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Tree volume estimation methods for forest inventory in Quintana Roo

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Executive Summary

Current inventory practice in Quintana Roo requires the measurement of height on every tree sampled. Volumes are calculated from equations using tree diameter and height which were developed by MIQRO some 30 years ago. The height measurement process constitutes about 40% of the cost of forest inventory. This study considers whether the height measurements can be avoided by using updated tree volume equations based only on tree diameter.

The statistical aspects of sampling errors in forest inventory are considered. Using tree volume measurements from Belize, comparisons are made between the inventory precision using a height-diameter volume equation, and one based on diameter only. It is found that the influence of the type of volume equation on inventory precision is negligible, and there are no strong statistical arguments requiring the use of the height-diameter equation for volume estimation.

Bias in a volume equation is a more serious factor. The bias that may exist in the MIQRO equations is unknown. Bias may arise from the form of the equation, from its application to smaller trees than those included in the sample, and to changes in species distribution. Volume equations of known provenance and sampling characterisics are important if bias is to be avoided.

The requirements for developing a new set of volume equations are set out. About 1000 trees need to be sampled, with no more than 50 trees from any one species. All sizes above 10 cm should be sampled. The probability of selecting a sample tree should be proportional to its basal area. Three practical methods for achieving this are described. Several locations (at least 9) should be sampled on a north-south gradient within the *Selva mediana* zone of Quintana Roo.

Trees to be measured should be felled, the bole cross-cut into 2-3 m lengths, and measured at the cut ends on 2 diameters over and under-bark and for defective core. Use of Relskop measurements on standing trees is considered inaccurate. Climbing and measuring trees is possible but likley to be very slow and will not provide defect information. It is possible if the need exists to combine the volume sampling with biomass studies for carbon sequestration information, but additional costs would be substantial. A sawmill recovery study could be combined with the volume sample at little extra cost.

It is estimated that measuring 1000 felled trees using two teams of 4 persons each will require about 85 days. The total duration of the work including preparation, training, field work, analysis and reporting would be 6 months. The benefits of this work would be a substantial saving in forest inventory costs for the foreseeable future, and a greater confidence in forest management information calculated from the volume equations.

Contents

Tables and figures

Abbreviations

Dbh.................. Diameter at breast height (1.3 m).
DFID................. Department for International Development of the United Kingdom.
Excel .... *Microsoft Excel*, version 5. Registered trademark of Microsoft Corporation.
FAO.................. Food and Agriculture Organization of the United Nations
GTZ.................. German technical assistance programme.
MIQRO............. Maderas Industrializadas de Quintana Roo SA.
PSP.................. Permanent sample plot.
VBA.................. Visual Basic for Applications. *Visual Basic* is a registered trademark of Microsoft Corporation.

Symbols used in equations

α,β .... *Coefficients to be determined by regression*
d .... *Tree dbh in cm.*
f .... *form factor*
g .... *Tree basal area in* m^2.
h .... *Merchantable height in m.*
k .... *The constant 0.00007854* ($\equiv g/d^2$)
μ .... *mean of a variable*
n, m, N............. *sample counts, according to contexts*
p .... *plot area*
σ .... *Standard deviation of a variable*
V....................... *Stand volume,* m^3/ha.
v .... *Tree bole volume in* m^3.

Disclaimer

This work is solely the responsibility of its author, and may not represent the formal view or policy of the United Kingdom Department for International Development.

Objective of study

This study examines tree volume estimation methods used in Quintana Roo and proposes changes and simplifications that will substantially reduce the costs of forest inventory without lowering the quality of information available. It gives a detailed biometric analysis and justification for the proposed changes.

It also describes practical sampling procedures required to develop updated volume equations. It suggests how this work can be undertaken within the context of the DFID Quintana Roo Forest Management Project.

Forest inventory in Quintana Roo

The majority of productive forest land in Quintana Roo is owned and managed communally by village societies known as ejidos. The ejidos themselves employ technicians and forestry specialists through corporate entities known as Civil Societies, each of which has a particular zone of geographic coverage dependent upon its constituent ejidos.

