PO Box 1127
Rotorua 3040
Ph: + 64 7 921 1883
Fax: + 64 7 921 1020
Email: info@ffr.co.nz
Web: www.ffr.co.nz

Theme: Radiata Management

Task No: F10405
Milestone Number: 4.05.04

Report No. FFR- R061

Single Tree Sampling: Cost Benefit Analysis

Authors:
M Fritzsche, C Goulding, A Gordon

Research Provider:
Scion

Date: June 2010

TABLE OF CONTENTS

EXECUTIVE SUMMARY

New Zealand production forest management is intensive and depends on detailed, “in-place” information specific to a management unit such as a stand or harvest area. In order to make decisions with some degree of reliability, inventory estimates must be adequately precise, requiring a high sampling intensity relative to other countries. Imprecise estimates can lead to poor decisions with loss in revenue. Company mensuration costs are correspondingly high. Small woodlot owners often cannot afford or are unwilling to pay for sufficient numbers of bounded plots that will provide adequate data for decision making.

This report documents, in detail, the next stage of research to improve the sampling efficiency of pre-harvest inventory. Single-, or individual-tree, sampling provides an alternative method of resource assessment to traditional, plot-based inventory. Whereas plot-based inventory requires an accurate measurement of the area of interest, single-tree sampling requires an accurate estimate of the total number of trees. The project is researching the use of semi-automated image processing to identify and count trees. It aims to provide a practical, efficient method of selecting individual trees to be measured in a stand that is as theoretically and statistically valid as possible.

The components of the proposed system are the use of the TIMBRS image analysis, tree-counting software developed at CSIRO; ATLAS GeoMaster to plan the inventory; single-tree sampling and measurement along pre-planned sample lines (transects) and standard inventory measurement / tools to collect the pre-harvest inventory data.

The report covers research on further testing the single-tree sampling concept on six stands larger in area than in previous work, and over a wider range of conditions. A new sample line layout was proposed (Z-plots) to further reduce field costs. A cost benefit comparison was made between single-tree sampling and plot-based inventory.

Single-tree sampling coupled with an estimate of the total numbers of trees offers potential for reducing inventory costs. For the six stands trialled using both inventory methods, direct inventory costs were reduced by some 26% over the existing bounded plot inventory. However, for one stand, single-tree sampling cost more than using bounded plots. This stand had difficult walking conditions, and blocks with differing past silviculture and levels of growing stock. If this type of stand were to be sampled by conventional bounded plots, then the average cost reduction of the other five stands rose to 39%.

Tree counts obtained by an experienced operator of TIMBRS using ortho-photography were found to be within 5% of the direct counts made by field teams on the ground. However, while TIMBRS is adequate for research use, it would need re-programming to become a practical commercial product. Commercial services for locating and counting trees on remotely acquired images are becoming increasingly available world-wide. The quality of the imagery is crucial for obtaining an adequate tree count. The commercial services demand better quality ortho-photography than is usually available from the companies themselves, but the original digital data may be suitable and may still be held by the image provider. Satellite imagery such as QuickBird is also usually suitable, but may be expensive to order if imagery is not already available. LiDAR offers real potential to provide more accurate tree counts.

A user manual has been prepared on inventory planning and field operations. Case studies with interested companies in FFR are commencing, 2010.

INTRODUCTION

This report documents in detail the next stage following the research in 2008, to improve the sampling efficiency of pre-harvest inventory in New Zealand production forests. It covers the testing of the single-tree sampling concept on six larger stands, resolving statistical sampling questions regarding correlation between sample trees, the implementation of software and conducting an indicative cost benefit analysis. As a consequence of the work completed, a user manual has been prepared on inventory planning and field operations.

Project Background

Single-, or individual-tree sampling provides an alternative method of resource assessment to traditional, plot-based inventory. Whereas plot-based inventory requires an accurate measurement of the area of interest, single-tree sampling requires an accurate estimate of the total number of trees. In plot-based sampling, the number of sample plots required for a desired precision in estimating volume by log grades is affected by both the variability between trees and the variability in volume per hectare across the stand. If a count of the total number of trees is available, then single-tree sampling need only be concerned with the variability between individual stems. Earlier research work indicated that there could be savings in field costs, because fewer trees need be measured for log grades and quality for an equivalent precision or Probable Limits of Error %. Especially for irregular-shaped, small stands or woodlots, problems in estimating the area could be avoided when total estimates are required rather than per hectare values.

While this concept is not new, there have been obstacles that have impeded its adoption by the industry, primarily obtaining a total tree count for the area of interest, having an unbiased method of selecting sample trees, and having software tools to analyse data of this type. A pilot project undertaken by a team from Scion was established to address these challenges. The components of the project were:

- TIMBRS tree counting software developed at CSIRO was used to locate individual trees from remotely sensed imagery and hence provide estimates of tree counts.
- The concept of single-tree sampling along pre-planned sample lines (transects) was developed to select individual stems to be measured.
- ATLAS GeoMaster was used to draw transects and produce maps for the field.
- PlotSafe and ATLAS FieldMan were used to collect the pre-harvest inventory data.
- ATLAS Cruiser was used to analyse the inventory data collected.

In 2008, a comparison of the results using these methods was made with standard, company plot-based inventories for the same areas in three small stands in Kaingaroa Forest (Fritzsche *et al* 2009). This comparison indicated that single-tree sampling has the potential to provide estimates of standing and recoverable volume more efficiently in these types of stands than using bounded plots as currently implemented operationally. Furthermore, trees selected by line sampling showed a good coverage of a stand, whereas in the three examples in that study, bounded plots established at the standard company-prescribed sampling intensity were too few in number to provide a good sample, with edge trees being under-represented. Individual tree sampling with semi-automated tree counting should improve the precision and confidence limits for smaller stands or woodlots where it is too costly to install sufficient numbers of sample plots to obtain a desirable Probable Limits of Error (PLE%).

Work in 2009 / 2010

The next stage of the project was to test the concept in larger stands over a wider range of conditions, trialling a proposed sample line layout (Z-plots) to further reduce field costs. An economic analysis compared the commercial viability of this method with traditional plot-based inventory. The overall objective of work in 2009/10 was to determine whether there is a reduction of inventory costs over conventional plot-based inventory. This involved sampling medium to large stands using commercial inventory field crews and verifying the accuracy of tree counts via TIMBRS under difficult conditions characteristic of New Zealand forestry.

Ortho-rectified photography provided by the forest companies was used in TIMBRS to identify the location of individual trees and hence estimate the total number of trees, in contrast to the QuickBird satellite imagery used in 2008. ATLAS Cruiser has the facility to analyse inventory data consisting of individual tree sample units as well as the more routine plot-based inventory.

Due to access issues of the TIMBRS tree counting software, further work planned on verifying the tree counting was not completed at the time of writing the report. Determining the error variance of tree counts produced by TIMBRS, including between-operator errors, will be carried out in the near future. The installation of a practical, prototype version of the software for determining an alternative, commercially-available image processing service is still in progress.

Following the field work in 2009, discussion arose over the effects on the calculation of the PLE% due to correlation between trees in a sample line. While the sampling method as trialled in the field, of selecting every tree encountered, produces an unbiased estimate, the estimate of sampling variance could be lower than the true value where the volume measurements of adjacent or near adjacent trees are significantly correlated. This resulted in a modification of the sample tree selection method and the re-calculation of the times and costs of the field work to provide a valid comparison with existing practice. A manual on planning and field procedures was written and refereed (Fritzsche and Goulding. 2010).

The work is a joint effort by the New Forests Group from Scion (including ATLAS Technology), cooperating with Timberlands Limited and Pan Pac Forest Products Limited, using commercial inventory field crews from Interpine Forestry Limited (Rotorua) and Forest Mensuration Services (Napier).

Objectives

1. Develop a method that integrates semi-automated individual tree counting from remotely acquired images (TIMBRS) with individual tree ground-based measurements.
2. Verify and improve on the method of single-tree sampling established in the previous stage of the project for different types of terrain, representing typical New Zealand forest characteristics, ensuring that the method is practical, statistically valid, workable in the conditions and delivers the required level of sampling intensity at reasonable cost.
3. Determine the most practical individual tree sampling method and its likely precision/sample size relationship for pre-harvest, merchantable volume assessment.
4. Conduct single-tree sampling using regular, professional inventory crews.
5. Report on the comparison of pre-harvest inventory data obtained through traditional inventory with single-tree sampling and TIMBRS.
6. Closely monitor time and costs during all steps of this method of inventory collection.
7. Based on those findings, carry out a cost-benefit analysis under operational conditions vis-a-vis the current practice of measuring plots.
8. If the method shows promise, prepare and distribute a guide to planning and field procedures.

METHODS

Approach

There were seven steps to the approach.

1. Identify six trial stands
2. Acquire aerial ortho-photography for each
3. Count trees physically on the ground for part of each stand
4. Count trees using TIMBRS for the same part and for the total
5. Acquire existing plot inventory data
6. Carry out individual tree sampling
7. Calculate costs / benefits for each method

Two forest management companies agreed to collaborate with the work; Timberlands Limited and Pan Pac. Six stands that were close to the time of harvest and had recent aerial photography were selected. The ortho-photographs of all six stands consisted of between two and four individual photographs, which were merged prior to tree counting in order to save time as well as prevent miscounting caused by image boundaries.

Each stand had previously been inventoried using conventional bounded plots on a systematic sampling design (see Goulding and Lawrence, 1992). Tree counting over the whole stand was completed using TIMBRS, allowing planning of the single-tree sampling field work. At the same time, the stocking on part of each of the stands was assessed both by using TIMBRS and by a count on the ground by the field crew to determine the accuracy of the tree counting procedure from the images. Due to some larger sized stands of up to 117 ha, the manual counts to verify TIMBRS tree counts were tested only for part of each stand. Each tree counted was marked with paint. These counts were not made available to the TIMBRS operator prior to the analysis, and the image processing numbers reported later are the original unaltered estimates.

Once the TIMBRS counts were determined for all stands, the sample-line length was calculated and maps were prepared using ATLAS GeoMaster. GPS coordinates for start and end points of the sample-lines as well as gaps were extracted from GeoMaster and made available to the field crews.

The same companies and same field crews that had carried out the bounded plot inventories were employed to trial single tree sampling to ensure that the time comparison was as realistic as possible. Measurements were carried out by field crews from Interpine Forestry Ltd and Forest Mensuration Services following some initial instruction. Execution and times of the new sampling approach were monitored closely by Scion staff. The software programs PlotSafe and ATLAS FieldMan were both used for data collection, and ATLAS Cruiser was later used to analyse the collected information.

Stand Characteristics

The six stands were selected to represent conditions typical for New Zealand forestry. The trial stands include sites on steep terrain, wind thrown areas and extreme stockings, located in two regions of the North Island of New Zealand, Central North Island and Hawkes Bay. The aim was to determine if the TIMBRS tree counting software is limited to flat terrain, medium density stocking or uniformly stocked stands, or is also suitable in difficult conditions, especially in larger stands with considerable hindrance and difficult terrain.

The stands were of *Pinus radiata* located in Kaingaroa, Esk and Mohaka Forests. The stands were due for harvest within one to three years. The bounded plot-based inventory in Kaingaroa Forest had been carried out by Interpine Limited in 2007 and 2008, while that for Esk and Mohaka was carried out by Forest Mensuration Services in 2006 and 2007.

The larger stands had to be separable into clearly identifiable smaller sections to enable a comparison to be made for part if not all of each stand. Stand borders were distinct.

At least two of the stands included steep terrain with slope angles of 30° or above to assess whether TIMBRS was limited to flat terrain and whether counting trees on steep slopes was feasible for the TIMBRS operator.

Another two stands contained wind-thrown areas to determine whether TIMBRS excludes or includes trees with broken tops and whether it can count windthrown stands without issues. A further aim was to determine whether single-tree sampling is suitable for stands with windthrown areas.

At least two stands were to have extreme stockings of below 200sph and above 450sph, while stands on difficult terrain with undergrowth were also to be included. The aim was not only to test whether the TIMBRS tree counting software is limited to medium density stocking or uniformly stocked stands, but also to explore whether the single-tree sampling methodology is practical in large stands with considerable hindrance.

All trial stands had to have recent ortho-rectified photography of a quality suitable for image processing (see the discussion for image specifications for the future).

Table 1. Summary of stands in the study.

Company	forest/stand	stand size (ha)	Terrain	# bounded plots	Measurement crew
TLL	KANG 9_5	7.67	Flat	19	Interpine
TLL	KANG 945_1	117.40	Steep in parts	65	
PanPac	Esk 127	69.91	Steep	71	Forest Mensuration Services
PanPac	Esk 131	32.78	Steep	33	
PanPac	Mohaka 180	39.76	Steep	40	
PanPac	Mohaka 181	38.78	Steep	39	

Image Analysis and Tree Counting

After successfully obtaining tree counts from QuickBird satellite images in the previous stage of the project, the focus in this study was on examining the use of aerial ortho-rectified photographs.

Satellite images such as QuickBird can contain more information than generic aerial imagery, as they include a fourth spectral band, the near-infrared band. QuickBird satellite collects panchromatic imagery at 60-70-centimetre resolution and multispectral imagery at 2.4- and 2.8-meter resolutions, but since the most recent satellite image for the six project stands was taken in 2004 and road lining as well as partial clear felling of some of the designated stands has occurred in the meantime, none of the QuickBird images were suitable for determining total tree counts.

Ortho-photos combine 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 planimetrical 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. Up-to-date ortho-photos are already available in many forest companies to aid mapping, planning and decision making processes for a multitude of forestry operations. The images can often also be obtained from Regional Councils at nominal cost.

TIMBRS is a user-interactive computer program that can be installed on any relatively powerful PC. The TIMBRS tree count procedure follows eight basic steps in a semi-automated process. The operator manually outlines the area designated for counting, decides on the level of masking, and ultimately selects the final tree count from a range of options; see Appendix 3 for a detailed explanation of TIMBRS procedures.

Inventory Planning and Design

Design

In general trees are selected by traversing a sample-line or transect, and measuring trees within a given distance from the line. The sample-lines were drawn onto maps prior to the field work. Sample-lines are not directly comparable to ordinary transect plots as they are not intended to give an estimate of stocking, and neither is the swath area considered in any calculations. The sample-lines are solely used as a way of selecting a pre-defined number of trees objectively. As such, plot boundary issues that may result in difficulties in deciding whether a tree is in or out affecting per hectare values are not relevant. 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 as for conventional area-based plots where it is important that the area of the plot is known accurately.

The sample-line's width should be narrow so that the total length is such that the stand area is adequately covered by the field crew, visiting all parts of the stand, resulting in the trees that were cruised for merchantable volume being widely spaced apart. In the trials so far, with stands small in area, all trees encountered in the sample-line were sample trees measured for dbh; in the Kaingaroa stands, only every third tree was selected as a sample tree.

When calculating the total length of the sample-line, the aim in this study was to measure at least 100 live trees, with half cruised for stem quality, the other half measured for diameter only (double sampling, Cochran, 1977). In routine operational practice, the number of stems to be measured should be determined sufficient to meet the minimum PLE% required and, knowing the total number of trees in the stand, the sample-line length necessary calculated to encounter that number. To ensure that the required number of trees will be encountered, this length was increased by a further 10%.

Sample Line Options

There are several different options that are considered suitable and outlined in the Field Manual (Fritzsche and Goulding, 2010) for single-tree sampling of plantation forest stands:

1. Parallel lines
2. "Z-shape"
3. Professional walk

So far two of the sample design methods have been trialled. In previous work, sample-lines were installed in two stands in much the same way as traditional transects, where all the lines run parallel, as described in the previous report (Fritzsche *et al.* 2009). In this year's study, "Z-shaped" swath designs were tested in more detail.

Z-shape

The Z-shape or “zig-zag” design, which was the focus of this stage of the project, consist of a set of parallel sample lines arranged equal distances apart, where both are connected by a third sample line, see Figure 1. The parallel sample lines run along the same bearing, whereas the connecting sample lines each have a different bearing that requires determination at the time of planning.

