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Literature Review
Robust Planning Through Improved Inventory

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Leadership in forest and environment management, innovation and research

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EXECUTIVE SUMMARY

The goal of this project is to investigate how uncertainty in inventory data impacts on decision making in the New Zealand forestry industry. Findings from this work will be used to direct future research in this area in the Future Forests Research (FFR) Radiata Management theme research programme. Objective 4 of this programme is targeted at improving forest inventory techniques, and contains a number of projects looking at improving specific inventory techniques ranging from single tree sampling to the use of hyper spectral imagery for forest health monitoring. The project outlined here is different in that it aims to research new methods of determining the true value of good quality inventory information and how that information affects decision making.

In forestry, inventory data has value when it is used in a planning model, which in turn is used to make forest management decisions. Although the cost of carrying out forestry inventory is relatively easily calculated, the value gained from possessing these data is substantially more difficult to calculate.

This report is a literature review of forestry planning systems, and also includes a summary of interviews with forest inventory and planning professionals. Topics covered include the strength of forest planning systems and techniques for valuing forest inventory information.

The major finding of the literature review and the interviews was that to date there has been no New Zealand-based research work completed in this area. Internationally the topic of valuing forest inventory information has been studied, with the majority of the literature focussed on trying to compare different inventory techniques, using methodologies such as cost-plus-loss. A key finding of this research is that researchers have found it very difficult to measure the value impact of improving inventory precision. Most of them didn't even try. It is doubt whether any of the researchers who claimed to have measured the value impact had actually quantified real value impacts as opposed to quantifying uncertainty in the measurement of value. New Zealand forestry management companies generally hold the view that current inventory levels are sufficient for planning and decision making, and an increase in intensity will not increase the value of the information. Future research work in this area should aim to give FFR stakeholders the ability to assess the cost of doing forest inventory versus the value gained from using that information in decision making.

INTRODUCTION

This paper aims to review the international research literature on the impact of the forest data quality on forest planning, and to canvas the New Zealand forestry industry on how they account for uncertainty in yield data in their planning processes. Findings from this work will be used to focus future research to be carried out in this area in the Future Forest Research (FFR) program.

Background

Planning can be defined as a “series of arbitrary or dogmatic decisions to a critical or sophisticated investigation into the whole range of possible choices open to an enterprise.” (Johnston, Grayson, & Bradley, 1967) Planning can be regarded as the middle three steps of the five steps of decision making:

- Identification of the problem
- Obtaining necessary information
- Production of possible solutions
- Evaluation of such solutions
- Selection of a strategy for performance

In forest planning, a range of mathematical modelling techniques is used to help practitioners make important management decisions; in New Zealand deterministic models are commonly used. Models such as FOLPI and Woodstock, primarily utilise linear programming (LP) to obtain optimal forest plans. Deterministic techniques have little ability to either include estimates of data uncertainty in the solution evaluation process, or communicate the impact of that uncertainty on the solution selection to the decision maker.

As in many other industries, most often the production and evaluation of solutions is driven by discounted-cash-flow (DCF) analysis, but to facilitate this process uncertainty in the input data is often underestimated or disregarded completely. Courtney *et al.* (1997) argue that “when the future is uncertain, the approach (DCF) is at best marginally helpful and at worst downright dangerous: underestimating uncertainty can lead to strategies that neither defend a company against the threats nor take advantage of the opportunities that higher levels of uncertainty provide”. The problems caused by these uncertainties are exacerbated due to forestry’s relatively long term production cycle.

Uncertainty can be reduced through obtaining higher quality data. Kätsch (2006) states “The quality of information can be described with several criteria, for instance accuracy, reliability, relevancy, timeliness, completeness and presentation.” (p 178). Regardless of the quality, data or information can only generate value when it is used to enable efficiency in decision making; with good information and the wise use of that information, the opportunity costs of making poor decisions may be minimised (Knoke *et al*. 2010).

