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: 4.03
Milestone Number: 4.03.01

Report No. FFR- R029

Improving Operational Forest Inventory The benefits of Integrating Single Tree Sampling with Advanced Remote Sensing Technology

Authors:
M Fritzsche, C Goulding, A Gordon, P Silcock and S Heine

Research Provider:
Scion

Date: December 2008

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Single tree sampling provides an alternative method of resource assessment to traditional plot-based inventory. While this concept is not new, there have always been obstacles that have impeded its adoption by the industry. The biggest obstacles are obtaining a total tree count for the area of interest, having an unbiased method of selecting sample trees, and having tools to analyse data of this type. A pilot project undertaken by a team from Scion and CSIRO was established to address these challenges. The TIMBRS image-processing, tree-counting software developed at CSIRO was used to provide estimates of tree counts from remotely sensed imagery, the sample-line, Z-plotting, concept was established for the selection of sample stems, and ATLAS Cruiser was used to analyse the data.

Comparisons of the results using a combination of these methods were made with standard plot-based inventories for the same areas in three small stands. These indicated that single tree sampling could provide improved estimates of standing merchantable volumes by log-grade. Single tree sampling offers opportunities to improve inventory efficiency. It may provide a better coverage of a stand through the use of sample-lines and, particularly in small stands normally inventoried with very few plots, could ensure that edge trees are appropriately represented. The next phase of the project will carry out a cost -benefit analysis to determine the commercial viability of this method over traditional plot-based inventory. It will verify the method of single tree sampling developed in the first stage of the TIMBRS-Cruiser project for different terrain types typical of New Zealand forests.

INTRODUCTION

Reliable information from forest inventory is critical for rational and efficient management of production forests; see Gordon *et al*. (1995) and MacLaren (2000). The cost of traditional mid-rotation and pre-harvest inventory is of concern to managers of both large and small forest estates. With on-going technological developments that improve efficiency, it is always worth considering alternative methods that can potentially provide a more effective result for the same level of investment. New techniques will be looked on favourably by an industry facing rising shipping and transport costs and lower log prices.

Traditional plot-based inventory has served us well for decades, but it has its weaknesses, such as the assumption that maps of stocked area exist and that they are accurate. Edge plots are always problematic, and although processes have been devised to manage these, the problem of getting the right density of edge plots remains.

As an alternative to plot-based sampling, single tree sampling has many advantages. It does not depend on estimates of area and avoids the problems with edge plots, as the method has a higher likelihood of edge trees being sampled in the correct proportion. It does, however, require an accurate assessment of how many trees there are within the population being assessed, and this has proved to be a difficult value to obtain with any certainty.

Under the Ensis partnership between Scion and CSIRO, a project was established that aimed at improving the efficiency of forest inventory by using single tree sampling with semi-automated tree counting from remotely sensed images. The project looked at establishing suitable field procedures for collecting individual tree data in an unbiased and cost-efficient manner. It also looked at the suitability of the TIMBRS automated tree counting software developed by CSIRO for reliably providing estimates of tree counts from remotely sensed images. The sample areas were assessed by a commercial inventory crew who carried out both single tree and plot-based sampling to allow a meaningful comparison to be made.

Forestry in New Zealand

The expansion of new forest establishment in New Zealand in the 1990s was largely undertaken by small growers (<10,000 ha), who now manage over one third of the New Zealand planted production forest estate (NZ Forest Owners Association 2006). Part of this estate is in small woodlots, often with irregular boundaries which can be long in relation to the block area. Their net stocked area is often unknown, or only a poor estimate is available, and area measurement in these circumstances can be expensive. The woodlot boundary may abut unstocked land and the edge trees' size and form may be substantially different from trees within the stand, more so than in a larger forest block.

Assessment of potential yield may be biased due to the number of edge plots that should be established in relation to plots within the stand, and the difficulty in defining exact stand boundaries. The cost of measuring an adequate number of sample plots can be high because of variability in stocking and stem form. As forestry on flat and rolling sites becomes less common, the proportion of stands with irregular and convoluted boundaries is likely to increase.

Most techniques for measuring timber resources in plantation forests assume that forest maps exist and that stocked areas are known reasonably accurately (Goulding & Lawrence,1992). Assessments of plantation forests aim at measuring the density of the resource per unit area, for example, volume of unpruned sawlogs per hectare. The estimate of the population total is then the product of the per hectare values within the stocked area, and a confidence interval about the estimate is constructed under the assumption that the area is known exactly, i.e., the variation in the area estimate is ignored.

Single Tree Sampling

With operational pre-harvest inventory in particular, the parameters of interest are the stand totals, such as the volume of unpruned sawlogs in a stand, and are not inherently area-based. It is possible to take a more direct approach and leave area out of the equation completely. The sample unit to be measured can then be a single stem. Stem-based inventory procedures have been used in forestry for some time, for example the 3P method (Grosenbaugh, 1979), where 3P is a variant of list sampling in which the list is not known prior to that sampling. The method works well when trees must be individually visited, for example to be marked for sale. However there are problems with 3P in that the sample size cannot be determined until sampling is completed, and there is no theoretically correct way to calculate the variance of the estimates. 3P sampling has not found general application in the New Zealand forest industry (Lee & Goulding, 2002).

Stem-based inventory has advantages when assessing small, irregular areas, as no area measurement is required and the population boundaries (hence the sampling frame) are usually easily identified. In small areas it is feasible to count every stem so the population size (*N*) is known. The number of trees in larger areas can be counted from aerial photography or other remote imagery, using automated or semi-automated tree identification image-processing software such as TIMBRS (Culvenor 2002).

This study compares the precision obtained and sample size required, from plot-based versus stem-based sampling of log product volumes where it is assumed that the total number of stems is known.

Double Sampling

Double sampling is a technique that exploits a relationship between a supplementary variable (x) and the variable of interest (y) (Shiver & Borders, 1996). It is especially effective when the supplementary variable is easily measured and has a strong relationship to the variable of interest. Stem basal area and stem product volume usually meet these criteria, so double sampling, where a proportion of the trees sampled are measured for DBHOB only, can be employed in stem-based inventory to increase efficiency.

METHODS

Approach and Stand Characteristics

The project had five objectives:

1. Determine the requirements to implement TIMBRS in New Zealand plantations and the training required for its use.
2. Evaluate the accuracy of the semi-automated image analysis by TIMBRS to estimate tree counts.
3. Develop a field sampling procedure to carry out single tree inventory.
4. Determine the precision of the combination of the estimated tree stocking and the estimated mean values for common stand parameters using single or double sampling.
5. Recommend a complete operational sampling method with indications of its likely efficiency.

The overall aim was to design a method that was unbiased, efficient and effective for practical use by commercial data capture crews. The method had to gather enough information to yield a statistically meaningful result, and ideally could be carried out by either a two-person crew or a person working alone. It should also be an efficient method for irregular-shaped, small woodlots with a high proportion of edge trees.

Three small *Pinus radiata* stands in Kaingaroa Forest were selected to trial the methods. The stands had various types of topography and levels of hindrance.

