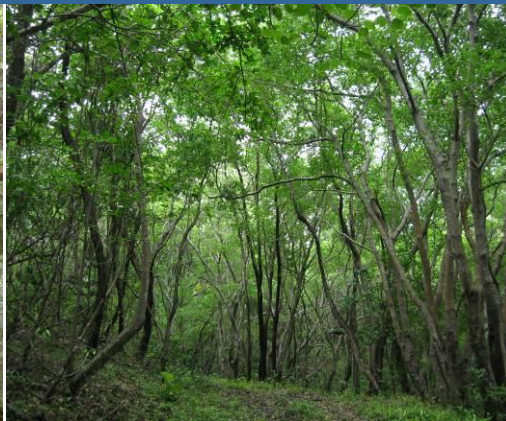


Presented to the European Commission and
Banana Industry Trust



**NATIONAL FOREST DEMARCATION AND BIO-PHYSICAL
RESOURCE INVENTORY PROJECT
CARIBBEAN – SAINT LUCIA
SFA 2003/SLU/BIT-04/0711/EMF/LC**

FOREST BIOMETRIC GUIDELINES

By

ROBERT B. TENNENT

Project Leader/Inventory Specialist

November, 2009



This project is funded by the
European Union



Finnish Consulting Group
International

Cover illustrations: Elfin Shrubland on Mount Gimie Range (Roger Graveson, FCG); Forest Inventory team at work (Bob Tennent, FCG); Deciduous Seasonal Forest at Grande Anse (Jenny Daltry, FCG-FFI).

THE OPINION OF THE AUTHOR DOES NOT NECESSARILY REFLECT THE OPINION OF FCG INTERNATIONAL LTD,
THE BANANA INDUSTRY TRUST (BIT), OR THE EU.

THE AUTHOR AND FCG INTERNATIONAL LTD TAKE NO RESPONSIBILITY FOR ANY MISREPRESENTATION OF
MATERIAL THAT MAY RESULT FROM THE TRANSLATION OF THIS DOCUMENT INTO ANY OTHER LANGUAGE,
NOR FOR ANY ATTEMPT TO USE THE MAPS OR GEOREFERENCES IN THIS DOCUMENT FOR NAVIGATIONAL
PURPOSES.

PUBLISHED BY

FCG International Ltd
Helsinki, Finland

COPYRIGHT

© 2009 Banana Industry Trust (Contracting Authority)

REPRODUCTION FOR RESALE OR OTHER COMMERCIAL PURPOSES IS PROHIBITED WITHOUT PRIOR WRITTEN
PERMISSION FROM THE COPYRIGHT HOLDER.

RECOMMENDED CITATION

Tennent, R.B. (2009) Forest Biometric Guidelines. Technical Report No. 9 to the National Forest
Demarcation and Bio-Physical Resource Inventory Project, FCG International Ltd, Helsinki, Finland.

The National Forest Demarcation and Bio-Physical Resource Inventory Project was funded by the
European Union under the auspices of the Banana Industry Trust, and implemented by the
Finnish Consulting Group (FCG) International Ltd in collaboration with
the Saint Lucia Forestry Department.

Table of Contents

INTRODUCTION.....	1
SECTION 1 - BASIC FOREST MENSURATION.....	1
TREE MEASUREMENT	2
LOG MEASUREMENT	7
AREA MEASUREMENT	9
USE OF A GPS (GEOGRAPHIC POSITIONING SYSTEM)	10
SECTION 2 - TROPICAL RAINFOREST INVENTORY	12
REASONS FOR CONDUCTING INVENTORY	12
OBJECTIVES.....	12
WHAT TO MEASURE.....	13
INTEGRATION	13
STRATIFICATION.....	13
FIELD PLOTS	14
PLOT TYPES	14
INVENTORY PLOT LAYOUT.....	14
ATTRIBUTE SAMPLING.....	15
FIELD PLOT MEASUREMENT.....	16
RANDOM SAMPLING DESIGN.....	17
SYSTEMATIC SAMPLING DESIGN	17
CALCULATIONS	17
COMPUTER SYSTEMS FOR PROCESSING FIELD DATA	17
INTEGRATION	18
REMOTE SENSING	18
GEOGRAPHICAL INFORMATION SYSTEMS	18
COMPLETE SYSTEMS INTEGRATION	19
PEOPLE	19
SUMMARY	19
SECTION 3 - YIELD CONTROL.....	20
INTRODUCTION	20
OBJECTIVES	20
NEEDS.....	20
TREE VOLUME EQUATIONS	21
GROWTH MODELS.....	24
SECTION 4 – SPECIFIC SAINT LUCIA TIMBER INVENTORY FACTORS.....	33
<i>INTRODUCTION</i>	33
FOREST TYPING	33
SAMPLE INTENSITY.....	34
STRATIFICATION.....	35
IDENTIFY FOREST STRATA	36

ENTER FOREST UNITS IN SLFMIS.....	36
SAMPLE PLOT LOCATION	36
SAMPLE PLOT SIZE	37
DIAMOND PLOT ESTABLISHMENT	38
ESTABLISH SAMPLE PLOT	39
MEASURE SAMPLE PLOT	39
ENTER SAMPLE PLOT INFORMATION	39
CHECK SAMPLE PLOT INFORMATION	39
EXAMINE STRATUM REPORTS	40
REDEFINE FOREST UNITS AS NECESSARY	40
STATISTICAL TERMS IN FOREST INVENTORY	40
ACCURACY OF INVENTORY	41
DIAMETER MEASUREMENT	41
HEIGHT MEASUREMENT.....	42
STRIP PLOT ESTABLISHMENT	42
PERMANENT SAMPLE PLOTS	43
REFERENCES AND RECOMMENDED READING	44
APPENDICES	45
APPENDIX 1. DIAMOND PLOT SIZES	45
APPENDIX 2. STRIP PLOT SIZES	46
APPENDIX 3. PLOT SHEET	47

Introduction

This technical report is a compilation of training and background materials prepared during the planning and implementation of the Saint Lucia forest timber inventory of 2009. The materials have been collated to make them readily available as a general reference source for forest mensuration, inventory, and yield control information. As such, there is some duplication of information between sections.

Section 1 - Basic Forest Mensuration

All forest management information is derived from information collected from individual trees. The process of collection such information is called **mensuration**.

Information from individual trees can be combined to provide statistics that provide information about a forest. Forest information cannot be collected directly, and must be calculated from tree information. The large number of trees in a forest means that trees must be sampled, which means that forest information relies heavily on statistical calculations. Such calculations are meaningless unless the information collected from each tree is accurate.

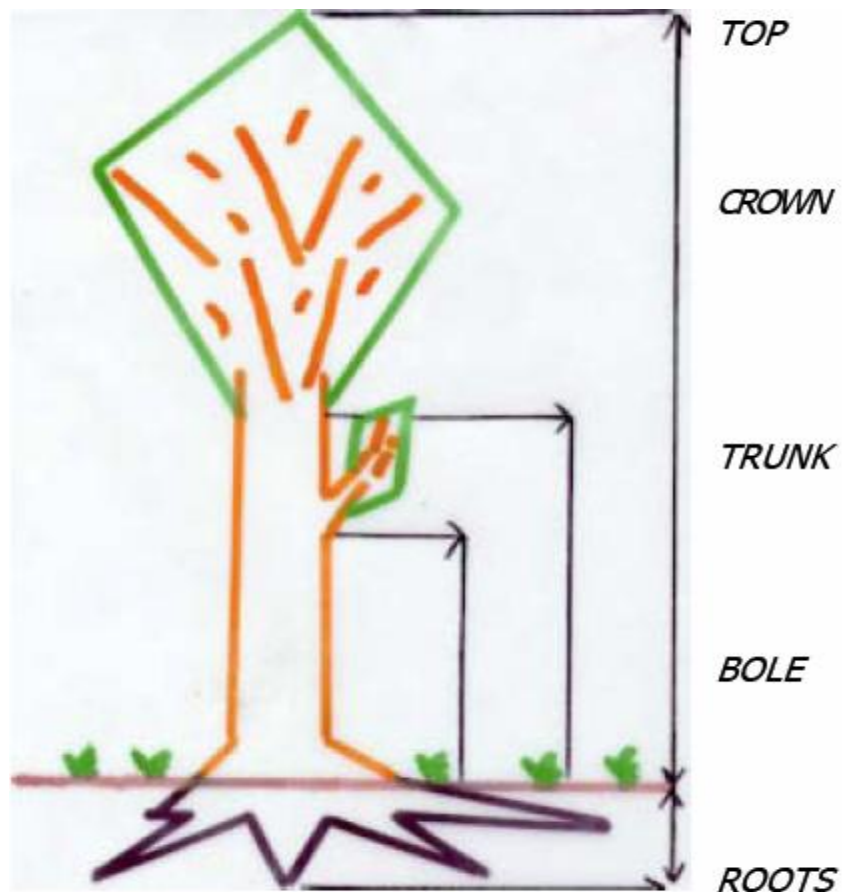


Figure 1 The parts of a tree

Tree Measurement

Count

The most basic measurement that can be taken from a tree is the presence or absence of the tree. The simplest form of forest mensuration is an enumeration of the number of trees in an area. Such an enumeration can be done in a variety of ways, such as counting trees in a plot on the ground, counting trees within a certain distance of a path, or counting trees in some part of an aerial photograph.

Species

After establishing the presence or absence of a tree, the next most important feature of the tree is the species. In some cases, such as plantation forestry, the species is clearly defined, as a decision will have been made to plant a certain species. In other cases, such as natural forest inventory, there may be a wide range of species.

Species identification should be given careful consideration when any form of forest mensuration is being considered. Different species have different economic and social values. Identification of species should ensure that the most valuable species are readily identified, as well as the most common species.

All field staff should be well trained in species identification. In regions where certain species may have different common names, care should be taken that standard names are used. Care should also be taken to ensure that the same name is not used for different species in different regions.

Diameter

The size of a tree is best described with the diameter of the tree. In forestry, diameter should always be used for the description of the tree. In the past girth has been used, but this is now no longer recommended.

Diameter is best measured with a diameter tape, which is a tape marked with units that convert the girth to the diameter. It is important to make sure that a correctly calibrated tape is used. If an ordinary tape is used, the diameter will be overestimated by more than 300%.

A carefully defined point should be used for measuring the diameter of the tree. In many cases, especially plantation forestry, this will be at 1.3 m above the base of the tree, measured from where the tree meets the ground.



Figure 2 Correct measurement of diameter

The diameter of each tree should be measured in centimetres to one decimal point (e.g. “14.7”) with a diameter tape at a point 1.3 m from the base of the tree, measured on the uphill side of the tree. This is defined as ‘diameter at breast height’, or dbh.

It is sometimes necessary to move the measurement point up or down from 1.3 m to avoid unrepresentative measurements if there is a stem irregularity or significant stem buttress. It is better to make a true measurement than to attempt to make an averaged measurement, as averaged measurements are often calculated incorrectly.

Diameters should be recorded on the sample plot sheet to one decimal place, e.g. “11.3”.

For some species, notably tropical rainforest species, buttressing will make a measurement at this point meaningless. Buttressing can also mean that diameter is better measured with a diameter stick.

In the case of severe buttressing, the diameter above buttress is the usual measurement collected. Field crew should be carefully instructed on how to define the point of measurement.