All data sources used by forest planning models include some degree of uncertainty. The sources of uncertainty in input data for forest planning can be categorized into the following:

- Yield data
    - Accuracy of models used for forecasting tree and stand parameters
    - Underlying inventory information
- Area data – underlying area statement
- Pricing and costs information

Changes in stumpage prices and silvicultural costs are generally beyond the control of forest management planners, and mathematical models are normally developed independently of forest planning and management organisations. The quality of timber inventory data is one area that can be improved upon through the action of a forest management company. However as with the acquisition of all good quality information, improving the quality of forest inventory information has an associated cost (Knoke *et al.* 2010).

In New Zealand, ground-based plot measurements are by far the most common form of forest inventory undertaken. These take place several times during a rotation which can, according to Goulding and Lawrence (1992), be classified as management or pre-harvest inventory. Management inventory tends to be carried out in early and middle rotation and designed to obtain reliable stand level parameters such as basal area, mean top height and stocking. Pre-harvest inventory is normally conducted at a much higher intensity than earlier measurements and is designed to obtain accurate assessment of the recoverable volumes of the different log products that will be produced at the time of harvest.

As with all measurement systems there are a number of potential sources of error in any forest inventory. They can be divided into three classes:

- measurement error;
- sampling error; and
- regression error.

Measurement error is the error associated with measuring the dimensions of trees, as well as mistakes made by the field crews, instrument variability and judgment variation in the decisions made by the measurement teams. A number of variables in forest inventory cannot be efficiently measured directly; these include the height of all trees, breakage, volume and taper. These important variables are normally estimated in regression equation and all regression equations have some level of error associated with them. Sampling error is the error resulting from the fact that only a subset of the population was actually measured.

If a forest inventory has been carried out in accordance with standard statistically valid sampling techniques, reliable estimates of inventory precision can be determined (Shiver and Borders 1996). The inventory analysis software packages used in New Zealand such as MARVL, YTGEN and ATLAS Cruiser have the functionality to report various measures of the variability of the inventory data. A commonly used measure of inventory precision in New Zealand is Probable Limit of Error (PLE). This term is peculiar to New Zealand, and refers to the confidence limits expressed as a percentage of the estimated mean (Maclaren 2000). Statistical methods of describing variability in the inventory data are often lost in the process of yield table generation; as a result their usefulness in decision-making purposes is limited.

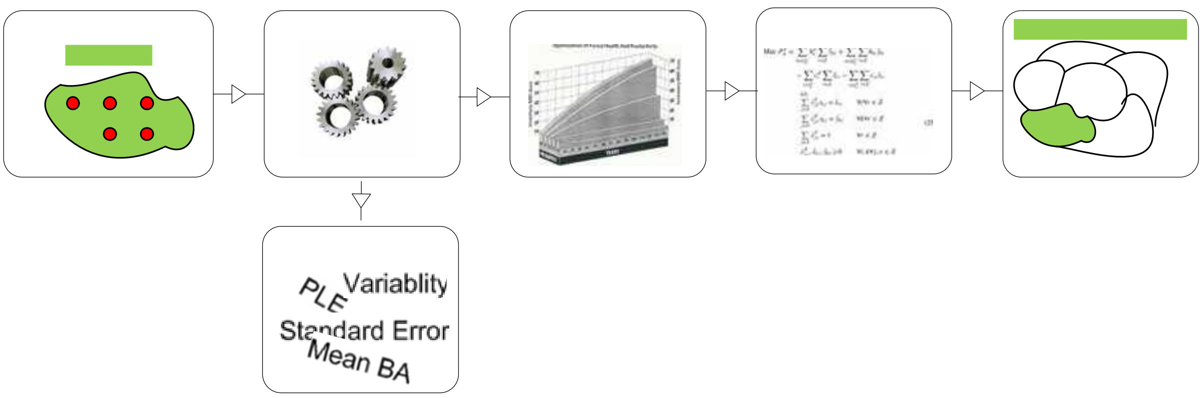

Figure 1. Typical data flow for yield information for forest planning.