Management of the forests by the ejidos is an initiative that originated in 1983 with the establishment of the Plan Piloto Forestal assisted by GTZ. Prior to that, forests in Quintana Roo were operated under a logging concession by a parastatal company, MIQRO. In those days, ejidos had few timber rights, and were mainly restricted to Chicle collection from the forests which they owned[1].

MIQRO used the so-called flower system of inventory, involving measurement of trees along petal-like tracts extending from subjectively located base camps. To support the analysis of this data, MIQRO developed a number of volume equations based on tree diameter at breast height (*dbh*), and the merchantable height of the stem.

Under the PPF, new, objective and statistically-based methods of inventory were tested. Initially, the Dawkins system of two linear transects within kilometre blocks was used, similar to that adopted in neighbouring Belize. This was not found to be statistically efficient, and the current method was evolved. This employs a systematic grid of small circular plots, each of 500 m^2 area. On each plot, all trees are measured for dbh and merchantable height, and the MIQRO equations applied to calculate volume[2].

Definitions

A volume equation is used to calculate the volume of a tree given either diameter, or diameter and height. Their use during routine surveys such as forest inventories avoids the very slow and expensive process of direct volume measurement on each tree.

A volume equation based on diameter only is generally called a single-entry equation. A volume equation that uses both diameter and height to predict volume is called a double-entry equation.

The use of volume equations is fundamental to forest management, and there is a considerable literature relating to them.

The MIQRO equations

The equations which were developed by MIQRO for use in Quintana Roo have the general form:

$$v = \alpha + \beta . d^2 h \qquad \{eqn.\ 1\}$$

The symbols used in this and other equations are defined on page *iv* and follow IUFRO conventions[3]. There are 5 different equations according to species. Cedro (*Cedrela odorata*) , Caoba (*Swietenia macrophylla*) , and Amapola (*Pseudobombax ellipticum*) have individual equations. Other species are grouped into Blandas (softer whitewoods) and Duras (harder timbers). The coefficients are given in the table below.

Table 1 Coefficients for the MIQRO volume equations

Species/Group	α	β
CEDRO	0.07055	0.000047705
BLANDAS	0.01247	0.000047554
DURAS	0.00842	0.000050894
AMAPOLA	0.03139	0.000038954
CAOBA	0.01711	0.000041591

The sampling characteristics upon which these equations were based is not known. However, it is clear that the equations are not suitable for use with trees below 30 cm as they become progressively more biased with smaller trees, due to the presence of the positive constant term α. For Caoba, for example, this corresponds to a tree of zero diameter having a volume equivalent to a cylinder of 10 cm diameter and 2 m height.

Because these equations require the measurement of both diameter and height to determine volume, inventory procedures have been developed in which every tree is measured for height, using a telescopic fibre-glass rod. This procedure considerably slows up sample plot work, and probably at least doubles the time to measure each plot. This can be translated directly into a cost factor in the inventory.

Use of Belizean tree volume data for examples

For this study, no tree volume data from Quintana Roo was available. As noted above, the sampling characteristics of the MIQRO equations are unknown. In order to test hypotheses regarding the efficiency of different types of equation in inventory, data from neighbouring Belize has been used. This is from a sample in which trees were measured for mid and upper stem diameter and merchantable height using a relascope, and Newton's formula applied to calculate stem volume[4]. There were 1218 trees of various species in the sample. The volume equations derived from this data were applied to sample plots from Nohbec ejido for the numerical examples which are discussed below.

