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User Manual
Planning and Field Guide for Single-Tree Sampling

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GENERAL INFORMATION

Preamble

This manual is the first version of a guide to planning and executing the field work for operational forest inventory utilising single-tree sampling (also known as individual-tree sampling). This report is in the format of a user manual.

Single-tree sampling requires an accurate estimate of the number of trees in the stand[1] in order to provide information on population totals; for example, the total recoverable volume in a forest block. This field method was developed to complement the semi-automated analysis of good quality ortho-rectified photography or high resolution satellite imagery by software systems such as TIMBRS. The TMBRS software developed at CSIRO is used to locate individual tree positions and provide estimates of tree counts. Details of how an accurate estimate of tree numbers may be obtained using TIMBRS are the subject of a separate guide.

The manual is divided into two main parts:

1. Planning the inventory
2. Field procedures to collect the data.

The guide will be of use to inventory foresters and private forestry consultants. It can form the basis for detailed specifications for inventory field crews.

Single-tree Sampling

Single-tree sampling provides an alternative method to the traditional bounded plot inventory for assessing forestry resources. Conceived as more efficient for small, irregularly shaped woodlots, it also shows potential for efficiency gains for larger stands in professionally managed forests. The number of area-based plots required for a desired precision in estimating volume by log grades is affected by both the variability between trees and the variability in stocking per hectare across the stand. When an accurate count of the total number of trees is available, single-tree sampling need be concerned only with the variability between individual stems. Using single-tree sampling could create savings in field costs, because fewer trees need to be measured for log quality and grade to obtain an equivalent precision[2] or Probable Limits of Error% (PLE %) on the estimates of totals as would be required when valuing a woodlot for sale. Plot-based inventory requires a measurement of stocked area, which may not be accurate for a farm woodlot.

Conditions that favour single-tree sampling are when:

1. it is difficult to obtain an accurate estimate of the area of the stand, where boundaries are highly irregular and/or difficult to define;

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[1] The term “stand” is used throughout this guide in place of the more correct term “population”. For the purposes of this guide, an inventory stand could comprise a woodlot or one or more blocks of forest, not necessarily contiguous, and is the entity on which the inventory is carried out.
[2] The “precision” of an estimate refers to the variability of numerous inventory estimates about their mean and is usually expressed in terms of a confidence interval about the mean for a single inventory. “Accuracy” refers to the closeness of the estimate to the true value.

2. edge correction methods such as the mirage or reflectance method are difficult to implement;
3. there is variability in levels of stocking and volumes per hectare across the stand, but stem quality is relatively uniform between trees (for example, in a structural regime and where the crop is of adequate piece size with little malformation); and
4. appropriate resolution aerial photography or satellite imagery is available or easily acquired, or the number of stems is otherwise easily and accurately determined.

Inventory System Overview - Software Used

The inventory system has four major steps.

Step 1: Obtaining a total tree count, using either
- a) physical counting by a field crew, or
- b) digital tree counting

Step 2: Planning the sample-line design
- a) Choosing a design option
- b) Calculating the required number of sample trees
- c) Determining the sample line length and width

Step 3: Collecting the field data for pre-harvest inventory

Step 4: Analysing the data

Physical counting of each tree is generally confined to instances where the area is small and ground conditions are easy. Otherwise, semi-automated image processing methods can estimate the number of trees in a stand to varying degrees of accuracy. TIMBRS tree counting software developed at CSIRO uses currently available remotely sensed imagery such as ortho-rectified photography or satellite images to locate individual trees and hence provide estimates of tree numbers. LiDAR (Light Detection And Ranging) methods show great promise, but are currently under development, and collection of LiDAR data is not routine in New Zealand.

The line-sampling concept is developed to select individual stems to be measured. Four sample design options are discussed, varying in degree of statistical veracity and likely cost. Forest management GIS (Geographic Information Systems), such as ATLAS GeoMaster can be used to plan the inventory, calculate sample-line dimensions and produce maps for field use.

The field measurement procedures that are unique to this system are given in detail. Efficient field crew sizes can be three, two or one person in size and auditing procedures are described. Once a tree is selected to form part of the inventory, the individual tree-stem is measured and cruised in the conventional manner. Electronic data recorders utilising programs such as PlotSafe and ATLAS FieldMan are recommended when collecting the data.

The data can be analysed using any program such as ATLAS Cruiser that is able to process individual tree data in a double sampling scheme and estimate total log product yields. Provided an estimate of the age and stocked area is available, per-hectare values can be calculated and the data projected through several growing seasons using forest management software to estimate future yields.

PLANNING THE SINGLE-TREE INVENTORY

A Random Sample

Ideally, individual trees to be measured should be part of a random sample[3]. In theory two methods can be used:

1. List all the trees, draw a random sample from the list, visit and measure those trees.
2. Visit every tree in the stand and generate a random number at each tree in order to decide whether or not to measure the tree.

These methods are feasible only for very small or valuable stands[4].