Figure 1 indicates that for forest planning purposes the inventory data in combination with growth models are used to produce yield tables. Yield tables typically contain only information about mean volume per hectare at a particular age, and generally no information about the precision of these volume estimates is included. There is no formal method for communicating the measures of the underlying uncertainty in the inventory data through to the management plans. This means that the magnitude and impact of errors on the decision making process is seldom evaluated by forest managers.

Knoke *et al*. (2010) state that information in itself has very little value; rather, information generates value, because it enables effective decision making. As previously stated, forest planning inventory data have value only when used to make correct forest management decisions. The ability of the plan to remain feasible and optimal is a measure of its robustness. If plan is considered robust then its feasibility and optimality are unaffected by uncertainty in the underlying data. Little is known about the general robustness of forest planning models in New Zealand. Although the cost of acquiring forest inventory data is widely known, there is little knowledge of the value of the information for planning purposes.

The New Zealand forestry industry has little understanding of the true cost benefit of increased resource assessment costs vs the benefits which may results due to improved management decisions. Internationally there is a substantial body of work on improving inventory and planning systems, but very little research has been carried out in the area of assessing how the quality of the data impacts on forest planning decisions. To date there has been no published quantifiable analysis on how improving our knowledge of both the forest resource and the external market can improve the forest planning process in New Zealand.

Definition of Cost plus Loss

Many of the research papers reviewed in this report used the cost-plus-loss analysis technique to try to establish the true value of information derived from forest inventory. The following is a definition of cost-plus-loss:

> The inventory cost for a specific method is added to the expected loss due to non-optimal decisions caused by erroneous information derived from the inventory.

INTERNATIONAL LITERATURE REVIEW

The following literature review gives a brief summary (in table form) on all of the relevant English language literature that could be sourced on:

- valuing the impact of forest data quality on forest planning; and
- the robustness of the forest planning systems.

There is a small body of literature on this topic, with the majority of papers produced by a small group of authors. The majority of the research has been carried out in either USA or Scandinavia, mostly on the topic of assessing benefits for forest management from new inventory systems which generally include a form of remote sensing.

Valuing the Impact of Forest Data Quality on Forest Planning

Kangas (2010) published a review of the research carried out on valuation of information in different industries, and discusses the possibilities of using it for forestry applications. This article appeared in the latest issue of the European Journal of Forest Research, a special issue on "Linking Forest Inventory and Optimisation" (Knoke *et al.* 2010). Duvemo and Lämås (2006) also give a comprehensive summary of the literature in the area of assessing the value of forest data by including the cost of acquisition and the impact on planning decisions. Reviews of these two papers are presented first and the remaining reviews in this section consist of specific case studies where attempts have been made to place a value on the quality of forest inventory data.

Reference	**Duvemo and Lämås 2006**
Title	The influence of forest data quality on planning processes in forestry.
Interesting Information from Introduction	• It would seem that given that both the value impact of different forest management decisions and the cost of forest data acquisition are high, the trade-off between these two elements on the production forest profitability would be an interesting topic for research. • There has been very little research in this area. There is a large body of literature concerned with detailing different inventory techniques and new planning techniques, but very little research on how inventory and planning systems interact to help planning foresters make better decisions. • "Most forest planning research makes use of some available data but, in most cases, without giving any thought to how data capture can be optimized" (p 327-339).
Objective	The objective of this paper was to review the international literature on assessing the influence of forest data quality on forest planning processes.
Approach	The paper focuses on literature relating to the value of information. It divides the literature into two categories; those using analytical approaches and those using simulation. (It should be noted that many but not all of the papers summarised in this review are also covered by Duvemo and Lämås 2006)
Results	NA – No formal results are presented.
Full Citation	Duvemo K and Lämås T, 2006, The influence of forest data quality on planning process in forestry. Scandinavian Journal of Forest Research, 2006; 21; 327-339.

