The Forest as a Warehouse

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Abstract.—New Zealand's timber harvest is rapidly increasing and will continue to do so over the next 20 years. This increase provides opportunities for adding value and increasing profitability, but to achieve the full potential of the harvest, the best management decisions at strategic, tactical, and operational levels are required. The key to *market-driven harvest planning* in New Zealand is a greatly improved knowledge of the quantity, quality, and condition of the standing trees. Industry is demanding that pre-harvest inventory be intensified with more detail about the quality of the stems, more geographical precision as to the location of the potential log products, and more flexibility in the analysis of the data. Improvements in instruments for use in the forest, in remote sensing techniques, and in operations research and geostatistical algorithms should lead to better computer-based decision support systems.

New Zealand has 1.7 million ha of plantations, expanding at a rate of 75,000 ha per year, averaged over the last 5 years. The main tree species is radiata pine, which is intensively managed for wood production and for profit. Last year's harvest was 16 million m^3, and production is forecast to rise to 30 million m^3 by 2010. Much of this production is exported, so the needs of the international market determine marketing and harvest planning. Timely silviculture, involving heavy thinning and pruning of live green branches, produces logs with a high proportion of uniform-grained clearwood. However, fast growth with a tendency for large branches and stem malformation also produces chip-logs, where the low value is determined by poor quality, not necessarily by small end diameter alone. The differential in value between the highest and lowest value logs is wide, by a factor of 6 to 10 or more.

Marketing and facility planning require information well in advance of the start of harvesting. A 3- to 5-year forecast of production is required, prepared in conjunction with marketing exercises or new facilities and product-line planning. Here, marketing is defined as determining what products potential customers require that the organization can supply, as opposed to sales, which is defined as finalizing an agreement to supply a given product.

In the past, there was a lengthy delay between when a decision was made to fell a block of trees and when the timber, panel, or paper products were delivered to the final customer. The timing of the decision was mainly production driven, derived from the long-term yield regulation and management plan, modified by operational logging schedules. The sale of the end product following sawmilling, peeling, or pulping was made with only limited ability to take the short-term needs of the market into account.

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Current mechanized harvesting, high-speed processing facilities, and short drying or pulping schedules can shorten the time between deciding to harvest and producing the end-product ready for delivery to less than a week. Logging and processing operations can be *just in time*, where trees of the appropriate quality are felled only when required to fill a sales order for an end product. Within the constraints imposed by longer term plans, short-term logging planning now has the potential to become truly *market driven*.

Both intermediate and short-term *market-driven* plans will require estimates of total standing and recoverable log-product volumes for each potential coupe, rather than broader based estimates at the stand or age-class level. They will also require calculations to be made of the marginal rate of return obtained by leaving a coupe to grow a further year, either explicitly or implicitly within a short-term mathematical programming system.

The area of a New Zealand stand can be large, covering several coupes. Even though it contains one even-aged species, variability across a stand can be high. The trend is for coupes to become smaller, and a harvest plan will comprise many such coupes, each requiring accurate inventory, in detail and to a strict level of precision. Using only ground-based inventory techniques will require very high proportions of the trees to be measured and are too expensive to be carried out at this intensity except on a cursory, quickly executed basis. Logging planning is forced to place great reliance on past experience, theoretical models, and ocular estimates. Currently, the best estimate for the next week's production in a coupe is what was produced last week. The results from such assessments are not ideal for quantitative, computer-based planning in a rapidly changing environment.

If inventory can be improved so that the flexibility of the trees to yield differing volumes of logs in response to changing relative values and specifications is known, the forest can be considered as a *warehouse* of potential log products. It is essential that the whereabouts of those trees able to produce logs of the required type are precisely known. This also implies more intensive assessment of the stem to more precisely determine the quality characteristics required by each potential log type.