Figure 3 Example of tree with severe buttress

When a tape is used for the measurement, the tree should be cleared of all loose bark and vines, and the tape wrapped tightly around the tree, so that the smallest measurement is taken. The tape should be placed around the tree so that the numbers can be read directly.

Never permit field crews to take measurements with a tape held upside-down.

Height

After the diameter, height is the next most important variable that can be measured on the tree. The height that is being measured must be clearly defined. Height measurements that can be collected include total height, height of dominant leader, height to lowest green branch, height to crown break, and pruned height. The field crew must be in no doubt over what height is to be measured.

The team leader should be careful to ensure that only representative trees are measured. He should not measure short trees with large diameters, or tall trees with small diameters.

In mixed species stands a range of species should be included in the height tree sample.

Height can be measured directly for small trees, by holding a height pole beside the tree. The pole should be placed as close to the base of the tree as possible, on the uphill side of the tree. The height should be read from the tree by an observer standing at right angle to the tree.

Height can also be measured indirectly with a hypsometer, which is a tool for measuring the angle from the observer to a point. The observer must pick a suitable point, where the top and the bottom of the tree can be seen. In some cases the bottom of the tree may be obscured, and another point picked on the tree as a measurement datum.

The observer must measure the distance from the tree to the observation point, and then read the angle to the top of the tree, and the bottom of the tree, or to the datum point. The height of the tree can be calculated from these measurements, either with a calculator, or with a table of heights.

$$A = \tan \text{Angle } a \times D$$

$$B = \tan \text{Angle } b \times D$$

$$\text{Tree Height} = A + B$$

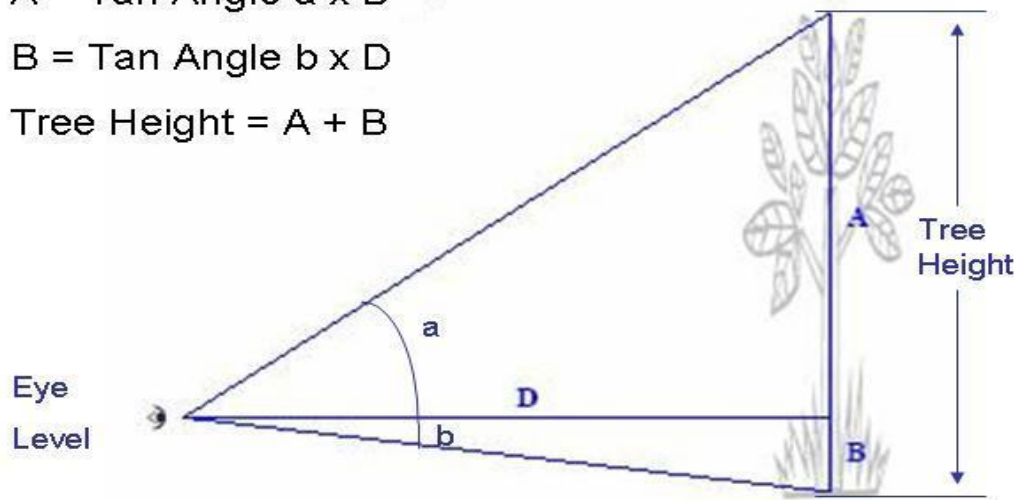


Figure 4 Trigonometry of tree height calculation

Some hypsometers come with a range finder. This is a graduated pole that the observer views through a prism, to find a point at a certain distance from the tree. If a range finder is used, the angles from the hypsometer can be converted directly into height readings.

Because a prism is used for finding the observation point, the range finder automatically corrects for any ground slope. This means that the nominal distance read from the range finder is not the exact distance.

Never use a range finder distance to calculate a height with a calculator or set of height tables

Measuring heights with the Suunto PM-5

The Suunto PM-5 can be used to measure heights directly or indirectly. The PM-5 has two scales for reading heights directly, and an angle correction chart on the side.

Direct height measurement

To read a height directly, the observer should use a tape to locate a position exactly either 15 m, 20 m, 30 m, or 40 m from the tree measured horizontally. The distance should be more than the height of the tree.

The observer then sights the tree through the PM-5, so that the top of the tree can be seen to the left of the scale. The left scale shows the height for a 20 m distance. The right scale shows the height for a 15m distance. For 30m or 40 m distances the reading from the PM-5 must be doubled.

The observer should take a reading to the top of the tree, and then a reading to the bottom of the tree, and add the two readings together to get the total height of the tree.

NB. When taking the lower reading, be careful! If the reading is down, like in the example in Figure 4 above, the scale will be negative. The absolute value should be added to get the total. For example, if the scale shows -2.5, 2.5 m should be added to the upper reading.

If the lower reading is up, then the scale will read positive, BUT the value should be subtracted from the upper reading. So if the scale shows +2.5, then 2.5 m should be SUBTRACTED from the upper reading.

NB. If the lower reading is up, how was the distance measured? Best practice is not to measure heights from a position below the base of the tree.

Indirect height measurement

Many times it will not be possible to locate a position exactly 15 m, 20 m, 30 m, or 40 m from the tree where the observer can see the top and the bottom of the tree. In these cases the height must be calculated indirectly. The best way to do this is to take the measurements in the field, and calculate the height later back in the office.

The procedure to be followed is this.

1. Locate a position where the top of the tree can be seen, as well as part of lower 2 m of the tree.
2. Record the distance from the observer's eye to the lower part of the tree, which is called the datum.
3. Record the height to the datum
4. Read the left (20 m) scale of the PM-5 to the top of the tree.
5. Convert the reading to the angle to the top of the tree using the conversion on the side of the PM-5 and record this angle
6. Read the left (20 m) scale of the PM-5 to the datum, convert the reading to an angle, and record the angle. Remember that the angle is usually negative.

When a height is measured indirectly, the distance from the tree should be more than the height of the tree, so that the upper angle is less than 45 degrees.

Bark Thickness

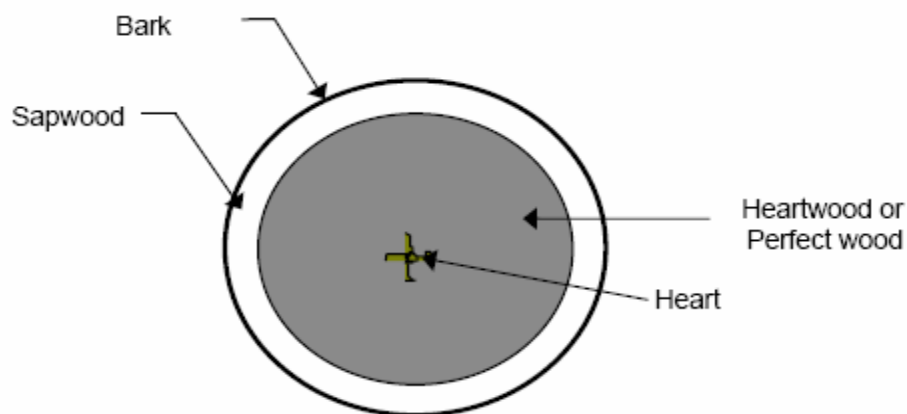


Figure 5 Cross section through a tree

Some species have bark that sheds, and others retain their bark. This means that some older trees can have an extremely thick bark, or a bark that varies in thickness. In most cases the valuable section of the tree is not the bark, and so measurements must be taken of the bark thickness.

Bark thickness can be measured on a standing tree with a bark gauge. Commercial bark gauges can be bought that have a scale calibrated on the gauge, and which have a handle suitable for use. The gauge is placed against the tree, and the sharp cutting edge is pushed until the wood is hit. The thickness of the bark is read from the gauge.

Commercial gauges may not be available, or may be too expensive. A bark gauge can be made from a chisel or screwdriver, by filling graduations into the side of the instrument.

When using a bark gauge, it is important that the gauge is pushed through the bark, but not into the timber. The field crew should practise the technique before collecting measurements.

Some species have bark that is too hard to penetrate with a bark gauge. These species may have their bark thickness measured by cutting the bark off with an axe. If the species is a particularly valuable one, the axe wound should be painted with a substance designed to prevent wood rot.

Some species have a deeply fissured bark. The bark thickness is collected to allow an estimate of under bark diameter, and so the bark thickness should be taken at points around the tree to give an average thickness.

Log Measurement

Log measurement is an important basic mensurational skill. There are considerable similarities between measuring logs and measuring trees, as the basic attributes are similar, but log measurement has a special set of problems, as the log may come from any section of the tree, and as such, will vary in shape.

Logs can be measured at various points, ranging from in the forest at the stump, to at a skid site, on a logging truck, or at the mill. The point selected for the assessment should be carefully considered. Measurement at the stump may be appropriate for high value species, while measurement at the skid site may allow more efficient use of resources.

Diameter

Diameter is the most important variable measured on a log. Log diameter may be measured at a number of points, depending on the value of the log, and the shape of the log. For high value straight logs, measurements can be taken at both ends and in the centre. Volume functions are available which can calculate the volume from such measurements.

Lower value logs can be measured at one point, typically the mid-point. Alternatively, in high turnover operations, the small end diameter may be selected as the measurement point. The decision where to measure the diameter is influenced by the measurement location. Midpoint diameters cannot be collected from logs in a stack or on a truck.

When the diameter is measured, allowance should be made for any log distortion. Cankers, abnormalities, and buttressing should not be included in the measurement, which should reflect a normal stem form. This applies to both log end measurement and midpoint measurement.

Length

The length of the log is an important variable for calculating the volume of the log. Length should be measured after the log has been cut to its final size.

The length measured is generally the shortest distance between the cleanly sawn ends of the log. If the log end is uneven, the log should be measured to the nearest normal section, with allowance being made for trimming the log. Total log length is used for volume calculations.

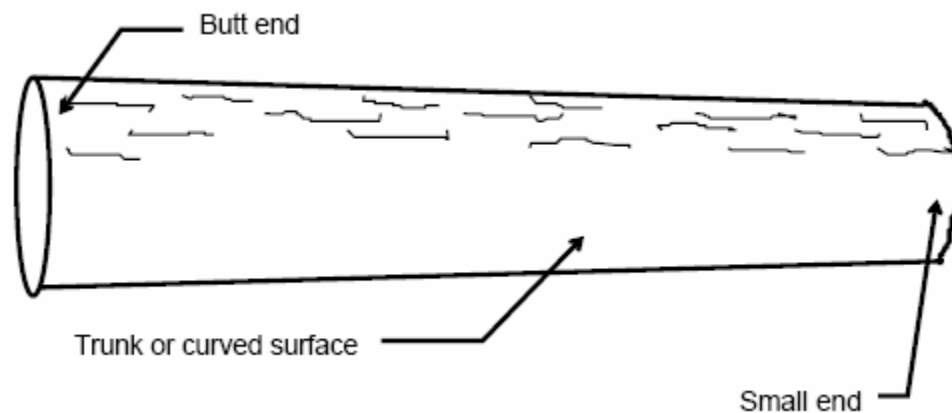


Figure 6 A simplified diagram of a log

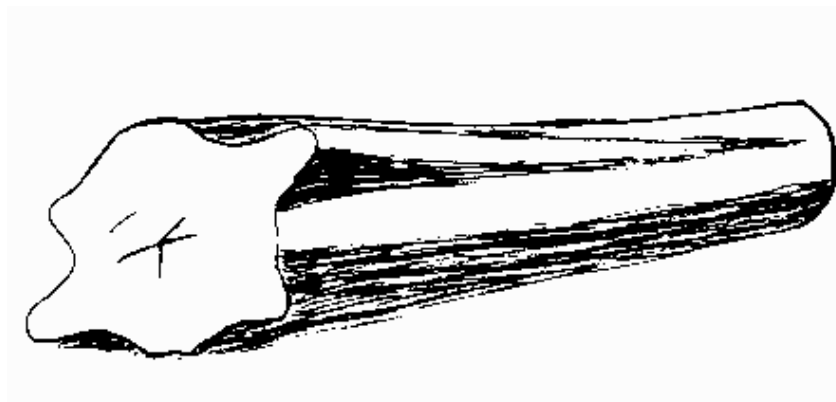
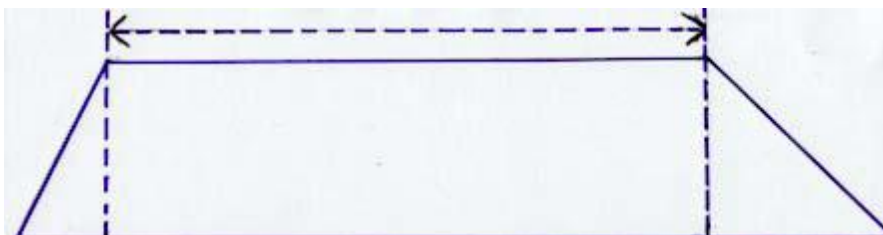