Other Interesting References	

Reference	**Kangas 2010**
Title	Value of Forest Information
Interesting Information from Introduction	• The value of information in decision making is the difference between project value of the decision made with the information and the project value of the decision made without the information. • Information can have value from two different sources: intrinsic value and value in the decision/making.
Objective	The objective of the paper was to review the research work on determining the value of inventory information in the forest industry.
Approach	The author gives an excellent overview of the concept of value of information (VOI) and its importance to the forest industry. Kangas also reviews the cost-plus-loss methodologies used in other papers, many of which are also reviewed in this document. The paper also presents VOI methodology that uses Bayesian decision theory. This approach has been traditionally used in the insurance and advertising industries, and the theory is illustrated using a very simple example. The advantage of the Bayesian approach over cost-plus-loss analyses is that it accounts for prior information. This means that by using the Bayesian value analysis, cases may be revealed where acquiring new data is simply not profitable.
Results	NA – No formal results are presented.
Full Citation	Kangas A.S. (2010) Value of Forest Information. European Journal of Forest Research. DOI 10.1007/s10342-009-0281-7.
Other Interesting References	Macauley M.K. (2006) The value of information: measuring the contribution of space derived earth science data to resource management. Space Policy 22:274-282.

Reference	**Kätsch 2006**
Title	Precision forestry and information – information management a forgotten task?
Interesting Information from Introduction	• "The benefits from using information depend in particular on its quality. Wrong or insufficient information may become quite costly, if decisions based on it lead into a wrong direction." (p 176). These costs are often unknown.
Objective	This paper aimed to "raise awareness of the problems related to information management with a specific focus on information quality in forestry."
Approach	Information quality can be defined as the sum of all requirement expected from information. The most important criteria for information quality are: • Accuracy • Reliability • Relevance • Timeliness • Completeness • Presentation

Results	NA – No formal results are presented.
Full Citation	Kätsch C (2006) Precision forestry and information – information management a forgotten task? In: Ackerman PA, Längin DW, Antonides MC (eds) Precision forestry in plantations, semi-natural and natural forests. Proceedings of the international precision forestry symposium. Stellenbosch University, South Africa, pp 175-186.
Other Interesting References	

Reference	**Eid, Y. 2000**
Title	Use of Uncertain Inventory Data in Forestry Scenario Model
Interesting Information from Introduction	• Evaluations of inventory methods usually stop when the error level is stated, while the uncertainty accompanied by using the data is seldom considered. • Long-term timber production analyses and the uncertainty related to inventory data (present state of the forest) tend to be paid less attention, in spite of the fact that accuracy can be improved.
Objective	Address uncertainty in inventory in long-term timber production analyses.
Approach	The paper used computer-generated inventory data for 25 Norway spruce stands, each with an area assumed to be one ha. The dataset was then replicated introducing different levels of random errors for different stand parameters. The long term planning LP model GAYA-JLP was used and Net Present Value (NPV) was calculated for each model run. The NPV loss from the errors was calculated by subtracting the NPV of the model with errors from the NPV of the reference data (without errors).
Results	A real rate of discount of 3 % and an error level of 15 % resulted in expected net present value losses of 1 NOK/ha for basal area, 63 NOK/ha for mean height, 210 NOK/ha for site quality, 240 NOK/ha for stand age, and 499 NOK/ha where random errors occurred simultaneously for all these variables. The expected net present value-losses varied considerably.
Full Citation	Eid, T. 2000, Use of Uncertain Inventory Data in Forestry Scenario Models and Consequential Incorrect Harvest Decisions. Silva Fennica 34(2)
Other Interesting References	

Reference	**Kangas A.S. and Kangas J. 1999**
Title	Optimisation Bias in Forest Management Planning Solution Due to Errors in Forest Variables
Interesting Information from Introduction	• Yields predicted with statistical models include uncertainty which has four main sources; (i) model mis-specification, (ii) random estimation error of the model coefficients, (iii) residual variation of the models, and (iv) errors in the independent variables of the models.
Objective	This paper studies the effect of uncertainty in forest yields on