A cost-efficient method of selecting trees is a compromise between practicality, convenience and cost on the one hand and the need to have a random, unbiased sample on the other. A sufficient number of trees need to be sampled to provide estimates of totals within desired confidence limits. When using one of the suggested methods, or when modifying a method to tailor the design to specific circumstances, points to consider are:

1. trees should be selected in an objective, unbiased manner,
2. as near to randomly as possible,
3. each tree in the stand should have (nearly) the same chance of being measured,
4. the correlation between consecutive trees selected should be minimised, and
5. the field work should be auditable.

Current forest inventory sampling practice frequently utilises systematic sampling, with plots located on some form of grid laid across the area being inventoried. This is not random sampling, but in practice the same formulae used to calculate confidence intervals for random sampling are used for systematic sampling. With certain provisos, this provides estimates that are more reliable than the confidence intervals would suggest and systematic sampling designs are thought of as "random".

Type and Number of Sample Trees

The principles for determining the number of trees to be selected for measurement to obtain a desired confidence interval or PLE% are the same as for any sampling design. Sampling intensity will be a function of the inventory objectives, stand conditions and the types of attributes or log-types of key interest. The numbers suggested below are a guide only and should be adapted for local circumstances.

Double sampling, where all trees selected for measurement are measured for DBH but only a proportion are cruised by a complete assessment of the stem, has been shown to be very efficient for single-tree sampling.

Trees that are fully measured are termed the Primary Sample trees. Those measured only for DBH are the Secondary Sample trees. Usually, every second sample tree is a Primary Sample tree but this proportion can be varied **–** for example two Secondary trees to every Primary tree. A minimum

[3] Random means that there is no pattern and no "subjective" or operator determined selection - each individual tree has the same chance as any other of being picked, and any combination of trees has the same chance as any other combination.

[4] If the stand is small and very valuable, there are more appropriate sampling systems than random single-tree and the reader is advised to consult further.

of about 50 trees should be fully cruised which, with the 50 secondary trees, may be sufficient for well-tended trees with uniform branching characteristics.

Where there are relatively rare, important log-types (for example, veneer grades present in only every third tree or fewer), or there is much variability in stem features between trees, upwards of 150 primary trees should be measured. Figures 1 and 2 below depict the PLE% for total stem volume against number of primary trees for two of the stands measured during trials of the method.

The first stand of 600 stems per hectare was pruned, had an irregular boundary with large gaps through the stand, and between-stem variability appeared high. Double sampling with two secondary trees to every primary was used. The second stand of 190 stems per hectare was on steep land with mapped gaps and undergrowth. It was pruned and stem quality was uniform among trees. Equal numbers of primary and secondary trees were sampled. While the two graphs are provided as examples until more experience is gained by individual companies, there is no guarantee that between-tree variability in a company's own forests will be similar.

Additionally, at least 30 trees should be measured for total height to provide data to calculate a height / DBH regression, which is used to predict the height of cruised trees and derive volume. The height sample trees are usually selected from the primary sample for efficiency, but it is acceptable to include secondary trees also. Trees with broken tops are not suitable for a height sample, but multi-leadered stems, where the tallest leader is measured, are acceptable. Height trees should be selected across the DBH range, with perhaps proportionally more trees in the larger DBH classes.

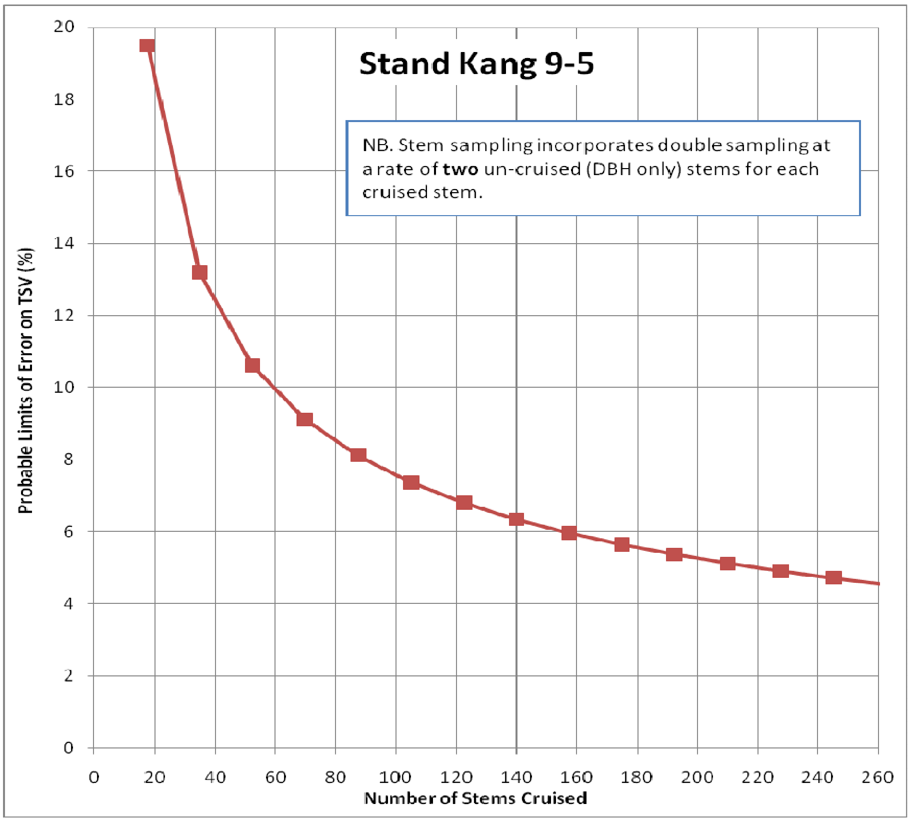


Figure 1: 600 stems / ha, two secondary (DBH only) trees for every primary (cruised) tree.