The key requirement of the field sampling procedure was that each tree had an approximately equal probability of being selected for measurement, minimising any auto-correlation between adjacent sample trees. The theoretical way of obtaining an individual tree list, selecting a random sample from this list, then locating and visiting the sample trees, is impractical. After some experimentation, it was decided to include every tree encountered in a set of very narrow sample-lines oriented across the stand, measuring each tree for Dbh. With double sampling, a proportion of the trees (here in this study, every second tree) are then measured and cruised for stem characteristics as in a conventional pre-harvest inventory to estimate log product yield. The sample-lines are not area-based transect plots, but are merely a convenient method of obtaining an individual tree sample.

In a previous desk study, Gordon & Budianto (1998) had analysed the between-tree variance using data from an inventory of a typical large Kaingaroa stand. Using these results for this study, it was decided to attempt to obtain at least 100 individual tree sample units in any inventory, half of which would be cruised. Given the estimate of total tree numbers from TIMBRS and a map of a stand, the total sample-line length required was calculated using a 4 m wide swath or transect. The 4 m width was chosen because a height pole could be used to determine whether a tree was inside the transect without having to leave the sample-line or do complicated and time-consuming measurements to calculate it. The transect length was then laid out on the stand map, subdivided to fit the stand appropriately (see Figure 1). The trees selected to be cruised for merchantable log yield were spaced approximately 20 to 26 m apart on the sample line.

The selected stands had been measured at the start of the project by pre-harvest inventory using existing practices by Timberland's regular commercial inventory contractors. This provided the control method. The field data were collected by an Interpine Forestry, Rotorua crew using the PlotSafe data capture programme (Herries 2007). Actual total stocking in each of the stands was obtained by physically counting all the stems in the field. Tree locations were identified using the TIMBRS software and displayed by a mapping tool developed for the project.

Stand 1, 849/1, (Figure 1) had a total size of 7.5 ha and was 27 years old at the time of measurement. The stand was flat with a low to medium level of hindrance due to blackberry, broom and windthrown trees.

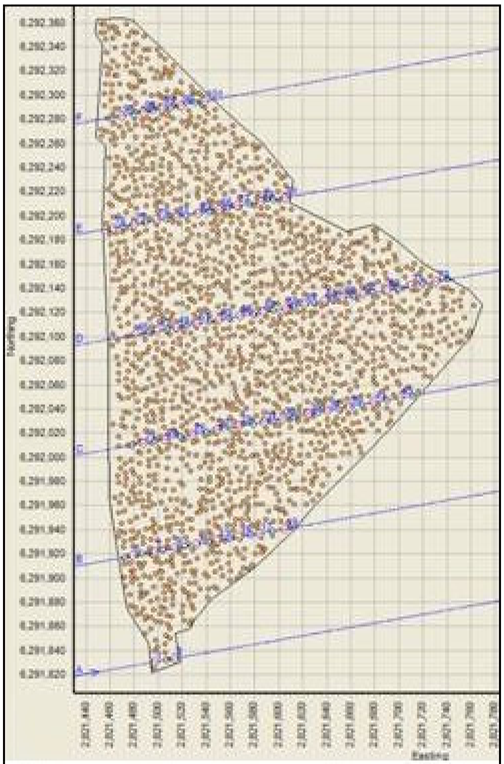


Figure 1. Plotting map for Stand 1

The second stand 893/1 (Figure 2) was approximately 4.5 ha and had a medium level of hindrance due to native regeneration and significant wind-throw. Two of the boundaries were well defined, while the south east boundary bordered a stand remnant that was only two years younger and therefore very difficult to distinguish. The transect bearing was chosen to avoid the ill-defined boundary. Single-person and two-person crews were used to assess this stand.

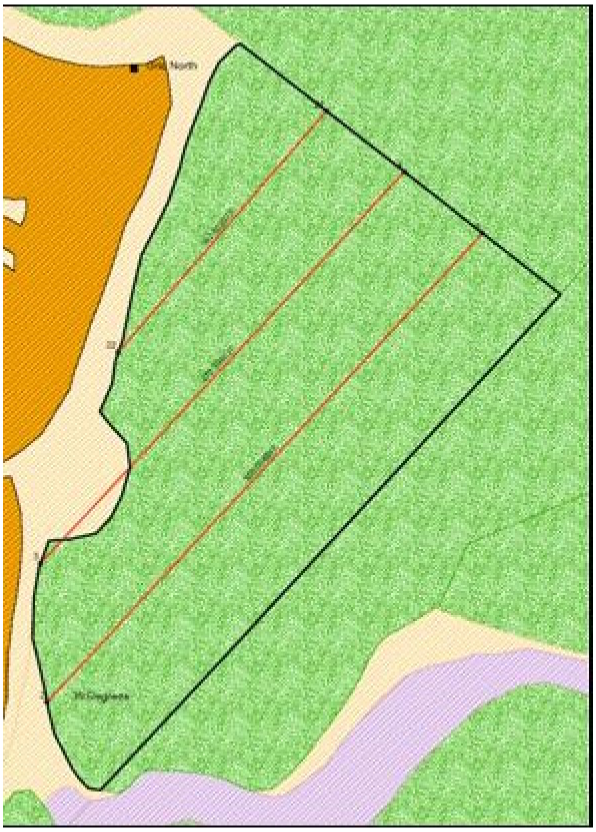


Figure 2. Transects for Stand 2

The third stand 106/2 of the project (Figure 3) of approximately 4 ha, had variable topography and was bounded by native bush. The hindrance was high due to a dense native understorey and a very steep-sided gully with wind-thrown trees. The stocked area was poorly represented in the GIS. A zigzag sample-line design (termed “Z-plotting”) with pre-determined fixed bearings was trialled to reduce the delays caused by negotiating the heavy hindrance at stand edges. It was only necessary for the crew to measure the last tree on the sample line, before turning back into the stand on the prescribed bearing. This method was deemed to minimise unproductive delays. It also avoided issues where boundaries were not easily defined on the ground, as the sample-line lengths can be measured while plotting. An alternative but similar concept to zigzagging is that of the “structured walk”, (MacLaren & Goulding, 1993) where a “walk” through the stand is planned, mapped, and distances and bearings pre-determined prior to entering the field. (NOTE: the layout with a specific fixed-bearing for each sample line depicted in Figure 3 results in a biased sample. See *Discussion*, later.)