	Optimisation through the use of simulation. The effect of two different sources of error, the correlation structure of these errors and relations among the objective variables are considered, as well as the effect of two different Optimisation approaches.
Approach	The effect of uncertainty of the forestry optimisation planning model is studied through the use of simulation. The study used twelve simulated stands with the same area. The stands varied in age and standing volume. The effect of two difference sources of errors was considered: the correlation structure of these errors and relations among the objective variables.
Results	The results show that both correlation structure of these errors and relations among the objective variables have a notable effect on the optimisation results.
Full Citation	Kangas, A.S. and Kangas, J. 1999. Optimisation bias in forest management planning solutions due to errors in forest variables. Silva Fennica 33(4): 303-315.
Other Interesting References	Hof, J.G., Kent, B.M and Pickens, J.B. 1992 Chance constraints and chance maximization with random yield coefficients in renewable resource Optimisation. Forest Science 38: 305-323. Hof, J.G., Bevers, M. & Pickens, J. 1996. Change-constrained Optimisation with spatially autocorrelation forest yields. Forest Science 42: 118-123. Mendoza, G.A., Bare, B.B. & Zhou, Z. 1993. A fuzzy multiple objective linear programming approaches to forest planning under uncertainty. Agricultural Systems 41: 257-274. Pickens, J.B. & Hof, J.G., Kent, B.M. 1991. Use of chance-constrained programming to account for stochastic variation in the A-matrix of large-scale linear programs. A Forestry application. Ann. Oper. Res. 31 511-526. Stahl G. 1994. Optimal stand level forest inventory intensities under deterministic and stochastic stumpage value assumptions. Scandinavian Journal of Forest Research 405-412.

Reference	**Border *et al.* 2008**
Title	The value of timber inventory information for management planning.
Interesting Information from Introduction	• "Simulation approaches to investigating this problem have become more common as computer power has increased over the past 10-15 years. The typical approach for simulation exercises is to compare the value of a timber management plan developed from an error-free population with timber management plans developed form timber data containing some level of error" (p 228). • The value of the inventory for timber sales is well understood, but this is not the case for planning purposes. • Timber inventory is usually carried out using some sort of probabilistic sample design. All sample designs are subject to sampling error and non-sampling error. Sampling error can be minimised by utilising the correct sampling strategy at an appropriate level. In practice non-sampling error is often assumed to be minimal in timber inventory applications. However this is not always the case.

	• Unfortunately there has not been a great deal of research into the cost of using poor quality timber inventory data in strategic and tactical planning operations. • Clearly, relatively large NPV losses can result from the use of forest plans that utilise inventory data of a poor quality.
Objective	The objective of the work described in this paper was to determine the value of timber inventory for management planning.
Results	Their results were dependent on forest type, sampling error and discount rate, and ranged from 5 to 382 US$ ha^{-1} (8 - 542 NZ$ ha^{-1}, at exchange rates of the 10 March 2010). In addition, they found that NPV losses in the southeast US were greater in younger stands than in older stands, and greater in faster growing more intensively managed plantation than in slower growing natural pine or extensively managed hardwood stands".
Full Citation	Borders B.E., Harrison W.M., Clutter M.L., Shiver B.D. and Souter R.A. (2008). The value of timber inventory information for management planning. Canadian Journal of Forest Research 38: 2287-2294.
Other Interesting References	Duvemo, K. and Lamas, T, 2006. The influence of forest data quality on planning processes in forestry. Scand. J. For. Res. 21: 327-339. Duvemo, K., Barth, A., and Wallerman, J. 2007: Evaluating sample plot imputation techniques as input in forest management planning Can. J. For. Res. 37: 2069-2079. Holmstrom, H. Kallur, H. and Stahl, G. 2003. Cost-plus-loss analyses of forest inventory strategies based on KNN-assigned reference sample plot data. Silva Fenn 37 381-398.