Figure 7 An example of a typical tropical log



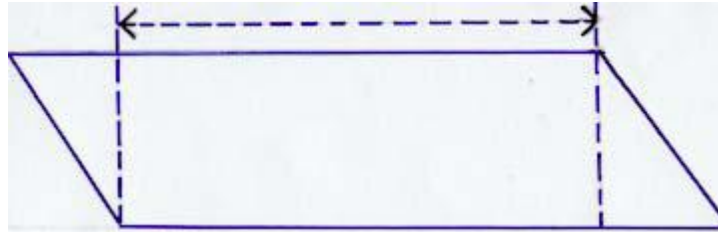


Figure 8 Examples of differing commercial lengths

Weight

An alternative to measuring individual logs is weight scaling. This will require the presence of some mechanism for weighing logs, usually a weighbridge scale. The principle is to weigh a loaded truck and subtract the weight of the truck, to get the weight of the logs. The weight of the logs can be converted to a volume, by the use of conversion factors.

Weight conversion factors should be prepared for each log type that is being assessed. There are many factors that need to be taken into account, such as the age, position in the tree, the amount of bark still on the logs, and the moisture content of the logs. For an accurate conversion, the truck should be carrying similar logs, of the same species, same moisture content, and same felling period.

If appropriate weight conversions are not used, the volumes calculated can be extremely inaccurate.

Area Measurement

Measurements collected from trees need to be converted to area based information for management decisions. This requires the measurement of the area where the information is collected. The typical method is to establish a sample plot, measure the trees within the plot, and convert the tree measurements to area measurements using the known area of the sample plot.

Plot shape and size

There are a variety of plot shapes that can be used in forest mensuration. These include square, rectangular, diamond, and circular.

Laying out a sample plot involves deciding the size to use, calculating the dimensions, and location the plot in the forest.

The plot size is affected by forest conditions such as terrain and stocking, as well as the number of years the plot is likely to be observed. For plantation forestry, smaller plots can be used. One guideline is that the plot should contain at least 20 trees at the end of the plot's life.

Tropical forest requires larger plots, as the range of species can be considerable. The plot size should ensure that empty plots are infrequent.

Slope correction

When plots are being established, the area to be sampled is the flat projected area. This means that the actual dimensions of the plot on the forest floor need to be calculated considering slope corrections. For a square or rectangular plot, each side must have an individual slope correction. If the slope is even, a diamond plot can be established, with two corners across the slope, and two corners up and down the slope. If circular plots are established, the radius of the plot must be increased to ensure that a large enough area is sampled.

Use of a GPS (Geographic Positioning System)

GPS basics

A GPS is an instrument which uses data collected from satellites to calculate the position of the GPS on the earth. The GPS uses information from as many satellites as it can locate. The more satellites the GPS can locate, the more accurate the position estimate is.

The GPS works out the position by calculating how long the signal from each satellite takes to reach the GPS unit. The satellite radio signals are not very strong, which means that the GPS needs to have a clear view of the sky. Things like roofs and tall buildings can stop the signal. In a car, the radio signal can easily go through glass, but not steel. This means that a GPS will get a more accurate reading when the unit is sitting on the dashboard than when it is inside the car.

This means that GPSs have problems working under forest canopy. The GPS will provide a more accurate position out in the open. Unfortunately we usually have to work under the trees. However, modern GPS units can often give a fairly accurate position under tree canopy when they have been outside the canopy at the previous time.

GPS configuration

A GPS has a number of settings which can be used to make sure that the information the GPS provides is suitable. These include:

- Scale. The GPS should be set to the measurement scale used locally. For Saint Lucia this is the metric scale.
- Time. Some GPSs can be set to a different time than that of the location of use. This is usually only of use for aviation and marine uses. For Saint Lucia the GPS should be set for UTC -4, with no daylight savings.
- Map Datum. GPS units use a map datum to correct for differences in the shape of the earth. For Saint Lucia the GPS should be set to North American Datum 1927, or NAD27.
- Compass True or Magnetic. The GPS can be set to show the True bearing or Magnetic bearing. For most uses the True bearing should be selected.
- Coordinate system. The GPS unit can show the location in different coordinate systems. For the Saint Lucia inventory the UTM coordinate system will be used.

GPS use

For forest inventory the GPS is mainly used for navigation and for recording positions. A GPS can show the direction that the unit is travelling when it is not staying still. This can help when moving along a compass bearing. However a compass is more reliable in many cases.

The GPS can show the speed of travel, and can show the direction to a certain point. This can be used in inventory to move to a random point. Random points are sometimes used in inventory, although not usually in natural forest inventory.

The main use of the GPS in forest inventory is to record the location of a sample plot. The GPS operator should be positioned in the centre of the sample plot, and a waypoint recorded. A waypoint is a position stored in the GPS.

Section 2 - Tropical Rainforest Inventory

Reasons for conducting inventory

There are many reasons for conducting a forest inventory. At the heart is the desire to know more about the forest, for environmental reasons and commercial reasons.

Too often an inventory is begun from a sense of lack of knowledge, and a feeling that an inventory will fill all the gaps in a manager's knowledge of the forest. It will not.

Inventory can be conducted with a range of aims, including the following.

- To quantify what is there
- To quantify where is it
- To plan forest use
- To monitor change
- To monitor diversity
- To monitor harvesting

The key consideration at the start of the inventory is to ensure that the objectives of the inventory are clearly identified.

Objectives

The objectives of the inventory should establish what is to be assessed. This could include the following.

- Standing volume
- Standing value
- Harvestable volume
- Species distribution
- Floristic diversity
- Changes from past assessments

The number of elements that must be assessed will increase the cost of the inventory. There is a common mistaken belief that including many different elements can increase the value of an inventory. This can lead to an inventory becoming logistically complicated, with a subsequent increase in cost. The additional elements may influence the inventory unduly, to the extent that the principle aims are underachieved.

The required accuracy of the inventory will need to be determined. This should be realistically assessed, as the level of accuracy has a significant influence on the cost of the inventory.

What to measure

One of the first decisions is what to measure in the inventory. What is to be measured depends on the objectives of the inventory. There are a large number of variables that could include the following.

- Diameter
- Height
- Volume
- Biomass
- Crown structure
- Floristic composition
- Fauna
- Bio diversity
- Water

A key factor to be considered at this stage is the analysis of the results. One principle that must be adhered to is that the analysis must be predetermined. Every measurement collected must have a predetermined method of analysis.

Too often inventories will include measurements collected because someone thought that the information could be of value, and might as well be collected while the inventory team is there, with the analysis details to be worked out later.

Such information is never used, and adds greatly to the cost and difficulty of the inventory.

Integration

Other data sources should be considered. These could include the following

- Remote sensing data
- GIS
- Earlier inventories
- Growth models
- Planning systems

Such data should be used for planning the inventory. A previous inventory may provide information for stratification. Growth model plots may allow sampling with partial replacement to be used.

Stratification

One of the best methods of refining an inventory design is the use of stratification. Stratification may be required as part of the inventory design, as often estimates may be required for different regions.

Stratification allows some of the variation within a forest to be removed to variation between strata. The greater the difference between strata, the greater the reduction in variation, and the more efficient the inventory. Stratification reduces the number of samples required, which reduces the overall cost of the inventory.

Stratification should be based on information that is available before the inventory commences. This could include the following

- Land use
- Forest use type
- Forest type
- Geographic boundaries
- Socio-political boundaries

Field plots

The typical method of conducting a forest inventory is through the measurement of a field plot. Field plots provide a means of finding out what is in the forest, in a form which can be combined with other data, and which can be used for management planning.

Plot measurements should be collected by trained field crews who are capable of taking measurements that can be verified in a repeatable fashion.

Plot types

There are a considerable number of plot types. These include inventory plots and growth plots, often call ***permanent sample plots (PSP)***. Inventory plots are designed to find what is in the forest at a point in time, and are temporary. Growth plots are designed to measure what is in a forest, and at what rate the forest is growing over time, and are permanent.

Inventory plots and growth plots need different standards of measurement. As a growth plot will be remeasured, it is important that individual trees can be compared for growth over time. This requires a greater measurement precision. Temporary plots can be measured with tree callipers, as the resultant measurements provide an unbiased estimate of diameter, but this is not suitable for growth plots.

Inventory plot layout

There are many different plot designs. The design will depend on the objectives of the inventory. The basic designs are round plots, square or diamond plots, and rectangular plots. The strip plot is a form of rectangular plot often used in tropical rainforest inventory.

The design of the field plot should consider the plot size as well as the shape. The size of the plot is affected by the density of the population being assessed. The plot size should generally be large enough to ensure that an average of 20 individuals is in a plot. The inventory will be biased if too many empty plots are encountered.

An inventory may use a range of plot sizes, such as a series of concentric circles. An inner small plot may be used to capture data for smaller seedlings, with an intermediate plot size capturing information on medium size trees, and a larger radius capturing information on crown trees.

The choice of what plot should be used depends on many factors, not least the skill required to establish the plot, and the type of plot the staff involved are used to working with.

Attribute sampling

In many ecological surveys the estimate to be made may be the presence or absence of a species, or the proportion of individuals falling into a category. This is different from the estimation of the population total. In particular, the total population of a rare or infrequently observed species is difficult to estimate accurately using conventional sampling techniques. Under conventional estimation techniques, a high proportion of empty plots leads to a biased estimation of the population total.

A more suitable method of obtaining estimates for rare or infrequent species is to estimate the proportion of areas containing the species.

Such estimation is termed attribute sampling, or proportion sampling.

As in conventional forest sampling, the population is divided into sampling units. Instead of the variable of interest being the number or size of the individuals within the sampling unit, the variable observed is the presence or absence of the species of interest. If one or more individuals are present, the observation is recorded as a 1, and if no members of the species are present, the observation is recorded as 0.

The estimate of the proportion of the sampling units containing the species is

$$p = a/n,$$

where p is the sample proportion, a is the sum of sampling units containing one or more individuals, and n is the total sample size.

This estimate is an unbiased estimate of the population proportion.