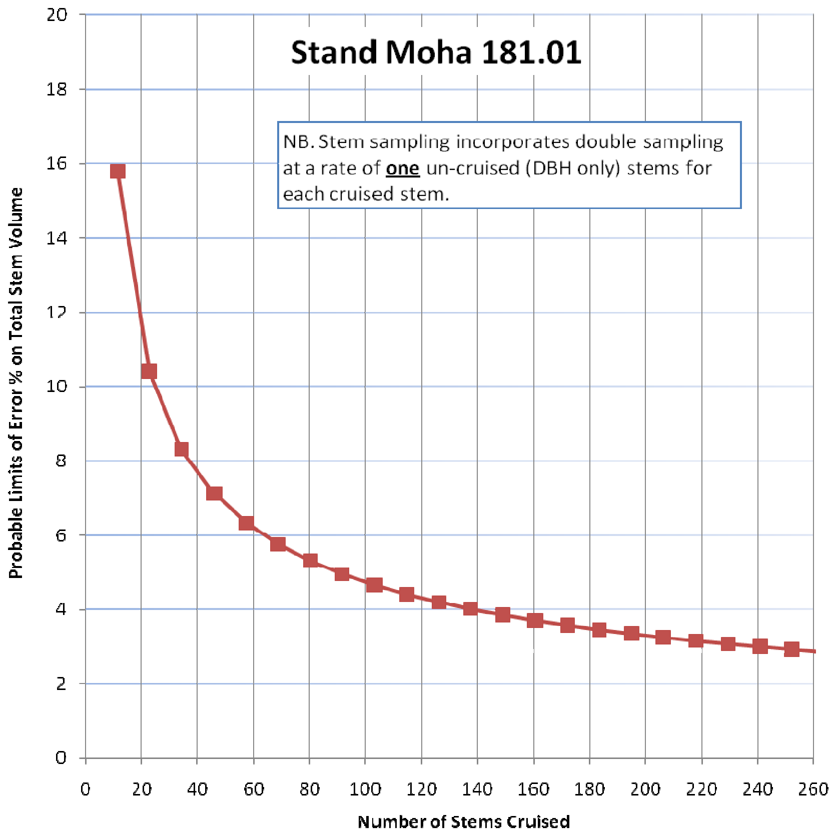


Figure 2: 190 stems / ha one secondary (DBH only) trees for every primary (cruised) tree.

Design Options

Three different options have been considered suitable for single-tree sampling of plantation forest stands. The three sample design methods are:

- parallel sample-lines,
- Z-shaped sample-lines,
- professional, "structured" walk,

Trees are selected by traversing a sample-line or transect and measuring trees within a given distance from the line. Provided that there is no systematic bias in the way marginal trees are included or excluded, the width and hence area of the sample-line is not as critical to the same degree as conventional area-based, narrow strip plots, where it is important that the area of the plot is known accurately.

Parallel Arrangement

This design option consists of parallel sample lines distributed evenly across the stand, as in conventional strip sampling. All sample lines follow the same bearing at an equal distance apart, from stand edge to stand edge. Attention must be paid during the planning stages to ensure that the bearings do not match systematic patterns in the environment, e.g. not run parallel to ridge lines or planting lines. The most manageable swath was found to be either 3 m or 4 m wide in total. Every second or third tree encountered along the sample line is to be selected and measured.

In low-stocked stands, a sample comprising every second tree encountered is acceptable. This reduces the correlation between adjacent sample trees selected on the line to insignificant levels. Alternative sample trees (odd-numbered) are primary trees and need to be fully cruised, whereas even-numbered trees are considered secondary trees and will be measured only for DBH. The numbering of the trees should be in sequence to enable auditing. Figure 3 below depicts an ideal from the viewpoint of statistical correctness, where trees and lines are approximately equal distances apart..