This method is expected to have the advantage that it reduces the time walking from one sample line to another without measuring and is likely faster than the parallel sample line method under many conditions. The field crews do not have to exit the stand at the end of each transect, walk outside the stand and then re-enter on the next sample-line. The transfer from one sample-line to the next is fluid, the field crews simply change the bearing once they have reached the end of a transect. The crews find it easier than parallel lines alone when there is heavy vegetation hindrance at stand edges and no easy path or road to the next sample-line.
It has the disadvantage that it could over-sample around the apexes and, depending on the shape of the stand, could over-sample narrow parts of stands.

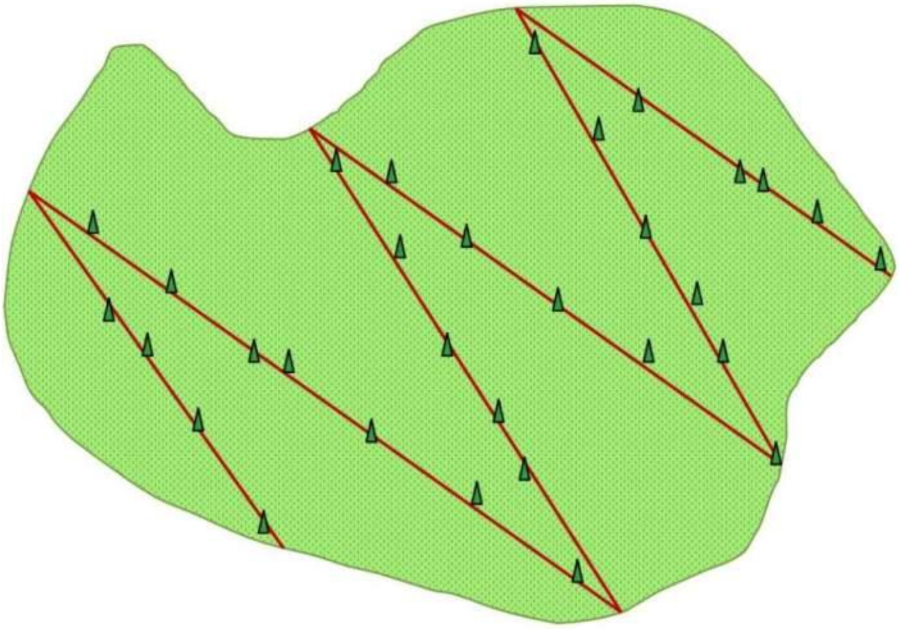


Figure 1. Z-shaped sampling design.

Planning Software

Once TIMBRS had been used to obtain final tree counts from the aerial images. planning the dimensions and layout of the sample-lines was carried out using recent modifications to the inventory planning module of the ATLAS Geomaster forest management GIS. GeoMaster is able to plan for sample-lines laid out either in parallel or as Z-shape. Each stand was planned individually. The TIMBRS analysis provides the expected number of trees in each stand and stand records provide an estimate of the area, The ratio of measured trees to trees encountered and a convenient swath width were then defined taking into consideration the stand characteristics and terrain. These parameters enable the total length of the sample-line to be calculated and its orientation over the stand prescribed by Geomaster which prepares maps for the field crews showing start points, bearings and distances.

Field Work and Data Collection

Manual Tree Counts

Every standing tree within a clearly defined part of each of the six stands was counted on the ground by an experienced two-person field crew to test the accuracy of the TIMBRS count. Since five of the six stands were 32 ha or larger, it was not practical to manually count the entire stand. The boundaries of each part-stand counted in the field were readily observed both on the ground and on the aerial photograph. Live trees, trees with broken tops, as well as leaning and standing dead trees were marked with paint on two or more sides of the stem to ensure that no trees were missed and a check was carried out to verify that none had been missed or double counted. It is highly unlikely that any trees were double counted.

Field Procedure

Each of the six stands was measured using sample-lines arranged in a zig-zag or Z-shape design. Based on experience from the first stage of the research, a minimum of 100 trees were to be measured for dbh and 50 trees cruised to estimate recoverable volume and log yields. This number of samples should provide a good estimate of between-tree variance. Every tree encountered within the swath was measured for dbh for the Esk and Mohaka stands, while dbh was measured for every third tree encountered in the two Kaingaroa stands. Every second tree measured for dbh was also cruised for stem quality and measured for total tree height; see Appendix 1 for details pertaining to each stand and refer to the Field Manual for a detailed general description of the field procedures.

ATLAS FieldMan was used to collect data for PanPac Forest Products Limited. It provides the option of single-tree sampling, which can be analysed in ATLAS Cruiser. PlotSafe was used to collect data for Timberlands Limited, and data were later converted into Cruiser format for data analysis.

Only in one stand, Esk 131 were there any difficulties in using the approach. Trees in the stand were variable; part of the stand was un-thinned and un-pruned with heavy malformation. The sample lines crossed many gaps in the canopy and gullies, with high hindrance. Three of the gullies were unexpectedly too steep to cross safely and the crew had to exit the stand, negotiate their way around the obstacle, then re-locate the sample-line using maps, GPS, bearings and distances. Walking through the stand was difficult. This reduced the advantages of the single-tree sampling as currently defined for this stand.

Time Study

A detailed time study was carried out during all steps of the project. Pre-harvest inventory data of the standard bounded plot method were obtained from Timberlands and PanPac for all six stands. During the individual-tree sampling inventory, the same field crews were timed by observers who did not participate in the inventory in any other manner. The following data were recorded:

- departure time for work,
- arrival time at the stand,
- setup time at the vehicle,
- time spent walking from the vehicle to the transect start point,
- time during each transect, including all start / finish times of breaks, start / finish times when walking around obstacles such as creeks,
- departure time from the stand, and
- arrival time at base.

Unproductive walking time was included in the time study but not time spent planning the inventory, nor in data management. Measurement times were obtained using different numbers of crew members at Esk forest, trialling two-, three- and four-person crews. To enable valid comparisons between measurement companies, costs were later calculated on a “time at stand” basis, i.e., from the arrival time at the stand through to departure time from stand. The times to and from the base are a useful indication of the allowance that must be made for unproductive time spent travelling.

Tree Count Software Modifications and Alternatives

Due to issues with screen flickering and licensing, the TIMBRS software became non-operational during the study. Scion therefore acquired the licence to modify, upgrade and modernise the TIMBRS code from CSIRO to be able to address those issues. Parallel to the field work, ATLAS Technology carried out the repair of the screen flicker and facilitated the licensing component to make TIMBRS more user-friendly, reliable and safe to operate.

Due to the issues with access to the software it was infeasible to have more than one person complete the tree counting with TIMBRS during this study. It is expected to have at least two more trained operators capable of using the package and able to repeat the counts on the stands used in the first and second stage of the project.

Scion has begun to look into alternative options to obtain tree counts. So far one European service provider, landConsult, Germany, has been identified and approached. This contact is continuing at time of writing.

A further alternative to obtain counts of trees semi-automatically is the use of LiDAR (Light Detection and Ranging). Research has commenced into segmentation algorithms with radiata pine under New Zealand plantation conditions. There would be several advantages to the successful use of LiDAR; the analysis is independent of shadowing and the results would be expected to be more reliable given the additional information from the LiDAR height measurements.

RESULTS

Image Analysis

Several key issues concerning the quality of the ortho-photographic images were recognised during the study. The discussion in this section concerning image borders, quality and processing, the nature of the stand, leaning trees, stocking variation and shadows is presented to document our experience. These issues can be overcome with good quality photography that is essential if the tree counts are to be reliable.

Image Borders

The photography for each stand was split into between two and four individual images, which had to be merged prior to being imported into TIMBRS. If the images are not merged and are counted individually in TIMBRS, a considerable number of trees along the image borders would be missed. This is visible on the image below, Figure 2, where tree locations of stand Esk 127 are displayed after the images were counted separately, and the tree locations were imported into a GIS afterwards. The two crossing lines are the edges of the four images and clearly show that trees along the image boundary do not get counted by TIMBRS. This is most likely due to the fact that the image border cuts across tree crowns, which then lose their typical crown shape. Hence those trees are not recognised as trees and are excluded from the total count. Merging individual images correctly produces an image that can be counted correctly, see Figure 3.

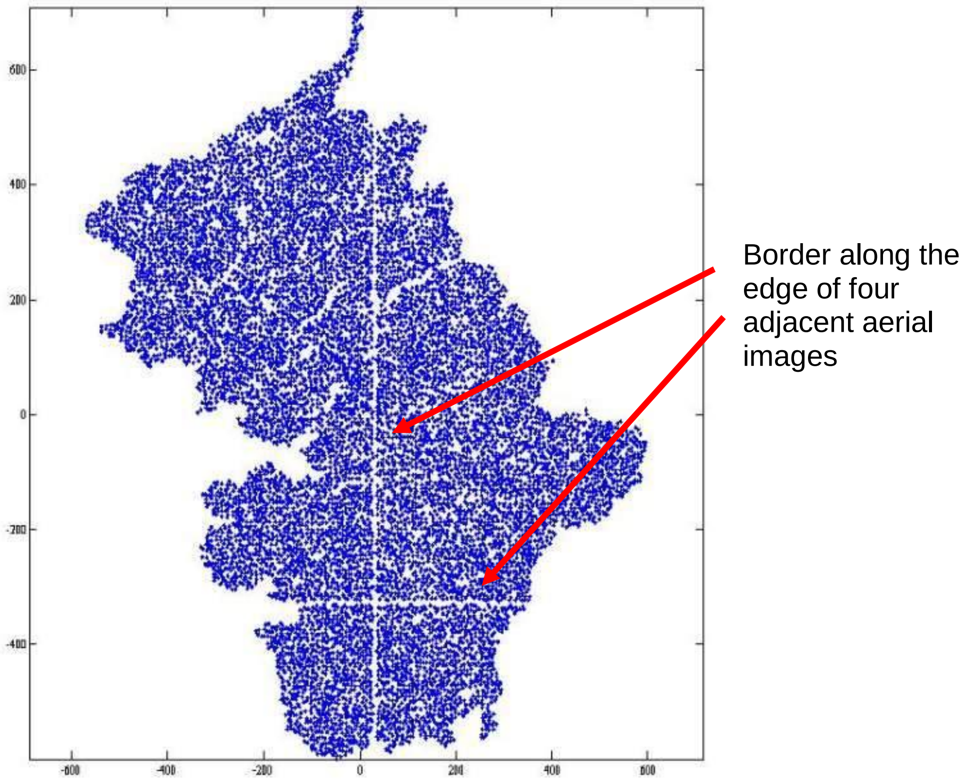


Figure 2. Esk 127 tree locations- erratic count.

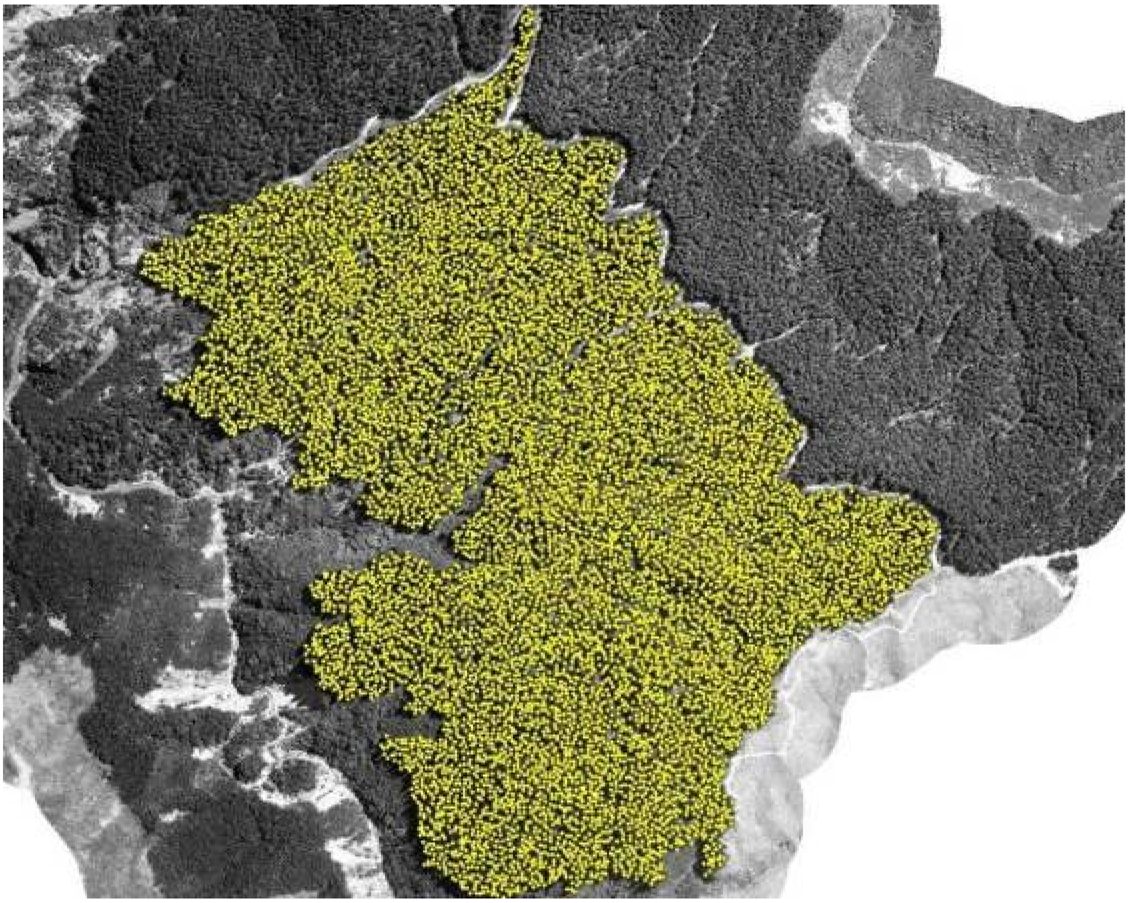


Figure 3. Esk 127 tree locations - correct count.

Image Quality and Specifications

Natural (landscape) factors as well as image handling errors can reduce the quality of an image to a degree that makes the image unsuitable for TIMBRS tree counting. The acquisition and pre-processing of the imagery remain a crucial step, and only if the data quality is known can the settings of the algorithms be adjusted correctly.

Specular Reflectance

One of the natural quality reducing factors can be specular reflectance from water bodies, which occurs when the angle of incidence of the sun light striking a smooth water surface is the same as the angle of reflection with the camera. An example of specular reflectance is highlighted in Figure 4, with the area of interest encircled. This effect significantly affects the performance of TIMBRS and the condition should be avoided when the image is acquired.

Figure 4. Mohaka 181- specular reflectance

Image Processor Errors

Errors can include things such as lines between merged parts of an image, perhaps due to a lack of data. Features such as scratches or dirt on the image and tonal differences due to merging separate images together can affect the image quality adversely (Burtch, R. 2004). Dirt specks generally appear as dark spots on the aerial photo and can be mistaken for small water bodies (Smith, G. 1995). Hair or lint usually appear as wavy lines or grey or white spots. Like the dirt specks they can intrude into the image during scanning processes.

Figure 5 shows an aerial photograph of stand 181 in Mohaka forest, which appears to have a change in colour tone between the upper part and the lower part of the image. This is a result of merging different images that were taken on separate days. When using TIMBRS to obtain total tree counts, the parts with different colour tone have to be counted separately, as different masking parameters have to be applied.