Statistical aspects of volume equations in inventory

Some basic formulae are needed for the precision of inventory estimates depending on the type of volume equation. For this purpose, a method described by Calliez (1980) is used[5]. This is based on a weighted volume equation with the general form:

$$v/x = \alpha/x + \beta \qquad \{eqn.\ 2\}$$

where x is given by either:

$$x = k.d^2h \qquad \{eqn.\ 3\}$$

or

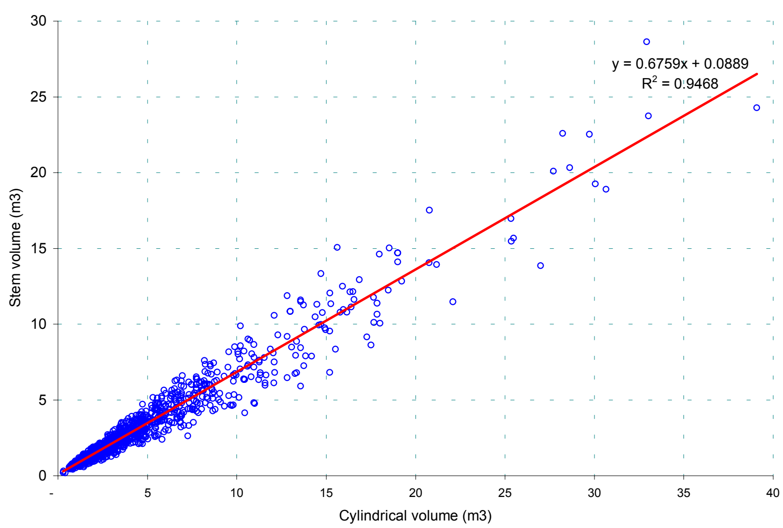
$$x = k.d^2 \qquad \{eqn.\ 4\}$$

These are weighted forms of the more familiar equations relating bole volume v to the volume of a cylinder of the same diameter and height:

$$v = \alpha + \beta.\ (k.d^2h) \qquad \{eqn.\ 5\}$$

or the equation relating tree volume to tree basal area:

Figure 1 Bole volume versus cylindrical volume for Belizean tree data



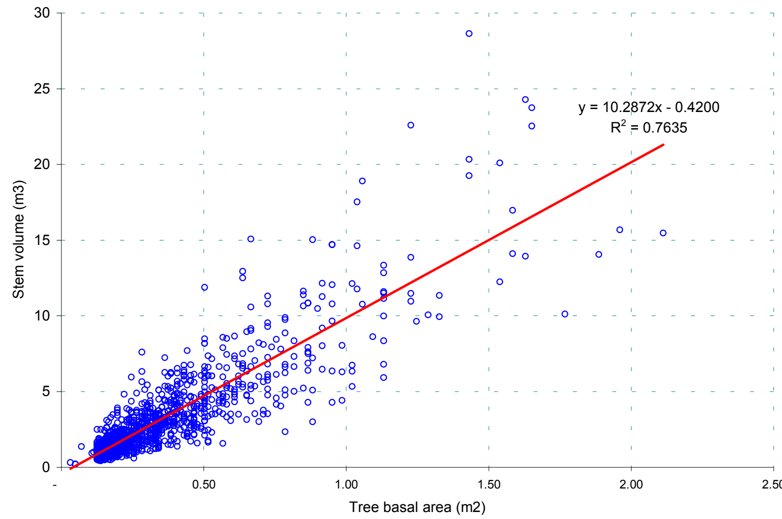


Figure 2 Bole volume versus tree basal area for data from Belize

$$g = k.d^2 \qquad \{eqn.\ 6\}$$

$$v = \alpha + \beta.g \qquad \{eqn.\ 7\}$$

Equation 5 is the same form as the MIQRO functions and is called here the *cylindrical volume equation*. Equation 7 is referred to as the *basal area volume equation*. Graphs of both these functions are shown for the Belizean volume data in figures 1 and 2. These data combine all species.

The lower precision of the basal area volume equation is apparent. It has a coefficient of determination (R^2) of 76%, as opposed to 95% for the cylindrical volume equation. Superficially, this may be thought as providing an argument against the use of a single-entry equation; however, as we shall see, the R^2 is almost completely irrelevant to the ultimate precsion of volume estimates in an inventory.

The heteroscedacity that is typical of tree volume data may be seen in these figures. The variance of the data about the regression increases approximately in proportion to volume. The weighting provided in equation 2 corrects this effect, and is necessary if linear regression theory is to be used to estimate the precision of plot volumes.