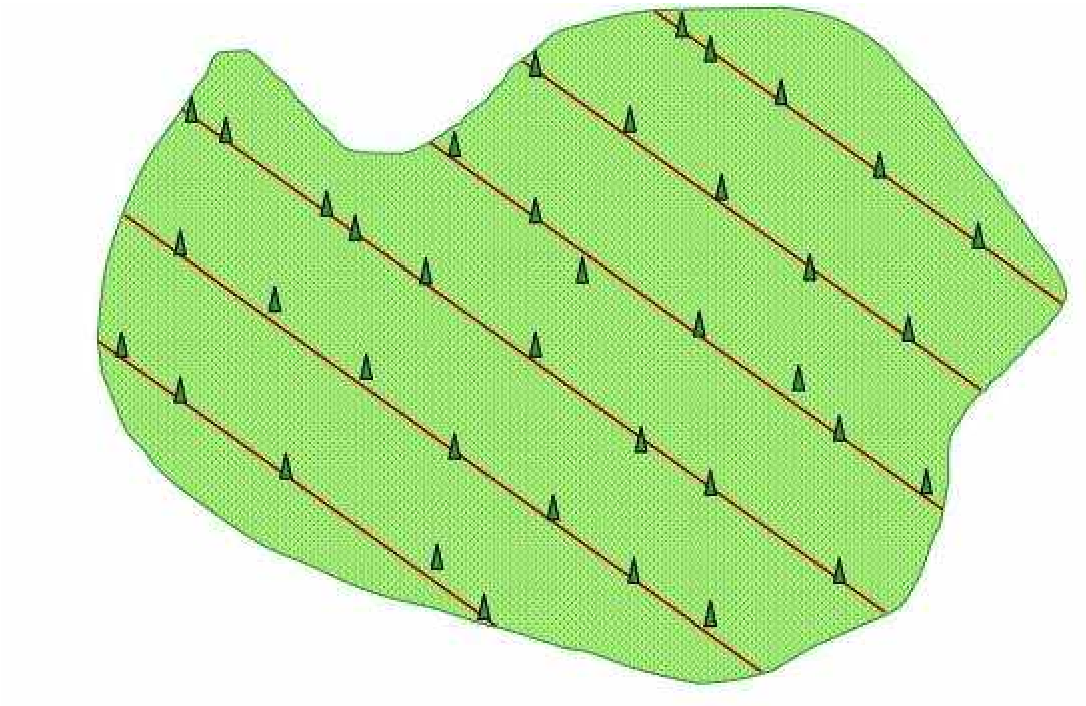


Figure 3: Sampling with parallel lines

Z-shape

The Z-shape or "zig-zag" design consist of a set of parallel sample lines arranged equal distances apart, that are connected by a third sample line. The parallel sample lines run along the same bearing, whereas connecting sample lines each have a different bearing that will require determination at the time of planning.

This method has the advantage that the field crews do not spend time walking from one sample line to another without measuring and is likely faster than the parallel sample line method. The transfer from one sampling line to the next is fluid. The field crews simply change the bearing once they have reached the end of one transect. The crews find it easier than parallel lines alone when there is a considerable amount of hindrance at stand edges and no easy path or road to the next swath. It has the disadvantage of over-sampling at the apexes and, depending on the shape of the stand, could over-sample narrow parts of stands.

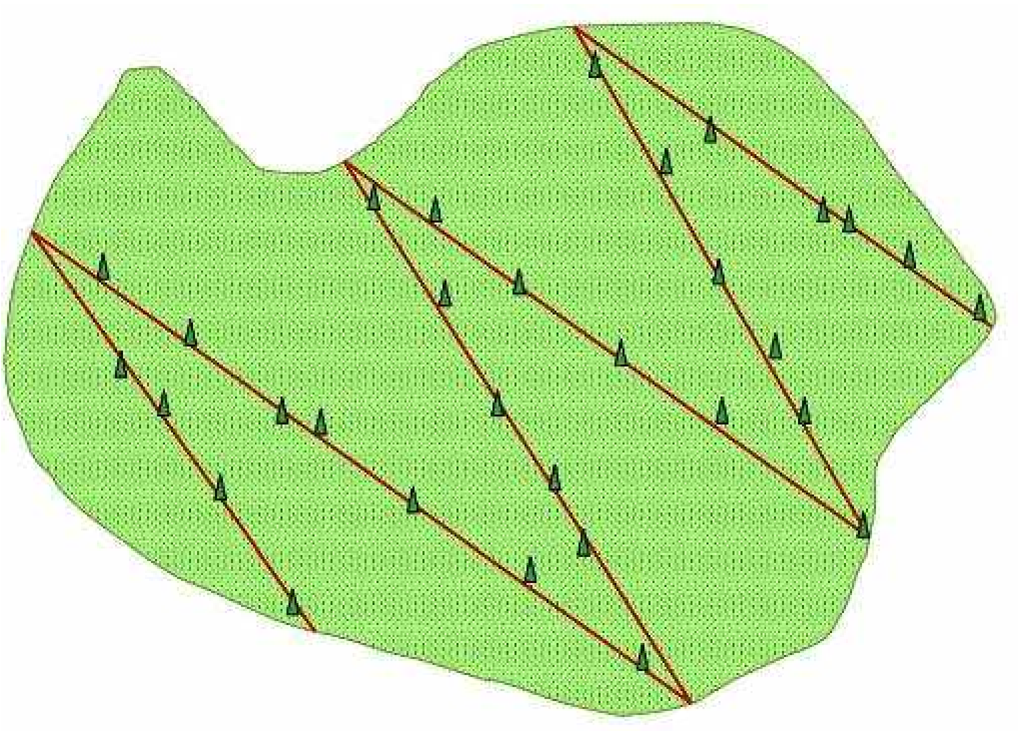


Figure 4: Sampling with lines arranged in a “zig-zag” method

Professional, "Structured" Walk

The professional or structured walk is a pre-planned walk through the stand to be carried out only by a skilled, experienced forester[5]. It is a method often used by forestry consultants when they are assessing other characteristics beside recoverable volume, when the size of the stand is small and time is limited, when similar stands have been assessed many times before and when the professional reputation of the forester is at stake. Here, the quality of the overall advice is more important than statistical technique.