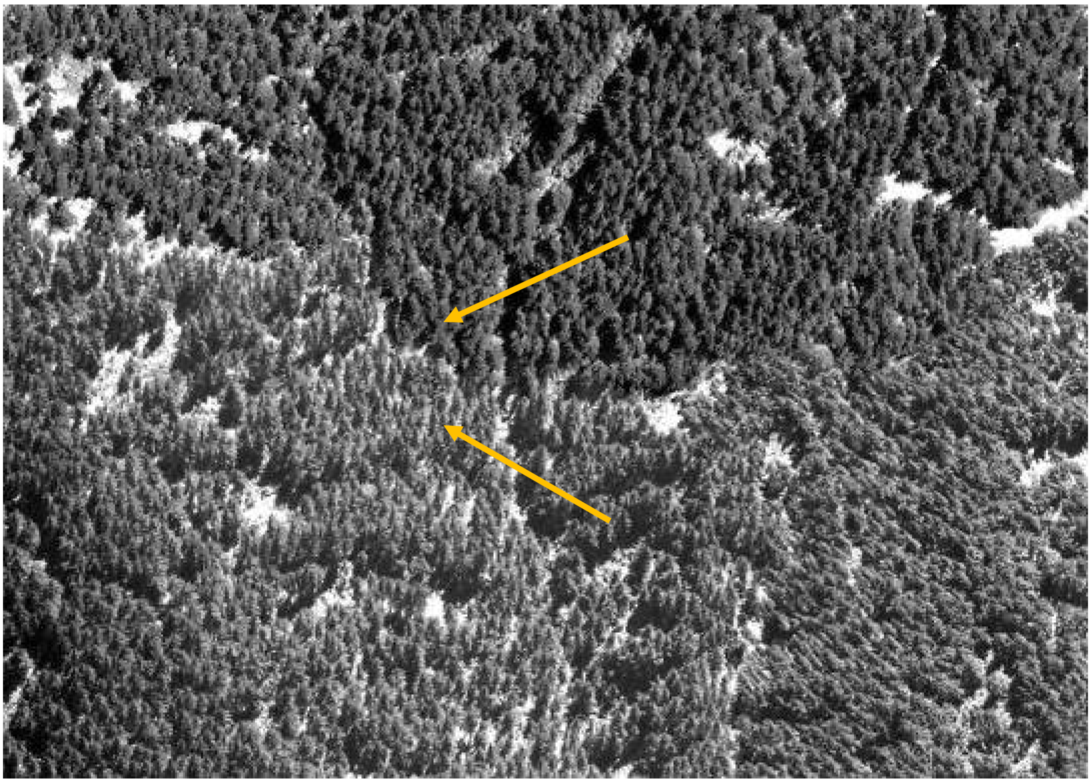


Figure 5. Mohaka 181 - tonal difference due to different mosaics.

Shadows

Deep shadows are caused by low sun angles and are an issue especially in hilly terrain with deep gulleys. Heavily shaded areas can lead to erroneous tree counts.

Clouds

Another natural quality-reducing factor can be clouds. In the previous part of the project, clouds were an issue when acquiring satellite images, such as QuickBird, GeoEye or WorldView2. Some of the imagery could not be used for tree counting, as the desired stand area was not visible due to cloud cover. Before acquiring imagery, especially satellite images, it is useful to check with the image provider to ensure the area of interest is cloud-free.

Trees with Real or Apparent Lean

There is some difficulty, especially with steep areas, due to the fact that images often display trees as if lying on their side, rather than appearing upright, which would show a roughly circular crown. This can be a result of the plane tilting during the image recording, often caused by wind. It should be addressed with the image provider and will most probably result in re-flying the area. There is speculation that the tree counting algorithm used in TIMBRS, and for that matter in any other two-dimensional tree counting software, might not be reliable when used on reclined trees, as the algorithms are based on a circular shaped crown, as when viewed from above.

During the use of the TIMBRS software, it appeared that the software did count leaning trees, but the degree of difficulty posed on the operator during the decision making process is significantly increased. The dot, which is placed on each tree crown at the end of the counting process might not end up on the tip of the crown, but instead anywhere along the conically shaped tree crown. This can be misleading and there is an increased chance that it will result in wrong decisions on the final tree count. It is arguable whether steep-sloped sections or stands that have been subjected to some wind damage in the past are counted accurately or whether the user's eye 'picks' a count that seems reasonable.

Limitations Due to Variations in Tree Stocking

Kang 945/1 and Esk 131 showed a significant change in stocking within the stand as, clearly, past silvicultural operations had not been applied uniformly. The change in stocking was detectable when using TIMBRS, and the different stocked areas had to be counted separately using different distance filters (see Figure 6). The stands could have been stratified in the planning process with different sampling schema. Tree form was noticeably different.

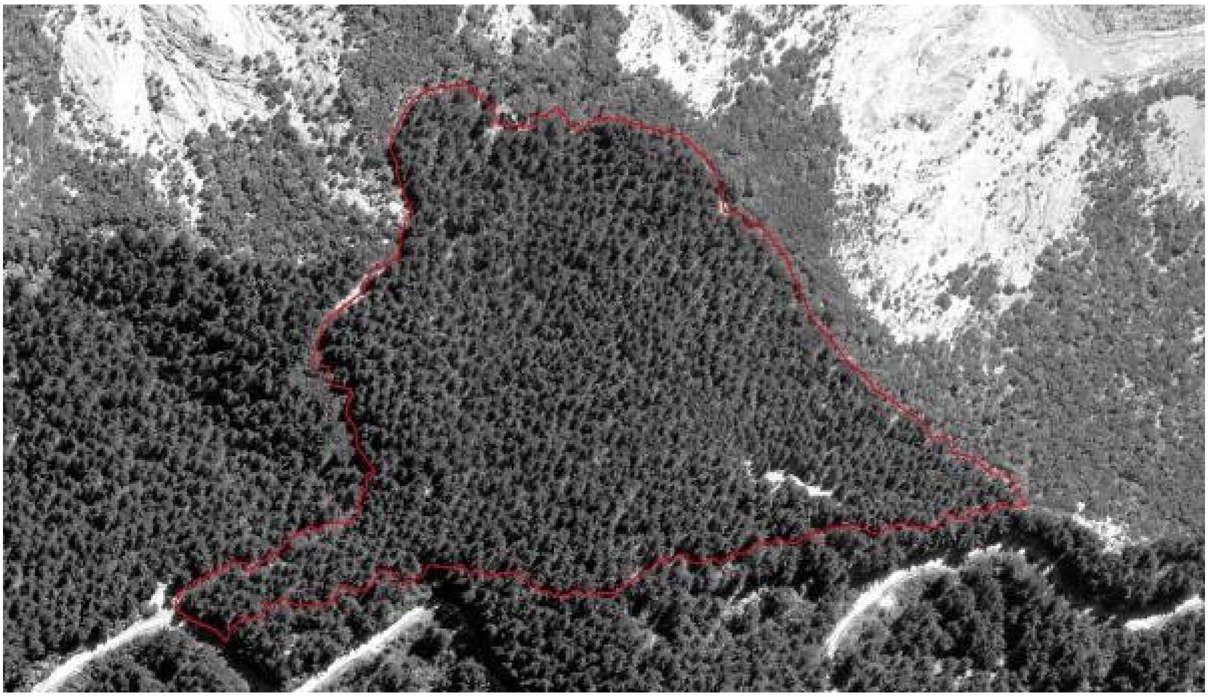


Figure 6. Esk 131- heterogeneously stocked area

Tree Counts

The senior author of this report used TIMBRS to determine tree counts for the whole of the stand and for the part that had been counted on the ground by the field crew. As in the previous study, TIMBRS was used without knowing the results of the ground surveys. By now, the operator had become moderately experienced, having carried out the same exercise in the previous year. In the field the crews distinguished between live trees, dead trees, dead tops and top outs and leaning trees that were not in the canopy.

Tables 2 and 3 show that TIMBRS can present accurate results when comparing the live trees standing, but does not seem to account for dead trees, trees with dead or broken tops, or trees that are heavily leaning where the crown does not reach the top of the canopy. Distinguishing between these characteristics was not feasible using TIMBRS, and only the total figure was produced.

Table 2. Manual versus TIMBRS tree counts, all trees.

Forest	Timbrs tree count	Manual count all trees					% difference including dead trees (Total/Timbrs)	% difference live trees (live/Timbrs)
		alive	dead	dead top & top out	leaning	Total		
Kang_9_5	763	765	0	25	6	796	-4%	0%
Kang_945_1	481	478	0	137	16	631	-31%	1%
Esk_127	502	485	0	3	2	490	2%	3%
Esk_131	238	238	0	2	1	241	-1%	0%
Moha_180	172	169	3	2	1	175	-2%	2%
Moha_181	150	150	0	3	1	154	-3%	0%
Average							**-6%**	**1%**

Table 3. Manual versus TIMBRS tree counts, live trees only.

Forest	TIMBRS tree count	Manual count	Difference # of trees	% difference live trees
		Live		
Kang_9_5	763	765	-2	0%
Kang_945_1	481	478	3	1%
Esk_127	502	485	17	3%
Esk_131	238	238	0	0%
Moha_180	172	169	3	2%
Moha_181	150	150	0	0%
Average				**1%**

Data Analysis

The company inventories using bounded plots took place up to three years earlier. To make a valid comparison between the different inventory methods, the plot-based results were grown forward in time so the analysis date was identical with the single tree sampling date, see Table 5. The PPM88 growth model was used to project the Kaingaroa stands forward; the Hawkes Bay Forests growth model was used for the four PanPac stands.

Table 4. Measurement dates and simulation times.

Stand	Bounded plot meas. date	Single tree meas. date	Prediction time (in months) for bounded plots
Kang 945_1	16/07/2007	1/04/2009	21
Kang 9_5	10/01/2008	26/03/2009	15
Esk_127	15/11/2007	29/04/2009	17
Esk_131	17/12/2007	30/04/2009	16
Mohaka_180	2/05/2006	14/05/2009	36
Mohaka_181	23/05/2006	14/05/2009	36

ATLAS Cruiser was used to analyse all the data, both those collected during conventional plot-based inventory and those gathered using the single-tree sampling approach. The cut pattern used was that provided by each company, with six or seven log grades. Probable Limits of Error of total recoverable volume, the different log products and the stand parameters of stocking, basal area and mean diameter were determined for all six stands. To convert totals to per hectare values, net stocked areas were obtained from the company stand records, despite doubt about their accuracy in some cases. Differences between the boundaries demarcated on the GIS compared to the photography were evident in some stands. No attempt was made to estimate the size of errors in these area figures.

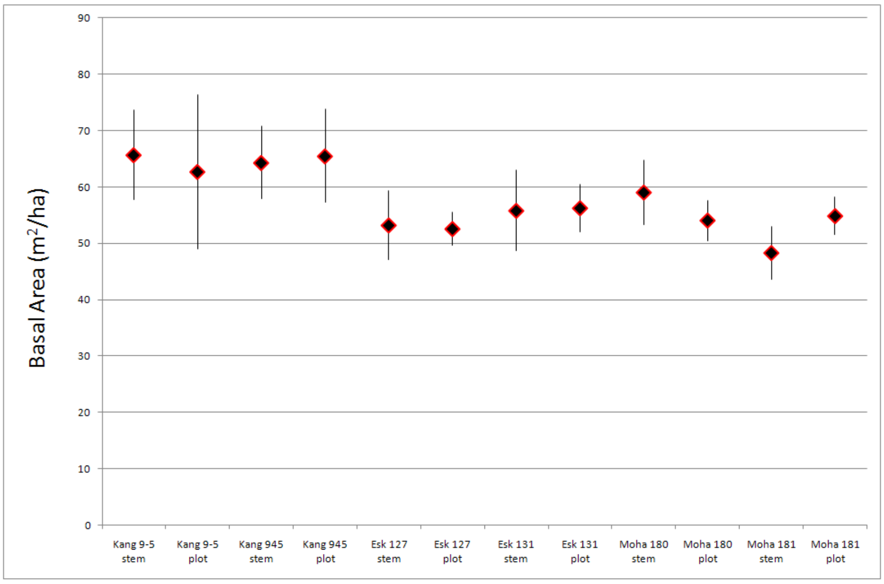
For the conventional inventory, each plot was assumed to be from a simple random sample, ignoring that plots were established systematically on a grid design. For the single-tree approach, sampling error was calculated by assuming that each tree measured was an independent random sample; double sampling ratio of means estimators were used to calculate volumes as a function of the basal area of each tree, calculated from its measured dbh.

Table 4 shows the comparison of estimates of stand parameters between the two different inventory approaches for each of the six stands measured. Stockings for stem-based sampling were determined using the TIMBRS tree counting software.

Table 5. Comparison of estimates and precision (PLE percent) of stand parameters between the single-tree sampling approach and plot-based approach.

	Stocking (stems/ha)		Basal Area (m^2/ ha)		T.R.V. (m3/ha ± PLE %)	
Stand	***Tree***	***Plot***	***Tree***	***Plot***	**Tree**	**Plot**
Kang 9-5	598	579 ± 14.2%	65.7 ± 12%	62.71 ± 21.8%	772.1 ± 14.3%	745.6 ± 23 %
Kang 945-1	303	352 ± 10.8%	64.31 ± 10%	65.49 ± 12.6%	800.4 ± 10.9%	781.8 ± 13.7%
Esk 127.01	160	148 ± 7.8%	54.19 ± 7.0%	52.54 ± 5.6%	556.9 ± 9.9%	516.5 ± 5.9%
Esk 131.01	263	263 ± 12.4%	53.44 ± 7.2%	56.24 ± 7.4%	484.5 ± 10.8%	540.9 ± 7.6%
Mohaka 180.01	167	171 ± 6.9%	56 ± 6.0%	54.05 ± 6.6%	653.1 ± 8.6%	646 ± 6.7%
Mohaka 181.01	184	190 ± 6%	48.49 ± 6.0%	54.84 ± 6.1%	574.2 ± 7.1%	591.2 ± 7%

These values are displayed graphically in Figure 7, showing the mean value (marker) and the 95% confidence interval (vertical line) for each stand and sampling strategy.



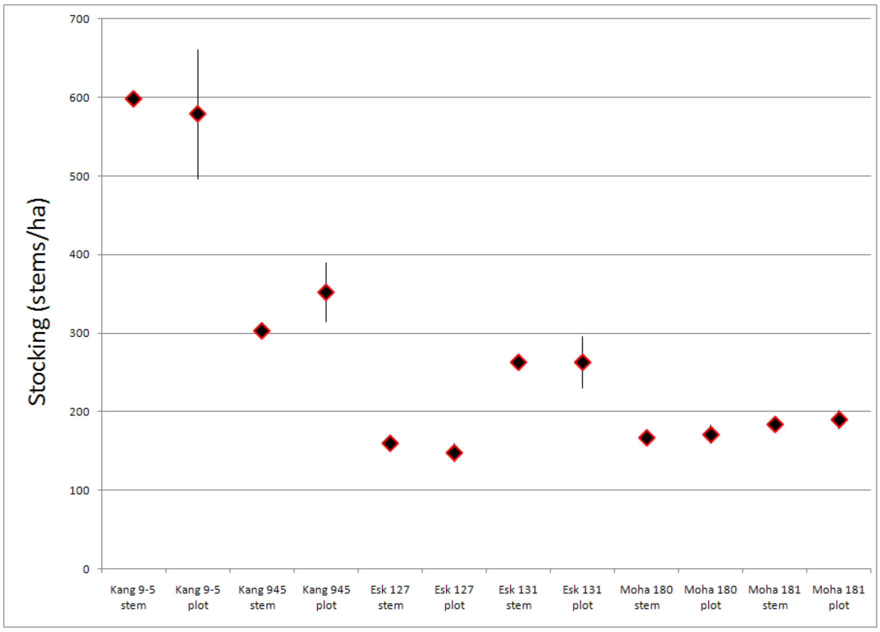
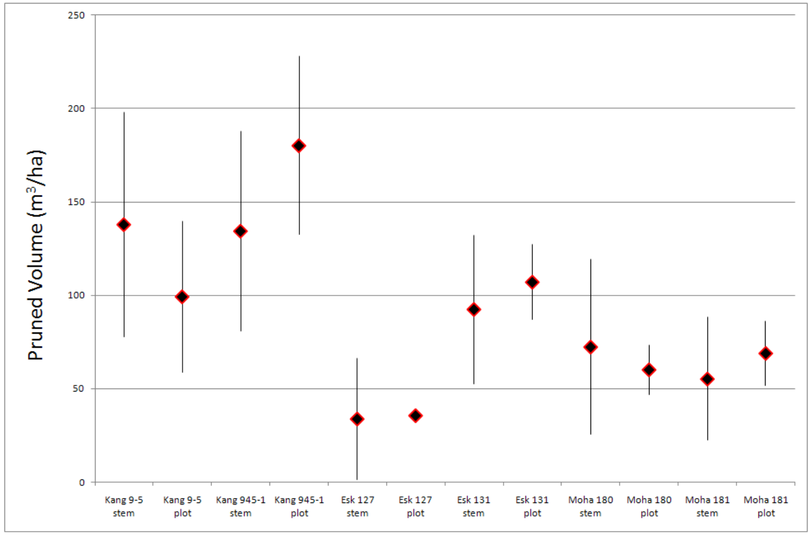


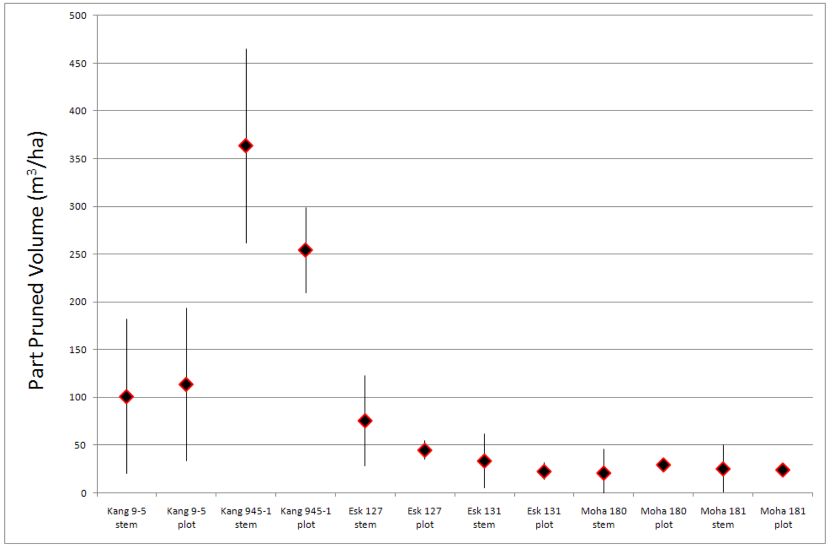
Figure 7. Comparison of Stand Parameters. Means and Confidence Intervals.