It may also be noted that the slope of the regression lines correspond closely to conventional form factor and form height. Form factor is defined as:

$$f = v/(kd^2.h) \qquad \{eqn.\ 8\}$$

and is approximately equal to 0.68 from figure 1. Form height is given by the ratio of tree volume to basal area (*v/g*) and is about 10.3 m from figure 2.

The data set used for this example comprises trees over 40 cm dbh, except for 3-4 observations down to 20 cm. The intercepts of the equations would therefore tend to bias inventory results if applied to smaller trees.

Referring again to equation 2, Cailliez (*op. cit.*) gives formulae for estimating the precision of the volume of a sample plot when this equation is applied to estimate the volume of individual trees. The residual variance from the regression based on equation (2) is given by:

$$\sigma_r^2 = [(\Sigma y^2 - (\Sigma y)^2/n) - a.\ (\Sigma xy - \Sigma x.\Sigma y/n)]/(n-2) \qquad \{eqn.\ 9\}$$

where y is v/x in equation 2 and n is the number of data points. The variance of the α coefficient is given by:

$$var(\alpha) = \sigma_r^2 / (\Sigma x^2 - (\Sigma x)^2/n) \qquad \{eqn.\ 10\}$$

The variance of the β coefficient is given by:

$$var(\beta) = \sigma_r^2 / n + (\Sigma x/n)^2.var(\alpha) \qquad \{eqn.\ 11\}$$

The covariance of α and β is given by:

$$cov(\alpha,\beta) = -(\Sigma x/n).var(\alpha) \qquad \{eqn.\ 12\}$$

The variance of the estimated volume V in m3/ha for a plot of p ha due to the volume equation will be:

$$\sigma_q^2 = [N^2.var(\alpha) + (\Sigma x)^2.var(\beta) + 2N.\Sigma x.cov(\alpha,\beta) + \Sigma x^2.\ \sigma_r^2]/p^2 \qquad \{eqn.\ 13\}$$

where N is the number of trees sampled on the plot, and x is the measurement being used (kd^2h or g) to predict volume for each tree on the plot.

The between-plot variance σ_p^2 in volume estimates will be given conventionally by the formula for simple random sampling:

$$\sigma_p^2 = (\Sigma x^2 - (\Sigma x)^2/m)/(m-1) \qquad \{eqn.\ 14\}$$

where m is the number of sample plots.

The between and within plot variances can be combined to obtain total variance in the volume per ha estimate from m plots:

$$\sigma_v^2 = \sigma_p^2 + (\Sigma\ \sigma_q^2)/m^2 \qquad \{eqn.\ 15\}$$

The standard error of the estimated mean volume $\sigma_{\mu(v)}$ for all the plots will then be given by:

$$\sigma_{\mu(v)} = \surd(\sigma_v^2/m) \qquad \{eqn.\ 16\}$$

The mean plot volume is conventionally calculated as:

$$\mu_V = (\Sigma V)/m$$

A numerical example

In order to compare the effects of using double and single entry equations on inventory data, two sources of data have been used:

- For the volume equations, as discussed above, data has been used from Belize.
- For the inventory plots, permanent sample plot data from Nohbec has been used[6]. These are of the same design as normal inventory plots (500 m^2).

Calculations were made using the formulae given above in an *Excel* workbook called INVDEMO.XLS*. The Belizean tree volume data, graphs and equations are included in this workbook, exactly as reproduced in Figures 1 and 2. The PSP data from 33 plots is also given, tree by tree. There are two macros, written in VBA, to perform calculations:

- REGSE calculates the regression coefficients, variances, covariance and residual standard deviation for either type of weighted volume equation according to the formulae discussed above.
- PLOTSUM calculates the mean plot statistics for volume using the single and double entry volume equations. This includes the within plot variance and coefficient of variation of within-plot volume estimates due to the error in the volume equations.

It was found from these calculations that the coefficient of variation due to the volume equation alone averaged 8.1% for the double entry equation, and 20.1% for the single entry equation.