To achieve this requires research to improve:

- software systems for pre-harvest inventory
- the intensity of measurement on the standing tree of external features of stem quality, such as branches and stem sweep and of intrinsic wood quality, and the way size and quality can be projected into the future
- the spatial resolution of inventory, so that results at an acceptable level of sampling precision can be geographically interpolated across the stand's area
- methods to keep track of trees and logs during harvest, and to forecast what can be harvested during the next few weeks

PRE-HARVEST INVENTORY

The standard pre-harvest inventory method used by New Zealand and Australian forestry companies is the Method of the Assessment of Recoverable Volume by Log-types, MARVL (Deadman and Goulding 1979, Goulding *et al.* 1993). A key feature of the system is that it recognizes that merchantable yields depend on the types of log products to be harvested and on their relative values. When these change, the volumes of the various products harvested will change (see Puumalainen 1998). Field assessment uses simple-, stratified-random, or double sampling with bounded or Bitterlich plots. It measures a sample of trees and objectively assesses quality changes up the stem independently of log specifications. Computer analysis models the breakage, volume, taper and grades of the tree stems based on the field data, and then predicts the yield of log products by mimicking bucking. Dynamic programming is used to calculate the bucking pattern so that the total value of the logs obtained is maximized for each stem. A list of log products and their specifications, including their relative values, is supplied by the user at the time of each analysis, and the inventory data can be reanalyzed many times with different sets of specifications.

Varying the log-product specifications and reanalyzing the data allows marketing or planning personnel to determine the sensitivity of the yields to changes in those specifications. Growth routines can project the inventory data forward a few years, and the results can be reanalyzed to assess the change in the volumes of the various products. When a stand is marginal with respect to meeting the minimum size requirements of valuable logs, rescheduling the date of logging could give extra growth and allow the minimum size to be achieved, with an increase in value greatly in excess of the volume increment.

The latest version of the MARVL system is implemented under MS Windows™, closely integrating the analysis modules with growth prediction and with a database capable of linking to a GIS (Gordon *et al.* 1995). A major upgrade is being carried out now. The most visible new features are improved user friendliness; the ability to cater for mixed species, as found in tropical forests for example; and an increase in the level of detail that a stem can be assessed for quality. The redesign should more easily allow inventory modules to be incorporated into systems that optimize log allocation to customers (Cossens 1996).

INTENSITY OF MEASUREMENT

Because stem quality is assessed visually in the MARVL field procedure, there is a limit to the accuracy with which characteristics such as branch size can be estimated. The effect of stem sweep on potential log-product yield is difficult to judge accurately. Although the analysis procedures allow changes in log specifications, results can only be predicted if the requisite qualities are assessed first in the field. A supplementary method was required that could take precise measurements on trees without felling or climbing, and could allow re-calculation or re-measurement some time after the first analyses were carried out.

A research program funded by the New Zealand forest industry began in 1994 to develop a new measurement procedure with the desired accuracy. The method uses terrestrial photogrammetry to provide mensuration data from images of a sample of standing trees. Initial tests have shown that under operational conditions it should be possible to routinely measure the heights of branch clusters and other stem features to within ±0.1 m and upper stem diameters to within ±10 mm. Errors in measuring branch diameters range from an underestimate of 2 mm to an overestimate of +7 mm. The method also provides a permanent photographic record that enables measurements to be checked or reworked.

Work is being carried out to determine optimal double sampling systems, where the large sample of trees is either measured only for dbh, or receives the regular ocular estimate of stem qualities. Alternatively, multiphase sampling may be employed, using the results of the photogrammetric measurements to stratify stands or to develop regression models.

SPATIAL DISTRIBUTION

In New Zealand plantations, trees are planted in rows laid out fairly precisely, and the tree planters are able to correctly space the trees within the rows to achieve the prescribed number per hectare. Even so, the trees are not in a perfect matrix, and rows waver around natural obstacles. With unthinned stands, mortality due to competition can be severe after age 20. Many stands are thinned at least once, either "thinning to waste," where the trees are not extracted, or "production thinned," where access rows are removed and selective thinning occurs in between. Especially with machine thinning, clumps of trees can be missed, or trees felled to leave gaps for equipment maneuverability. The number of stems at rotation time is often less than one quarter of the number planted. This, combined with site differences, causes spatial variability between and within what appear to be uniform stands.