The standard deviation of the estimate of p is estimated from

$$s_p = \sqrt{\frac{\hat{p}(1 - \hat{p})(1 - \frac{n}{N})}{(n - 1)}}$$

where N is the total number of possible sampling units. In most cases, N is sufficiently large that the variance reduces to

$$s_p = \sqrt{\frac{\hat{p}(1 - \hat{p})}{(n - 1)}}$$

Field plot measurement

Every field plot should have the desired details recorded accurately, either on a plot sheet, or with a portable data recorder.

The plot sheet should include space for the plot location, which could include one or more of the following.

- Map sheet number
- State/division/region
- Forest district

The plot size should be recorded, and the forest type, both as according to any stratification in use, and as is found at the site. Other location information could include:

- land use category
- land form
- altitude
- slope
- aspect
- soil type

For all trees the information collected will typically include

- species
- diameter
- bark thickness
- height
- crown class
- defects

It is important to note that all information to be collected must be realistic. The field crew should be capable of recognising the major species in the area, and should be trained in diameter and height assessment. Diameters should be measure at predetermined points, such as above buttress, and all field crews should be recording the same measurements.

If plots are to be remeasured in future, trees should be identified with a suitable method, such as paint, or tags. Reference nails can be used to indicate the point of diameter measurement.

The standard measurement methods should be clearly laid out in a field manual, along with any codes that are to be used.

Random sampling design

Conventional statistical analysis requires that the population of interest, the forest, be divided into sampling units, each of which is equally likely to be sampled. This condition is usually met by random sampling.

Simple random sampling requires the plots to be located wherever the random selection determines. Simple random sampling is generally not efficient, and often impractical. The analysis is comparatively simple.

Stratified random sampling can reduce the number of plots, but is again often impractical.

Systematic sampling design

Systematic sampling violates the basic assumption that each sampling unit is equally likely to be selected. In systematic sampling a line is selected, and plots placed at regular intervals. This means that after the line has been selected, many sampling units are predetermined.

The theoretical objections to systematic sampling can be reduced by randomising the location of plots along the sampling lines. This allows the logistic advantages of stratified sampling to be captured, and minimises the departure from theoretical optimality.

Calculations

After the data has been collected, the inventory analysis will need to use standard calculation methods. These should be prepared before the inventory has commenced. If this is not possible, the analysis methods should be tested on the first data to be collected, and the field methods refined if necessary.

Tree volumes may need to be prepared, and the equation form should be considered before data collection.

The summary information from the inventory must be prepared to answer the questions the inventory was designed for. Any utilisation figures must reflect current utilisation standards, including merchantability criteria, and suitability of species.

Computer systems for processing field data

The processing of the field data should be considered at the start of the inventory. Computers should be used to ensure that the processing is carried out accurately, and quickly.

Any computer systems should be flexible enough to meet any changing needs. Complex systems should be avoided, as the training required may mean that the system may not be able to be maintained at all times.

The equipment should be appropriate to the circumstances, and should be given necessary protection. This may require an air conditioned room.

All systems should be well documented, so that the users can keep the system running without the assistance of costly specialists.

When computer systems are under consideration, remember that computers are now a disposable item, and the cheapest system that will do the current job should be selected. Money can be wasted by attempting to buy a system which is intended to be used for another purpose at the end of the inventory. This can lead to a system which is too powerful for current uses, and which is too slow for future uses.

Integration

An inventory is a snap shot in time. For effective forest management, the inventory must be integrated over time with alternative sources of data. These may include

- Remote sensing
- Aerial photography
- GIS
- New technologies

Information from other agencies and other inventories may be of value.

The inventory design should ensure that the results of the inventory can be used with growth models in a planning system.

Remote sensing

Remote sensing is the use of information from a range of sources for forest analysis. These sources include Landsat and SPOT satellite imagery, as well as a variety of radar imaging techniques.

Remote sensing is a powerful source of information, but demands a high degree of technical skill. A combination of ground truthing and remote information is needed.

It must be remembered that forest managers use areas of land, not pixels. Remote sensing cannot be used in isolation.

Geographical information systems

Geographic information systems have developed considerably in the past few years. However there is a tendency to regard the GIS as the solution to all problems, which it is not.

A GIS system is highly demanding, and requires a considerable degree of technical training, as well as powerful computer hardware and software. The training requirements mean that implementing a GIS is likely to require a considerable training budget, which is often overlooked.

Setting up a GIS system is complex and time consuming. Such systems can provide a considerable amount of data for forest managers, but typically take over two years to implement.

Complete systems integration

The ultimate desire of forest managers is a completely integrated forest management and planning system. This is not a practical aim, although it often appears so.

The different components of such a system are continually changing, and as such the maintenance of the system can come to take up more time than if separate systems were used. The complexity of the system can rise to the extent that very few system users understand more than a part of the system. At this point, the benefits of integration have been lost.

The most desirable system is one that permits related systems to exchange data with ease, yet allows individual systems to be operated by different users, without unnecessary complexity.

People

One of the key considerations in any inventory is the people involved. For an inventory to be successful, a wide range of skills and training is required. The inventory design must be made with the assistance of someone who has a high degree of training and experience. As the effectiveness of the inventory depends on the design, the design should not be left to chance. Here is one of the places that a consultant can provide best return for the cost. A short term consultant can be used to either assist in the preparation, or fine tuning of the inventory.

The field staff are best picked from people with experience of the local conditions. The staff selection should always be made bearing in mind that a combination of local experience and inventory experience will provide a strong team.

Staff training should ensure that all members of the team are skilled in the major points of the inventory. Some specialist training may be needed, for example, in the use of point sampling or relaskopes. Training should not be rushed, and should be followed by spot checks, and plots audits, where a plot is remeasured to ensure the measurements are being taken correctly.

Summary

The inventory must be driven by the forest managers needs, ***not their wants***. Technicians who understand their own technology, but not the needs of users should not unduly affect the inventory.

Specialists and consultants should be used to ensure that the inventory is carried out efficiently, but the forest manager should ensure that the specialists don't change the inventory to reflect their past experience.

The inventory manager should never lose sight of the overall objectives that were defined at the start of the inventory. The manager should stop from time to time, and consider whether these objectives are being met.

Section 3 - Yield Control

Introduction

Before a forest manager can begin to manage his forests, he must know how much forest he has, what amounts of forest products his forest contains, and how fast his forest produces these products.

The first stage is inventory. After a well designed inventory has been conducted, the manager should know the answers to all the questions given above.

The next stage is to assess the rate at which the forest changes over time, if the forest manager does not harvest the forest.

The final stage is to examine the effects of management on the forest, combining the inventory information with the yield information.

Objectives

To predict allowable cut

The objective of a yield control system is to predict how much timber or other forest products can be removed at any particular time, without running out of wood in the future, and without building up too much surplus wood.

The key element is understanding what yield can be achieved from a forest. This is achieved through yield tables and growth models.

Given an understanding of the yield available from a forest, and the structure and area of forest types, the effects of various cutting strategies can be simulated, either manually or by computer.

Needs

Inventory information

Yield calculations are based in inventory data, both current and past. Current inventory data is used to prepare forest types, and to evaluate the current conditions.

Past inventory data is used to prepare yield predictions. One of the best sources of data for preparing yield calculations is remeasured sample plots.

Such plots should be large, of about 1 hectare in size. Trees should be numbered if possible, and recorded in diameter classes by species if individual numbering is not possible.

For the preparation of the most accurate yield predictions, the position of each tree should be recorded. This can be challenging, but if done, more accurate growth models can be developed.

Growth models

Growth models are of three main types, stand models, diameter distribution models, and individual tree models.

Stand Models

Stand models are the simplest to prepare. Inventory data is used to prepare averages over time, and these averages are used for prediction purposes.

Diameter distribution models

Diameter distribution models predict the change in status of a diameter distribution over time. They are suitable for tropical rainforest, although they require a considerable amount of data.

Individual tree models

Individual tree models predict the growth of individual trees in a forest. The growth of each tree is predicted after assessing the effect of surrounding trees.

Individual tree models have considerable potential for tropical rainforest growth prediction, although they require a high degree of expertise to prepare, as well as demanding specialised inventory data.

Tree volume equations

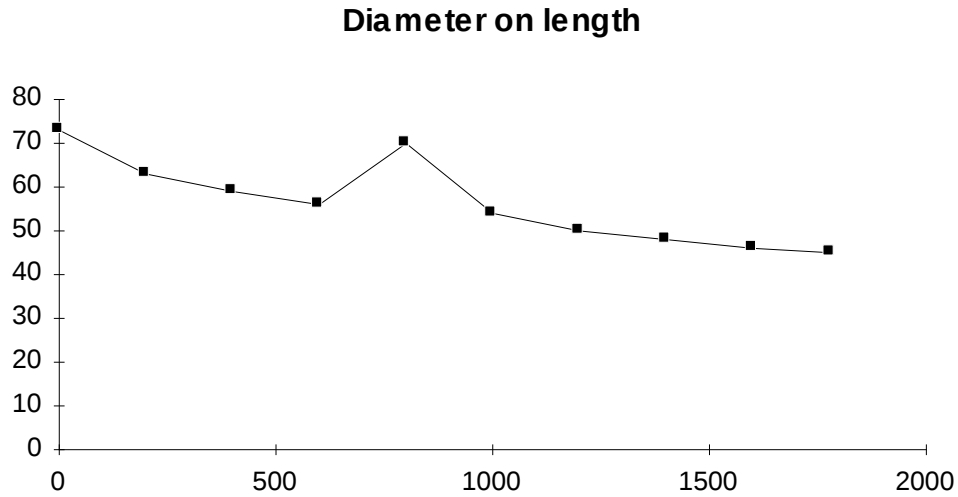
Tree volumes are needed for yield prediction, as most inventories concentrate on measuring diameter and a sample of heights.

Tropical rainforest species typically have a flared buttress, a bole, and then a crown break. The stem may be hollow, or have cankers and other defects on it. Tree volume equations are prepared for normal well formed trees, and an assessment is made of the amount of timber recovered, to allow for the defects mentioned above.

Tree volume functions are prepared as follows.

1. A sample of trees is measured, either by climbing, felling, or relaskope.
2. On each tree the diameter above buttress is measured, along with the height of the measurement above stump, and the height to the top of the bole.
3. Further measurements are taken along the stem, recording the diameter and the height of the measurement point., and the bark thickness on at least a sample of trees
4. Other information is recorded, such as the species and location of the tree.

After the data has been collected, it is next punched into computer form, and cleaned. The cleaning is best done by graphing each tree, and inspecting the graphs for punching errors.



The next step is to calculate the volume of the tree, either over or under bark. This is done by adding up the volume of the segments. Each segment is assumed to be a conic segment. The volumes are usually calculated by using one of the following formulae.