However, when the overall calculation of variance was made including between-plot variation due to sampling, the effect of the different volume equations became completely negligible. Table 2 shows an analysis of the results.

Table 2 Components of error due to sampling and volume equation in test inventory

	Method of volume estimation		
	V_{MIQRO}	f(D,H)	f(D)
Mean	166.9	184.0	202.0
Plots	33	33	33
Variance			
Sampling	18438.1	21479.1	22331.1
Equation		9.7	58.3
Total	18438.1	21488.8	22389.3
CV%			
Sampling	81.4%	79.6%	74.0%
Equation	0.0%	1.7%	3.8%
Total	81.4%	79.7%	74.1%

* Copies of this can be obtained by E-mail from the author at: D-ALDER@EUROBELL.CO.UK.

Some interesting effects will be observed from Table 2. Although, as noted above, the coefficient of variation of volume is about 8% and 20% respectively, on average, for plot volume per ha, the contributions shown on the table are given as 1.7% and 3.8% respectively. This is because, overall, the contribution of the volume equation to variance is reduced by the factor $1/m^2$ in equation 15, where m is the number of plots sampled.

Secondly, it will be noted that the between plot variance is lower with the single-entry than the double entry equation. This is due to the additional variation arising from the height measurements on the plots, and does not reflect any significant difference in the true variances of these inventories.

Thirdly, the volume calculated by the MIQRO equation is substantially lower than that of the two-entry equation from the Belizean data. The equation used was that for mixed hardwoods (Duras) in table 1; this difference in the mean could be due to any of a number of factors.

It can be concluded that, unless dealing with a very small number of plots, the contribution of the volume equation to the overall error estimate in an inventory is effectively negligible. Hence the practice, almost universally adopted, of ignoring the error from the volume equation when calculating sampling errors in an inventory.

The issue of bias

Although the precision, or sampling error, of an inventory is not much influenced by the precision of the volume equation used, the accuracy of the results will be directly affected by any bias in the equations.

In theory, a regression equation is unbiased. However, the resulting predictions will only be unbiased if the population to which they are applied has identical characteristics to that used to fit the regression coefficients.

In the present context, there are four principle sources of bias.

- *Range of diameter measurement*, especially minimum diameter. Typically older volume equations (both in the MIQRO and Belizean example used here) are based on samples of trees of commercial size, 40 cm and above. Such equations will be biased if applied to smaller trees.

- *Species mixture*. Volume equations developed for individual species can clearly be expected to be biased if applied to other species. However, equations developed for groups will be biased when applied to data in which the preponderance of species differs from that in the sample.

- *Transformation of the y variate*. Fitting equations to the logarithm of volume, and then applying them to predict volume, results in a bias. Equations based on the log transform of volume can be corrected as described in Alder (1980:139)[7].

- *Variations in mean height or form*. An equation based on a sample from one locality will be biased when applied elsewhere, due to variations in the mean height or form factor of the trees. This possibility can be tested if data is collected in a suitable way at several localities, and corrected by developing local volume tables if necessary.

Number and selection of trees

As figure 2 shows, the variance of the residual from a volume regression is approximately proportional to diameter squared, or basal area. An efficient sample for estimating the regression is therefore obtained by making the probability of selection proportional to tree basal area.

If this principle is not followed, and volume trees are selected systematically, then there is a very considerable over-sampling of smaller and medium-sized trees. This involves a great waste of energy (and unnecessary cost) since the information gathered adds almost nothing to the regression. Figure 2 shows the typical consequence of such systematic sampling, which was adopted in Belize. There is a dense concentration of points at the lower left part of the graph, whilst the more variable, large dimension trees are relatively under-sampled.

There are three basic ways to achieve sampling proportional to basal area:

- *Use an angle count device* (prism, Relaskop etc.). If linear transects are laid through the area to be sampled, then points can be established every 50 m, and trees selected using a metric basal area factor of 4. This will lead typically to the selection and felling of about 5-6 trees at each point.