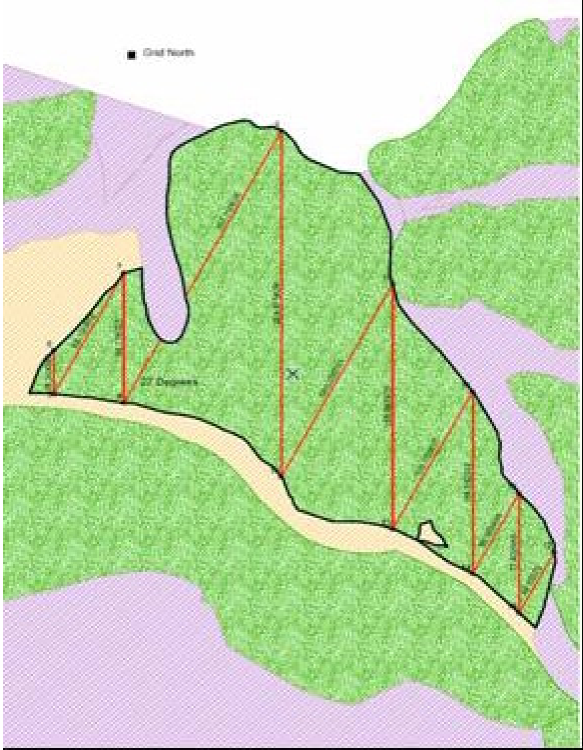


Figure 3. Transects for Stand 3

Data

Kaingaroa stands 849/1, 893/1 and 106/2 were measured in April/May 2007 using a plot-based design (bounded, circular plots systematically located) following the forest management company’s standard operational inventory procedures and sampling intensity. Stems were cruised using the RAD05 quality descriptions (see Appendix A – Cruising Dictionary RAD05). In October 2007 these stands were remeasured by Interpine Ltd using a stem-based design with the same quality descriptions.

Quickbird satellite images of these stands were used to count the total number of stems in each stand. The counts and stand areas are listed in Table 1.

Table 1. Stand areas and description

Stand	Year of Establishment	Stand Area (ha)	Stocking (stems/ha)
106/2	1980	7.50	246
849/1 -C	1978	4.63	365
893/1	1975	4.40	221

Table 2. Numbers of plots and stems measured

	Plot-based design			Stem-based design	
Stand	**Number of Plots**	**Plot Area (ha)**	**Number of cruised stems**	**Number of cruised stems**	**Number of DBH (un-cruised) stems**
106/2	5	0.08	107	54	53
849/1 -C	13	0.07	340	62	51
893/1	8	0.07	123	54	51

Stand 849/1 originally comprised three sections divided by mapped tracks. Due to problems identifying the boundaries, only one of the sections (4.63 ha) was used in this study.

Procedure

Data from both the plot-based and stem-based assessments were imported into ATLAS Cruiser (Gordon *et al.* 2006). Cruiser distinguishes between area-based assessment and stem-based assessment and handles the sample unit appropriately in each case. A set of four log products was defined based on the standard domestic log grade specifications (MAF, 2007) (see Appendix A. Log Product Specifications).

All assessment data were analysed at ‘time of measurement’, i.e., without any growth projection. To model bucking, a dynamic programming algorithm is used by Cruiser to find the mix of logs that can be cut from each stem piece between stump height and the break point that will produce the highest value (Deadman & Goulding 1979).

The standard ‘population summary’ report from Cruiser provided estimates of per hectare yield by log product and the probable limits of error (PLE) associated with the estimates. A 95% confidence level was used in all cases.

The volumes of all logs cut from the stems in the stem-based assessment was exported and summed by log product within stem to form a dataset of five volumes for each stem. This was merged with the uncruised (secondary) stems to calculate the variances and co-variances needed for examining the utility of double sampling. As mean top height is an area-based parameter, which is evaluated from the mean diameter of the 100 largest stems per hectare, it is not possible to derive an estimate of mean top height for each unit with stem-based sample units unless the areas of the stands are known.

Estimates of stand parameters and log product volumes and their PLEs were compared. The variations between sample units were used to predict the likely precision that would be obtained by different sized samples. The likely precision from different stem-based double sampling strategies was calculated. The population size was incorporated in the PLE calculation (finite population correction) to give a more realistic prediction of the precision that can be expected for these stands.

Automated Tree Counting

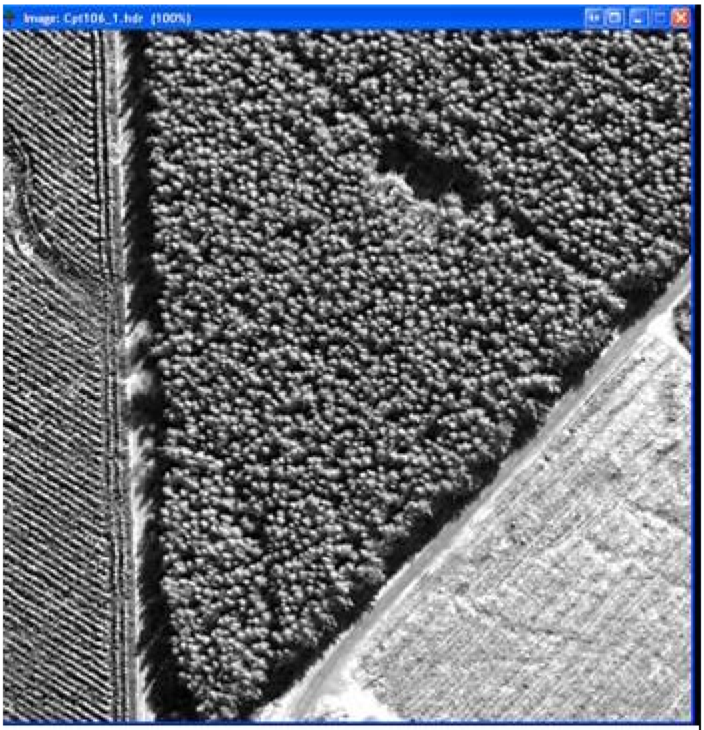
All trees in each of the three stands were marked and manually counted in the field to obtain an accurate benchmark. This method remains vulnerable to human error such as fatigue, unclear marking of trees or confusing ridge and gully systems. Therefore the manual count cannot be assumed to be 100% correct, but it still remains the most accurate method.

TIMBRS was then used to identify the peak of each tree crown, and hence obtain a count of the total number of trees within a stand as defined by a polygon delineated on an image. The spatial resolution of imagery required by TIMBRS for accurate tree counts depends on the type of forest and its age class. Good quality satellite imagery from the QuickBird high spatial resolution sensor was available for the study area. The imagery has approximately 2.4 m spatial resolution in its multispectral bands (blue, green, red and near-infrared) and 0.6 m spatial resolution in a single panchromatic band. The multispectral bands were spatially sharpened by Darius Culvenor (CSIRO) to an effective spatial resolution of 0.6 m using the panchromatic band. This was done prior to importing the images into the tree-counting software and processing the images.

Fully automated tree counting without any user interaction may be highly desirable for resource foresters, but this cannot yet be achieved with any degree of confidence. With some experience however, semi-automated tree counting from remotely sensed imagery appears to generate sufficiently accurate estimates of tree counts.

The satellite imagery was loaded into TIMBRS, and boundaries for each stand were digitised over the imagery in order to define the area of interest. Typically, existing stand boundaries that are held in a GIS could not be used, as they are not recorded for the purpose of ensuring that individual crowns are included or excluded from the stand. Where stand boundaries are clearly defined, such as by roads, the digitising is easier. When stands are adjacent to other similarly aged stands, on the other hand, the definition can become difficult and errors might occur by mistaking trees of neighbouring stands with trees of the current stand and either over- or undercounting the total number of trees.

All semi-automated tree counting was carried out by a forestry scientist at Scion who had no previous experience in using TIMBRS or any other image-processing software.