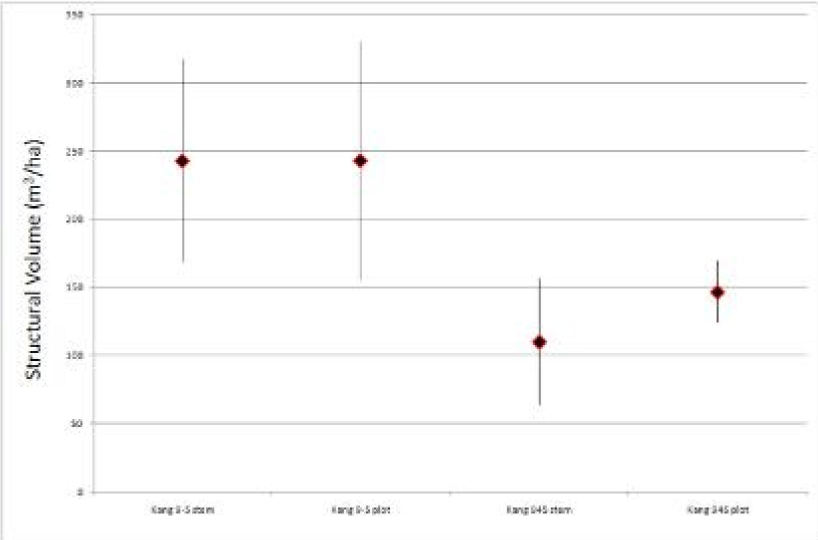
Estimates of the four log product volumes and total recoverable volume (T.R.V.) with their precision, by stand and sampling method, are shown in Table 5, Figure 8 and Figure 9.

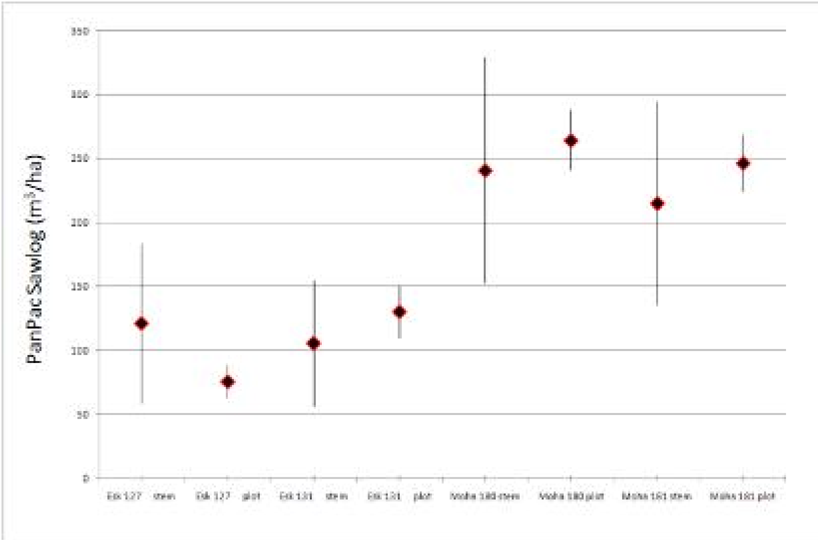
Table 6. Comparison of estimates and precision (PLE in percent) of product yield.

	Inventory method	Owner	Esk 127.01	Esk 131.01	Mohaka 180.01	Moha 181.01	Kang 9-5	Kang 945-1
Pruned (m3/ha ± PLE%)	**Plot**	**TLL + PanPac**	35.3 ± 6.84	107.0 ± 18.9	60.3 ± 22.0	69.0 ± 25.1	99.3 ± 40.8	180.1 ± 26.5
	Stem		46.0 ± 46.1	87.7 ± 25.5	96.0 ± 25.3	47.9 ± 36.5	137.9 ± 43.5	134.4 ± 39.7
Part Pruned (m3/ha ± PLE%)	**Plot**	**TLL + PanPac**	47.4 ± 20.5	22.8 ± 38	29.7 ± 22.9	24.4 ± 27.6	113.8 ± 70.2	254.2 ± 17.5
	Stem		62.1 ± 43.4	41.1 ± 41.1	17.1 ± 78.8	34.3 ± 51.3	101 ± 79.8	363.3 ± 28
A Grade Sawlog (m3/ha ± PLE%)	**Plot**	**PanPac**	4.1 ± 51.2	26.0 ± 37.6	46.0 ± 21.4	20.1 ± 22.8	-	-
	Stem		18.7 ± 87.1	15.9 ± 70.8	37.9 ± 52.9	66.0 ± 35.9	-	-
Structural (m3/ha)	**Plot**	**TLL**	-	-	-	-	242.9 ± 36	146.4 ± 15.6
	Stem		-	-	-	-	242.7 ± 30.7	110 ± 42.1
PanPac Sawlog (m3/ha ± PLE%)	**Plot**	**PanPac**	76.3 ± 16.9	130.8 ± 15.5	259 ± 9.1	243.6 ± 9.2	-	-
	Stem		112.3 ± 28.5	129.9 ± 23.1	246.3 ± 19.2	199.5 ± 19.2	-	-
Utility (m3/ha ± PLE%)	**Plot**	**TLL + PanPac**	229.2 ± 9.4	115.9 ± 12.3	142.4 ± 12.0	143.3 ± 13.9	22.8 ± 50.7	18.8 ± 19.4
	Stem		209.4 ± 25.1	122.0 ± 25.6	156.9 ± 23.9	138.9 ± 29.6	12.5 ± 109.2	19.4 ± 90.3
Industrial (m3/ha ± PLE%)	**Plot**	**TLL + PanPac**	14.7 ± 27.3	20.3 ± 35.3	8.4 ± 40.6	5.4 ± 48.8	83.4 ± 31.2	58.4 ± 41
	Stem		12.5 ± 83.1	8.5 ± 75.0	11.9 ± 128.4	4.2 ± 114.6	75.2 ± 62.6	88.9 ± 73.8
Pulplog (m3/ha ± PLE%)	**Plot**	**TLL + PanPac**	109 ± 12.6	118.1 ± 18.2	99.9 ± 9.8	85.2 ± 8.5	183.3 ± 15.6	123.9 ± 13.2
	Stem		95.9 ± 31.0	79.3 ± 24.0	87.0 ± 26.1	83.5 ± 23.7	202.8 ± 28.6	84.5 ± 41
T.R.V. (m3/ha ± PLE%)	**Plot**	**TLL + PanPac**	516.5 ± 5.9	540.9 ± 7.6	646.0 ± 6.7	591.2 ± 7.0	745.6 ± 23	781.8 ± 13.7
	Stem		556.9 ± 9.9	484.5 ± 10.8	653.1 ± 8.6	574.2 ± 7.1	772.1 ± 14.3	800.4 ± 10.9


Pruned Volume (m3/ha)
250
200
150
100
50
0
Kang 9-5 stem
Kang 9-5 plot
Kang 945-1 stem
Kang 945-1 plot
Esk 127 stem
Esk 127 plot
Esk 131 stem
Esk 131 plot
Moha 180 stem
Moha 180 plot
Moha 181 stem
Moha 181 plot


Part Pruned Volume (m3/ha)
500
450
400
350
300
250
200
150
100
50
0
Kang 9-5 stem
Kang 9-5 plot
Kang 945-1 stem
Kang 945-1 plot
Esk 127 stem
Esk 127 plot
Esk 131 stem
Esk 131 plot
Moha 180 stem
Moha 180 plot
Moha 181 stem
Moha 181 plot


Structural Volume (m3/ha)


PanPac Sawlog (m3/ha)

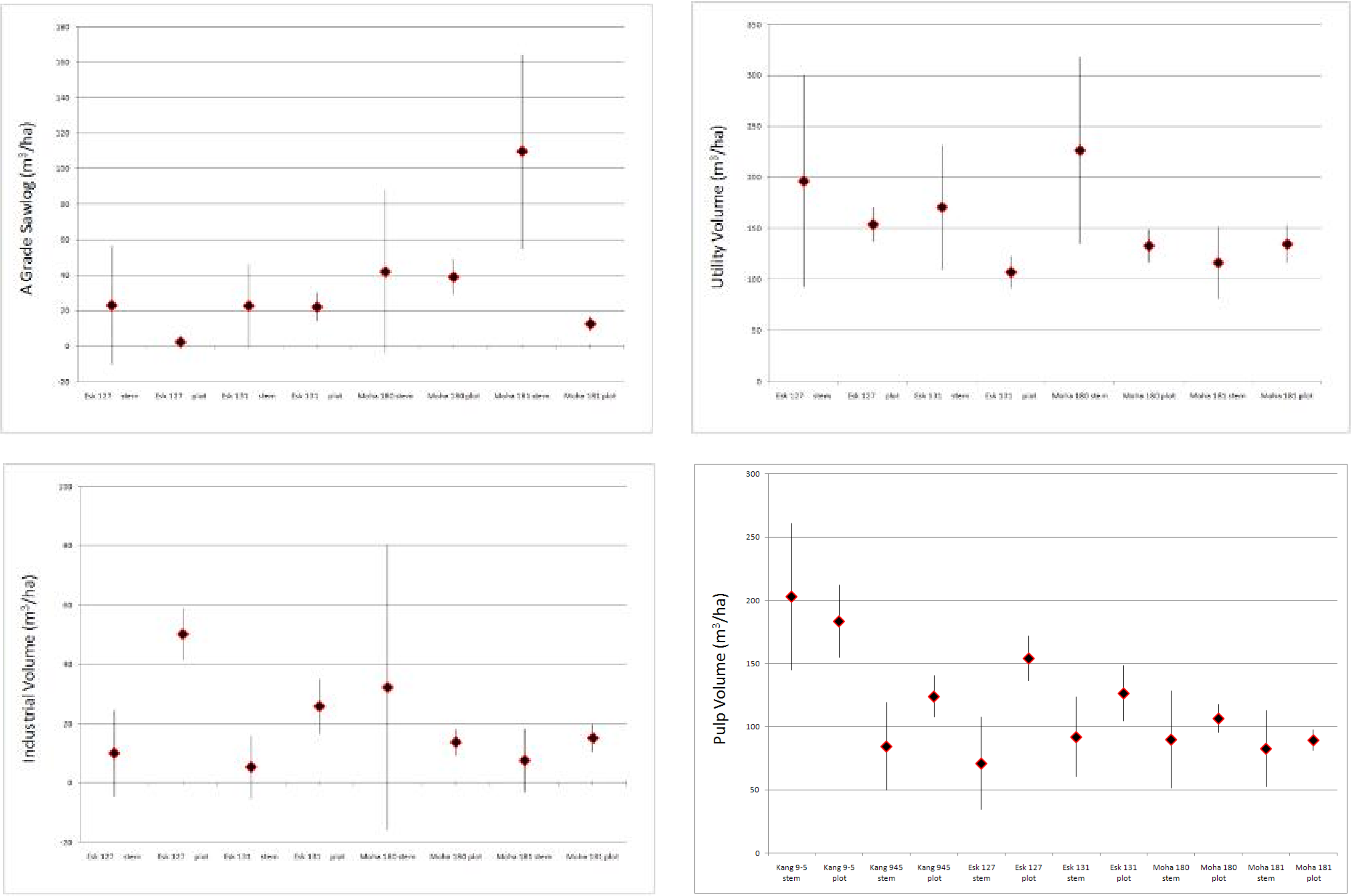


Figure 8. Comparison of Log Product Yield. Means and Confidence Intervals.

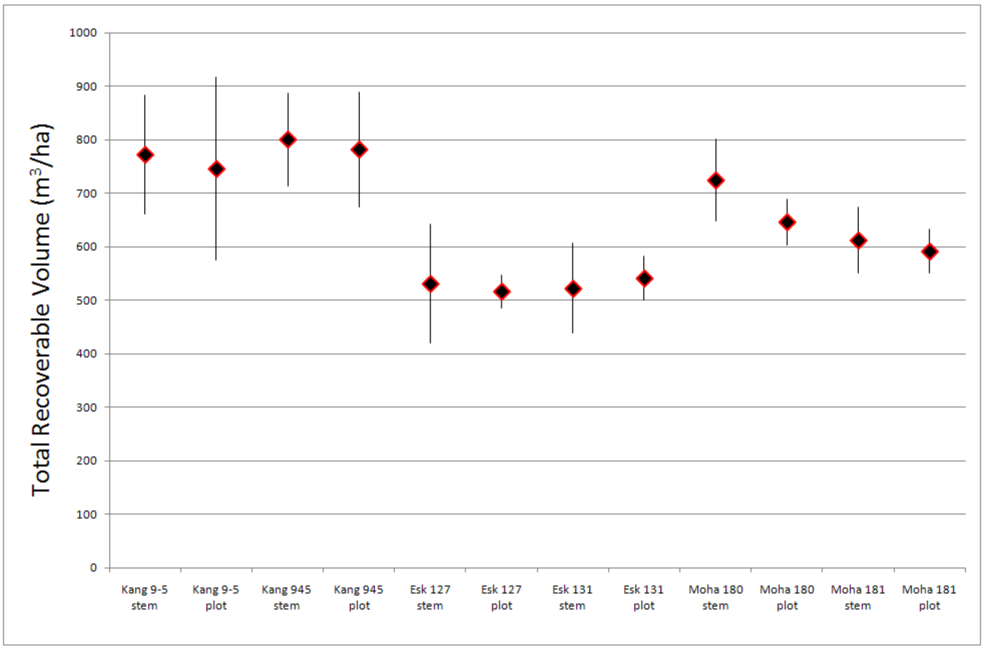
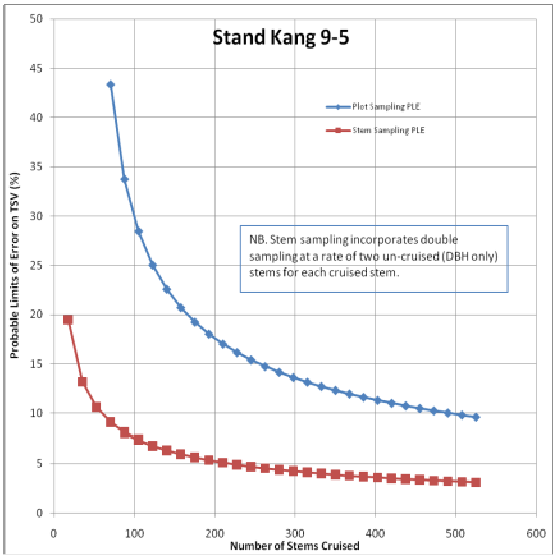


Figure 9. Comparison of T.R.V. Means and Confidence Intervals.

The relationship between precision and sample size is illustrated in Figures 10 and 11 for Total Standing Volume (T.S.V.). The graphs for the Kaingaroa stands assume that the proportion of cruised (primary) to un-cruised (secondary) stems is 1:2. The graphs for the Esk and Mohaka stands assume stem-based double sampling remains constant in each stand at 1:1.