- *Select trees whose distance from the transect is proportional to dbh²*. Transects are laid through the forest, and trees selected whose $dbh^2/4$ is less than their distance in cm from the line. Thus a tree of 20 cm would need to be within 1 m of th line to be selected, but a tree of 100 cm could be up to 25 m away. This rule is equivalent to working with a metric basal area factor of 4.

- *Tally trees as they are selected by basal area classes, and reject trees as necessary to keep the tally between classes approximately equal*. This is very suitable for working in an arbitrary area, such as along a potential road, or within an active felling area. Trees can be checked at random and paint marked or flagged for inclusion in the volume sample. Convenient equal basal area classes are given by the diameter limits 10, 30, 41, 50, 57 cm. All trees above 57 cm are included, and all below 10 cm rejected.

The effect of applying a selection proportional to basal area is shown in Figure 3 for the 33 PSPs in Nohbec. In the 10-20 cm class,

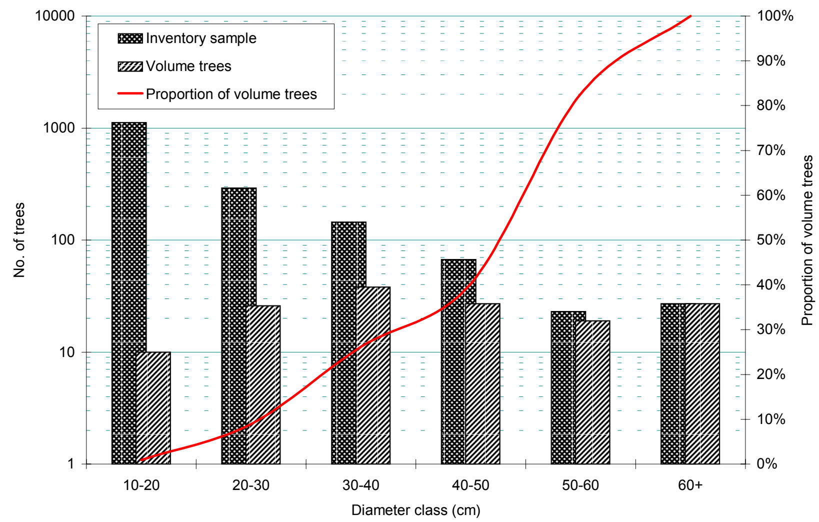


Figure 3 Volume trees selected with probability proportional to dbh^2

about 10 trees out of 1000 are selected (1%). In the 20-30 cm class, 25 trees out of 300 are chosen (about 10%), and so on.

Although it is convenient to combine volume measurement with harvesting, a certain number of trees need to be felled and measured which will be below the legal harvesting size. Special permits may be required for this purpose. *It is very important that the sampling is not restricted to the legal minimum felling diameter, as otherwise the volume equations cannot be applied in an unbiased way to estimating whole stand volumes including smaller trees.* The recommended minimum size for bole volume estimates is 10 cm dbh.

It is recommended that the total sample size should initially be about 1000 trees, with not more than 50 of any one common species. This is based on the assumption that tree sizes in the sample will be selected according to the method described above.

Location and species selection of sample

It is usually most convenient to carry out volume sampling in an area close to and ahead of current harvesting operations. This will ensure that those sample trees that are of commercial quality and species will not be wasted as a result of the harvesting process. The chainsaw work can also usually be arranged at minimum cost.

Species selection should include all trees, regardless of their current commercial value. However, as sampling proceeds, the number of trees for each species should be monitored. Once 50 trees for one species have been obtained, they should not be selected again. It is important not to oversample a species at one location if possible, and omit it from others. However, the gregarious tendencies of trees may make this difficult to achieve without exceeding the basic sample size.

There is a need to review species selection *daily* as work proceeds, and advise teams in particular localities of those species which should no longer be sampled.