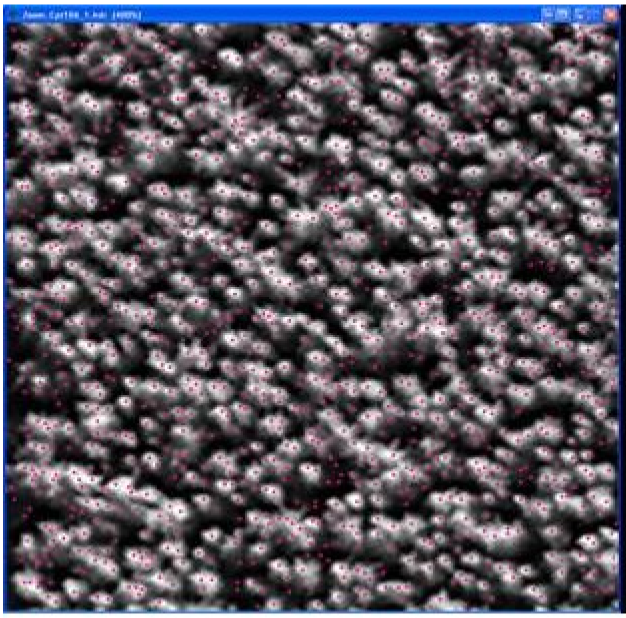


QuickBird satellite image of Stand 1

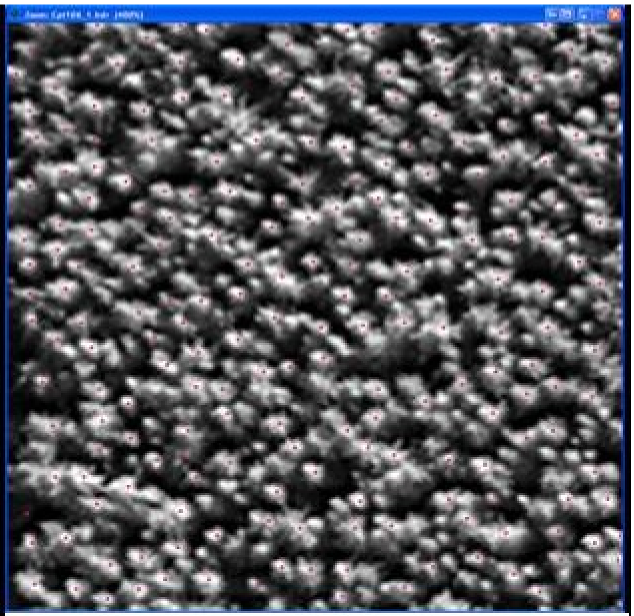
When parameterising TIMBRS for image analysis, a number of factors need to be considered, in particular which bands will provide the best definition. NIR (near infrared) generally produces the most precise tree counts, although all spectral bands are typically used to help distinguish stocked and unstocked regions of the imagery. During the TIMBRS process the image runs through several ‘masking’ procedures, which are necessary to specify regions that should be ignored during all quantitative image-processing operations. These masking procedures reduce the processing time of the image and increase the accuracy of final tree counts.

For a given stand, tree counts from TIMBRS are sensitive to the spatial resolution of the imagery supplied to the algorithm. TIMBRS exploits this variability using an in-built optimisation process that involves incremental smoothing of the imagery. The process assumes that the imagery in its raw form is sufficiently detailed to produce a stocking overestimate, i.e., branches being interpreted as separate crowns. Theoretical optimum tree counts are suggested to the user, based on analysis of stand-scale tree counts, as the imagery is incrementally smoothed.

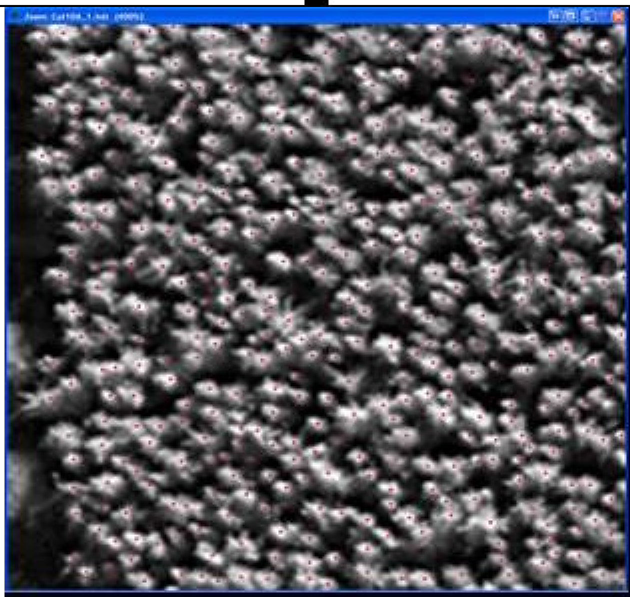
Below are examples of the variability in tree counts as a result of the image smoothing process. The optimum tree count lies somewhere between these extremes. The dots indicate TIMBRS estimate of the top of a single stem.



Overestimated tree counts



Underestimated tree counts



Acceptable tree count

RESULTS

After becoming familiar with using TIMBRS, operators found that an acceptable result could usually be obtained from an image within an hour. In this trial, the operation of TIMBRS was carried out in advance of any field work, so there was no way that the operator could know the exact number of trees in the test stands. The comparison of the total tree numbers estimated by TIMBRS with the field-based count is shown below in Table 3.

Table 3. Comparison of actuals and TIMBRS estimates of total numbers of trees

Site	Stand	Age	Area	Mapped no of trees	Manual tree count	TIMBRS Tree count	Comparison
1	106/2	27	7.5ha	1910	1865	1846	99%
2	849/1	30	4.6ha	2056	1691	1691	100%
3	893/1	32	4.4ha	1030	974	1025	105%

The comparison of estimates of stand parameters between single stem sampling and plot sampling is shown in Table 4 for each of the three stands. Note that despite doubt about the accuracy of the values of the net stocked area obtained from Timberland's stand records, these values are used unchanged in the table to convert totals to per hectare values. Stocking for stem-based sampling is determined from the TIMBRS stem count.

Table 4. Comparison of estimates and precision (PLE percent) of stand parameters

	Stocking (stems/ha)		Basal Area (m2/ha)		Mean DBH (mm)	
Stand	Plot	Stem	Plot	Stem	Plot	Stem
106/2	268±18%	246	47.52±9%	52.31±8%	478±6%	514±6%
849/1	374±20%	365	52.14±15%	54.13±8%	430±7%	425±5%
893/1	220±24%	221	45.78±21%	46.05±7%	520±4%	508±5%

These values are displayed graphically in Figure 4 showing the mean value (marker) and the 95% confidence interval (vertical line) for each stand and sampling strategy.