The results provided from the MARVL inventory method have been sufficiently accurate and useful for the amount of pre-harvest inventory in New Zealand to have greatly increased over the past decade. To estimate population totals within the confidence intervals desired by management requires 20 to 50 or more plots, involving 2 or more days' work for a single field crew. Reducing the area of a population does not necessarily greatly reduce plot variability, and providing estimates for smaller and smaller size areas is limited by the amount and cost of the additional field work required. Precise information is not available for areas with much fewer than 12 to 15 plots. To mitigate this problem and to provide the increased spatial information required, three approaches are being considered.

The first uses geostatistical procedures, such as kriging, to interpolate between values measured on plots with known locations. Hock *et al.* (1993) used kriging to provide estimates of site index across the 160,000-ha Kaingaroa forest, interpolating between estimates provided by permanent sample plots, combined with other available information. Gunnarson *et al.* (1998) describe the potential of kriging to assist in Scandinavian forestry, including the estimation of total standing volume, and its subdivision by species classes. A difficulty with New Zealand inventory plots is the high between-plot variance, due to the traditional relatively small size of the plots. These are usually less than 0.06 ha in area, or have a basal area factor that counts 8 to 10 trees per point. The variability is very noticeable when predicting "rare" products, which may not be present in every tree, but which are valuable none the less. An attempt to predict a 3-D surface model of the geographical distribution of volume in a stand by using non-statistical, numerical analysis techniques failed because of this reason, despite there being as many as 58 closely spaced inventory plots.

Of the two alternative methods under research, one combines satellite imagery with stand maps and inventory plots in a multisource inventory procedure and the other uses automatic image processing of large-scale aerial photography to identify the location of each individual tree.

Multisource Satellite Inventory

Satellite imagery has been available for more than 20 years, producing spectacular photos and promising detailed forest management information. This promise has not materialized under New Zealand's exotic forest conditions, nor, apparently, elsewhere (Holmgren and Thuresson 1998). However, recent collaborative work with the Finnish Forest Research Institute and with Landcare Research NZ has shown that combining satellite imagery with estimates from inventory ground plots can produce estimates of product volumes geographically distributed within stands. This "multisource" inventory method is used in the Finnish National Forest Inventory (Tomppo 1996) where it is increasingly a source of management and operational planning data. Many ground plots are inventoried, the data from which are combined with data from other sources—stand maps and Landsat TM satellite imagery, or its equivalent. For each 25-m square in the forest depicted by a pixel on the satellite image, the forest parameters of interest are estimated using a nearest neighbor estimation method combining the data from six wavebands of the image with the data from the field plots. A GIS can be used to display maps of species composition, volumes of growing stock, biomass, or other parameters. Each estimate for a 25-m square is very imprecise, but when the individual values within a defined area are averaged, estimates specific to localities smaller than those of the original inventory populations are produced.

Our initial research was to determine if the system could be applied to New Zealand radiata pine with the estimates of log-product volumes derived from MARVL. If so, then the method could predict log-product volumes for small coupes and define within-stand variability. A trial forest block of 1,000 ha consisted of radiata pine ranging from new planting through to mature 28-year-old stands. The former Forestry Corporation of NZ supplied data from 188 of their inventory plots in the block. A Landsat TM image taken in December 1990 was also available. For selected stands within the block, estimates were made of the total standing volume and the volumes of pruned logs, saw logs, and pulp wood for each 25-m square (Tomppo *et al.* 1996). Figure 1 depicts a raster map of estimates of total standing volume across two compartments in the forest.