Ideally the trail is planned before visiting the stand. The start point is somewhere convenient for access. A route is planned that visits all parts of the stand and returns to the starting point, sampling some edge trees. It can be very low cost, but clearly has the risk that the sample of trees may be inappropriate and result in a biased estimate.

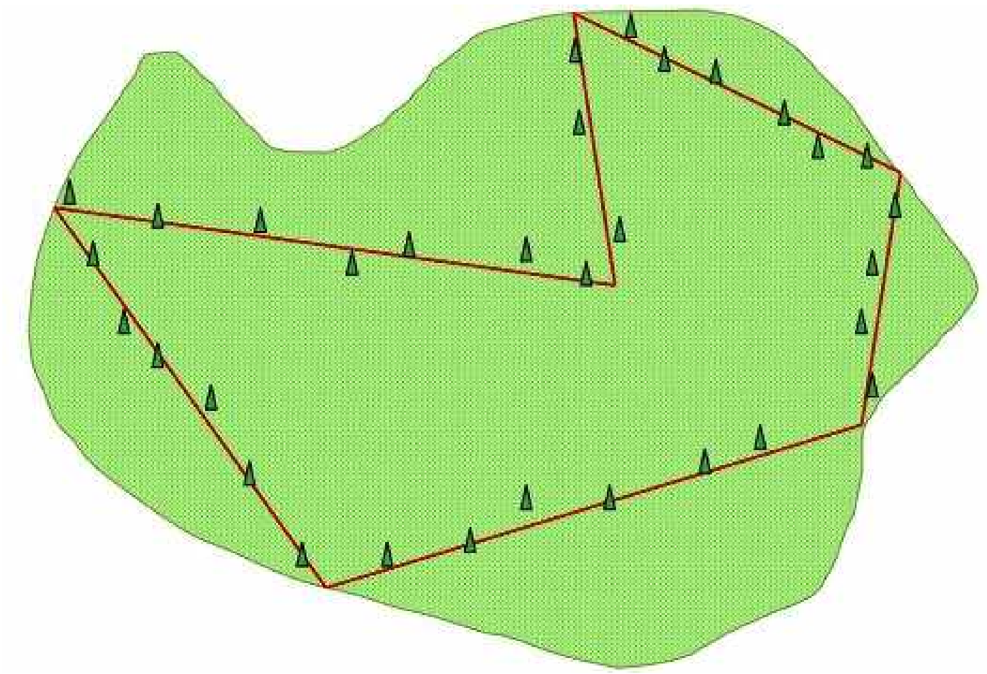


Figure 5: Sampling with a pre-planned, "structured walk"

Sample-line Width and Length

In order to plan the inventory once the desired total tree count that will provide the necessary precision has been determined, the inventory planner needs to calculate the width and length of the sample line. The length is based on the total number of trees present in the stand, its approximate area and the desired width of the sample line. As only every second or third tree encountered along the sample line is to be measured, the inventory planner must plan the sample swath accordingly and double or triple the number of trees expected to be encountered.

It is conservative practice to increase the number of trees expected by around 10% to ensure that the desired sample size will be attained. Depending on the swath width, the total length of the sample line will vary. For larger stands a narrow swath of no more than 3 m width is generally

[5] See MacLaren, P. and Goulding C.J. 1993: The structured walk - a practical inventory system. New Zealand Journal of Forestry 37(4):20-23.

recommended to ensure good coverage of the total stand area. For smaller stands of less than 10 ha, 4-m-wide sample swaths were found to be very effective during the trials.

The distance between lines may be greater than the average distance between sample trees, provided this is not taken to extremes with very few swaths. With the limited experience of this method, it is suggested that the distance between lines should not be greater than five times the expected distance between cruised trees.

Example:
In this example inventory, the aim is to obtain an estimate of structural sawlogs to a desired PLE%, and the planner has decided that at least 100 primary trees will be required plus a further 100 secondary trees, utilising double sampling. If every second tree encountered is excluded from measurement, 400 trees need to be encountered in the sample line. When allowing for an additional 10%, to ensure that at least the desired number of trees will be measured, the total number of trees in the swath should be 440 stems. The owner believes there are about 9000 individual trees over about 30 ha, based on their best guess of 300 stems /ha.