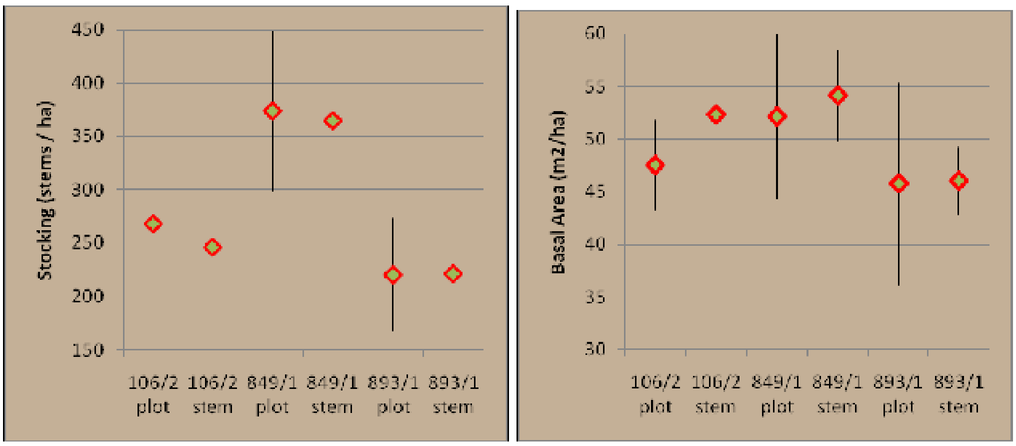


Figure 4. Comparison of stand parameters. Means and confidence intervals

Estimates of the four log product volumes and total recoverable volume (TRV) with their precision, by stand and sampling method are shown in Table 5, Figure 5 and Figure 6.

Table 5. Comparison of estimates and precision (PLE in percent) of product yield

	Pruned (m3/ha)		SSawlog (m3/ha)		LSawlog (m3/ha)		Pulp (m3/ha)		T.R.V. (m3/ha)	
Stand	Plot	Stem	Plot	Stem	Plot	Stem	Plot	Stem	Plot	Stem
106/2	51±27	57±45	89±72	75±51	94±84	56±45	306±45	386±18	540±10	573±10
849/1	10±63	18±77	34±41	114±33	80±29	68±32	318±18	250±22	443±17	450±9
893/1	37±50	35±56	22±47	64±39	52±38	50±52	270±28	232±17	381±25	380±8

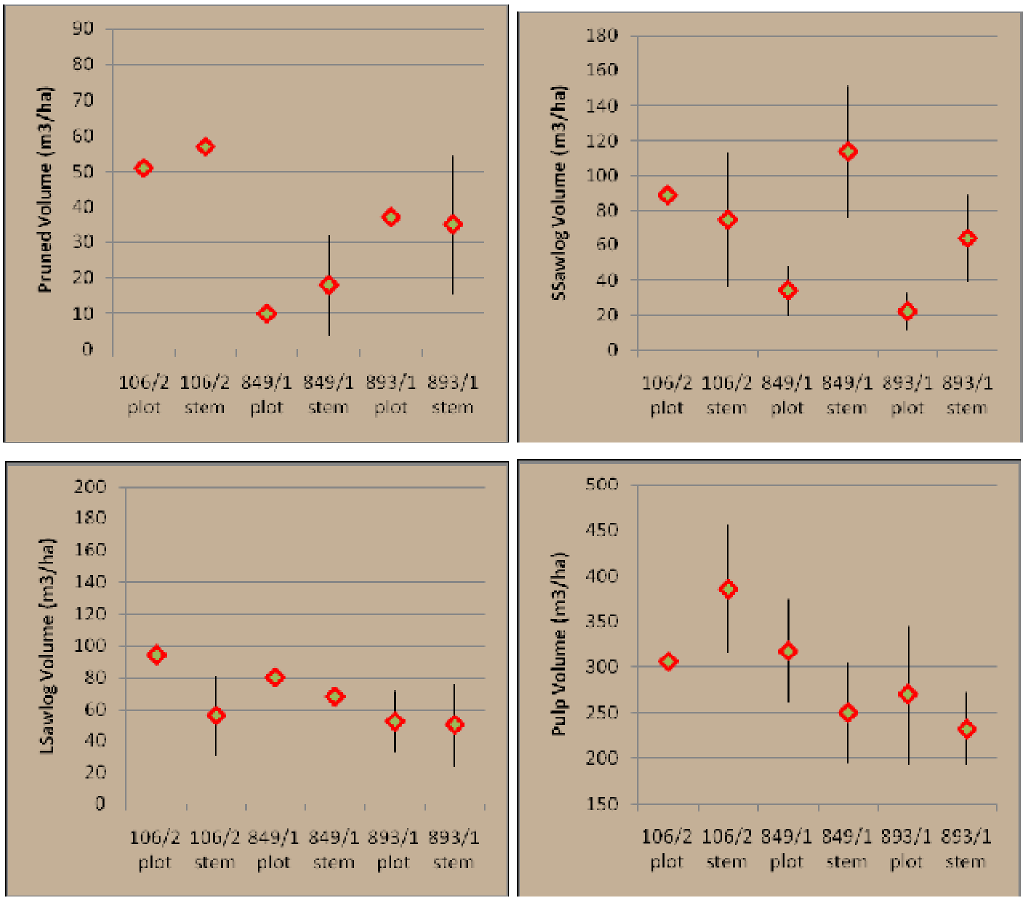


Figure 5. Comparison of log product yield. Means and confidence intervals

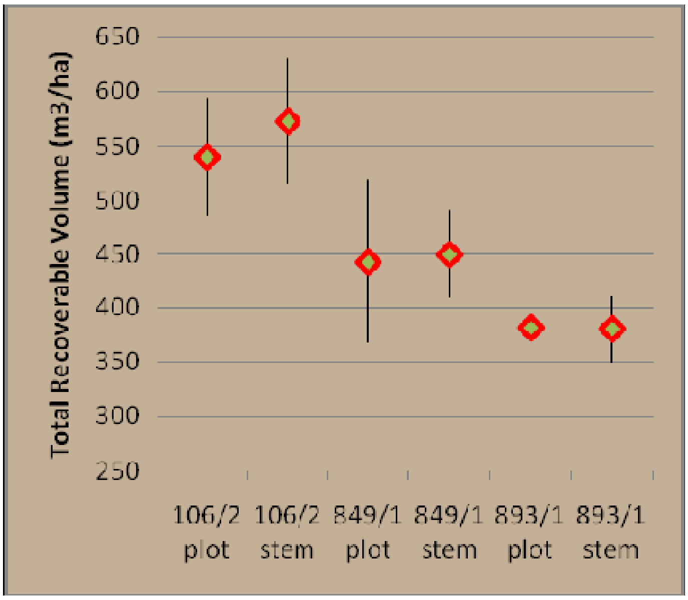


Figure 6. Comparison of T.R.V. Means and Confidence Intervals

The relationship between precision and sample size is illustrated in Figure 7 for Total Recoverable Volume (TRV). This graph assumes stem-based double sampling, i.e., the proportion of cruised (primary) to uncruised (secondary) remains constant in each stand at 1:1.