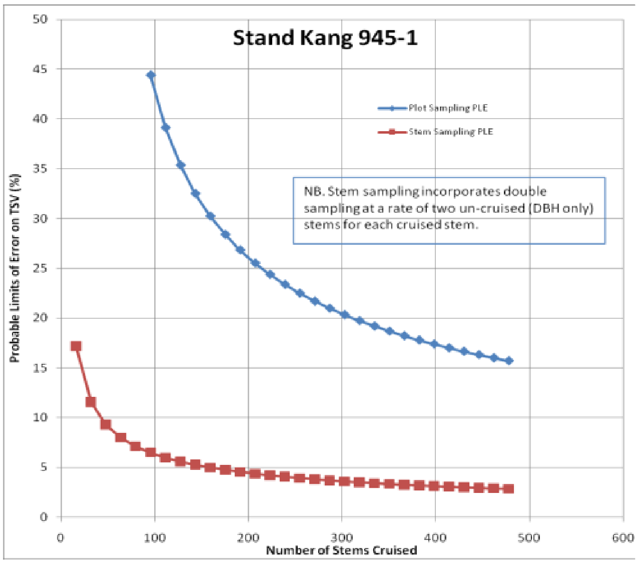


Figure 10. Proportion of primary to secondary tree is 1:2.

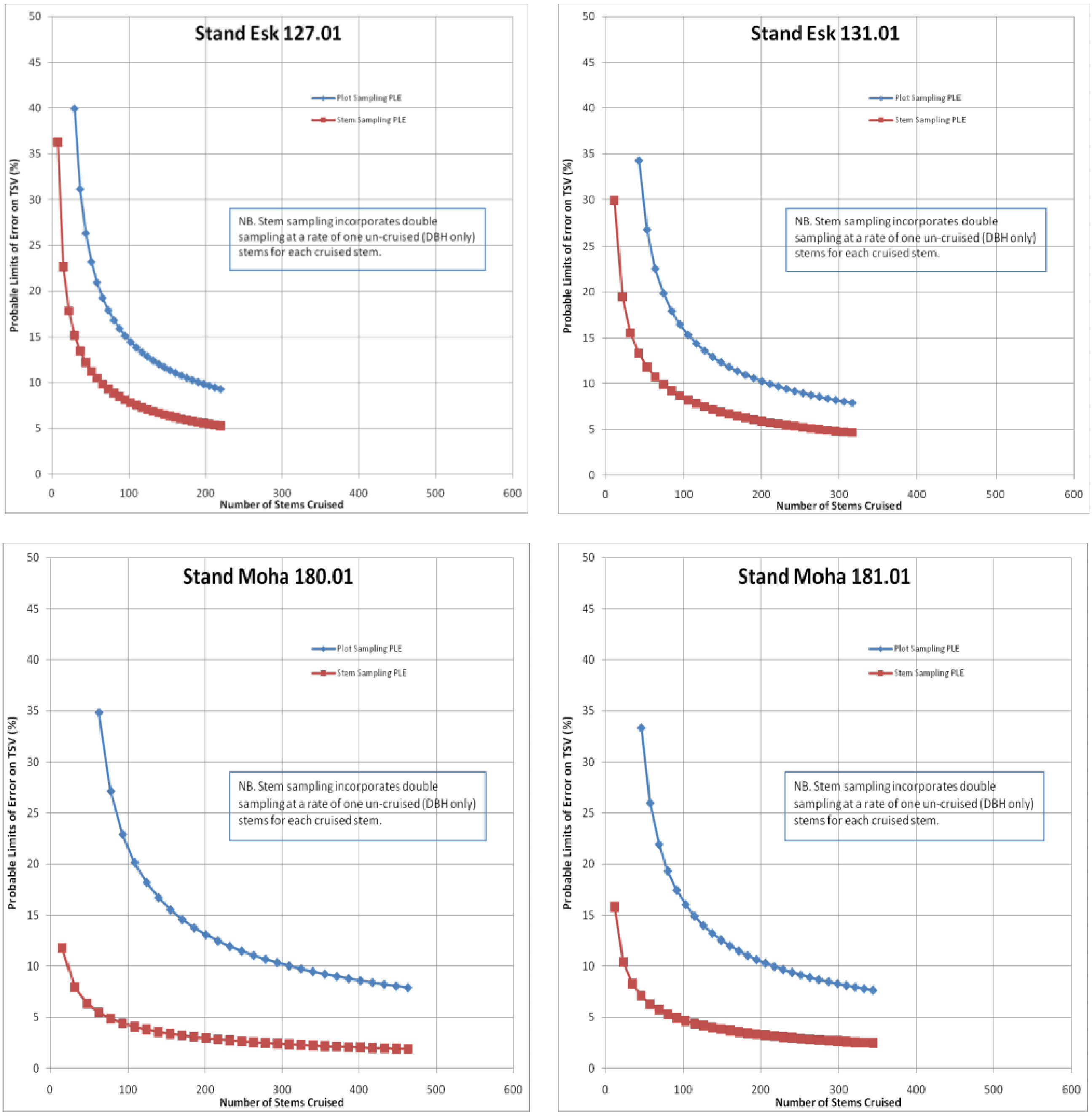


Figure 11. Proportion of primary to secondary tree is 1:1.

Time Study

The main focus in this report is on time spent measuring. The time at the end of the measurement for each tree and plot measured was available from the bounded plot inventory data-files. During single-tree sampling, the following times were recorded: departure time for work, arrival time at the stand, setup time at the vehicle, time spent walking from the vehicle to the sample line start point, all start and finish times of breaks, time per transect, as well as start and finish times when walking around obstacles such as creeks. For the individual-tree method, time recording started with the walk into the forest and finished with the arrival back at the vehicle at the end of the day. All breaks were included, as well as the total time spent walking without measuring. Unproductive walk time was included in the time study. In three cases during single-tree sampling, field crews came across insuperable obstacles like creeks and cliffs that had to be bypassed; the time taken to do so is included.

Table 7 shows the actual total times spent measuring trees for both sampling methods, without adjusting for equivalent PLE%. This time summary includes walking time as well as actual time spent measuring trees, but does not include travel time to and from the forest, rest breaks or time spent setting up. Appendix 2 shows the times in detail as carried out for single-tree sampling in this study.

Table 7. Measuring time.

Stand	Stand size	Bounded plot method		TimberLine method	
		h:min	days	h:min	Days
Moha 181	38.78 ha	48:48	6.1	09:59	1.3
Moha 180	39.76 ha	42:31	5.3	11:00	1.4
Esk 131	32.78ha	50:39	6.3	12:27	1.5
Esk 127	69.91ha	79:34	10	16:44	2.1
KANG 9_5	7.67ha	06:34	0.8	05:04	0.7
KANG 945_1	117.40 ha	29:27	3.7	06:59	0.9

The field crew measuring both Timberlands stands spent on average 2.9 minutes per tree, whereas the PanPac field crew took longer, on average 4.2 minutes per tree, due to the larger amount of data recoded by the PanPac crew. Furthermore the crew measuring the PanPac stands were new to the method, whereas Interpine was already familiar with the field procedures from the previous year's trials.

Travel and Non-productive Times

Travel times from base to the forest were recorded for all six stands. On average at least one third of each crew's working day was spent travelling to and from the site. Hence for crews that are remunerated for the time spent travelling, one third of the total inventory cost is assigned to travel alone. Travel time itself cannot be reduced other than by limiting the need to travel repeatedly.

The time components of setup time, walking time and time spent on breaks is on average less than 10% for each component individually, and in total is less than 20% of the total working time. The various time components differ for each inventory. The ranges as a percentage of the total of a full working day are:

Walking time adds between 5% and 15%,
Rest breaks between 4% and 12%,
Setup between 1% and 7%,
Travel to the forest between 25% and 45%,

Actual measuring occupies between 29% and 61%.

When the total measuring time using single-tree sampling is significantly less than plot-based inventory, fewer days are required for the inventory. Savings in travel time can decrease total costs further, as crews are not required to return to the stand as often. This has not been accounted for in the cost-benefit analysis as the logistical arrangements between different measurement companies and contracts differ markedly, with different policies regarding reimbursement of travel expenses.

Number of Crew Members

The method was trialled using different crew sizes in the two Esk stands of PanPac. Measurement times and practicality were compared for two-, three- and four-person crews. Only the active measurement time was taken into account in the analysis, which is however limited to a very small sample. Any time spent on travelling to and from the stand, breaks, setup times or time spent walking through mapped unstocked areas was not included when comparing efficiency due to field crew size.

On average the total time saving is highest for three-person crews with 45% time saving (Table 8) compared to the ordinary two-person crew. Using a four-person crew rather than a two-person crew resulted in a 19% time saving, but costs 62% more, due to the fact that twice as many people are occupied. It was observed that the method is manageable with both three- and four-person crews, although the four-person crew did not fully occupy all crew members at all times, whereas the three-person crew continuously made full use of all members.

Table 8. Comparison of number of crew members and associated time and cost savings.

No. in the field crew	No. trees measured	time per crew (min)	time per crew (h)	time saving (%)	$ ($30 per person/ hr)	cost saving (%)
2	100	456	7.6	-	456.00	0%
3	100	260	4.3	45%	390.00	14%
4	100	370	6.2	19%	740.00	-62%

Auto Correlation Between Trees on a Sample Line

In order to make a valid comparison between the costs of conventional bounded plot and single-tree sampling inventory, it is necessary to calculate the precision of each estimate and then to re-calculate the times and costs for equivalent levels of precision.

There has been criticism of the single-tree method as applied in this study because trees selected in the Pan Pac stands were adjacent within a sample line (in Kaingaroa, the two stands were inventoried by measuring every third tree on the line). This could lead to correlation between adjacent or near neighbouring sample trees such that the conventional double sampling formulae used underestimated the confidence limits of the sample.

Within sample lines, there is evidence of weak spatial autocorrelation, with the size of neighbouring trees being positively correlated (see Figure 12). The correlation coefficient (r) is less than 0.1 in absolute size, but is significantly different from zero in some cases.

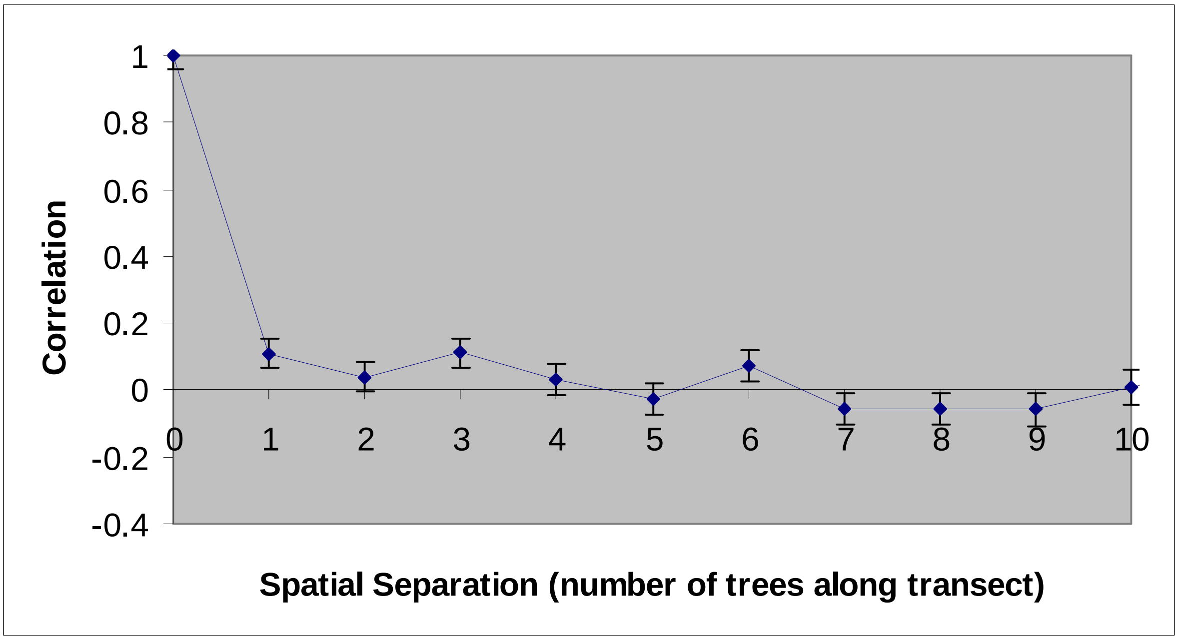


Figure 12. Spatial autocorrelation within transect averaged across all transects and stands. Error bars are standard errors.

The standard formula for calculating PLEs in forest inventories is based on the assumption that the sample units are randomly located. However, most forest inventories actually use systematic designs, and there is no theoretically correct method for calculating confidence intervals for these (Mandallaz, 2008). Using random sampling formulae is considered acceptable because experience has shown that the PLE formula is conservative on average when applied to a systematic design, especially to a square grid design.

The method employed in single-tree sampling is also a systematic design, but with the spacing between trees along the sample lines being closer on average than the spacing between lines, except at the apexes of the “zig-zag” layout. When the between-line to within-line spacing ratio is less than 5:1 it is expected that the PLE formula is still conservative, although less so than for a square grid design. As this ratio increases, the PLE will eventually tend to be under-estimated due to the auto-correlation effects between sampled trees, although the value when this occurs (perhaps 10:1?) is not known.

To ensure that no unfair cost advantage was attributed to the single-tree sampling method, it was decided to recalculate times as though every third tree had been selected to measure along a line, effectively tripling the walking distance in the four PanPac stands. This would reduce any autocorrelation effects to near zero and ensure that cost comparisons were on equal terms with regard to levels of precision. Even when all trees encountered in the sample-line were measured for dbh, with every second tree for merchantable volume, the sample method remains an objective sample and is unbiased.

Cost-benefit Analysis

Each of the six stands had been measured using both conventional bounded plots and single-tree sampling, by the same inventory companies, albeit several years apart. Given that the two inventory methods resulted in different levels of precision after the inventories, it was necessary to re-calculate the sample size on one of the methods for each pair of comparisons so that the analysis compared the costs of two methods achieving the same PLE% of total recoverable volume. The number of sample units that were required to give a PLE equivalent to the most precise estimate of each pair of comparisons was calculated. The cost for that inventory was then adjusted upwards. The costs of travel to and from the forest from base and for operational field supervision were excluded from the comparison; they are assumed to be identical for each method. No costs were included for inventory planning and analysis in the office. The experimental nature of the research made estimating these problematic for the individual tree sampling method. It is hypothesised that should this method become operational, office costs would decrease given some experience, and become comparable to any other inventory method.

Cost components included:

- image acquisition and software licensing;
- time to carry out image analysis for tree counting; and
- field measurements from time of arrival to time of departure from a stand.

It could be argued that the cost of ortho-photo images is zero for forest companies who have already acquired the images for other purposes, or where images can be obtained from local authorities free or at nominal cost. For consultants and others on the other hand, the image cost could be up to $250 per inventory, depending on the size and shape of the stand. Here, the cost was arbitrarily assigned to be $1 per ha plus another $4 per ha for the licensing cost of the tree counting software TIMBRS.

In the two Timberlands stands, every third tree encountered along the sample line was measured for dbh by single-tree sampling, and every ninth tree was cruised, with the average distance between cruised trees being 39 and 98 m for the 7.7 ha and 117 ha stands respectively. It is argued that this distance leaves sufficient space between the sample trees to reduce any impacts of auto-correlation between adjacent trees on the true sampling variance to negligible proportions. The PLE%'s of the bounded plot inventories were higher than those achieved by single-tree sampling, so the costs of the bounded plot inventories were inflated relative to estimated to provide equivalent PLE%

In the four PanPac stands, every tree along the sample line was measured for dbh, and every second tree was cruised for recoverable volume. The low stocking resulted in average distances between cruised trees of 47 m, 21 m, 25 m and 32 m, but it was decided to calculate costs as though only every third tree on the sample line had been measured for dbh, and every sixth tree for recoverable volume. Walking distance along the sample line would therefore be effectively tripled, so that average distances between trees would rise to 141, 63, 75 and 96 m respectively.. Times and costs were increased proportionally over those incurred by the field teams in the trial. The PLE%'s of the bounded plot operational inventories carried out earlier by PanPac were lower than those achieved by single-tree sampling. The numbers of trees to be measured of the single-tree sampling inventories were increased to equalize PLE% and costs were further inflated appropriately.