Sampling must be carried out at several locations on a North-South gradient within the *Selva mediana* zone of Quintana Roo, to encompass the range of form-heights associated with the rainfall gradient. Since species associations tend to be gregarious, multiple locations will also ensure a good mixture of species. Over-sampling at a single site because of convenience of access, congenial accomodation, and so on, should be avoided. It is suggested that three distinct locations are sampled at three points on the gradient between southern and central Quintana Roo, giving 9 distinct locations in all.

Measurement of volume trees

Once a tree has been selected as volume tree, it should be measured standing for dbh, merchantable height, crown-break height, form and health according to the normal classification and methods for forest inventory. The species should, of course, be identified.

The tree should then be felled, and cross cut at intervals of 2-3 m. up the bole. Sections which are defective* should be cut at each end even if they are quite short. The cross-cutting length of commercial stems needs to be discussed to ensure that timber is not cut to a dimension that will lead to its wastage.

Each section is measured at the top end on two diameters at right angles, over and under bark. Crayon should be used to mark the lines of measurement so that measurements can be checked or repeated if necessary.

The diameter of any central core of defect is also recorded on the field forms.

The butt section is also measured in the same way on the cut stump or on the bottom section of log. It can be cut clean with the chainsaw after felling to ensure good measurements. The approximate height of the stump should be measured. Good chainsaw practice should be employed when felling to ensure that the stump is as low as possible, although with large buttressed trees, a low stump is difficult to achieve.

Measurements should be continued up to the higher value of the commercial or crown break point. If the crown breaks below the commercial height (ie. there is at least one good log within the crown) then the section including the branches should be cut out

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* Due to excresences, rot, holes, dead branches, splits etc.

and measured as a defective section. If the commercial height is below crown break, due to rot, damage, etc., then measurements should continue up to the crown point, recording one (or possibly more) defective sections.

Measurement of standing trees

There are many examples (including the data from Belize used in preceding analyses) where measurements for volume studies are made on standing trees using Relascopes. The author considers this method to be too inaccurate unless certain conditions are followed:

- The relascopes must be tripod mounted.
- Wide-angle relascopes must be used with at least 6 bands subtended by the stem at dbh.
- Operators must be very carefully trained and constantly checked against each other to avoid operator bias.

Under these circumstances, volume can be measured to about ±10%[*]. The main problem is that there is a tendency for bias (overestimation) as the eye goes out of focus due to fatigue.

Relascope measurements cannot give underbark volume or internal defect information. The author's own experience is that the measurement bias may be considerable[8] and he recommends the use of felled tree measurements in preference.

It is also possible to climb trees and measure them standing. This is accurate but slow, and again does not obtain good information about defect and bark thickness. Quintana Roo has many chicleros skilled in tree climbing, and this option could be considered. The author however does not recommend it as a general procedure.

Coordination with sawmill recovery studies

It is logical to combine a sawmill recovery study with the volume sampling. If this is required, then each log should have a section number and tree number painted on the end during the measurement process. These logs can be stockpiled at the sawmill and run though as a single batch to facilitate measurement of the sawn product. From the point of view of the volume sampling *per se*, this process will not add significantly to costs.

Total volume and biomass studies

The measurements described above give suitable information for timber production management. However, information on total above ground volume and biomass may be useful for management issues relating to carbon sequestration and forest fire. These could be coordinated with the volume study but would add substantially

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[*] Under the best circumstances, relascopes can measure diameter to about ± 5% This gives a volume error of about ± 10%.

to costs. Generally, total volume or biomass studies require measurement of the above-ground woody parts of the tree to a 5 cm diameter limit, with 2-phase sub-sampling below this limit. Weighing and drying equipment is needed for the second phase sampling. Measurement time approximately doubles with each halving of the diameter limit, and it would take about 4 hours per tree to measure to a 5 cm top, as against 1 hour to fell and measure bole volume, or 2 hours to a 10 cm top.

Underground biomass involves extraction of stumps and larger sized roots and may be quite costly, requiring perhaps one day per tree to extract the stump and cut it into sections for weighing. Some two-phase sampling is also required to establish the fractal dimension of the root system and extrapolate biomass to the finer roots which are not directly measurable. Laboratory work is required to establish fresh and dry weight ratios.