$$sampling\ intensity = \begin{matrix} 2\ if\ every\ 2nd\ tree\ encountered\ is\ sampled \\ 3\ if\ every\ 3rd\ tree\ encountered\ is\ sampled \\ etc \end{matrix}$$

$$swath\ length = \left[\left(\frac{((n\ primary\ trees + n\ secondary\ trees) \times sampling\ intensity) + 10\%}{n\ trees\ within\ stand}\right) \times stand\ size(m^2)\right] / swath\ width\ (m)$$

$$swath\ length = \left[\left(\frac{((100 + 100) \times 2) + 10\%}{9{,}000}\right) \times 300{,}000\ m^2\right] / 3\ m$$

$$swath\ length = 4{,}890m$$

A 3-m-wide swath in this stand therefore needs to be at least 4,900 m long in order to ensure that at least the desired number of trees will be measured. To ensure sufficient height sample trees and to simplify instructions to the field crew, every third cruised tree is measured for total height. If the 30-ha stand in this example is roughly square in shape and a parallel sample line design is used, nine swaths at 61 m apart will be required. Planning the actual layout is best carried out using maps and/or a forest management GIS.

The calculation of swath quantity and distance for a roughly square stand is as follows:

$$stand\ width = \sqrt{stand\ area\ (m^2)}$$

$$stand\ width = \sqrt{300{,}000m^2}$$

$$stand\ width = 548\ m$$

$$number\ of\ swaths = \frac{total\ transect\ length\ (m)}{stand\ width\ (m)}$$

$$number\ of\ swaths = \frac{4{,}890\ m}{548\ m}$$

$$number\ of\ swaths = 9$$

$$swath\ distance = \frac{stand\ width\ (m)}{n\ swaths}$$

$$swath\ distance = \frac{548\ m}{9}$$

$$swath\ distance = 61m$$

Each primary tree to be cruised in this stand is on average expected to be about 45 m away from its next neighbouring primary tree, and the resultant sample design will resemble a systematic rectangular grid, 61 x 45 m.

With “reasonable” hindrance, assuming a walking speed of 2 km/hour (including measuring secondary trees for DBH only), 4 minutes to cruise each primary tree and another minute if total tree height is to be measured, a field crew of two should be expected to measure this stand within just over 10 hours, excluding travel, unloading and rest-break times. The total time would be composed as follows:

4.5 km sample-line, 2 km/h walking speed = approximately 2 h 15 min walk time
110 primary trees, 4 min/tree measuring time = 7 h 20 min measuring time
37 height trees, 1 min/ tree measuring time = 37 min height measurements
Total: 10 h 12 min

For stands with high hindrance levels and large gaps and gullies that cannot be crossed safely, the expected walking speed would be expected to drop to around 1 km/h, and tree cruising speeds should be adjusted to 6 min per tree plus 2 minutes per height tree.

In this case the total time would be composed as follows:

4.5 km sample-line, 1 km/h walking speed = approximately 4 h 30 min walk time
110 primary trees, 6 min/tree measuring time = 11 h measuring time
37 height trees, 2 min/tree = 1 h 14 min height measurement
Total: 16 h 44 min

For stands on flat land with low hindrance levels, the expected walking speed can be assumed to be 5 km/h, and tree cruising speeds should be adjusted to 2 min per tree plus 0.5 min per height tree.

In this case the total time would be composed as follows:

4.5 km sample-line, 5 km/h walking speed = approximately 54 min walk time
110 primary trees, 2 min/tree measuring time = 3 h 40 min measuring time
37 height trees, 0.5 min/ tree measuring time = 19 min height measurements
Total: 4 h 55 min

DATA COLLECTION

Field Procedure

1. Navigate to the start point of the first sample-line using GPS.
2. From the start point, move along the sample line at the designated bearing. Select every n^{th} tree within the designated swath width. The field crew will be told in advance whether every 2^{nd} or 3^{rd} tree along the sample line is to be selected and measured, and what is the width of the swath (usually 3 or 4 m).
3. A tree is to be selected if the mid-point of its stem at breast height is closer than half the swath width to the sample line (i.e. within 1.5 or 2 m).
4. Every second tree selected is a **primary tree** that is cruised for stem quality and defect while every other tree is a **secondary tree** measured for DBH only,
5. The aim is to cruise a minimum of 50 trees and measure DBH on at least 100 live trees The number of trees measured depends on the objective of the inventory. If, for example, recording rare, important logs, the number of primary trees measured should be in the order of 150, thus increasing the total number of trees measured for DBH to 300 if the ratio of primary : secondary is maintained.
6. If the **primary tree** is dead, ignore it and use the next tree along the sample line as a primary tree. For each primary tree, cruise the stem and record stem attributes, quality characteristics and DBH.
7. At least 30 trees must be measured for **total height**. It is usually more cost-efficient to measure the primary trees. If it is easier to measure the height for all primary trees then do so. Total height trees may be multi-leadered, but should not have broken tops.
8. If the tree is a **secondary tree**, measure only the stem's DBH. If the secondary tree is dead do not include it as one of the sample stems. Instead, use the next possible tree as secondary tree.
9. Proceed along the swath until the edge of the stand is reached (drip line of the forest edge). If possible, record the end point of the swath on the GPS for auditing purposes.
10. Continue with next sample-line and apply the same rules. Proceed until completed.
11. When a **Z sample design** is employed, the end point of one sample line is the start point of the next. The bearings of each swath are to be provided on a map. Any tree within a stand is cruised only once. Around the apex of two sample lines a tree might be encountered twice, but should only be measured once and simply ignored on the second encounter.