Table 9 is a summary of the final calculated costs using a two-person crew in all cases. The 18 and 63 bounded plots in Kaingaroa represent the sample size to provide a PLE% equivalent to single tree sampling. For the PanPac stands, the 366, 254, 88 and 108 trees sampled (measured for dbh) are those required for the single-tree sampling method to produce PLE%'s equivalent to those of the PanPac bounded plots. The numbers of bounded plots established by PanPac are those given in Table 9; the actual bounded plot numbers at Kaingaroa were somewhat lower than shown. The numbers of trees measured and sample-line distances are given for each stand in Appendix 1. A larger, more detailed spreadsheet of the predicted costs and comparison is available.

Using the field crew and image processing rates of the study, the total costs for all six stands were $19,741 and $14,686 for the bounded plot and single-tree inventory respectively, a difference of $5,054 or 26% of the costs of the current operational inventory.

However, in one stand, Esk 131, the cost of the single-tree sampling was much higher than with bounded plots. This stand had very rough conditions with several gullies where it was necessary to walk out to the roadside, cross the obstacle, then return to find the sample-line. Walking was difficult and time consuming, especially when the distance calculated to be walked was increased so that only every third tree encountered was sampled. One part of the stand was untreated and had heavy malformation so that the stem characteristics and tree sizes were very different from the remainder of the stand. Some 250 trees were required to be measured for dbh (125 to be cruised) to obtain a PLE with 7.5%. This type of stand would be better sampled using bounded plots, rather than using long, sample lines through the stand where walking extensively through the stand is a disadvantage rather than an advantage. If this stand (and others of a similar type) is removed from the cost analysis, then the difference between conventional bounded plot inventory and single-tree sampling rises to 39% of the bounded plot cost (bottom row of Table 9).

Planning the single-tree sampling did not take into account the information provided from the company's GIS and from the individual tree map obtained from TIMBRS while counting trees. If this had been taken into account, and given the experience from this trial, it would have been possible to greatly improve the efficiency of the field crew through stratified sampling and the use of pre-planned GPS way points to circumvent inaccessible gullies. Stratified sampling would also have improved the bounded plot inventory.

Table 9. Two-person crew plotting cost for adjusted PLEs. Results for all stands and with results for Esk 131 omitted.

			Bounded plots			Single tree sampling			Difference (bounded-z)			
Owner	Stand	stand size (ha)	# plots	TOTAL cost $	field time (hrs)	# trees measured	TOTAL cost $	field + tree count time (hrs)	TOTAL cost $	%	Total time (hrs)	Equivalent PLE %
TLL	KANG 9_5	7.67	18	$1,283.58	15	100	$581.82	7	$701.75	55%	8	13.3
TLL	KANG 945_1	104.3	63	$4,280.44	49	112	$1,552.11	14	$2,728.33	64%	35	10.5
PanPac	Esk 127	69.91	71	$5,092.27	80	366	$4,222.52	61	$869.75	17%	19	5.8
PanPac	Esk 131	32.78	33	$3,240.53	51	254	$4,210.75	64	-$970.22	-30%	-13	7.5
PanPac	Moha 180	39.06	40	$2,721.07	43	88	$2,197.69	31	$523.37	19%	11	6.7
PanPac	Moha 181	38.78	39	$3,123.20	49	108	$1,921.31	27	$1,201.89	38%	22	6.6
		Total		$19,741.08			$14,686.20		**$5,054.88**	**26%**	**81**	
Eak 131 omitted				$16,500.55			$10,475.45		**$6,025.10**	**39%**	**94**	

CONCLUSION

Single-tree sampling with an estimate of the total numbers of trees in an inventory population offers potential for reducing inventory costs if the desired precision is held constant, or providing an acceptable level of precision when a full bounded plot inventory is too costly. For the six stands trialled in this study, if every third tree encountered in a sample-line were to be selected and measured for dbh, with the second or third tree so selected being cruised for recoverable volume, it is estimated that direct inventory costs might be reduced by some 26% over the existing bounded plot inventory. Cost estimates included those of tree counting from remotely sensed imagery and of field operations, but excluded travel from base to and from the forest. Because of the experimental nature of the work, the times spent in planning and in analysis in the office were also excluded.

For one stand in the trial, the cost of using single-tree sampling was greater than conventional bounded plots when the length of the sample line was increased to select only every third tree encountered. This stand was moderately large, had very difficult, slow walking conditions with impassable obstacles requiring exit to the road to bypass them. In hindsight, the single tree sampling for this stand could have been better planned, with stratification and use of pre-planned GPS way points. Stands of this character, where walking within a stand should be minimised as far as possible, are most likely better inventoried using bounded plots or some form of cluster sampling.

If this stand is removed from the cost analysis, then the calculated cost reduction for the other five stands averaged 39%. These cost reductions ranged from 17% to over 60% for individual stands.

The method performs very well relative to bounded plots when walking within the stand is easy and individual tree form is relatively uniform. In these situations the method would perform best relative to bounded plots where there is also variability in recoverable volume per hectare across the stand. As in the previous trial, single-tree sampling estimated recoverable volumes in the small 7-ha stand with a reasonable precision (± 13%), whereas the current plot sampling intensity as implemented by the company under its routine procedures did not.

Any auto-correlation between trees on a sample-line affects only the accuracy of the estimate of PLE%, not the accuracy of estimates of means. This correlation can be reduced to negligible proportions by sampling every third tree encountered, perhaps every second tree. Ideally, the layout of the locations of the trees selected for cruising should look nearly “square”. Tree means and statistics can then be estimated using standard double sampling with a random sampling approach and a ratio of means estimator.

Field procedures are easy to carry out and can be used with existing equipment. GeoMaster has been modified to assist in designing sample lines, as could any other reputable forest management GIS.

Accurate tree counting is possible to within ±5%. TIMBRS is adequate for research use, but would need re-writing and upgrading to become a practical commercial product.

Commercial services are becoming increasingly available internationally but will demand good quality imagery. Satellite imagery is adequate. Current NZ ortho-photographs obtained directly from forest companies are not always adequate, but the original digital data may be suitable and may be still held by the image provider.

The use of LiDAR to count trees offers great promise, as it is impervious to shadows caused by broken terrain and provides information on the third dimension, height, to assist in distinguishing tree from tree. Research is needed on the best way to conduct inventories using LiDAR under New Zealand conditions.

ACKNOWLEDGEMENTS

We would like to acknowledge Timberlands Limited, Rotorua, and Pan Pac Forest Products Limited, Napier, for their support in providing stands and past data. The commercial field crews of Interpine Forestry Limited, Rotorua, and Forest Mensuration Services, Napier, deserve thanks for being constructively forthcoming in trying this rather new and different approach to pre-harvest inventory, regardless of the blackberry and terrain.

Scion staff (and ex-staff) involved in various stages of the work were Paul Silcock, Rodrigo Osorio, Jason Bennett, Luke Bettis, Brian Clement and Christian Pilaar. Mark Kimberely, Scion, assisted with the auto-correlation analyses. He and Dr Cris Brack, ANU/Waiariki reviewed the statistical theory and problems, and both suggested practical solutions or constraints.

REFERENCES

Adams, T H; Goulding, C J; and Pont, D. 2010. The opportunities for LiDAR in forest management and harvesting. FFR report R060 - F10104 – 2, submitted.

Burtch, R. 2004. Orthophotography as a Gis Mapping Product. The Center for Photogrammetric Training. Ferris State University. IMAGIN Annual Conference 2004. 17pp

Cochran, W.G. 1977. Sampling Techniques. 3rd Edition. John Wiley & Sons, New York. 448pp

Culvenor, D.S., 2002. TIDA: An Algorithm for the Delineation of Tree Crowns in High Spatial Resolution Remotely Sensed Imagery, Comput. Geosci. 28 (2002), pp. 33–44.

Culvenor, D.S., Coops, N.C., Preston, R. and Tolhurst, K. 1998. A spatial clustering approach to automated crown delineation. In, Hill, D.A. and Leckie, D.G. eds. “Automated interpretation of high spatial resolution digital imagery for forestry”. Victoria, British Columbia, pp 67-80.

Deadman, M.W. and Goulding, C.J., 1979: A Method for the Assessment of Recoverable Volume by Log-types. New Zealand Journal of Forestry Science 9(1): 225-39.

Fritzsche M.F., and Goulding, C.J. 2010. User Manual - Planning and Field Guide for Single-Tree Sampling. FFR internal report. 27pp.

Fritzsche, M.F., Goulding, C.J., Gordon, A.D., Silcock, P., Heine, S. 2009. Improving Operational Forest Inventory -The Benefits of Integrating Single Tree Sampling With Advanced Remote Sensing Technology. FFR internal report. 32pp.

Goulding, C.J. and Fritzsche, M.F. 2010. Improving Forest Inventory for the Woodlot Owner. New Zealand Tree Grower, May 2010: 10-12.

Goulding, C.J. and Lawrence, M.E. 1992 Inventory Practice for Managed Forests. FRI Bulletin 171, Forest Research Institute, Rotorua. 52pp.

Mandallaz, Daniel. 2008. Sampling techniques for forest inventories. Chapman & Hall, Taylor & Francis, Florida. 256 p.

Smith, G. S. 1995. Digital Orthophotography And Gis. ESRI Conference Proceedings. http://proceedings.esri.com/library/userconf/proc95/to150/p124.html

APPENDICES

Appendix 1. Stand Details

KANG 9/5

Forest owner: Timberlands Limited

Stand details
The stand was planted in July 1984 with an initial stocking of 1670 sph. The current stocking is estimated to be 562 sph and occupies a total stand area of 7.67 ha. The stand was pruned in three lifts. The first lift was carried out in June 1990 to 3.2 m (333 sph), the second lift occurred in September 1992 to 6.5 m (263 sph) and a third lift followed in September 1992 to 4.6 m (250 sph). One thinning was carried out in June 1990 to 567 sph.

Sample line details
The sample line was 4 m wide, and every third tree was measured for dbh, with every third sample tree (i.e. every ninth tree encountered) being fully assessed. The aim was to measure 100 trees in total for dbh. At least 30 trees were to be measured for height. The total sample line length was 1297 m (the target was 1287 m) and consisted of five individual lines arranged in a zigzag pattern across the stand, see Figure 6. The average distance between trees cruised for merchantable volume was 39 m.

Notes
The hindrance level varied from mostly no undergrowth and flat terrain in the first part of the stand to heavy hindrance due to scrub and blackberry in the second part of the stand. The walking line ran between two rows of trees for a sequence of four trees along one of the sample lines. Along the fourth sample line part of the stand was regenerating and was not measured. No bounded plots were installed in that area either. The sample line ended up being shorter than anticipated due to the shortened sample line four, and another sample line was added in the field to get the 100 trees anticipated. This could have been avoided if the aerial photograph was used as a visible layer when planning the sample line design, rather than relying on maps based on stand shape estimates, where the stand records did not include information on the regenerating area.

Picture 1 Map Kang 9/5

KANG 945/1

Forest owner: Timberlands Limited

Stand details

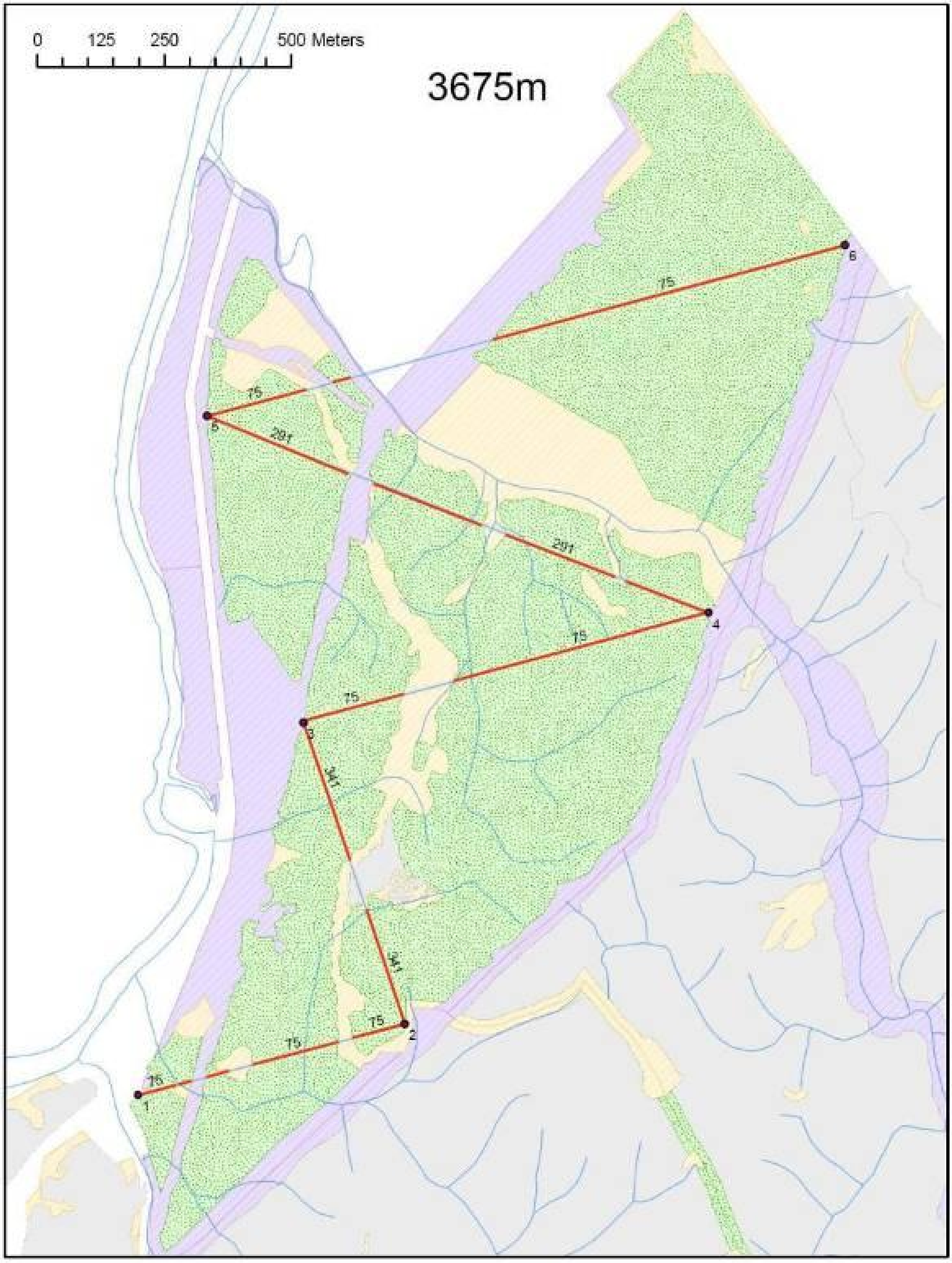
The stand was planted in January 1981 with an initial stocking of 1666 sph. The current stocking is 273 sph across a stand area of 117.4 ha. The stand has been pruned twice with the first pruning lift being carried out in March 1986 to 4.5 m (250 sph) and the second lift carried out in August 1989 to 6.2 m (252 sph). Two thinnings occurred, with thinning one being carried out in March 1986 to 385 sph and thinning two occurring in September 1989 to 242 sph.

Sample line details

The sample-line was 3 m wide, with every third tree being sampled and every third sample tree (i.e. every ninth tree encountered) being cruised. The sample line was required to be at least 3475 m, but in practice was determined to be 3675 m long. Five individual sample lines were arranged in zigzags, with 112 trees measured in total for dbh. The average distance between trees cruised for merchantable volume was 98 m

Notes

The stand had heavy hindrance with very rough terrain, plenty of blackberry, pongas and other undergrowth that made walking very difficult. Parts of the stand were very steep, some gullies were present, as well was unstocked areas including cutover and fire breaks full of blackberry. The western part of the stand had a much higher stocking, but was done on the same sample line. Stratification prior to planning the sample lines would have improved sampling efficiency.