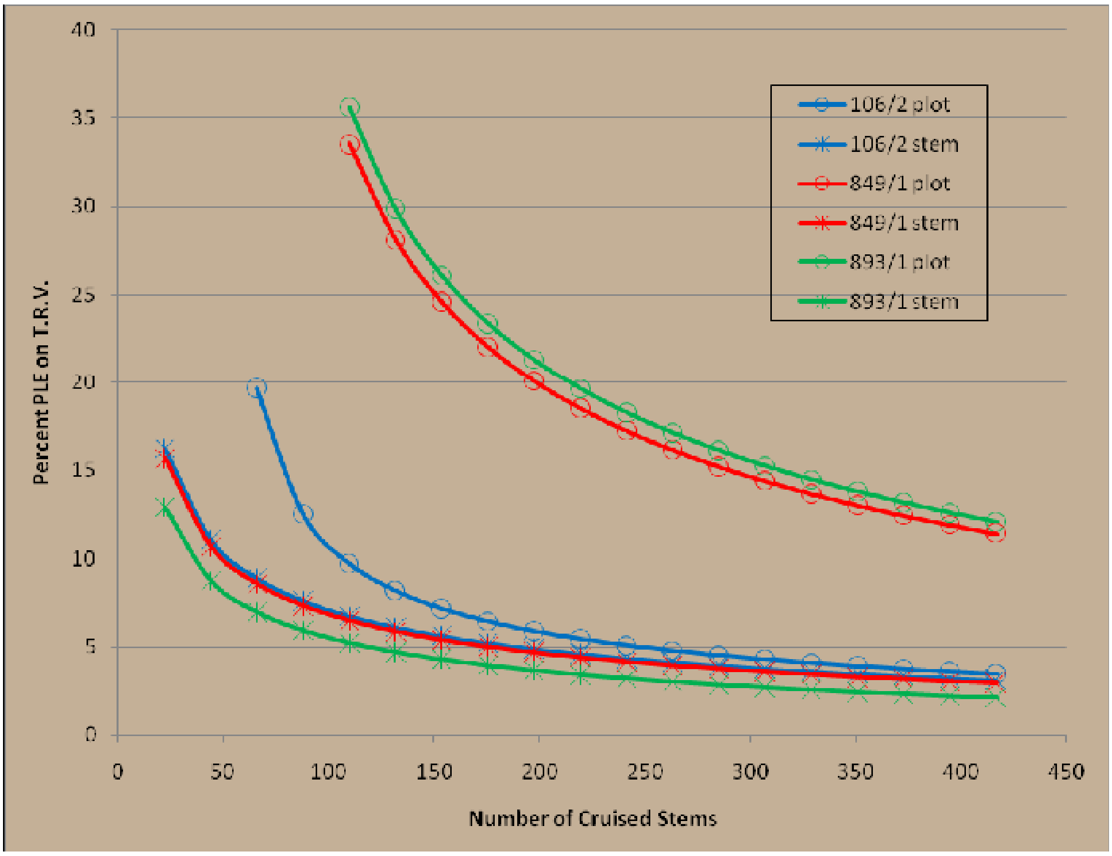


Figure 7. The change in Precision of TRV estimate with sample size. Plot- and stem-based

Pruned log volume is illustrated in Figure 8, which shows the precision expected for estimates of the yield of this product under different sampling strategies and sample sizes.

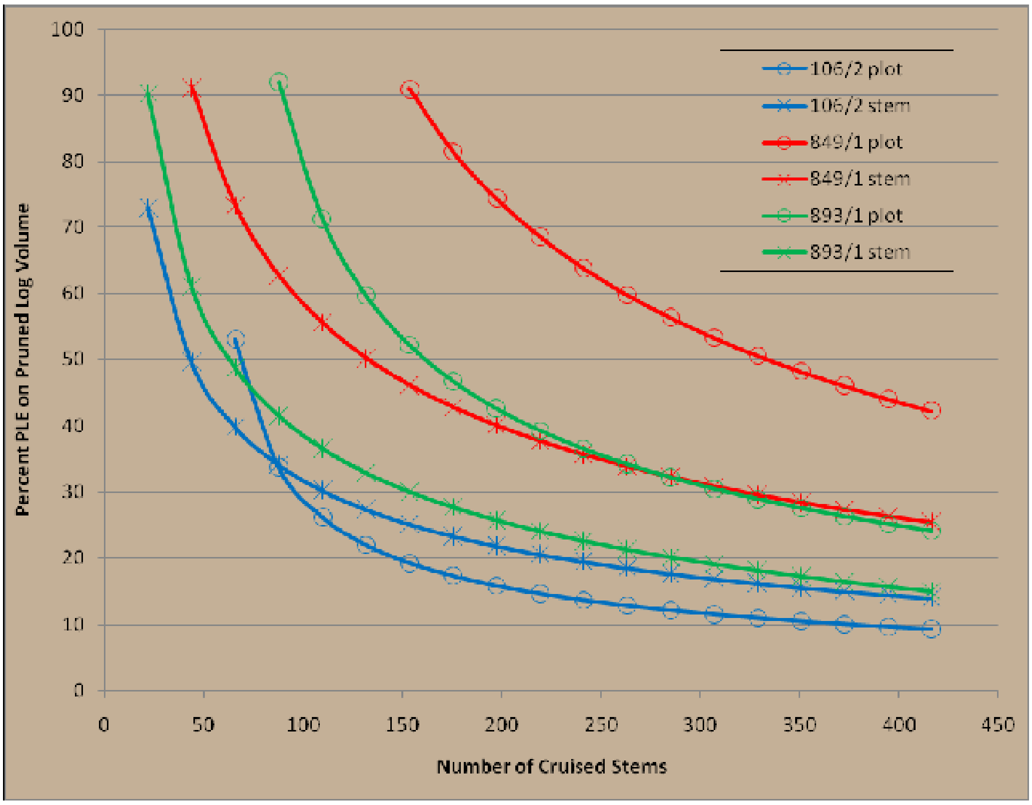


Figure 8. The change in precision of pruned volume estimate with sample size. Plot- and stem-based

Figure 9 is based on the stem-based assessment of stand 849/1 and shows the likely precision about estimates of TRV using a simple stem sample and three double sampling strategies.