Marking

1. Marking the start of each sample-line at the stand edge: Mark the first and last tree measured in each swath by painting the transect number and 'start' or 'end' on the first/last tree in the swath (e.g.: **S1 start** and **S1 end**). Preferably record the start and end points on the GPS at the drip line of the forest boundary and not at the base of the tree.
2. Mark the sample-line on the ground with a dashed line of paint, so the person behind can easily see and follow the line. The marking is also useful when the field crew has to leave the sample-line to measure DBH, height or assess stem features, as it facilitates returning to the sample line to carry on.
3. Number every tree measured (primary as well as secondary) in order of appearance and mark the side of the tree facing the end of the swath with a dot. Put the mark at approximately 2 m height, so when looking back on the sample line it leaves a clear trail. Tree numbering must always be in the correct order to ensure easy auditing. Trees within the swath that do not get measured should be marked with two dots, one facing the start and another facing the end of the sample line. This will make it easier to follow the sample line when it comes to auditing.
4. Clearly mark height trees.

Crew Responsibilities

The following description of gear and responsibilities between crew members is flexible and the methods presented here proved to be the most suitable when trialling single-tree sampling in 2009. Two-, three- and four-person crews have been trialled. Overall the four-person crew was more expensive to run. On the one occasion trialled, the 3-person line-up was faster than the 2-person crew, resulting in a 14% cost saving.

For a **two-person crew** the first person generally carries compass, map and GPS if available, as well as paint, a handheld computer and Vertex. Person 1 walks in front, finds the transect start point and records coordinates for start as well as end point of each sample line. Sample lines can be interrupted due to adverse hindrance such as gullies or larger water bodies that are unsafe to cross. Such treeless areas can be bypassed and the sample line can be re-entered once the obstacle has been cleared. The person in front occasionally marks the ground or shrubs along the sample-line with paint, while following the bearing. Crew member 1 measures tree heights of at least 30 trees and records measured data for all cruised trees.

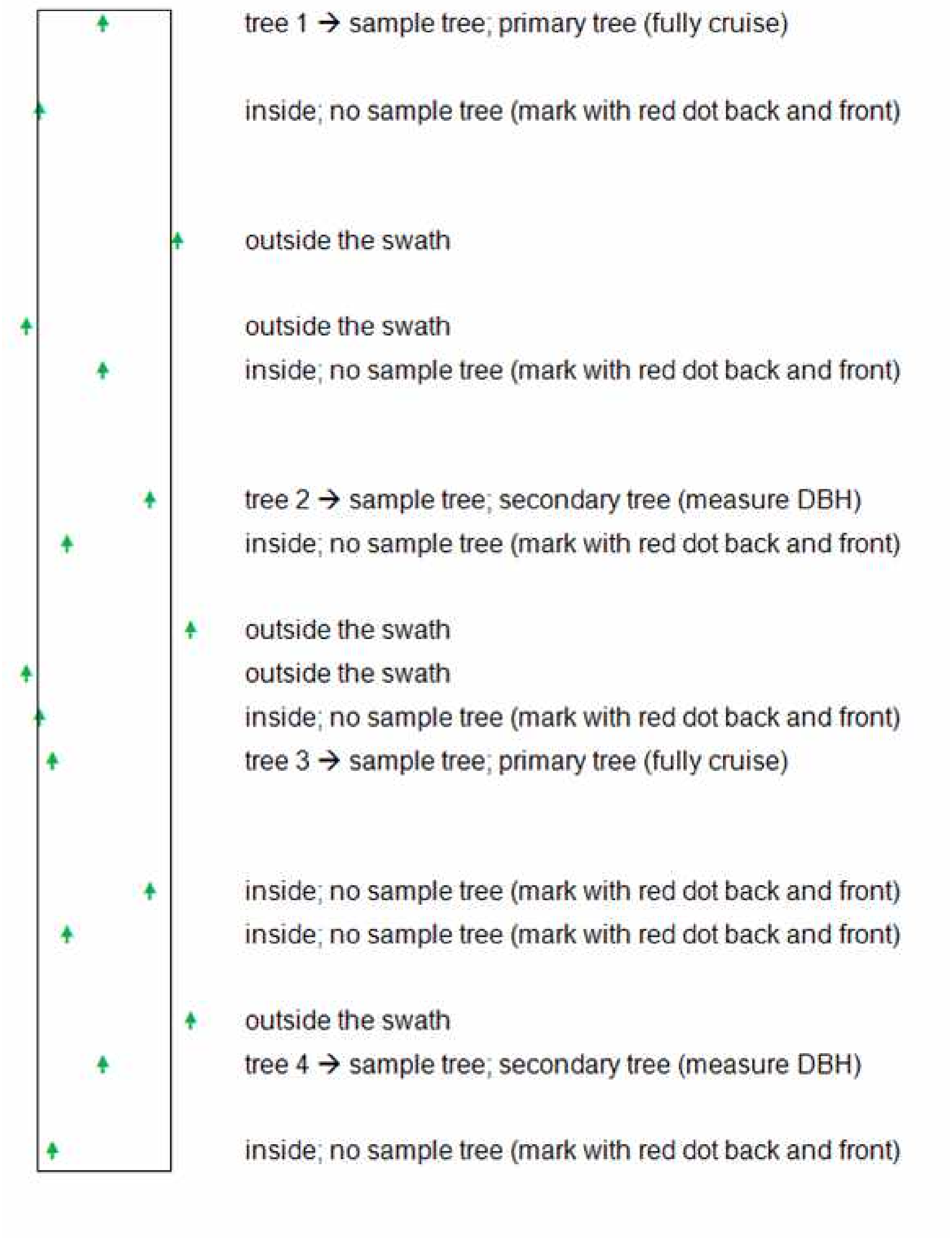
Person 2 carries DBH tape, paint, the transponder and a tool, such as a height pole, to ensure the correct swath width along the sample line. Person 2 follows Person 1 along the marked trail holding the height pole at mid-chest (1.4 m high) to decide which trees are inside the swath. The length of the height pole is to be set to half the swath width. Hence, if the swath width is 4 m, the height pole has to be 2 m long. If the centre of a tree is within reach of the height-pole while walking along the sample line, the tree is classified to be inside the swath and will have to be marked with a dot facing the start of the sample line and another dot facing the end of the sample line. If it is a sample tree it will need to be marked with a number facing the end of the sample line, so when looking back on the sample line the tree number of the last few trees is visible.