Reference	**Duvemo, Barth and Wallerman 2007**
Title	Evaluating sample plot imputation techniques as input in forest management planning.
Interesting Information from Introduction	
Objective	The objective of the research presented in this paper is to evaluate forestry planning data obtained from recently developed sample plot imputation methods based on laser scanner and satellite image data. This evaluation was done using a costs-plus-loss analysis.
Approach	The trials were carried out in two different forest estates in Sweden. Five different inventory methods were analysed using the cost-plus-loss methodology: • Plot10 – simulated 10 plots per stand field inventory • Plot5 - simulated 5 plots per stand field inventory • ImpLS – imputation of sample plots supported by both laser-scanner and satellite data • ImpLa – imputation of sample plots supported by laser-scanner data • ImpSp – imputation of sample plots supported by satellite data The cost included all the direct costs associated with carrying out the inventory. The decision losses were restricted to the actual

	forestry operations. "The difference in NPV between such a management scheme and a truly optimal scheme, based entirely on the reference data ("error" free data), is considered to be the decision loss arising from using that particular data set". Only management decisions from the first 10 years of the model were included in the decision loss calculations. The actual decision losses were determined by simulation harvesting planning (Forest Management Planning Package (FMPP)).
Results	Overall the study showed the mean cost per loss per method favours sample plot inventories to provide the data for management planning. These sample plot inventories are by far the most expensive inventory method included in this study. For the imputation methods, the results indicate that the mean decision losses are between four and fifty times as large as the data cost. The imputation methods tend to favour small stands (<2 ha), whereas for the medium- and large sized stands the field inventories are still optimal.
Full Citation	Duvemo, Barth and Wallerman (2007) Evaluating sample plot imputation techniques as input in forest management planning. Can. J. For. Res. 37 2069-2079.
Other Interesting References	

Reference	**Holmström et al. 2003**
Title	Cost-Plus-Loss Analyses of Forest Inventory Strategies Based on kNN-Assigned Reference Sample Plot Data
Interesting Information from Introduction	• "Planning based on accurate data should generally, not surprisingly, result in better decisions than planning based on poor data." • There is always a trade-off between how much money should be spent on inventories and what is lost through sub-optimal decision making.
Objective	The objective was to carry out a cost-plus-loss analysis of the possibilities of using kNN-assigned reference plots as inputs to forestry planning.
Approach	Stand level cost-plus-loss analyses were carried out to compare: 1) Traditional stand record information based on visual assessment. 2) Plot-wise aerial photograph interpretation in combination with stand record information. 3) Sample plot inventory with 10 plots per stand. 4) Sample plot inventory with 5 plots per stand. Data from two test sites, Brattaker and Remningstorp, were used. The cost-plus-loss analysis was carried out in the standard way. The field inventory cost was greater than 10 times that of the kNN methods.
Results	The results indicated that for large mature stands, with a relatively short time to the next treatment, accurate methods should be employed, while with smaller less valuable stands the less accurate approach can be used.
Full Citation	Holmström, H., Kallur, H. & Stahl, G. 2003. Cost-plus-loss analyses of forest inventory strategies based on kNN-assigned reference sample plot data. Silva Fennica 37(3): 381-398.
Other Interesting References	

Reference	Holopainen, M. & Talvitie M, 2006
Title	Effect of Data Acquisition Accuracy on Timing of Stand Harvests and Expected Net Present Value
Interesting Information from Introduction	• "Reliable inventory data are essential for forest planning." (p 533) • "Few studies have compared the various inventory methods from an economic point of view." (p 534)
Objective	The aim of the research presented in this paper was to compare the traditional compartmentwise forest inventory method with individual tree-based 2D and 3D measurement of digital aerial photographs and airborne laser scanning.
Approach	Four different inventory methods were compared using the cost-plus-loss methodology: • Compartmentwise • 2D measurements • 3D measurements • Laser scanning The decision loss was calculated using $NPVloss_{ij} = NPV_{referencei} - NPV_{invmethodij}$.
Results	The compartmentwise inventory showed the smallest NPV losses of all inventory methods. However as the study area was small the cost of the remote sensing was quite high. The compartmentwise and 3D methods outperformed the 2D method, due to their greater accuracies. The authors point out that discount rate is always important in this type of analysis.
Full Citation	Holopainen M & Malvitie, M (2006) Effect of data acquisition accuracy on timing of stand harvests expected net present value. Silva Fennica 40(3): 531-543.
Other Interesting References	

Robustness of Forest Planning System Solutions to Uncertainty in Forest Data

Only two papers have been found on measuring the robustness of planning systems in the forestry industry. The first paper is a good example of testing the robustness of a harvest scheduling planning model. The second uses a New Zealand case study to illustrate robust optimisation using a transportation problem. The other papers reviewed in this section are examples of applying operational research techniques to take into account input data uncertainty.