The research confirmed that the method is sound over larger areas in New Zealand plantations. However, it also showed that for even-aged stands of 40 ha or less, volume estimates were biased; that is, volumes on stands with low volumes per hectare were overpredicted, while those with high values were underpredicted. Further work (Trotter *et al.* 1997) showed that it is possible to produce unbiased estimates at the stand level by estimating the coefficients of linear regressions with volume as the independent variable and Landsat TM band 4 the dependent variable, then inverting the equation. The estimates for very small areas still have wide confidence limits, but even at this level of imprecision, the methods give useful additional information on the spatial distribution of volume. Areas of damage are clearly visible, as are patches of higher and lower volumes that cannot be determined from plot data alone.

Automatic Delineation of Individual Trees

An alternative method of determining the spatial distribution of product volumes is to automatically identify the location of each individual tree within a stand or coupe, stratify if necessary, count the trees, and combine the count with measurements from an individual tree sample. For small woodlots, area estimates may be poor due to indistinct boundaries; a good way of providing an owner with volume estimates for the whole woodlot is to multiply average tree parameters by the total number of trees present.

It is sufficient if the tree location is determined to within several meters or so, and the problem reduces to one of correctly identifying a single tree apart from its neighbors. When the locations of trees are entered into a GIS, it will be possible to accurately count the number of trees in any coupe or subdivision of a stand, or to subdivide areas into