The tree number or a dot will also be marked on the side facing the start of the sample line to ensure that the sample line can be easily traced in either direction. This facilitates numbering and auditing. If the height pole does not touch the tree, it is considered outside the swath and will not get measured or marked. The person following also measures tree diameters and calls out whenever coming across a primary tree, so that the person in front can assess the tree and measure the height.

With a **three-person crew**, the responsibilities change, with person one carrying a compass, a GPS and paint, while being in charge of navigation, marking the sample line on the ground and marking trees with a dot if they are clearly inside the swath. Persons 2 and 3 are responsible for selecting and numbering the trees using the pole for marginal trees. They measure and assess the trees and record all data, dividing the responsibilities as in a two-person crew. Between them they carry paint, a handheld computer, DBH tape, Vertex and transponder as well as the height pole.

An Example of the Field Procedure

Measure every 3rd tree inside a 3-m swath.



DATA ANALYSIS

Any software package that has the ability to analyse single-tree sampling data can be used to analyse data collected via the Single-tree sampling method. For the research trial, ATLAS Cruiser was used to analyse the collected data and project it forward through time where necessary.

Selecting every second or third tree along the sample-line lowers the correlation between sample trees to levels where the covariance between trees is small relative to the variance of the trees. Typically in a stand of 300 sph with a swath width of 3 m where every second tree encountered is sampled with equal numbers of primary and secondary trees, the primary trees will be an average distance of 44 m apart. Provided that the rule of thumb that the distance between sample-lines not be more than four or five times the expected distance between primary trees, the sample layout of the primary trees cruised for log-products will resemble a systematic grid (see Figure 3 above).

In a large stand of medium or high stocking it might be more feasible to sample every third tree encountered, e.g. in an area with a final crop stocking of 300 stems per hectare, every third tree selected for measurement along the sample-line would result in an average between-primary-tree distance of 66 m.

Accordingly, the individual tree data can be analysed as though it were a “systematic random” sample, with a double sampling option. With sampling options 2 and 3, this assumption is stretched, and the calculated PLE% should be interpreted with caution but should still be a guide as to the likely range within which the true mean may lie.

GLOSSARY OF TERMS

***Bounded plot* –** area-based sample plot

***Cruising a tree* –** measuring a tree and assessing its stem characteristics, such as sweep, resin bleeding, branch sizes, etc., to estimate recoverable volume by log types.

***DBH* –** Diameter at breast height (New Zealand standard DBH is 1.4 m)

***Double sampling* –** is a technique which exploits a relationship between a supplementary variable (x) and the variable of interest (y). It is especially effective when the supplementary variable is easily measured and has a strong relationship to the variable of interest. Stem basal area (x) and stem product volume (y) usually meet these criteria, so double-sampling can be employed in inventory to increase efficiency.

***Ortho-rectified photography* –** combines the image characteristics of an aerial photograph with the geometric qualities of a map, where distortion and relief displacement is removed so ground features are displayed in their true planimetric position. Unlike an uncorrected aerial photograph, an ortho-photograph can be used to measure true distances and if used in TIMBRS is able to provide GPS coordinates for each tree crown location.

***Primary Sample trees* –** trees that are measured for DBH and are fully cruised for stem characteristics.

***Probable limits of error (PLE%)* –** the confidence limits expressed as a percentage of the estimated mean.

***Secondary trees* –** sample trees that are measured for DBH only.