Because of the substantial additional costs involved, the question of biomass sampling is not considered further in this report. However, if there is a motivation to undertake such work, it is logical and helpful to try and coordinate it with the timber volume study. Substantial elements of double work could be avoided relative to project preparation, training, tree selection and felling, measurement of larger dimension stem components, and analysis.

Volume measurement of Chicle trees

There may be practical restrictions on the felling of Chicle trees (*Manilkara zapote*) for the volume sampling. If this is the case, it is recommended that upper stem measurements are made by climbing the tree and using a girth tape. Bark thickness can be estimated using a bark-thickness guage.

Considerably more accurate measurement will result if trees can be felled. A combined sample can be made including some trees (past their productive life) which are felled and measured conventionally, and others which are climbed and measured for girth.

The girth measurement on Chicle trees will be quite inaccurate due to the effect of the scars from gum extraction. However, in a double sample, it will be possible to establish a correcting regression by measuring about 10 trees over-bark for girth, and then for diameter at cut sections at the same point. There may be 5-10 sectional measurements for each tree, giving about 50 points to establish such a regression.

However, it will be much simpler if it can be agreed to fell and measure conventionally the Chicle trees in the same way as for other species.

Data analysis The basic development of volume equations is quite straightforward and should not require specialised biometric assistance. However, there are issues regarding the selection of the best form of equation, testing and correction for bias, and the grouping of equations by species, that may require some additional support. Much depends on the personnel available to the project and their experience in this field.

However, it is probable that the following consultancy inputs would be helpful:

- Initially, during the training phase and first two weeks of field work, to fine-tune procedures, field forms and sample selection methods. Data entry procedures can also be designed in this phase.

- Once all data has been gathered, to complete the analysis and ensure that it is carried out with suitable rigour. This should be done in conjunction with counterpart staff, to permit training and transfer of knowledge. This would require about 4 weeks, to encompass actual analysis, *ad hoc* training, and report writing.

Cost of field work The author's experience suggests that bole volume measurements require about 1 hour per tree. Each measurement party requires a chainsaw operator, a technician, and two measurers. Completion of a sample of 1000 trees would therefore require about 670 man-days, assuming 6 trees are processed per working day.

Using two teams, and based on 20 working days in the field, the sampling could be completed within 85 days (4 months)..

An additional initial month is required for preparation and training, and a final month to complete analysis and report writing.

A qualified forest engineer is required to supervise and plan operations overall, control logistics and personnel movements, etc. A biometrician is required during the training and analysis phases unless the forest engineer has strong competence in this field.

Data entry, checking and editing requirements can keep pace with the field work if a single technician is assigned for this purpose.

Elimination of height measurement on inventory

As the analysis on page 10 shows, there is no useful advantage in using a 2-factor volume equation that requires height measurement on every tree. Inventory can be greatly speeded up by measuring diameter only and using a single-entry volume equation.

This is a commonplace practice in tropical forest inventories, as for example those carried out by FAO and DFID.

In the context of the ejidos of Quintana Roo, the benefit may amount to a 40% reduction in inventory costs, if time saved on field work is translated directly into a cost reduction.

Need for new volume equations

The existing MIQRO volume equations are now some 35 years old. Their original sampling characteristics are unknown, but it is clear from the form of the equations that they will be biased if applied to smaller trees. There is an urgent need for new volume equations of known statistical provenance.

The simplified inventory procedure also requires development of single-entry volume equations based on diameter only. This therefore requires new sampling.

Implementation

A felled sample of 1000 trees is required, selected according to the procedures discussed on page 13. With two teams employed, each led by a forest technician, this can be accomplished in 4 months. An additional month is required for startup and training, and a month is required at the end to complete data processing, analysis and report writing.

Thereafter an extension process will be required to ensure the new equations are incorporated into field and data processing procedures for inventory.

The final result will be a very substantial long-term benefit to the ejido communities through cost savings. There will also be more confidence in the forest management process through the use of volume equations of known provenance.

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