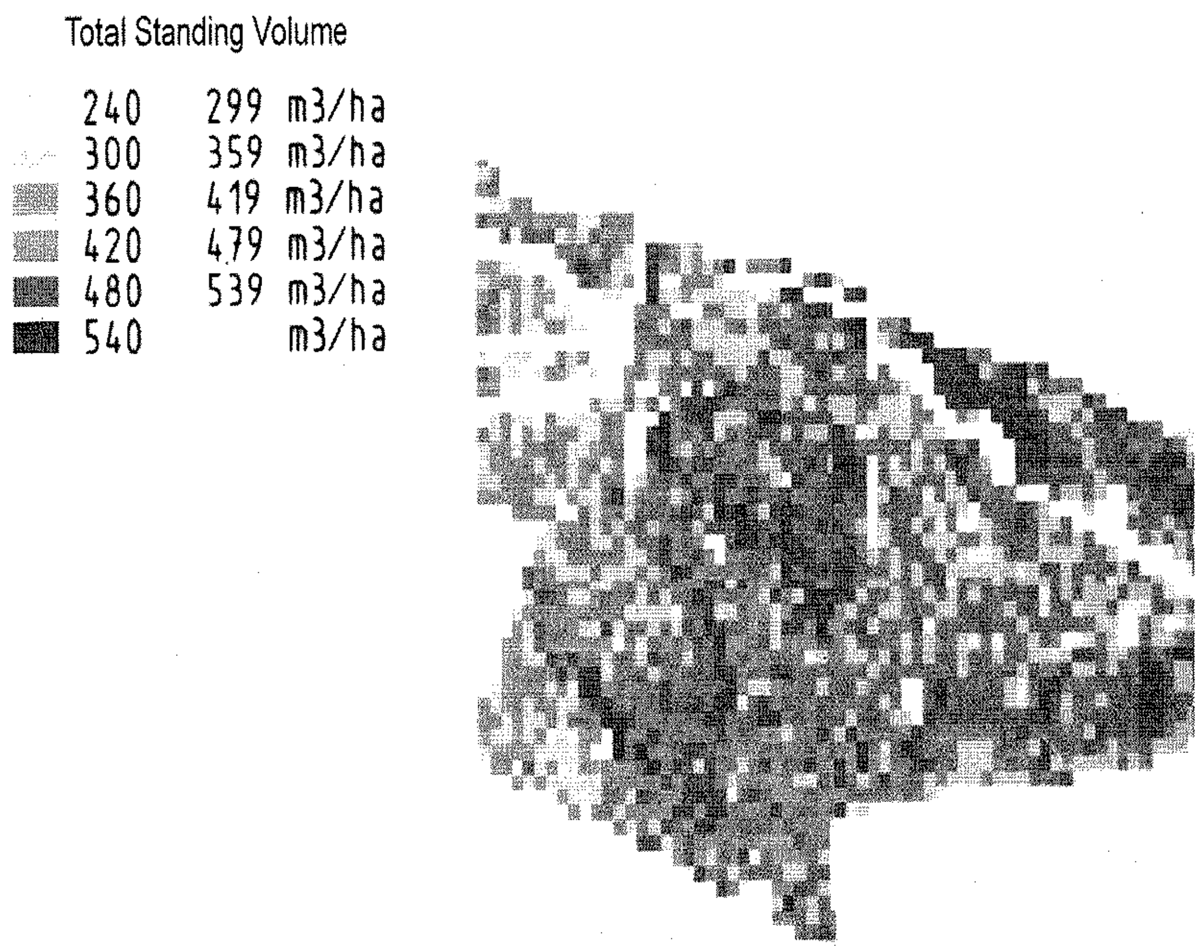


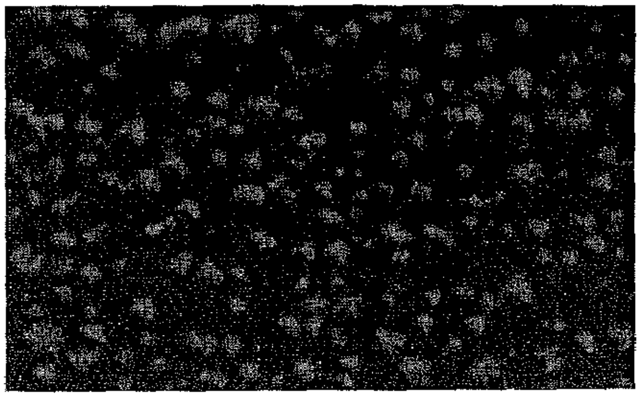
Figure 1.—*Total standing volume predicted for each 25-m square in two compartments.*

more uniform blocks. Given an accurate count, and the additional knowledge of the spatial distribution of the stems, it should be possible to use individual tree sampling techniques to indicate the spatial distribution of log products.

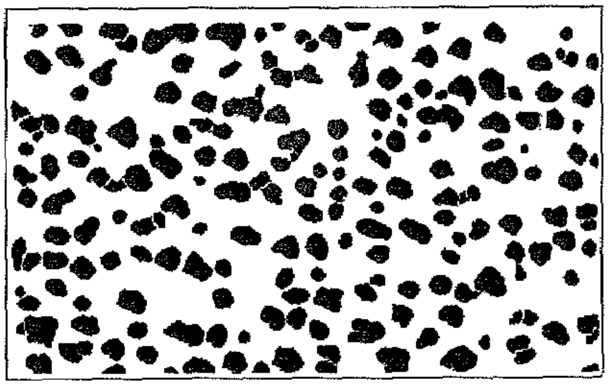
In the last 6 or so years, methods of automatically delineating tree crowns from aerial photography have been reported in the literature. Large-scale photographs are scanned, and the reflectance values of each sub-meter pixel analyzed. For example, on planted Norway spruce in Denmark, Dralle and Rudemo (1996) carried out a method of kernel smoothing and then counting maxima above a threshold level. They reported being able to locate trees in stockings ranging from 367 to 1,257 per hectare in a thinning experiment, with tree count errors of less than 7 percent. We recently tested the method described by Gougeon (1995, 1997). This method is described as a "valley following" method, where areas of shaded ground vegetation are eliminated first, and tree crowns are delineated by proceeding from one such area to the next by forming "valleys" of low reflectance valued pixels. This algorithm is then followed by a second, rule-based algorithm to further delineate crown boundaries.

Radiata pine does not have a narrow, regular, conical crown. The branches in the upper half of the crown grow upwards, and although height growth is vigorous, apical dominance can easily be lost if the main shoot is damaged. Double or multiple leaders can occur. From above, the tips of branches of the topmost branch cluster can easily be mistaken for individual trees under some circumstances. The crowns are seldom circular in shape, because branches grow into gaps or areas of less crown competition and quickly become large.