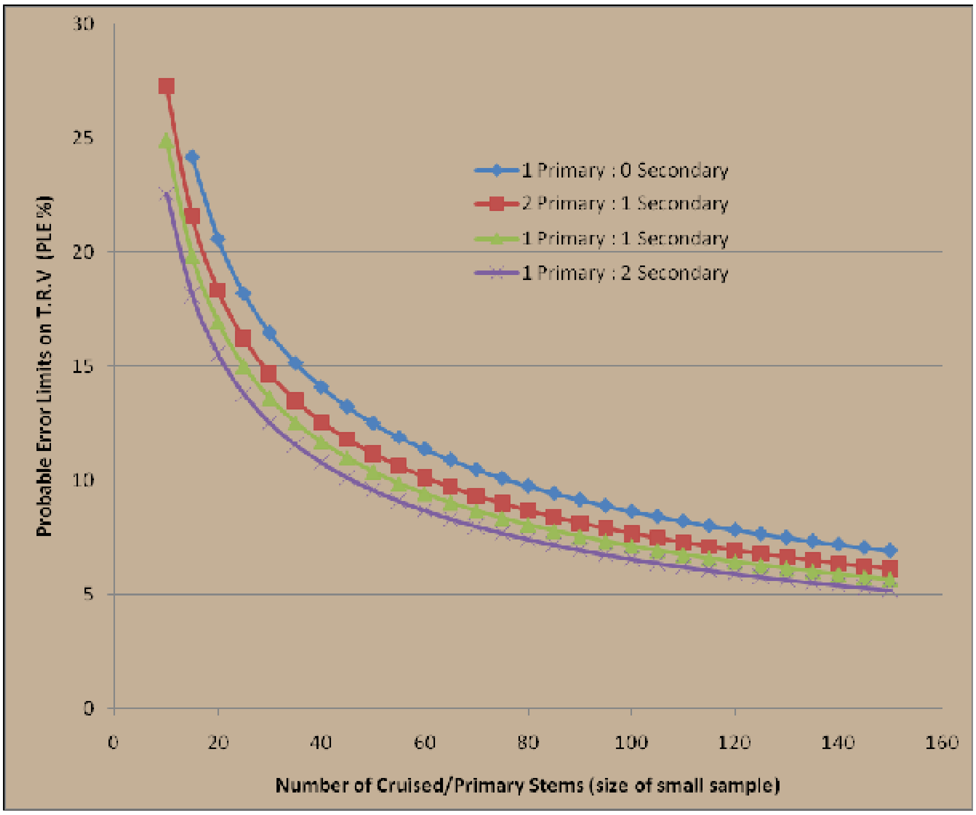


Figure 9. Precision of 849/1 TRV estimates under different stem-based double-sampling strategies

DISCUSSION

It was clear from the remote imagery that in several cases the mapped stand boundaries were incorrect, with consequent inaccuracies in the records on net stocked area. However there were no significant differences in the plot-based stocking estimates from the stem counts (Table 4 and Figure 4), partly due to the large PLEs around the plot-based estimates (±18% or more).

Only stand 106/2 produced significantly different basal area estimates. This appears to be a result of the bounded plots being closely located to one another away from the boundary, and with no part of any plot including edge trees. These five plots had very similar basal area (Figure 10), which accounts for the atypically high precision on TRV (Figure 7). Rather than this stand being exceptionally uniform, it seems likely that the small sample size of five plots located in the middle of the stand has resulted in an underestimate of the variance between plots across the stand.

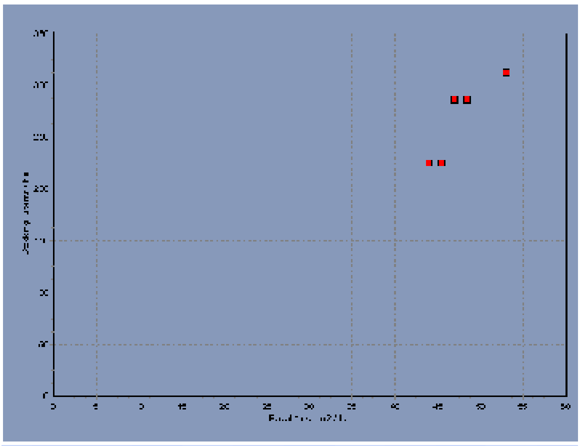


Figure 10. Plot stocking over basal area. Stand 106/2 assessment

“Z-plotting”, or sample-lines laid out in a zigzag manner, was successful from the field crew’s viewpoint in avoiding negotiating the very heavy undergrowth typically found on an open boundary. However, note that the layout of the sample-lines depicted in Figure 3 for stand 106/2 produces an incorrect sample of trees, in that there is a higher probability of a tree located in the south-east corner of the stand being selected and measured than elsewhere. This method is to be further refined in the next stage of the project to ensure representative coverage of line sampling across the stand.

Planning of transects can be more flexible than with a grid-based plot sample, allowing more skill and judgement but also increasing the risk of poor implementation. For a small consultancy company whose clients are mainly farmers or woodlot owners, and where it is important to obtain an ‘as representative’ sample as possible rather than one that is statistically sound but too expensive for the forest owner, the sampling problem becomes one of measuring enough trees to estimate the mean tree accurately, rather than both enough trees and enough plots to obtain accurate and precise mean per hectare values. Although there is no statistical problem preventing the inclusion of edge trees with bounded plot sampling, in practice with small areas and low numbers of plots, edge trees are often under-represented in the inventory, as illustrated in this trial. One advantage of a stem-based sampling strategy is that the sample stems can be selected across the whole stand, so producing a more representative sample. Edge trees will be included as each sample-line starts and ends at the stand boundary. It will be the responsibility of the inventory planner to ensure that this occurs so that sampled edge trees are in approximately the same proportion of the sample as they are in the stand as a whole.

The trial carried out in stand 849/1 showed a one-person crew could feasibly carry out the fieldwork at a rate/person comparable to that of the two-person crew (approximately 20 trees per person-hour). The method therefore could be suited to a forest consultant operating alone while a reduction in the total costs of non-productive time such as travel would be attractive to larger companies. However, using a two-person crew provides for higher quality data collection and lower worker fatigue. Sharing the equipment load, helping with sample-line delineation and the intrinsic benefits of a two-person crew (such as 'error checking'), showed better performance, especially when fatigue towards the end of the day reduces concentration.

When the log yield is amalgamated as TRV (Figure 6), there appear to be no significant differences between the plot-based and stem-based estimates. Both 849/1 and 893/1 are within 1.5% of each other. Figure 7 illustrates the relationship between precision and sample size for TRV. Apart from the 106/2 plot assessment, the plot-based PLE is more than twice the stem-based PLE for the routine, company-specified density of plots. To achieve a PLE of 10% or less, only about 50 cruised stems and the same number of uncruised stems need to be measured in a stem-based assessment of these types of stands. To approach a 10% PLE using area plots would require about 20 plots (over 400 cruised stems) for both 849/1 and 893/1.

Some of the estimates of log-product volumes (Table 5, Figure 5) show quite different estimates of log yield. For example, the SSawlog yield predicted by the plots in 849/1 and 893/1 is significantly less than the yield predicted by the stem sample, matched by the converse with regards to LSawlog and Pulp. The small sample size has clearly affected the precision of the product yield estimates in percentage terms for both the plot and individual tree sampling. Improving the estimates of log product volumes could be achieved by cruising 100 or so of the trees in the individual tree sample rather than double sampling, or by increasing the sample size in total and the corresponding length walked in the line sample.

The effect of double sampling on the precision of estimates from a stem-based sample is shown in Figure 9. The PLE on TRV for stand 849/1 has been used. The improvement in precision is not large in this case, but the curves indicate that a PLE of 10% is likely to be achieved, for example, by measuring either 75 cruised stems or 50 cruised stems and 50 DBHs.

Note that the correlation between stem basal area and TRV is high (0.799 for stand 849/1), which makes double sampling an attractive option for this variable. Generally the correlation must exceed 0.5 for double sampling to be more efficient than single sampling, given similar relative variation in both the variable of interest and the supplementary variable (Schreuder *et al.* 1993). The ratio-of-means estimate is appropriate, as the relationship between stem basal area and product volume is linear through the origin and the variance of product volume increases with stem basal area.