- Smalian's Formula

$$v = \pi \frac{d_t^2 + d_b^2}{8} l$$

- Huber's Formula

$$v = \pi \frac{d_m^2}{4} l$$

- Newton's Formula

$$v = \pi \frac{d_b^2 + 4d_m^2 + d_t^2}{24} l$$

where d_b = diameter at bottom of segment

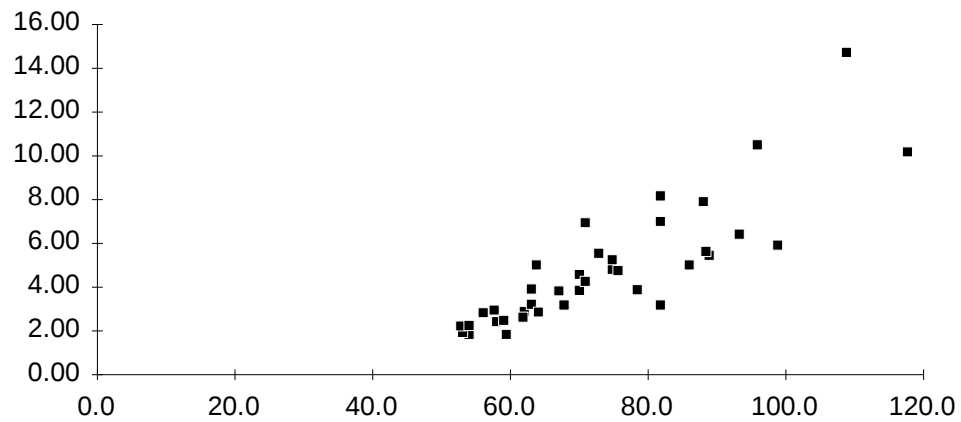
d_m = diameter at middle of segment

d_t = diameter at top of segment

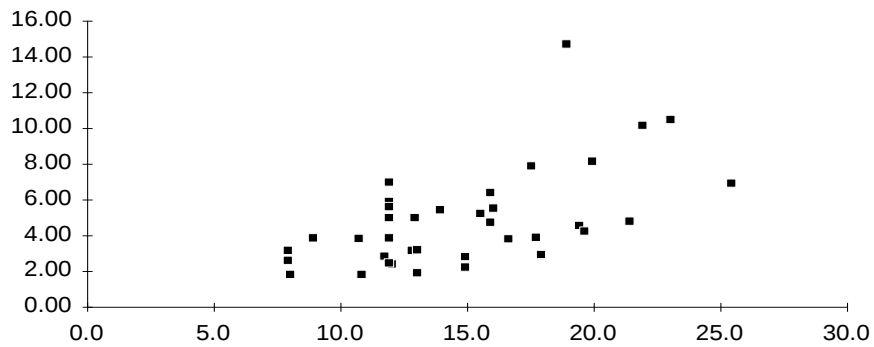
Newton's formula is more accurate, but the inaccuracies of Smalian's formula can be reduced by decreasing the distance between measurement points at the base of the tree, where measurement intervals of about 1.5m are required. Above the 3m height, 3 m lengths can be used.

The volumes can now be plotted on diameter and length, to inspect the data for bad data points.

Volume on Diameter



Volume on Length (cm)



Graphing the data points will show any suspect points, which can be eliminated from the data set.

The data may need to be weighted, to remove bias.

The clean data set is next used to calculate a set of function coefficients.

There are many functions that can be fitted to the data. The following are often used.

$$v = b_0 + b_1 d + b_2 d^2$$

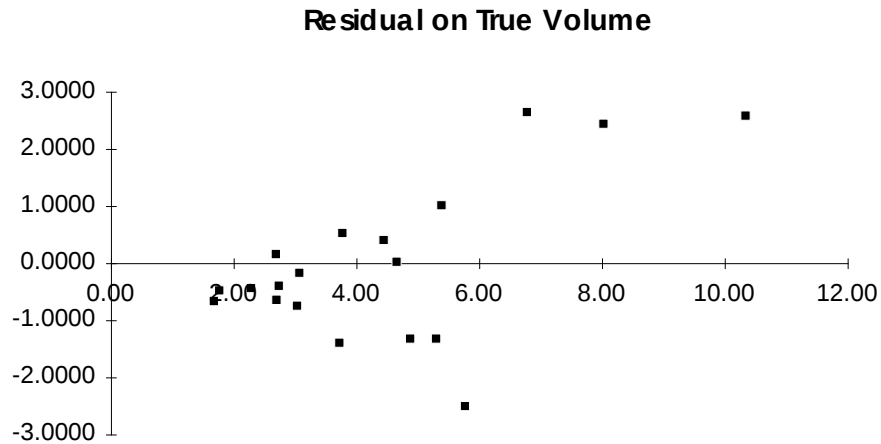
$$v / d^2 = b_0 + b_1 l$$

$$\ln(v) = b_0 + b_1 \ln(d)$$

$$\ln(v) = b_0 + b_1 \ln(l) + b_2 \ln(d)$$

Further functions can be found in published volume tables.

The functions selected should be fitted with a statistical package. The residuals, the difference between the volume of the tree and the predicted volume, should be plotted on the predicted volume, to test for bias.



The graph of residuals should be inspected. If the pattern is not even, the data will either need to be cleaned further, or a new equation selected, and the function coefficients re-estimated.

After the volume function has been prepared, the function can be used in a growth model, or to produce a volume table.

Growth models

Growth models require a set of data derived from inventory plots or long term measurement series from sample plots

The principle behind a growth model is that past growth can be used to predict future growth. The assumption is that the future growth of forest under investigation will be similar to forest that has been measured in the past.

If the two forest types are markedly different, the assumption will be incorrect, and the growth model will be unlikely to provide accurate assumptions.

Simple Growth Model

The simplest form of growth model for tropical rain forest is to assume that recruitment balances mortality in a steady state climax forest. After making this assumption, inventory data is inspected to determine the commercial harvest volume that can be obtained from a climax forest and an estimate is made of how long the forest will take to recover.

Given these assumptions, a per annum growth figure can be calculated. For example, if a volume of 50 cubic metres can be taken, and the forest is assumed to require 50 years between harvests, the growth model estimate is 1 cubic metre per annum.

Matrix Growth Models

One form of growth model that has been used extensively is the matrix growth model. A matrix model is a form of diameter distribution model.

The data required for a matrix model are diameter distributions measured at intervals over time. Matrix models can be constructed from a range of data.

Like all growth models, matrix models have limitations. The limitations are based on the principle that past growth is used to predict future growth.

The form of the matrix model is as follows.

$$\mathbf{n}_{t+1} = \mathbf{Q} \cdot \mathbf{n}_t$$

where $\mathbf{n}$ is a vector containing the diameter distribution at time t .

The matrix model predicts the future diameter distribution from the current diameter distribution, multiplied by the transition probability matrix $\mathbf{Q}$

As an example we will build a matrix model which predicts the change in a diameter distribution over a five year period.

From an inventory we calculate the following diameter distribution, where we have 10 cm diameter classes.

Diameter	10	20	30	40	50	60	60+
Frequency	130	90	60	40	20	15	10

We use past inventory plots to calculate that non-suppressed trees grow at approximately 1 cm in diameter each year. This means that in one five year period we can expect trees to grow 5 cm.

However, our long term plots also show that small trees are likely to be suppressed, and large trees are not likely to be suppressed. We find out from the inventory that the following proportions of trees are likely to be suppressed during a five year period.

Diameter	10	20	30	40	50	60	60+
Suppressed	.5	.4	.3	.2	.1	0	0

We also find out that small trees are more likely to die, and that the large trees to die ultimately. From the records we work out the following mortality rates over a five year period.

Diameter	10	20	30	40	50	60	60+
Mortality	.25	.20	.15	.10	.05	.01	.04

We now know that a 10 centimetre tree has a 50% chance of being suppressed, and a 25% chance of dying. We also know that the remaining trees are growing at an average rate of 5 cm every five years, which means that on average half of them will grow out of our 10 cm class every five years.

This means that the out of the trees in our 10 cm class, 12.5% will grow into the 20 cm class, and 25% will die, leaving 62.5% still in the 10 cm class. Similar calculations show that in the 20 cm class 20% will grow into the 30 cm class, and 20% will die, leaving 60% still in the 20 cm class.

This means that at the start of the next period, the 20 cm class will consist of 60% of the trees currently in the 20 cm class, plus 12.5% of the trees currently in the 10 cm class.

We can calculate the following transition probability matrix, which shows the proportions of trees left in each class, and the proportion which grow into the next class.

.625						
.125	.6					
	.2	.575				
		.275	.55			
			.35	.525		
				.425	.495	
					.495	.96

This table is the basis of our matrix model. However the model has no provision for ingrowth. We have not allowed for small trees growing into the 10 cm class.

Ingrowth is one of the biggest limits of Matrix models. Ingrowth is difficult to estimate, as the structure of the forest has a considerable effect. The shape of the diameter distribution affects the amount of ingrowth. A forest with many large trees will have little ingrowth, due to shade suppression. A forest with many little trees will have little ingrowth due to competition.

Ingrowth is added to the model through the addition of a vector to the row of the Q matrix. This vector will vary with the structure of the forest. A number of different vectors may be needed for different forest structures.

The following vector will be used for example.

.1	.05	.02	.0	.0	-.1	-.2
----	-----	-----	----	----	-----	-----

The negative elements indicate that large trees suppress ingrowth, while the positive elements indicate that where there are some small trees, there is likely to be more ingrowth.

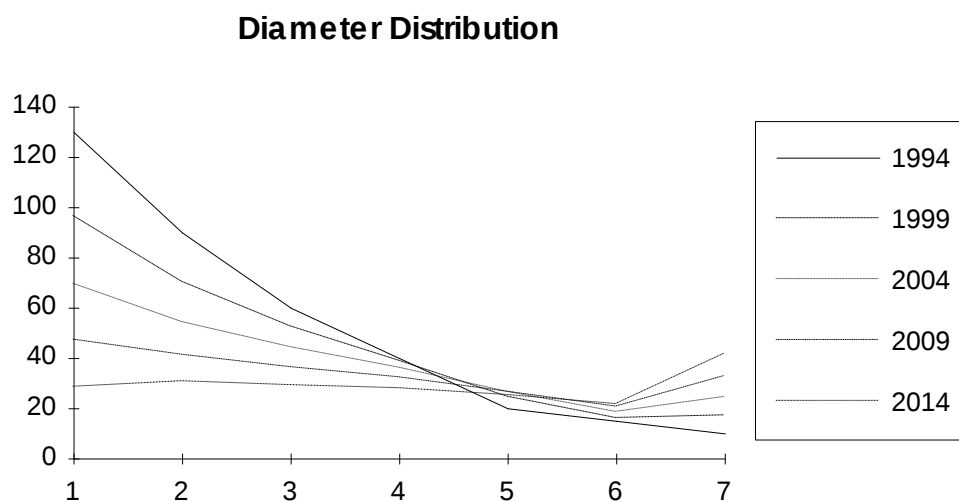
The final form of our transition probability matrix is as follows.

.725	.05	.02	.0	.0	-.1	-.2
.125	.6					
	.2	.575				
		.275	.55			
			.35	.525		
				.425	.495	
					.495	.96

This produces the following predicted diameter distributions over time.

Period	10	20	30	40	50	60	60+
1994	130	90	60	40	20	15	10
1999	96	70	53	39	25	16	17
2004	69	54	44	36	26	18	24
2009	47	41	36	32	26	21	33
2014	28	31	29	28	25	22	42

The following graph shows the distribution over time.



A matrix model is conceptually powerful, and can be prepared with the aid of a computer spreadsheet. The model can be used to prepare predictions over time, and if prepared in a spreadsheet form, the results can be subjected to sensitivity analysis with ease.

Disturbance

Catastrophic change renders most models inaccurate. Minor change can often be assumed to not invalidate the model. The table below shows what predictions the model would make if all stems above 30 cm were removed, along with 20 % of remaining stems.