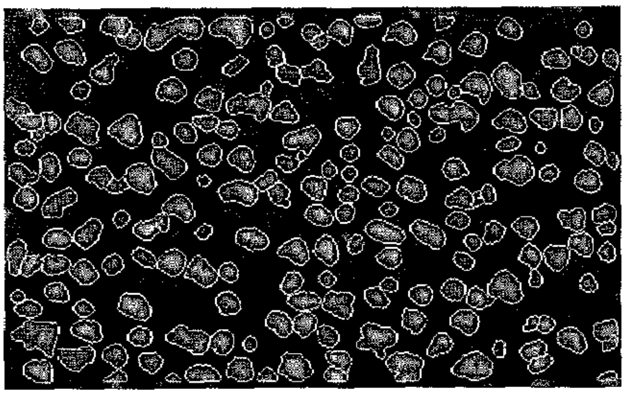
These initial trials found that Gougeon's method holds promise. Using infrared photographs was a useful first start, rather than color photography, because there was a loss of resolution of the lower branches, and the central tallest portion of the crown became more readily observable in contrast to the dark lower periphery. To date, we have implemented the method, with some modifications to the rule-based algorithms specific for radiata pine, and have made subjective comparisons with the original aerial photographs. Figure 2 shows the original infrared photograph, the outcome of the method, and an overlay of the edges of the delineated crowns with the original color photograph. Future work will involve a more rigorous testing over a range of conditions. From the air, the crowns of a stand of radiata pine change dramatically through time. Following thinning, there are large gaps between crowns, and it has been suggested that shortly after the final thinning may be the best time to acquire photography to locate individual trees. Shortly before harvesting, a second image could be acquired, and the



a: Original infra-red image



b: Output from the Rule-Based Algorithm



c: Edge of the successfully delineated crowns obtained from the Rule-Based Algorithm over the original image

Figure 2.—*Automatic delineation of the locations of individual radiata pine trees.*

analysis repeated, making use of the first estimate. Given even radiata's inability for its leader to move far from its original position, we believe the individual tree location problem is solvable at an economic cost.

INVENTORY DURING HARVEST

During the harvest, short-term log allocation planning attempts to ensure that equipment is optimally used and that all product commitments are being met. The situation changes rapidly and these plans are updated weekly. New Zealand harvesting emphasizes value recovery, that is obtaining the maximum value from the coupe by optimum bucking while meeting all constraints imposed by past sales and existing production commitments. Optimally planning which set of bucking instructions to give to one of many logging gangs or machines and the subsequent control and monitoring of performance requires detailed information about the trees that are to be cut over the next day or week. Some of this information can come from pre-harvest inventory and from the geospatial analysis. A major source of information is the immediate-past yield from the coupe. These data can be collected by a log-stocks and delivery information system. Real-time information of the trees currently being harvested can be collected by on-board computers of processors or by electronic calipers used by motor-manual logging gangs as they are bucked. A current research topic is how best to integrate these sources of data, and then provide the information in a practical decision support system. Empirical or hierarchical Bayes procedures (Green and Strawderman 1992, Burk and Ek 1982) are being investigated as a method of defining what amount of weight to give to each of the sources of information.

CONCLUSIONS

Defining the most appropriate markets and then improving the allocation of log products to current commitments offer the potential to greatly improve the profitability of New Zealand's production forests. Good management needs good information. Pre-harvest inventory has increased in use, especially over the last decade, and this increase has generated a greater demand for more precise and spatially accurate information about the potential yield of log products. New electronic measurement equipment such as ultra-sound or laser hypsometers and computerized calipers, new ways of using photogrammetry incorporated into mapping workstations, and geostatistical and image-processing systems offer the means to provide that information economically.

In the near future, it should be possible to describe the potential recoverable volumes in more detail than is possible by the inventory systems currently in use, and to give indications, at least, of the geographic location of potential log products within a stand or a coupe. Information about the forest as a warehouse should be available in quantitative form and be suitable for input for log allocation and wood flow decision support systems.

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