paper, Session 4C, Making the best use of investment resources. 12th Commonwealth Forestry Conference, Victoria BC, Canada.

KRAMER, P. J. and KOZLOWSKI, T. T. (1979). *Physiology of Woody Plants.* Academic Press, New York.

LEECH, J. W., SUTTON, M. W. and ARCHER, G. R. (1989). Recording field measurements on Husky Hunter microcomputers. *Aust. For. 52, 2,* 68-73.

LIEBERMAN, D. (1983). Seasonality and phenology in a dry tropical forest in Ghana. *J. Ecol.* 70,791-806.

LUND, H. G. (1986). A primer on integrating resource inventories. USDA For. Serv. Gen. Tech. Rep. WO-49.

MCQUILLAN, A. G. (1984). Growth and yield modelling: where do we go to from here? In D. D. van Hooser and N. van Pelt (compilers) Proceedings - Growth and yield and other mensurational tricks: A regional technical conference. Logan, Utah, No. 6-7 1984. USDA For. Serv. Gen. Tech. Rep. INT-193.

MARIAUX, A. (1981). Past efforts in measuring age and annual growth in tropical trees. In F. H. Bormann and G. Berlyn (eds) *Age and Growth Rate of Tropical Trees: New Directions for Research.* Proc. of Workshop on Age and Growth rate Determination for Tropical Trees, held at Harvard Forest, Petersham, Ma., 1-3 April 1980. Yale Univ. Sch. For. and Env. Studies. Bulletin 94.

MATIS, K. G., HETHERINGTON, J. C. and KASSAB, J. Y. (1984). Sampling with partial replacement - a literature review. *Commonw. For. Rev. 63,* 3,193-206.

MEAD, D. A. (1982). Evaluating the quality of data used for resource planning. In T. Cocoran and W. Heij (eds) Proc. of Working Party S3.04.01 Planning and Control of Forest Operations, XVII IUFRO World Congress 6-17 Sept 1981, Kyoto, Japan, Life Sci. and Ag. Exp. Sta., Univ of Maine at Orona, Misc. Rep. 264.

PAYANDEH, B. (1974). Spatial pattern of trees in the major forest types of northern Ontario. *Can. J. For. Res. 4, 1,* 8-14.

REED, D. D., LIECHTY, H. O. and BURTON, A. J. (1989). A simple procedure for mapping tree locations in forest stands. *Forest Sci.* ***35,*** *3,* 657-662.

RENNOLLS, K. (1978). Top height: its definition and estimation. *Commonw. For Rev.* ***57,*** *3,* 215-219.

ROMESBURG, H. C. and MOHAI, P. (1990). Improving the precision of tree height estimates. *Can. J. For. Res.* ***20,*** 1246-1250. SCHREUDER, H. T., BANYARD, S. G. and BRINK, G. E. (1987). Comparison of three sampling methods in estimating stand parameters for a tropical forest. *For. Ecol. Manage.* ***21,*** 119-127.

SNEDECOR, G. W. and COCHRAN, W. G. (1980). *Statistical Methods,* 7th ed. Iowa Univ. Press.

STRAND, L. (1970). Regression problems in yield table construction. *Madd. Norske Skogforsoksv. 27, 5,* 495-505.

SYNNOTT, T. J. (1979). A manual of permanent plot procedures for tropical rain forests. *Tropical Forestry Papers 14.* Commonwealth Forestry Institute, Oxford.

TENNENT, R. B. (1988). A New Zealand data collection procedure for growth modelling. In J. W. Leech, R. E. McMurtrie, P. W. West, R. D. Spencer and B. M. Spencer (eds) Modelling Trees, Stands and Forests. Proceedings of a Workshop in August 1985 at the University of Melbourne. School of Forestry, University of Melbourne, Bulletin No. 5, 112-120.

VANCLAY, J. K. (1988). A stand growth model for cypress pine. In J. W. Leech, R. E. McMurtrie, P. W. West, R. D. Spencer and B. M. Spencer (eds) Modelling Trees, Stands and Forests. Proceedings of a Workshop in August 1985 at the University of Melbourne. School of Forestry, University of Melbourne, Bulletin No. 5, 310-322.

VANCLAY, J. K. (1990a). Integrated resource monitoring: an Australian perspective of current trends and future needs. In Global Natural Resource Monitoring and Assessments: Preparing for the 21st century, Proceedings of the international conference and workshop, 24-30 September 1989, Venice, Italy, 650-658.

VANCLAY, J. K. (1990b). Effects of selection logging on rainforest productivity. *Aust. For.* ***53,*** *3,* 200-214.

VANCLAY, J. K. (1991a). Research needs for sustainable forest resources. In N. Goodberg, M. Bonell and D. Benzaken (eds) Tropical Rainforest Research in Australia: Proceedings of a workshop held in Townsville, Australia, 4-6 May, 1990. Institute of Tropical Rainforest Studies, Townsville, Australia, 133-143.

VANCLAY, J. K. (1991b). Aggregating tree species to develop diameter increment equations for tropical rainforests. *For. Ecol. Manage., 42,* 143-168.

VANCLAY, J. K. and PRESTON, R. A. (1989). Sustainable timber harvesting in the rainforests of northern Queensland. In *Forest Planning for People,* Proceedings of 13th biennial conference of the Institute of Foresters of Australia, Leura, NSW, 18-22 September 1989, 181-191.

WEST, P. W., RATKOWSKY, D. A. and DAVIS, A. W. (1984). Problems of hypothesis testing of regressions with multiple measurements from individual sampling units. *For. Ecol. Manage. 7,* 207-224.

WEST, P. W., DAVIS, A. W. and RATKOWSKY, D. A. (1986). Approaches to regression analysis with multiple measurements from individual sampling units. *J. Statist. Comp. Simul.* ***26,*** 149-175.

WEST, P. W., STOCKER, G. C. and UNWIN, G. L. (1988). Environmental relationships and floristic and structural change in some unlogged tropical rainforest plots of north Queensland. Proc. Ecol. Soc. Aust. 15. 49-60.

WHITMORE, T. C. (1989). Guidelines to avoid remeasurement problems in permanent sample plots in tropical rain forests. *Biotropica* ***21,*** *3,* 282-283.

WOOD, G. B. (1990). Choosing a portable data recorder. *Aust. For.* ***53,*** 3,173-181.