Period	10	20	30	40	50	60	60+
1994	104	72	48	0	0	0	0
1999	80	56	42	13	0	0	0
2004	62	44	35	19	5	0	0
2009	48	34	29	20	9	2	0
2014	37	26	24	19	12	5	1

Major change

Matrix models depend on a relationship between past growth and future growth. The model demonstrated above would be unlikely to give representative answers if the diameter distribution was subjected to massive change, as in a cyclone, for example.

Catastrophic change would result in all the coefficients being subject to change. In the above example, the 50% suppression figure would be likely to change markedly. The mortality figures would change, and the growth rate may change.

Extremely severe logging damage would constitute major change, and invalidate the matrix model. Matrix models can give satisfactory predictions for logging which is carefully controlled, does not remove a major amount of the forest, and does not damage surrounding trees.

Species mix

The matrix model shown above has combined all species into the one diameter class. This was for simplicity. The matrix model can be generalised, to allow for additional species. This is more complex.

Combining all species into one diameter frequency implies that any harvest removes species in the same proportion. If a harvest removes all of one species, and leaves another species entirely, subsequent growth may produce a different forest type from the original. This would invalidate any future growth predictions.

Sustained Yield Calculation

The most basic form of yield control is to calculate and apply a sustained non-declining yield.

The procedure is as follows.

- Inventory the forest to assess the merchantable volume of each forest type to be managed.
- Determine the area suitable for sustained management purposes. This should exclude any ecologically significant areas, any environmentally unstable areas, and any areas with social constraints.
- Calculate a cutting cycle, the period between harvesting the same area of forest. Note that the cutting cycle should be estimated conservatively, with allowance for risks such as typhoon and fire.
- The estimate of sustained yield is the total volume divided by the cutting cycle.

This is a rudimentary method, which is suitable for global planning at a national or regional level. The calculations must be done conservatively, as the method does not allow for any uneven distribution of forest by type. The figures calculated are of considerable use, and should be calculated if only to check any other figures which may be derived.

Yield Control Systems

Total approach

A Yield Control system takes data from an inventory, and uses a yield prediction system to predict the status of a forest at some point in the future, after a series of management operations.

Each element in the yield control system must be suitable for the required purpose. The inventory must have collected the appropriate data to a suitable level of accuracy. The yield prediction system must be capable of predicting future yield to a satisfactory level of accuracy. The management simulator must be logically constructed.

Yield control systems use combinations of similar forest term forest types. An inventory should produce results based on forest types. These forest types form the basis of the yield control system.

Preparation of inventory tables

The first step in using a yield control system is to prepare summary tables showing the area of each forest type that the forest manager has to manage.

This is done by using the inventory data to work out how many different forest types the manager has. The inventory results should already be in forest types, which may or may not be suitable for yield control. Inventory forest types can be combined if desired.

The area of forest in each forest type is calculated. Note that any time elements should be reflected within forest type, and not as a forest type.

Example of forest type table

Forest Type	Type Code	Area
Mixed Dipterocarp	MDIP	1200
Hardwoods	HARD	500
Degraded Forest	DEGF	2500
Logged Forest	LOGD	500

Yield Tables

A yield table should be prepared for each forest type.

Yield tables can be prepared from inventory data or growth models.

To prepare a yield table from inventory data, the inventory data for each forest type is averaged, providing an indication of the average yield for different forest conditions.

If a growth model is used, the growth model should be run to produce the predicted growth for each forest type.

The yield tables should show the yields from the current time period onwards.

In the example given below, the mixed Dipterocarp forest is growing slowly, the hardwood forest is not growing, the degraded forest has a low volume, and grows slowly, and the logged forest has no initial volume, but grows rapidly.

Example of Yield tables

Period	MDIP	HARD	DEGF	LOGD
5	45	60	20	0
10	50	60	22	5
15	55	60	24	10
20	60	60	26	16
25	60	60	30	22
30	60	60	34	28
35	60	60	38	34
40	60	60	42	40
45	60	60	44	48

Preparing a yield control plan

The forest manager can now begin to prepare his yield control plan.

This can be done either by hand or with specialist computer programs. The principles are the same. The manager must allocate timber from his forest to fill demand without overcutting the forest.

The manager must carry out a series of calculations. For each yield period he must allocate the cut from a certain area of forest to a certain wood use. The area cut must then be reassigned to a new forest type, such as replanted, or logged. The areas available are updated for the next period.

Example of yield scheduling

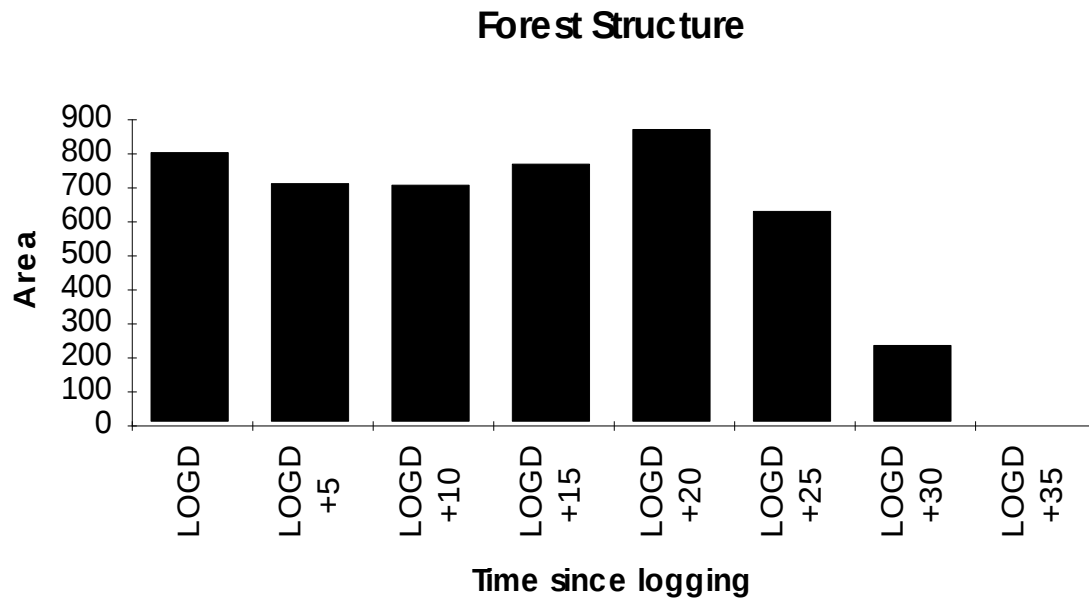
For the data given above, the manager decides to manage the 4700 hectare forest on a 40 year cutting cycle. He calculates that he can achieve a volume of 44 cubic metres. He plans to cut a volume of approximately 26,000 cubic metres over a period of five years. On average, he expects to log about 115 hectares per year, or about 590 hectares over a five year period.

The manager decides to cut the forest type HARD first, followed by MDIP, and DEGF. Each period the forest that was cut the following period is added into the class LOGD, which is classified by time since planting. After he has logged the entire forest, he will begin logging the previously logged forest in the LOGD class.

The manager plans to remove the following volume, from the classes shown over the next few five year periods.

Period	Volume	MDIP	HARD	DEGF	LOGD	Area
1995	26040		434			434
2000	26010	441	66			507
2005	26015	473				473
2010	26000	286		340		626
2015	26010			867		867
2020	26010			528	237	765
2025	26014				703	703
2030	26022				708	708
2035	26026				799	799

The logged over forest will have the following structure at the end of the period.



The forest manager should simulate the cutting of his forest over a long enough period to check whether he can meet projected demand. For this example we have simulated 9 periods. It would be more desirable to simulate for at least two cutting cycles.

From the information above, the manager can see that after three periods he will have to increase his area cut to meet his target of 5200 cubic metres per year.

Other constraints may enter. The manager may be required to start with a lower cut, and increase to a final target. To test a range of options can involve a considerable amount of calculating.

There are a variety of computer models that can do the bulk of the work. These include deterministic models, where the manager makes the decisions, and optimising models, where the manager imposes a set of constraints, and the computer provides a series of solutions.

Such models are available from universities and research institutes in Australia and New Zealand.

Section 4 – Specific Saint Lucia timber inventory factors

Introduction

This section outlines in broad details the recurrent activities to be carried out during the Saint Lucia Forest Inventory. The process of inventory is cyclic and ongoing, consisting of a repeated process of redefining the forest into more specific detail. This is achieved by a gradual refining of the forest stratification described in steps 1 and 2, followed by further sampling, and repeated analysis.

Forest typing

The first step in forest inventory is to develop forest type maps. This involves the delineation of areas occupied by forest on a map, either manually or digital, using either colour shaded maps or a GIS¹ software package. These areas are known as **forest units**.

The forest typing should identify the forest in terms of the location of the forest unit, the area of the forest unit, the managerial classification of the forest unit, and the species composition of the forest unit.

The typing may be broad or narrow, depending on the resources available. The typing can be extended at a later date, to allow more refined inventory results to be calculated. The more narrow the typing, the more sensitive the inventory.

The forest typing should identify the forest in terms of the location of the forest unit, the area of the forest unit, the managerial classification of the forest unit, and the species composition of the forest unit.

- Location
- Area
- Management class
- Species composition

The typing may be broad or narrow, depending on the resources available. The typing can be extended at a later date, to allow more refined inventory results to be calculated.

It is vital that the area of each forest unit is measured. The overall accuracy of the inventory estimates depends on the area measurement and the accuracy of the forest statistics calculated.

Once the forest units have been defined, the inventory can be carried out. It is possible for forest units to be defined after inventory has been carried out, but this is not the most efficient method of conducting forest inventory.

¹ Geographic Information System

Sample intensity

When an inventory is carried out, different sampling intensities can be carried out for different forest strata. The sampling intensity is the number of sample points measured in a stratum expressed as a percentage of the total area of the stratum.

The sampling intensity used in an inventory depends on a number of factors, including the following.

- Value of forest
- Cost of sampling
- Variation of forest
- Future management objectives

All forest inventories are carried out with a limited amount of funding, and as such the wise forest manager will allocate a higher proportion of his resources to the most valuable of his forests. The cost of establishing a sample point may vary between different regions in the forest, and will need to be taken into account in calculating the sample intensity.

Variation within the forest will affect the sample size. If a forest is not divided into enough strata, the inventory estimates will be less accurate. A manager may decide to allocate a smaller sample size to a stratum that contains a number of less important forest units, and a higher sample size to a stratum that contains more important forest units.

There are statistical methods of calculating the number of sample points needed to achieve a desired level of statistical accuracy. All these methods require some prior knowledge of forest variation, which is often not available. The estimates are not particularly accurate, and act as a guide only.

With the use of a FMIS, the necessity to have prior estimates of sample intensity can be avoided. The inventory can be initiated with a subjective estimate of the number of sample points required. An estimate of accuracy cannot be calculated with less than 3 sample points, and will be inaccurate with less than 10 sample points. As such, inventory can be initiated with the initial aim of collecting at least 10 sample points in each stratum. After this initial data has been input into the FMIS, the FMIS will calculate the stratum estimates, along with their accuracy, allowing the forest manager to decide whether he needs increased accuracy or not.

Stratification

Stratification is the procedure of dividing the forest up into collections of forest units that are of managerial interest. For example, a stratum could consist of all areas of forest that contain mature rain forest, or all areas planted with *Tectonis grandis* for slope stabilisation. Another definition of a stratum could be all areas with a slope greater than 20 degrees.