Picture 2 Map Kang 945/1

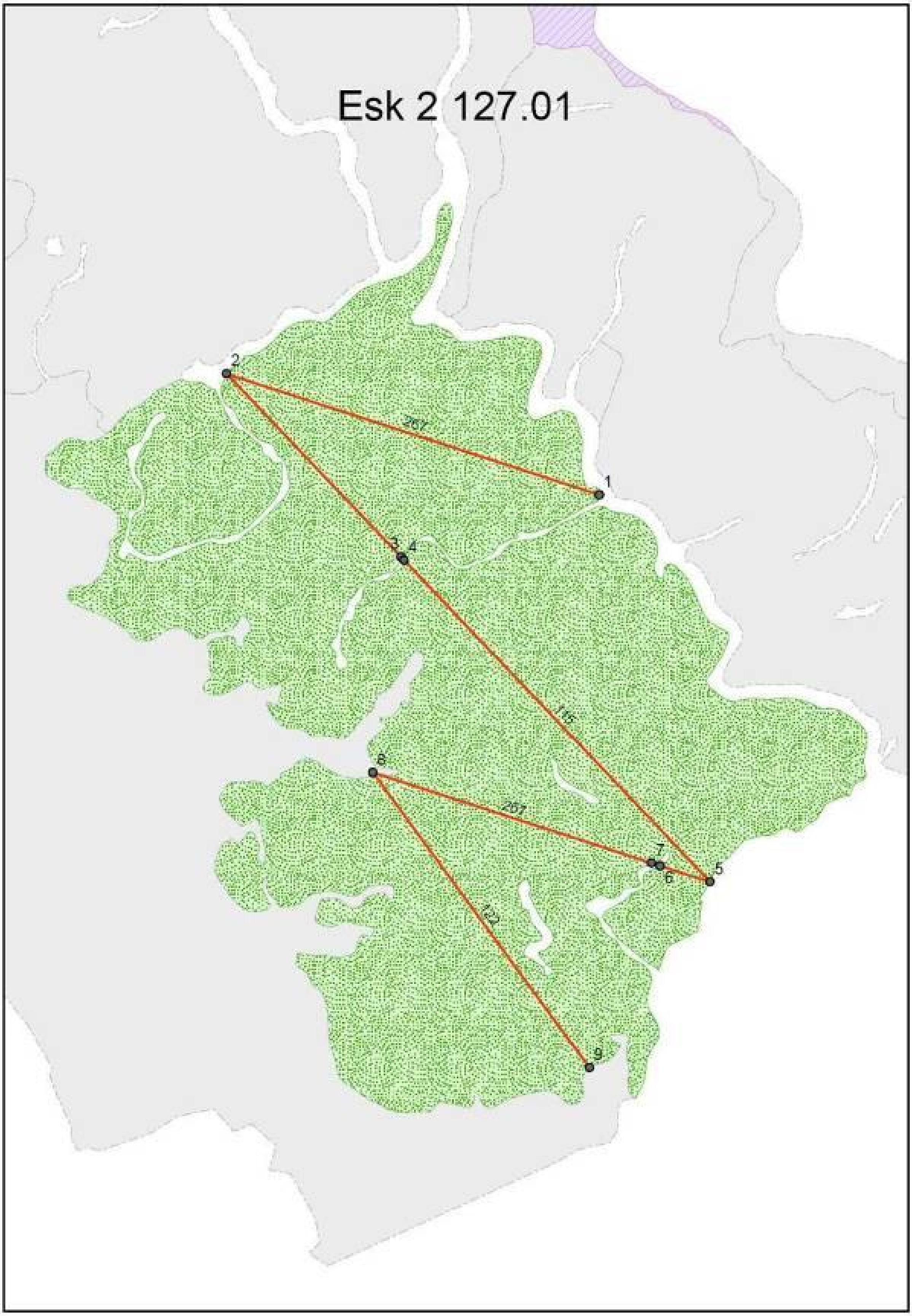
ESK 127

Forest owner: PanPac Forest Products Limited

Stand details
The stand was planted in July 1982 with an initial stocking of 1543 sph. The current stocking is estimated at 148 sph, with a total stand area estimated at 69.9 ha. One pruning lift was carried out in March 1989 (188 sph pruned to 4.2 m). Three thinnings occurred in 1987 to a final 200 sph.

Sample line details
The sample line swath width was 3 m, with every tree being sampled and every second sample tree being cruised. The 2560 m length (target length 2500 m, needed 2157 m) consisted of four zigzags with a total 110 trees being measured for dbh. The average distance between trees cruised for merchantable volume was 47 m

Notes
Part of the stand was harvested and there was some difficulty in finding the transect line after crossing the cutover area. Hindrance was medium to severe with plenty of undergrowth in parts of the stand, and many gullies and creeks, some of them impassable. The stand was steep with slopes between 22 degrees and 33 degrees.



Picture 3 Map Esk 127

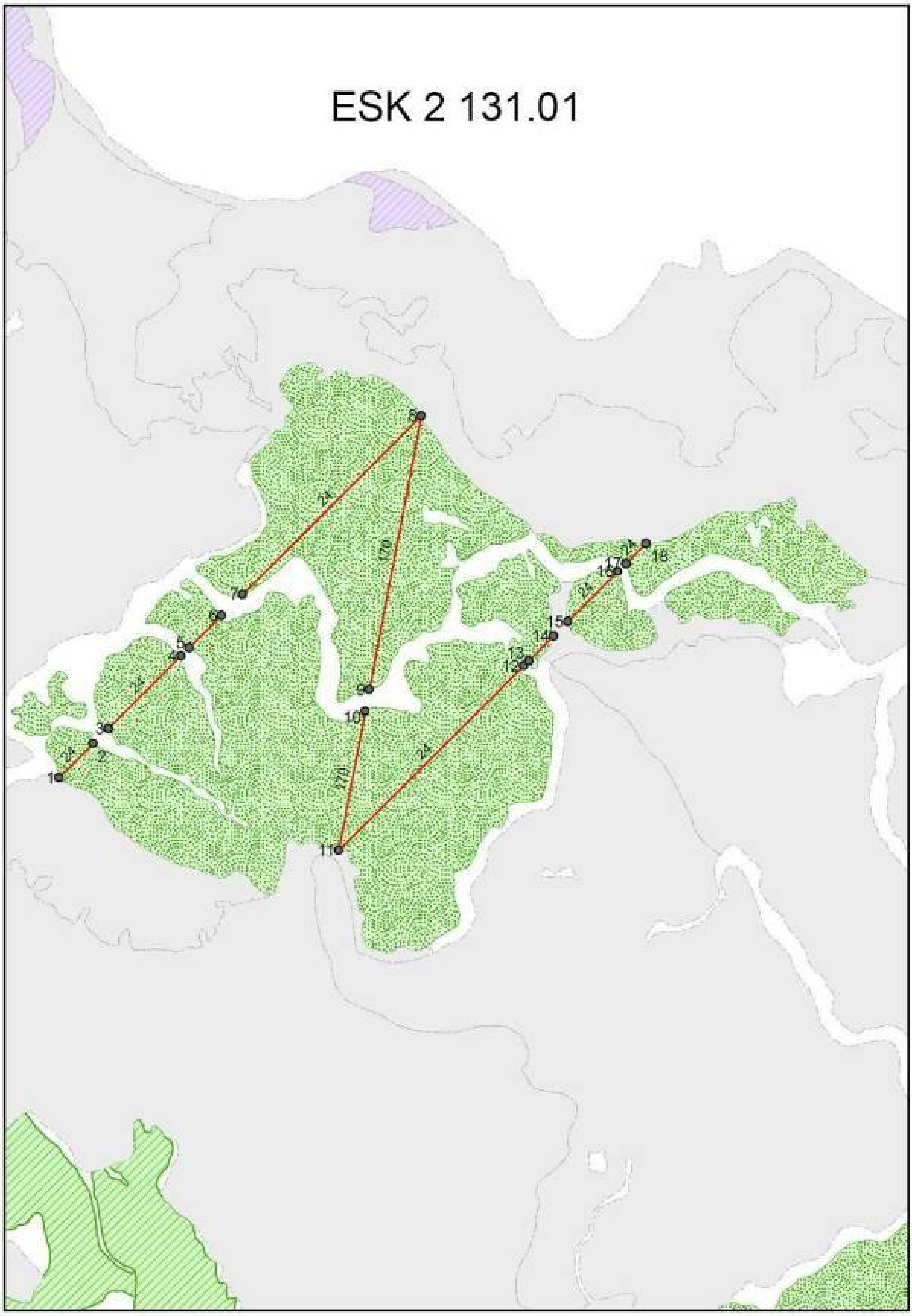
ESK 131

Forest owner: PanPac Forest Products Limited

Stand details
The stand was planted in July 1983 at an initial stocking of 1543 sph. The current stocking is estimated to be 264 sph over an area of 32.78 ha. The stand has been pruned in two lifts and thinned once in July 1989 to 250 sph. The first pruning took place in July 1989 to 3.2 m (251 sph) and the second lift occurred in September 1992 to 4.7 m (177 sph).

Sample line details
The sample line swath width was 3 m, with every tree inside the swath being sampled and every second sample tree cruised. The total length walked was 1873 m (a target of 1500 m was specified in planning, in order to ensure that the required 1248 m was achieved), consisting of three zigzags with 182 trees measured for dbh. The average distance between trees cruised for merchantable volume was 21 m

Notes
Part of the stand was neither thinned nor pruned. Nearly all trees in that section were double leadered, forking just above ground level into a larger and a smaller stem, making the tree distinctively different compared to the rest of the stand. Several gaps and gullies run through the stand, most of them intersected by the first transect. None could be crossed safely and the crew were forced to go back out of the stand to the road each time and continue the sample-line on the other side of the obstacle. More trees than expected were measured, due to the unexpected high-stocked area. This stand should have been stratified when planning the inventory, which, along with a more tactical layout of the sample lines, would have significantly improved sampling efficiency. In such a stand, planned and actual GPS coordinates would greatly help both the initial inventory and any subsequent auditing, see way-points 1-18 on Figure 9.



Picture 4 Map Esk 131

MOHAKA 180

Forest owner: PanPac Forest Products Limited

Stand details

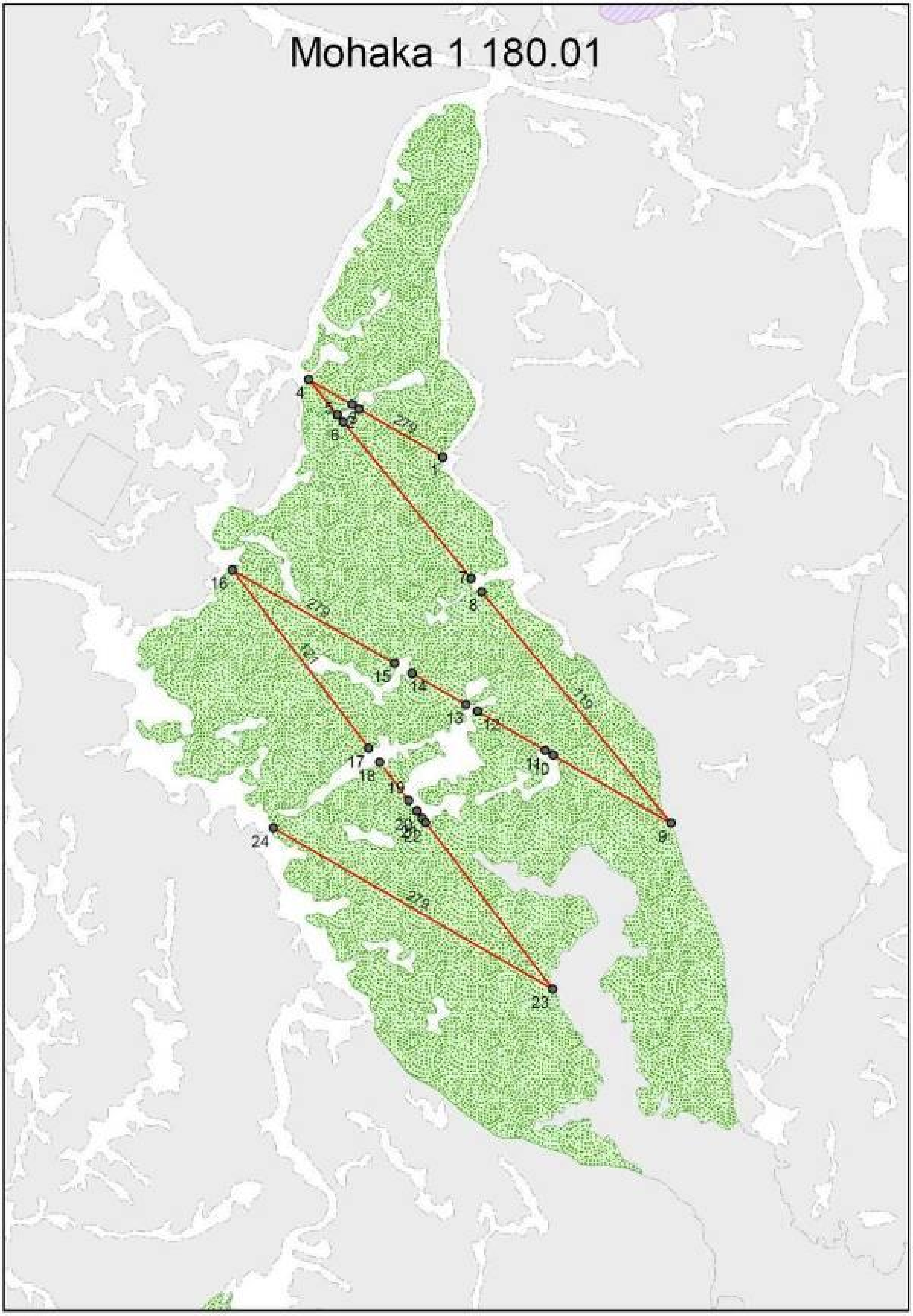
This stand was planted in July 1980, aged 29 at time of measurement. The initial stocking was 1543 sph, with the current stocking now at 171sph over a total area of 39.76 ha. Site Index 32.6 m. Two prunings and thinnings, first prune lift in September 1985 to 2.2 m (503 sph), second lift in August 1986 to 4.0 m (268 sph). Thinning one occurred in October 1983 to 653 sph and the second thinning was carried out in April 1987 to 211 sph.

Sample line details

Three metres wide, sampled every tree encountered for dbh and cruised every second sample tree. The sample line length was 2670 m (target 2300 m, required 1949 m) and consisted of five individual zigzags. In total 182 trees were measured for dbh. The average distance between trees cruised for merchantable volume was 25 m.

Notes

Part of the stand was harvested, which led to difficulty in determining where the start point after the cutover was. The start and end points of the transect were located on the drip line. The hindrance level was medium to high, with heavy undergrowth in parts of the stand and a multitude of gullies and creeks, some of them impassable. The average slope a long the line was 22 degrees with a maximum of 33 degrees.