It should be noted that the conventional estimator for the standard error of a ratio-of-means prediction has been used in the double-sampling calculations (and is used within the Cruiser forest assessment processing system). This has been shown to perform poorly in some circumstances, whereas the jackknife estimator seems to produce more reliable confidence intervals (Schreuder *et al., op. cit.*, referring to the work of Wu & Deng, 1983).

CONCLUSION

This study is limited to a test of three stands, small in area, where several trials of different methods of sample tree selection were carried out in the field on the first stand.

The results indicate that good estimates of stocking were achieved using TIMBRS and high-resolution satellite imagery (Quickbird). Given the small number of stands compared, it was not possible to estimate the variance of the errors between actual ground counts of tree numbers and estimates from image processing, nor to determine differences between operators.

Methods for single tree sampling have been successful and could be effective at improving precision. They are likely to reduce costs over traditional plot-based methods when used by commercial data-capture crews. The results also show that double-sampling procedures can be employed to further increase inventory efficiency.

Stem-based sampling assumes that the total number of stems is known, either from analysis of remotely sensed imagery or from field counts. If these methods are not appropriate, the total could be estimated from an area-based sample (tree counts in small, circular plots for example), but the variance of mean and total volumes must then be recalculated to correctly determine the PLEs.

For smaller stands with irregular boundaries, tree counting may reduce errors that are due to an inaccurate estimate of net stocked area. 'Z-plotting', which uses sample-lines laid out in some form of a zigzag design, was deemed the most effective form of sampling, as there was no time lost between the finish and start of sample-lines and no need to traverse the dense ground vegetation typically found at a boundary with open areas.

Although the field crews had not used this type of plotting before, they were able to follow the prescribed methodology without significant timing delays, and the markings left a clear audit trail for later quality control if required.

The sample-line method also allowed better coverage across the stand when sampling intensities are limited, as may occur in farm forests and small woodlots. The method ensured that edge trees were appropriately sampled.

Through the use of ATLAS Cruiser, data collected from single tree sampling was able to be used in conjunction with a stocking count to generate a total stand yield and log mix, including average tree and piece sizes and per-hectare estimates.

Next Stage of the Project

A full cost-benefit analysis needs to be carried out to identify the business case for using single tree sampling. A time study needs to be conducted using the same fully experienced, professional inventory crew for both methods for each stand and in order to ensure a realistic sampling pace.

Along with the costs of field work, the cost of image acquisition and the suitability of various types of images, including conventional aerial photography, needs to be taken into account. Consideration also needs to be given to the processing time required by a skilled operator to produce a reliable tree count from the remotely sensed imagery and the performance of the TIMBRS software for the various kinds of forest types that need to be investigated.

The proposed method needs to be tested on a wider range of stand types, particularly larger stands, on steep terrain, with different forest management and stand history.

Further work is required on single stem sampling to refine field procedures, including determining and accounting for any auto-correlation effects for single tree sample selection, or refining the field sampling method to eliminate this if necessary.

Provided the cost/benefits of the results from this project are favourable, modifications to ATLAS Assessment Planner should be made to automatically plan the layout of transects. TIMBRS also requires modifications to enhance its integration with a forest management GIS.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of Timberlands Ltd in providing data and access to Kaingaroa Forest stands, which enabled assessment and counting of trees required for this project.

REFERENCES

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

Deadman, M.W. & 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.

Gordon, A.D. & Budianto, M. (1998). *Tree-based Woodlot Inventory.* New Zealand Forest Research Institute, Unpublished report. Project Record No. 6112.

Gordon, A.D., Lawrence, M.E. & Pont, D. (1995). *Assessing the Potential Log Yield of Stands Prior to Harvesting.* In Proceedings of the Institute of Foresters of Australia 16th Biennial conference "Applications of New Technologies in Forestry." Ballarat, Victoria. 18-21 April 1995.

Gordon, A.D., Wakelin, S.J. & Threadgill, J.A. (2006). Using Measured and Modelled Wood Quality Information to Optimise Harvest Scheduling and Log Allocation Decisions. *New Zealand Journal of Forestry Science 36*(2/3), 198–215.

Goulding C.J. & Lawrence, M.E. (1992). *Inventory Practice for Managed Forests.* (FRI Bulletin No. 171). Ministry of Forestry New Zealand.

Grosenbaugh, L.R. (1979). *3P Sampling Theory, Examples and Rationale.* S. Dept. Interior. Bureau of Land Mgt. Tech Note No.331.

Herries, D. (2007). *PlotSafe Forest Inventory Data Capture.* Paper presented at Forest-Tech 2007 Conference. 13-15 March 2007, Rotorua, New Zealand.

Lee, K.H., & Goulding, C.J. (2002). The practicality of 3P sampling with accurate dendrometry for the preharvest inventory of plantations. *New Zealand Journal of Forestry Science 32*(2), 279-296.

Maclaren, J. Piers. (2000). *How Much Wood Has Your Woodlot Got?* (FRI Bulletin No.217). New Zealand Forest Research Institute Limited. ISSN: 1174-5096.

MacLaren, P. & Goulding C.J. (1993). The structured walk - a practical inventory system. *New Zealand Journal of Forestry 37*(4), 20-23.

MAF, 2007: LogGradespecification http://www.maf.govt.nz/forestry/statistics/logprices/specification.htm

Manley, B.R., Goulding, C.J. & Lawrence, M.E. (1987). *Stand Assessment by Log Grades Using MARVL.*(FRI Bulletin No. 132). Ministry of Forestry, New Zealand Forest Research Institute Limited.

New Zealand Forest Owners Association. (2006). NZ Forest Industry Facts and Figures 2005/2006. Joint publication with WPA and MAF. http://www.nzfoa.org.nz

Schreuder, H.T., Gregoire, T.G. & Wood, G.B. (1993). *Sampling Methods for Multiresource Forest Inventory.* John Wiley & Sons, Inc. ISBN 0-471-55245-3.

Shiver, B.D. & Borders, B.E. (1996). *Sampling Techniques for Forest Resource Inventory.* J Wiley & Sons, Inc. New York. 356 pp.

APPENDICES

Cruising Dictionary RAD05

Log Product Specifications

Log Product	Min SED mm	Price $	Lengths m	Allowed qualities
Pruned	300	120	4.1, 5.5, 6.1	Br_0, Br_1, Sw_8, Sw_S, F_B10+, F_F5+, F_NONE
SSawlog	300	80	4.6, 5.5, 6.1	Br_0, Br_1, Br_7, Sw_8, Sw_S, Sw_3, F_B10+, F_F5+, F_F10+, F_N5+, F_NONE, F_O1.2+
Lsawlog	200	60	4.6, 5.5, 6.1	Br_0, Br_1, Br_7, Br_10, Br_12, Sw_8, Sw_S, Sw_3, F_B10+, F_F5+, F_F10+, F_N5+, F_NONE, F_O1.2+, F_S7+
Pulp	100	40	3.7-6.1	Br_0, Br_1, Br_7, Br_10, Br_12, Br_25, Br_99, Sw_8, Sw_L, Sw_S, Sw_3, Sw_1, Sw_W, F_B10+, F_C, F_F5+, F_F10+, F_NONE, F_O1.2+, F_S7+, F_S10+, F_S16+, F_S25+