Reasons to stratify

Statistical

The statistical reason for stratification is to increase the between strata variance. This means that by defining strata that contain very different types of forest, variation in forest types can be limited to variation within similar forest types.

A farming example would be to measure the average weight of pigs and chickens separately, rather than the combined average weight, which is of no realistic interest. In this case the farmer has stratified his livestock into pigs and chickens.

A more realistic example is to calculate the average weight of male versus female pigs.

Managerial

From a forest manager's point of view, stratification gives information on management units, which the manager can use for management decision making. A forest manager may divide his forest into productive and non-productive forest, putting most of his managerial efforts into the productive forest. The forest manager gains a better understanding of his forest through the use of a carefully thought out forest stratification.

The forest stratum is the inventory component that provides estimates of forest statistics. No estimates of forest statistics are available for any lower level inventory components. A forest unit, for example, does not provide any estimates of forest statistics.

Allocation of forest units

The actual implementation of the process of stratification is carried out by allocating the forest units into different strata. This can be done before or after the forest units have been sampled. The process is carried out by merely selecting which stratum the forest unit belongs in. In a computer program this could consist of selecting the appropriate stratum from a list.

Each forest unit can belong in only one stratum. The forest inventory will not give any estimates for the forest unit, unless a particular forest unit is defined as a stratum as well as a forest unit. For example, a very large area of a valuable timber species may be important enough to be defined as a stratum. In this case the stratum would have only one forest unit, and a high sampling intensity would be needed for that forest unit. Separate estimates of the forest unit's forest statistics would be produced.

Most strata will have more than one forest unit in them. The number of strata can be increased as the inventory proceeds, by reallocating forest units to different strata that are defined during the inventory.

Identify forest strata

The second step is to divide the forest units into forest strata. A forest stratum is a collection of similar forest units, which will be managed together.

From a forest manager's point of view, stratification gives information on management units, which the manager can use for management decision making. A forest manager may divide his forest into productive and non-productive forest, putting most of his managerial efforts into the productive forest. The forest manager gains a better understanding of his forest through the use of a carefully thought out forest stratification.

The forest stratum is the inventory component that provides estimates of forest statistics. No estimates of forest statistics are available for any lower level inventory components. A forest unit, for example, does not provide any estimates of forest statistics.

The forest units identified above should be classified into forest strata. All forest units must be included in a forest stratum for the inventory results to be accurate.

Enter forest units in SLFMIS

The details of the forest units should be entered into the SLFMIS, with their strata definitions. This step is vital to classify the inventory to ensure that inventory results are as sensitive as possible.

The information entered in the SLFMIS will allow the forest manager to understand the structure and nature of his forest.

Sample plot location

A forest inventory is a statistical sample of the forest, intended to give unbiased and accurate estimates of forest statistics. As such, the location of sample plots is critical.

Sample plots should be located randomly within the forest unit to be sampled. In theory, the sampling design should ensure that all parts of the forest are equally likely to be sampled.

In practice this is difficult in forest inventory. Problems of access often make it extremely difficult to sample certain parts of the forest. Locating a specific part of the forest can be difficult for reasons of navigation. Some steep areas of a forest may be too dangerous to sample.

Systematic sampling

For these and other reasons most forest inventories use systematic sampling. Systematic sampling is sampling on a grid imposed over a forest. An example would be using the geo-reference grid found on many maps as a guide for sampling.

Systematic sampling can introduce bias, if there is a systematic pattern in the forest being sampled, such as a regular series of ridges and valleys. Any sampling scheme that had sample lines following a ridge or valley pattern would be likely to produce biased estimates.

In Saint Lucia systematic sampling is unlikely to introduce bias, due to the nature of the geography of the island.

It is important that any systematic sampling grid be established objectively. A grid line should be defined in such a manner that bias is avoided. An objective starting point should be determined.

For the forest inventory in Saint Lucia, sampling should be carried out by placing sample points on a gridline at random intervals averaging 100metres. The sample interval can be increased for large forest units, or decreased for small forest units.

Sample plot size

A further aspect of the inventory to be considered is the size of the sample unit, known as the sample plot in forest inventory. A sample plot may be of many different shapes, such as a square, rectangle, circle, hexagon, or even a star shape. In the case of the forest inventory in Saint Lucia a diamond plot shape has been selected.

A diamond plot is one in which a square plot is laid out on flat or sloping ground orientated up with its central axis running up and down the slope of the land the sample plot is established on. When theoretically projected horizontally, the square plot becomes a diamond shape. Diamond plots are simple to lay out, and can easily be corrected for slope, as is necessary in sloping forest ground.

Aim for 30 trees

The size of the sample plot is determined by the stocking of the forest the sample plot is established in. A sample plot should sample enough of the forest to gain a representative estimate of the nature of the forest, but should not be so large as to waste valuable manpower resources.

For statistical purposes approximately 20 trees sampled constitutes a representative sample. Due to the varied nature of most forest areas, a sample plot cannot be guaranteed to have 20 trees in most cases. It is better to have slightly more trees than 20, rather than slightly less than 20. Hence the sample plot size should be set so that approximately 30 trees will be included. This represents a slight degree of over sampling, but not to a troublesome extent.

As an example, an inventory team leader is establishing sample plots in a forest unit that he estimates has 600 stems per hectare. He calculates as follows:

$$\text{Sample size} = 30/\text{Stocking} = 30/600 = .05 \text{ ha.}$$

The inventory team leader now knows he should use a .05 ha sample plot for this forest unit.

It should be noted that the same sample plot size should be used within any particular forest unit.

Study of the 2009 and previous inventories in Saint Lucia indicates that a sample plot size of .05 hectares should be used.

Diamond plot establishment

A diamond plot is easy to establish on the ground, one of the reasons to use diamond plots. Figure 1 shows the general layout of a diamond plot.

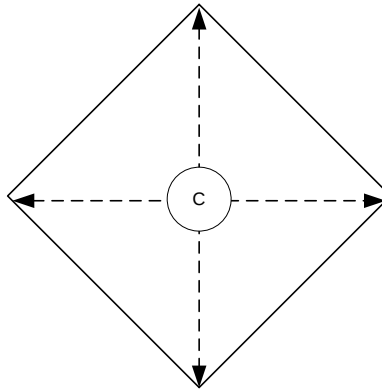


Figure 9. Diamond plot layout

Once the central point has been located, the sample plot centre should be marked with a peg. The slope should be measured both uphill and downhill, and the two measurements averaged to calculate the slope of the sample plot. The slope should be noted in the Comments section of the sample plot sheet. (See Appendix 3)

The slope should be measured with a hypsometer, such as a Suunto. Note that you should measure the slope to a point at your eye level.

Knowing the sample plot size and the slope, the length of the diagonal arm of the sample plot can be found in the table in Appendix 1.

For our example above, where the team leader has calculated he needs to use a sample plot size of .05 ha, Appendix 1 gives a diagonal area length of 15.8 m for flat land (slope 0), and 15.9 m for land with a slope of 10 degrees.

The diamond plot is laid out by measuring uphill the distance of the diagonal arm, 15.9 m for our example plot. At the 15.9 meter point a peg is hammered into the ground. Next a peg is placed 15.9 m downhill from the central peg. All three pegs should be sighted in line.

The final two pegs are laid out to the right of the central axis, and to the left of the central axis, at distances of 15.9 m and lined up on the central peg. This second axis should be at right angles to the central axis.

The resulting plot will occupy approximately 0.05 ha of land, adjusted for slope. If the two axes are not at right angles, a slight error in area will be made. This error is not great, and is self-correcting to a degree.

Once the sample plot has been laid out, all trees should be marked with spray paint marks to indicate that they are in or out. A tree is defined as being in the sample plot if more than half of it is inside the

line between two corner pegs. There is no need to number the trees, as the sample plot is a temporary sample plot, which we do not plan to revisit, except possibly for checking purposes within a week or two.

The trees in the sample plot can now be measured, sector by sector. After the sample plot has been measured, the pegs can be removed for use at the next sample plot site. The centre point should be marked in some way, such as with a temporary peg made from forest material, or perhaps a cairn of stones, so that the sample plot can be relocated should that be necessary.

The measurements to be collected within the sample plot are the species and diameters of all trees, and a sample of tree heights.

Establish sample plot

Field sample points should be established at each grid point location. The sample point should be either a sample plot, or a strip plot, depending on the nature of the forest.

The field team should travel to the sample point via a compass bearing from a suitable access point, such as a road.

The measurements to be collected within the sample plot are the species and diameters of all trees.

Measure sample plot

The diameter of a tree is the single most important measurement that can be taken from a tree. Tree diameter is closely related to tree height and volume. Accurately measured tree diameters can allow a forest manager to estimate forest volume with a reasonable degree of accuracy.

The diameter of each tree over 10 cm should be measured in centimetres to one decimal point (e.g. “14.7”) with a diameter tape at a point 1.3 m from the base of the tree, measured on the uphill side of the tree

Enter sample plot information

The sample plot information should next be entered into the SLFMIS computer system, after careful checking for transcribing errors, punch errors, and obviously bad measurement errors. It is vital that all data entered have been collected accurately, and recorded correctly.

If the data are not entered correctly, the inventory results will not be accurate.

Check sample plot information

The SLFMIS Plot details report should be run for each plot after data entry. This report lists any errors that can be found, such as zero dbh and zero plot areas.

The printouts from the SLFMIS should be compared with the field data sheets. Any incorrect or bad data should be corrected in the SLFMIS or removed from the database.

Examine stratum reports

After each batch of plots has been entered into the SLFMIS, the stratum summary reports should be run.

The reports present the inventory summary details for examination. These reports show see how accurate the inventory is, so that a decision can be made whether to carry out more sampling.

The examination of the summary reports will show the degree of accuracy that has been achieved in the inventory. This is the PLE² of the basal area estimate.

If the PLE is too high, over 15%, this indicates that either the sample intensity is too small, or that the stratum is too varied.

If the PLE is too high, either more plots need to be measured each forest unit, or the forest units need to be divided into smaller units with less variation within them.

Redefine forest units as necessary

If the stratum reports show that the strata are too large or poorly defined, it is necessary to redefine the forest units into more homogenous groupings, or subdivide the forest units.

This is done by remapping the forest units into smaller units, and allocating them to different strata. New strata should be defined to allow variation between strata to be excluded from the PLE estimate. After redefining the forest units, the analysis is repeated, and the process recommenced.

Statistical terms in forest inventory

A forest inventory is a process of statistical estimation. It is worth reviewing a number of statistical terms that apply in forest inventory, as in any statistical sample.

Random

All statistical samples should be taken at random. A random sample is defined as:

*“A sample of **n** units selected from a population such that each possible combination of **n** has an equal likelihood of being selected.”*

For forest inventory, this means that every point in a forest unit must have an equal chance of being selected.

Bias

Random sampling is designed to prevent bias. Bias is defined as:

“A systematic distortion of an estimate”

² Probable Limit of Error, the 95% confidence limit of the mean, expressed as a percentage.

A biased estimate is an estimate that is systematically different from the true value. An example of bias would be measuring diameters with a tape that had lost the first 2 centimetres. All the diameter measurements would be 2 cm greater than the trees in question.

Accuracy

Forest inventories are designed to provide accurate estimates. Accuracy is defined as:

“The closeness of an estimate to the true value”

For a forest with a true average diameter of 45 cm, an estimated mean diameter of 44 cm would be accurate, and an estimated mean diameter of 55 cm would be inaccurate.