Picture 5 Map Mohaka 180

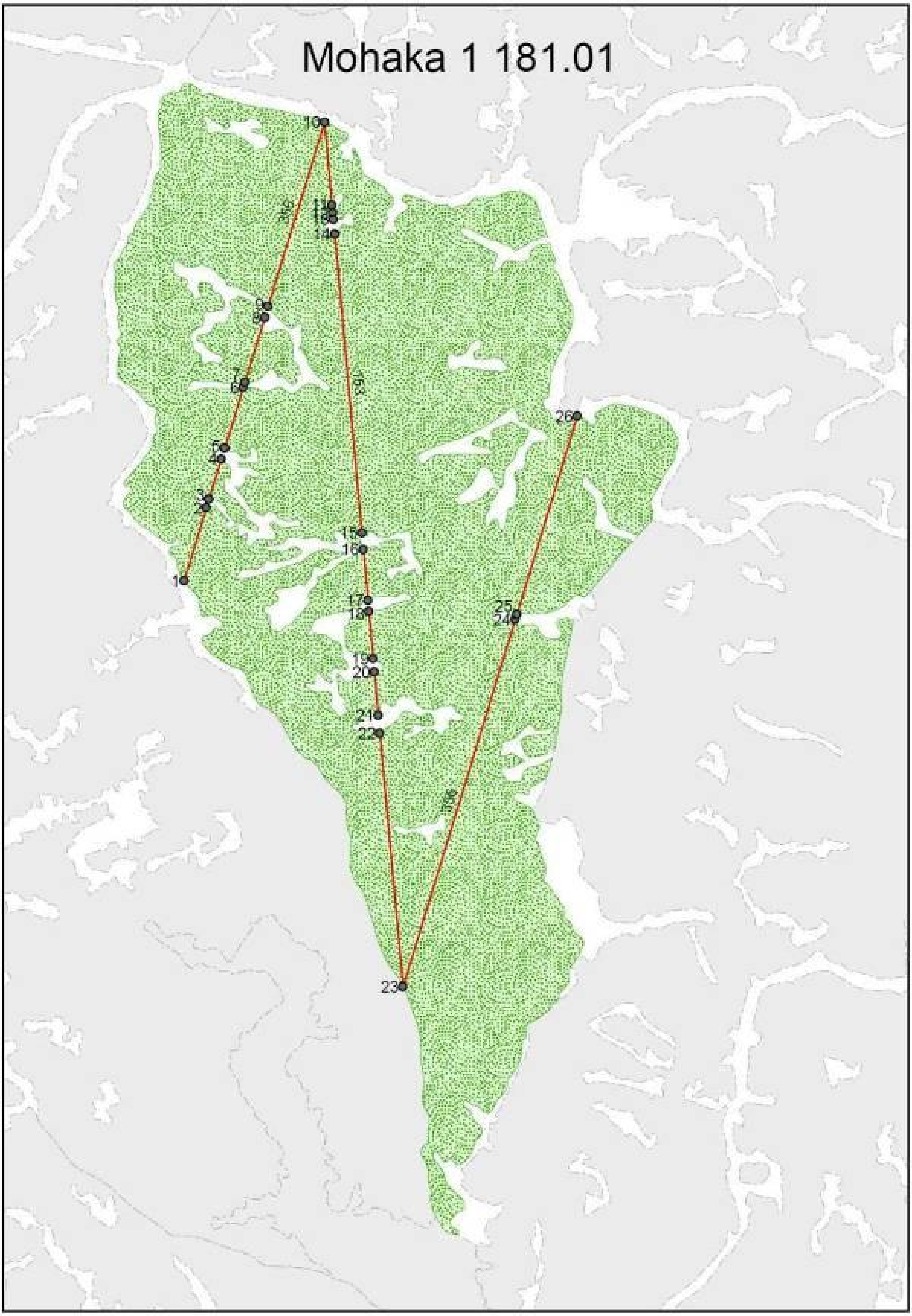
MOHAKA 181

Forest owner: PanPac Forest Products Limited

Stand details
The stand was planted in July 1980 with an initial stocking 1543 sph and was aged 29 at the time of measurement. Its current stocking was 190 sph over a net stocked area of 38.78 ha. The silviculture consisted of two prunings and two thinnings. The first pruning occurred in August 1985 to 2.2 m (484 sph); the second pruning was carried out in October 1986 to 4.3 m (261 sph). First thin was carried out in November 1983 to 650 sph; a follow up thinning to 235 sph occurred in March 1987.

Sample line details
Three metres wide, sampled every tree, cruised every second sample tree. The sample line was 2271 m long (target 2000 m, needed 1727) and spread over three zigzags, encompassing 144 trees in total measured for dbh. The average distance between cruised trees was 32 m.

Notes
All hindrance levels were present, varying from low to high. In places the undergrowth was heavy. Multiple gullies and creeks slowed walking, especially as some of them were impassable. The stand was steep in places, with an average slope of 23.5 degrees rising to 34 degrees, which again slowed the inventory.



Picture 6 Map Mohaka 181

Appendix 2. Detailed Times

Table 10. Single-tree sampling time allocation.

Stand	Date	Event	Time (min)	trees measured	time/ tree (min)	total time
Kang 9_5	*23/03/2009*	*travel*	115.0			**25%**
Kang 9_5	*23/03/2009*	*setup*	15.0			**3%**
Kang 9_5	*23/03/2009*	*walk*	22.0			**5%**
Kang 9_5	*23/03/2009*	*measure*	282.0	100	2.82	**61%**
Kang 9_5	*23/03/2009*	*break*	32.0			**7%**
Kang 9_5	*23/03/2009*	Total	466.0			7 h 46m
Kang 945_1	*23/03 + 1/04/09*	*travel*	319.0			**40%**
Kang 945_1	*23/03 + 1/04/09*	*setup*	27.0			**3%**
Kang 945_1	*23/03 + 1/04/09*	*walk*	98.0			**12%**
Kang 945_1	*23/03 + 1/04/09*	*measure*	321.0	112	2.87	**40%**
Kang 945_1	*23/03 + 1/04/09*	*break*	34.0			**4%**
Kang 945_1	*23/03 + 1/04/09*	Total	799.0			13h 28m
Esk 127	*30/04+1/05+13/05/09*	*travel*	401.0			**30%**
Esk 127	*30/04+1/05+13/05/09*	*setup*	44.0			**3%**
Esk 127	*30/04+1/05+13/05/09*	*walk*	72.0			**5%**
Esk 127	*30/04+1/05+13/05/09*	*measure*	774.0	130	5.95	**58%**
Esk 127	*30/04+1/05+13/05/09*	*break*	55.0			**4%**
Esk 127	*30/04+1/05+13/05/09*	Total	1346.0			22h 26m
Esk 127	*13/05/2009*	*travel*	158.0			**45%**
Esk 127	*13/05/2009*	*setup*	23.0			**6%**
Esk 127	*13/05/2009*	*walk*	54.0			**15%**
Esk 127	*13/05/2009*	*measure*	104.0	28	3.71	**29%**
Esk 127	*13/05/2009*	*break*	15.0			**4%**
Esk 127	*13/05/2009*	Total	354.0			5h 54m
Esk 131	*7/05/2009*	*travel*	237.0			**30%**
Esk 131	*7/05/2009*	*setup*	10.0			**1%**
Esk 131	*7/05/2009*	*walk*	61.0			**8%**
Esk 131	*7/05/2009*	*measure*	379.0	79	4.80	**48%**
Esk 131	*7/05/2009*	*break*	97.0			**12%**
Esk 131	*7/05/2009*	Total	784.0			13h 4m
Esk 131	*8/05/2009*	*travel*	258.0			**42%**
Esk 131	*8/05/2009*	*setup*	19.0			**3%**
Esk 131	*8/05/2009*	*walk*	39.0			**6%**
Esk 131	*8/05/2009*	*measure*	268.0	103	2.60	**44%**
Esk 131	*8/05/2009*	*break*	24.0			**4%**
Esk 131	*8/05/2009*	Total	608.0			10h 8m
Mohaka 180	*14/05 + 15/05/09*	*travel*	459.0			**36%**
Mohaka 180	*14/05 + 15/05/09*	*setup*	93.0			**7%**
Mohaka 180	*14/05 + 15/05/09*	*walk*	94.0			**7%**
Mohaka 180	*14/05 + 15/05/09*	*measure*	566.0	120	4.72	**45%**
Mohaka 180	*14/05 + 15/05/09*	*break*	52.0			**4%**
Mohaka 180	*14/05 + 15/05/09*	Total	1264.0			21h 4m
Mohaka 181	*14/05 + 15/05/09*	*travel*	459.0			**32%**
Mohaka 181	*14/05 + 15/05/09*	*setup*	53.0			**4%**
Mohaka 181	*14/05 + 15/05/09*	*walk*	175.0			**12%**
Mohaka 181	*14/05 + 15/05/09*	*measure*	599.0	144	4.16	**42%**
Mohaka 181	*14/05 + 15/05/09*	*break*	132.0			**9%**
Mohaka 181	*14/05 + 15/05/09*	Total	1418.0			**23h 38m**
		travel	2406.0			**34%**
		setup	284.0			**4%**
		walk	615.0			**9%**
		measure	3293.0	***816***	***4.04***	**47%**
		break	441.0			**6%**
		Total	7039.0			**117h 19m**

Table 11. Travel times from base to/from stands.

Average	Stand	Event	Date	Start time	Finish time	Total time (min)	Total time per day
37%	***Moha 181***	***to stand***	*14/05/2009*	6.30	7.40	70.0	2.3h
		from stand	*14/05/2009*	16.00	17.20	80.0	
		to stand	*15/05/2009*	7.00	8.00	60.0	
		from stand	*15/05/2009*	2.21	18.30	70.0	
	Moha 180	***to stand***	*14/05/2009*	6.30	7.40	70.0	2.3h
		to stand	*15/05/2009*	7.00	8.00	60.0	
		from stand	*14/05/2009*	16.00	17.20	80.0	
		from stand	*15/05/2009*	14.21	18.30	70.0	
	Esk 131	***to stand***	*7/05/2009*	5.00	8.23	147.0	4.1h
		to stand	*8/05/2009*	6.45	8.15	90.0	
		from stand	*7/05/2009*	16.50	18.20	90.0	
		from stand	*8/05/2009*	14.12	17.00	168.0	
	Esk 127	***to stand***	*30/04/2009*	6.45	8.20	95.0	3.1h
		to stand	*1/05/2009*	6.50	8.38	108.0	
		to stand	*13/05/2009*	7.00	8.05	65.0	
		from stand	*30/04/2009*	16.11	17.25	74.0	
		from stand	*1/05/2009*	16.26	18.30	124.0	
		from stand	*13/05/2009*	13.05	14.38	93.0	
29%	***KANG 9_5***	***to stand***	*26/03/2009*	7.10	7.48	38.0	1.9h
		from stand	*26/03/2009*	13.36	14.53	77.0	
	KANG 945_1	***to stand***	*26/03/2009*	1.35	2.53	78.0	2.7h
		to stand	*1/04/2009*	5.26	6.39	73.0	
		from stand	*26/03/2009*	16.38	17.58	80.0	
		from stand	*1/04/2009*	15.20	16.53	93.0	

Appendix 3. Tree Counting with TIMBRS

Select and import an image

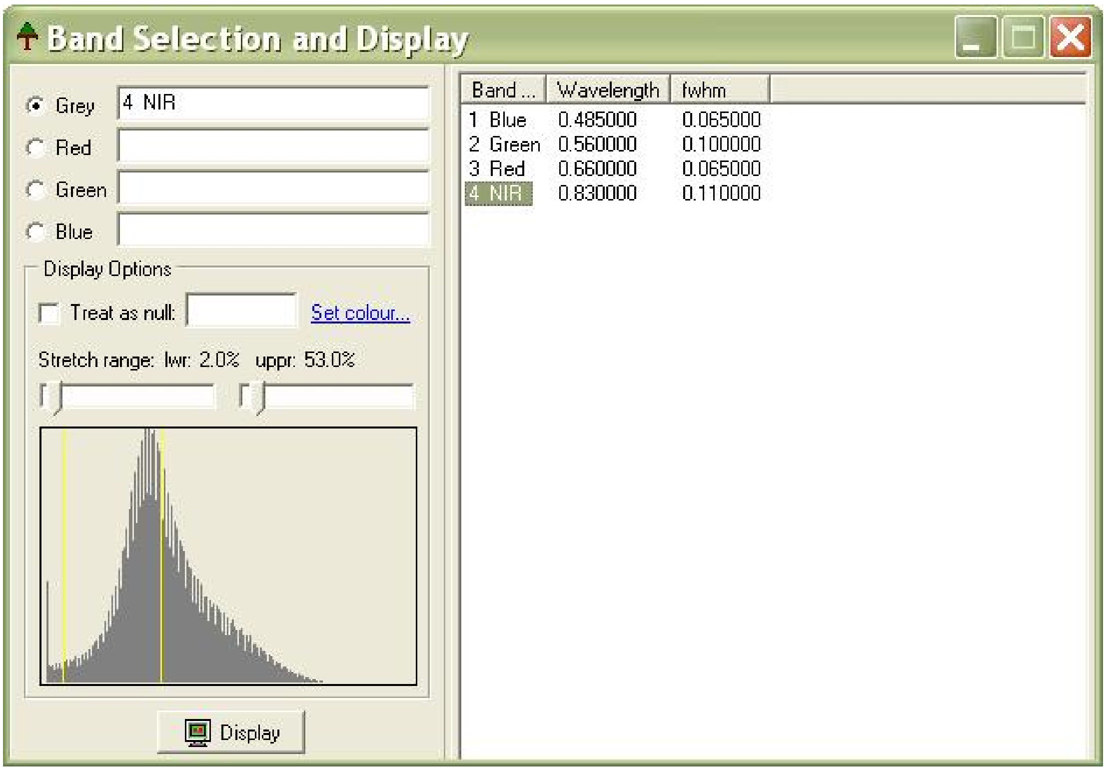
Generally the highest resolution image is the most suitable image as it will be easier for the operator to distinguish trees from non-tree material. If the operator cannot tell a tree from non-tree material, for example due to low resolution, clouded areas or distortion, the image will not be suitable for tree counts. In this study, all the ortho-photographs were of 0.5 m ground resolution.

Geographic information

Ortho-rectified images can be imported into TIMBRS and will provide Eastings and Northings for each individual tree at the end of the count. The coordinates can be exported in form of a txt file as well as a shape file.

Find a wave-band you wish to use

Ortho-photographs obtained directly from forest companies generally contain three wave-bands to choose from, while QuickBird satellite images contain a fourth band, the NIR (Near Infra Red) band. The provider of the aerial photography may be also able to provide NIR. The NIR band (wavelength around 0.83) contains the most information and is therefore most precise. The green band (wavelength around 0.56) reflects healthy trees brighter and the chance to miss out dead trees is higher, while the red band (wavelength around 0.66) reflects dead trees brighter and the chance to miss out healthy trees is higher. The blue band (wavelength around 0.485) contains the least information.



Picture 7 NIR image bands

Define a polygon

The area inside the user-defined polygon will be counted by TIMBRS. If no polygon is defined, the software will count the complete image. The operator can create as many polygons as desired and can delete or add polygons as he or she wishes.

Apply the 'Spatial Spectral Mask'

This step can be used to mask out dark or bright regions that are known to be non-tree material. Roads or skid sites for example generally appear brighter and can be excluded from the area to be counted without having to specifically draw a polygon around them. The 'Spatial Spectral Mask' may then be selected during the Gaussian smoothing or TIDA operation to improve processing time and minimise the number of 'cluster' objects identified in non-forested regions of an image.

Apply Gaussian smoothing

The Tree Identification and Delineation Algorithm (TIDA) is known to be sensitive to the spatial resolution of the supplied image data. Attempting to delineate individual trees in a very high resolution image (e.g. 10 cm) will most likely result in individual branches being delineated. Conversely, performing tree delineation on a coarse resolution image (e.g. 2 m) may result in multiple whole crowns being delineated as a single object. To address this problem, TIMBRS incorporates an Incremental Gaussian Smoothing procedure designed to help the user select a resolution that results in primarily single whole crowns being delineated. The Gaussian process takes a high resolution band and smoothes the image using a Gaussian filter, which is repeated for a range of (user-defined) Gaussian filters.

Tree Identification and Delineation Algorithm (TIDA)

At the core of TIMBRS is the Tree Identification and Delineation Algorithm (TIDA). This is a spatial clustering algorithm designed to identify and delineate tree crowns in high spatial resolution digital imagery, Culvenor (2002) and Culvenor *et al*. (1998). The algorithm follows a 'top–down', spatial clustering approach using local spectral maxima and minima to delineate crown centres and boundaries. Because image properties, acquisition conditions and forest structural complexity can vary greatly, there is no guarantee that TIDA will always delineate individual tree crowns in a forest. The delineated canopy objects may be parts of crowns, whole crowns or multiple crowns. In recognition of the limitations of automated tree crown delineation algorithms, the canopy objects delineated by TIDA are referred to as 'clusters'. Careful image acquisition and TIDA processing aims to ensure that each cluster corresponds to a single tree crown. TIMBRS has a number of functions to help the user select the optimum tree count results.

Optimisation and Export

The Optimisation and Export tools are designed to complement the Incremental Gaussian smoothing and TIDA tools. After TIDA is run on a series of incrementally smoothed bands, the optimisation and export tool can be used to help select which of the smoothed bands produces the best overall TIDA result and allows the user to export and / or visualise these theoretically optimum results. The individual optimisation and export tools include different options, such as minimum distance filtering to avoid multi-leaders being counted as individual trees, selecting the optimum band, saving the chart as an image, modifying the chart view, zooming the chart, overlaying tree positions as vectors and exporting tree positions. Estimated tree locations can be exported from TIMBRS to either an Arc View shape file or a simple ASCII text file. If the original input image contained geographic information, the shape as well as .txt file will contain the "Easting" and "Northing" coordinates for each tree instead of screen coordinates.