Precision

Precision is defined as:

“The closeness of sample values to their true mean”

In the case above, an inventory with sample diameter estimates of 43, 44, 45, 42, and 46 would be precise, whereas one with sample diameter estimates of 42, 46, 40, 48, 38 and 50 would be imprecise.

Probable Limit of Error

The accuracy of a forest inventory is often expressed in terms of the probable limit of error, or PLE. This is the 95% confidence limit of the mean, expressed as a percentage.

Accuracy of inventory

The Saint Lucia forest inventory is aimed at estimating the combined basal area of a stratum to the $\pm 15\%$ level at a 95% probable limit of error. The accuracy of the stocking per hectare figures will be calculated from the sampling intensity level of the basal area estimate.

Estimates of volume will be made using volume functions developed during the 1982 inventory conducted by Peltz. These volume functions predict volume using dbh alone. The accuracy of the volume functions cannot be given, as the raw data are no longer available. This means that the volume predictions cannot have error estimates. The volume error can be assumed to be higher than the basal area error estimate.

The accuracy of the inventory will be highly dependent on the success in dividing the forest into small homogeneous forest units. If the forest units are large, a high sampling intensity will be necessary to achieve the aimed degree of accuracy.

Diameter measurement

The diameter of a tree is the single most important measurement that can be taken from a tree. Tree diameter is closely related to tree height and volume. Accurately measured tree diameters can allow a forest manager to estimate forest volume with a reasonable degree of accuracy.

The diameter of each tree should be measured in centimetres to one decimal point (e.g. “14.7”) with a diameter tape at a point 1.3 m from the base of the tree, measured on the uphill side of the tree. This is defined as ‘diameter breast height’, or dbh.

It is sometimes necessary to move the measurement point up or down from 1.3 m to avoid unrepresentative measurements if there is a stem irregularity or significant stem buttress. It is better to make a true measurement than to attempt to make an averaged measurement, as averaged measurements are often calculated incorrectly.

Diameters should be recorded on the sample plot sheet to one decimal place, e.g. “11.3”.

Height measurement

A sample of heights may be measured to enable the FMIS to calculate the mean top height of the stand.³ The MTH is calculated from a regression equation. The FMIS needs the heights of about 10 to 12 trees to calculate this height.

The sample tree heights should include three smaller trees, three average trees, and four to six trees at the top of the range. This is to ensure that the regression can be calculated accurately.

The team leader should be careful to ensure that only representative trees are measured. He should not measure short trees with large diameters, or tall trees with small diameters.

In mixed species stands a range of species should be included in the height tree sample.

The height should be measured with hypsometer. The instructions for measurement are as follows.

The height should be recorded on the sample plot sheet in metres to one decimal place, e.g. “11.2”.

The hypsometer can also be used to collect other measurements which may be required, such as the length of the tree bole, or height to crown break.

Strip plot establishment

Some forest units may not be suited to the establishment of a diamond plot. These would include the following:

- Forest units with trees below 1.3m e.g. newly planted areas
- Forest units with non-forest species e.g. scrubland
- Dangerously steep areas
- Areas of low economic value
- Areas of natural forest with a high density and variety of trees.

In these areas a strip plot should be established. A strip plot is simply a plot running along the line of travel, where all trees within a fixed distance of the centre line are counted by species. Figure 2 shows the layout of a strip plot.

³ Mean Top Height, MTH, is the height corresponding to the quadratic mean diameter of the 100 largest diameter trees in the sample plot, calculated from a height-diameter regression curve.

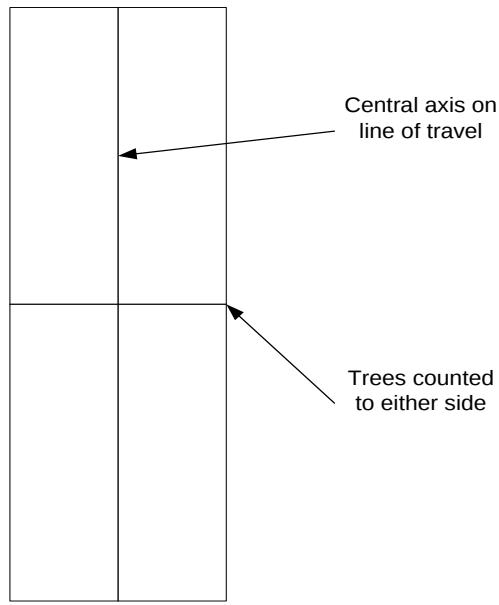


Figure 10 Example of strip plot. (Not to scale)

Strip plots should be put in in the direction of any slope, with the length adjusted for slope. Appendix 2 contains lengths and widths for a variety of strip plots at a range of slopes.

Appendix 3 includes a strip plot data sheet for your use.

Permanent sample plots

A permanent sample plot (PSP) is a plot established to measure the growth or change in the forest over time. Inventory plots and PSPs need different standards of measurement. As a growth plot will be remeasured, it is important that individual trees can be compared for growth over time. This requires a greater measurement precision. Temporary plots can be measured with tree callipers, as the resultant measurements provide an unbiased estimate of diameter, but this is not suitable for growth plots.

PSPs should be established using the techniques described for inventory plots, with added emphasis on accuracy of layout. While inventory plots should always be laid out with precision, any error in an inventory plot has a marginal error in the inventory estimates. However, an incorrect area in a PSP can lead to over or under estimation of growth. In general, a PSP should have a slightly larger area than an inventory plot.

One vital difference between an inventory plot and a PSP is that while inventory plots should be established randomly, PSPs do not need to be randomised. This is due to the variable of interest in a PSP being the growth of the PSP. As such, there should be PSPs established on high, medium, and low growth sites.

The lack of need for a random element should be taken advantage, and PSPs should always be established in areas that are easy to access. This will help ensure that the PSPs are remeasured frequently.

References and recommended reading

- Avery, T.E., & Burkhardt, H.E. 1994: *Forest measurements, Fourth edition*, McGraw-Hill, New York
- Bitterlich, W. 1984: *The Relascope Idea*. Commonwealth Agricultural Bureau
- Cochran, W.G. 1977: *Sampling Techniques*. John Wiley & Sons
- Cochran, W.G, Cox, G.M. 1957: *Experimental Designs*. John Wiley & Sons
- Freese, F. 1962: *Elementary Forest Sampling*. USDA Forest Service Agricultural Handbook 232
- Freese, F. 1967: *Elementary Statistical Methods for Foresters*. USDA Forest Service Agricultural Handbook 317
- Hammond, D. 1995: *Forestry Handbook*. NZ Institute of Forestry, Christchurch, New Zealand.
- Hogg, R.T, Craig, A.T. 1970: *Introduction to Mathematical Statistics*. Macmillan Publishing
- Raj, D. 1968: *Sampling Theory*. McGraw-Hill
- Spurr, S.H. 1952: *Forest Inventory*. Ronald Press.
- Spurr, S. H. 1960: *Photogrammetry and Photo-reinterpretation, second edition*, Ronald Press Co.

Appendices

Appendix 1. Diamond Plot Sizes

The following table includes diamond sample plot diagonal lengths for a range of plot sizes, including slope corrected diagonal lengths. The table also gives the expected number of trees in the plot for given stockings.

Slope (degrees)	Plot Size (ha.)							
	0.01	0.02	0.03	0.04	0.05	0.06	0.08	0.10
0	7.1	10.0	12.2	14.1	15.8	17.3	20.0	22.4
5	7.1	10.0	12.3	14.2	15.8	17.4	20.0	22.4
10	7.1	10.1	12.3	14.3	15.9	17.5	20.2	22.5
15	7.2	10.2	12.5	14.4	16.1	17.6	20.3	22.8
20	7.3	10.3	12.6	14.6	16.3	17.9	20.6	23.1
25	7.4	10.5	12.9	14.9	16.6	18.2	21.0	23.5
30	7.6	10.7	13.2	15.2	17.0	18.6	21.5	24.0
35	7.8	11.0	13.5	15.6	17.5	19.1	22.1	24.7
40	8.1	11.4	14.0	16.2	18.1	19.8	22.9	25.5
Stocking (s/ha.)	Number of trees in sample plot							
1500	15	30	45	60	75	90	120	150
1400	14	28	42	56	70	84	112	140
1200	12	24	36	48	60	72	96	120
1000	10	20	30	40	50	60	80	100
800	8	16	24	32	40	48	64	80
600	6	12	18	24	30	36	48	60
400	4	8	12	16	20	24	32	40
200	2	4	6	8	10	12	16	20
100	1	2	3	4	5	6	8	10

Table 1 Length of diamond plot diagonal and numbers of trees in plot for given plot size

Appendix 2. Strip Plot Sizes

The following table includes strip plot widths and lengths for a range of strip plots, including slope corrected lengths. The table also gives the expected number of trees in the strip plot for given stockings.

Strip width (m)	2	2	2	3	3	4	4	5
Slope (degrees)	Plot Size (ha.)							
	0.005	0.01	0.02	0.02	0.03	0.03	0.04	0.05
0	25.0	50.0	100.0	66.7	100.0	75.0	100.0	100.0
5	25.1	50.2	100.4	66.9	100.4	75.3	100.4	100.4
10	25.4	50.8	101.5	67.7	101.5	76.2	101.5	101.5
15	25.9	51.8	103.5	69.0	103.5	77.6	103.5	103.5
20	26.6	53.2	106.4	70.9	106.4	79.8	106.4	106.4
25	27.6	55.2	110.3	73.6	110.3	82.8	110.3	110.3
30	28.9	57.7	115.5	77.0	115.5	86.6	115.5	115.5
35	30.5	61.0	122.1	81.4	122.1	91.6	122.1	122.1
40	32.6	65.3	130.5	87.0	130.5	97.9	130.5	130.5
Stocking (s/ha.)	Number of trees in sample plot							
5000	25	50	100	100	150	150	200	250
3000	15	30	60	60	90	90	120	150
2500	13	25	50	50	75	75	100	125
2000	10	20	40	40	60	60	80	100
1500	8	15	30	30	45	45	60	75
1200	6	12	24	24	36	36	48	60
1000	5	10	20	20	30	30	40	50
800	4	8	16	16	24	24	32	40
600	3	6	12	12	18	18	24	30
500	3	5	10	10	15	15	20	25
400	2	4	8	8	12	12	16	20
300	2	3	6	6	9	9	12	15
200	1	2	4	4	6	6	8	10
100	1	1	2	2	3	3	4	5

Table 2 Length of strip plot and numbers of trees in plot for given plot size

Appendix 3. Plot sheet

St Lucia Inventory Plot Sheet

Estate				Forest Type			
Line/Sector Number		UTM	East	7	Waypoint ID		
Plot ID		20N	North	15			
Slope		Plot size					

Tree Number	Species Code	DBH	Tree Number	Species Code	DBH	Tree Number	Species Code	DBH
1			21			41		
2			22			42		
3			23			43		
4			24			44		
5			25			45		
6			26			46		
7			27			47		
8			28			48		
9			29			49		
10			30			50		
11			31			51		
12			32			52		
13			33			53		
14			34			54		
15			35			55		
16			36			56		
17			37			57		
18			38			58		
19			39			59		
20			40			60		

Attribute data

1	2	3	4	5	6	7	8	9

Team Leader _____ **Date** / /