Reference	**Border et. al 2008**
Title	A test for robustness in harvest scheduling models
Interesting Information from Introduction	• A critical assumption behind harvesting scheduling models is that the projected harvesting schedule is representative of the actual harvest schedule that will be implemented. The exact implementation of the harvest schedule is not necessarily required, because many of the schedules are closely related. • The authors believe that robustness testing reveals which model structures are appropriate for different uncertainty levels.
Objective	The objective of the paper is to present a robustness test that measures the level of deviation between projected plan and the implementation plan while still meeting project target levels.
Approach	• The robustness of the models was tested by introducing variation into harvest schedules and measuring the ability of the schedule to maintain the original target objective levels. • The paper investigates the ability of two types of harvest scheduling DSSs, simulators and optimizers to respond to changes between the projected and the implemented harvest schedules. • The paper tests the robustness of this model by measuring the number of changes that can be made to a predicted harvest schedule before it fails to achieve the objective targets. • The paper also investigated what the effect of reducing harvest volumes targets on the robustness of a harvest scheduling plan would be. • The authors developed a simulation and simulated annealing algorithm for use in this research. • A case study was carried out in the Kootenay landscape in the interior of British Columbia.
Results	The paper shows that when using a maximum sustainable volume objective, both the simulation and optimisation models have very little robustness. The optimisation model was relatively sensitive to changes to the harvest schedule. The simulation model was less sensitive, with 100% of the simulation failing when only approximately 2% of the harvest schedule was altered.
Full Citation	Boyland M., Nelson J., Bunnell F.L. (2005). A test for robustness in harvest scheduling models. Forest Ecology and Management 207. 121-132.
Other Interesting References	Cerda, J.P. 2002. Addressing uncertainty in forest planning. M.Sc. Thesis. University of British Columbia, Vancouver, Canada, p. 156.

Reference	Murphy and Stander 2007
Title	Robust Optimisation of Forest Transportation Networks: A Case Study
Interesting Information from Introduction	• In transportation optimisation numerous techniques have been used to solve the harvest scheduling, route allocation and infrastructure investment problems. Most of these techniques assume that the model parameters are known with certainty. • Uncertainty is not limited to the parameter values, but also extends into the realm of modelling approximation. All models are an abstraction of a real world situation; this generalization results in uncertainty. • Many practitioners resort to sensitivity analysis to evaluate the sensitivity of a given solution to uncertainty. Others use the worst-case analysis where all the parameter values are set to the worst possible expected value. • Numerous operations research methodologies such as stochastic linear programming, dynamic programming and chance-constrained methods have been developed over the years to overcome the issues of uncertainty. • The goal of robust optimisation is the 'find optimal solution that is not overly sensitive to some realisation of uncertainty". (p 118)
Objective	The objective of the research was to illustrate through the means of a case study that one way of dealing with uncertainty is through robust optimisation.
Approach	The authors carried out a case study in the North Island of New Zealand on a simple transportation optimisation problem. The methodology used is described in Kouvelis and Yu (1997). The methodology had the following steps: 1a. Generate sales with variable volume and product mix. 1b. Generate transport network with variable costs and revenues (10) 2 Derive 'optimal' solutions (100 trial scenarios) 3 Group solutions into abridged set of similar scenarios. 4 Generate data (1000 trials) by varying (-3 to +3 SD) stand volume, product mix, variable and fixed costs, revenues. 5 Select solution with 'best' robustness measure. The authors use seven different robustness performance measures; most frequent solution, highest average NPV, lowest variation in NPV, best/worst case NPV, highest NPV Signal-to-Noise Ratio, Highest Weighted NPV Sum and Lowest Threshold Probability.
Results	The research presented in this paper found that: • The deterministic solution is extremely unstable and highly reliant on a particular degree of uncertainty. • The robust solution is dependent on the robust performance measure used. • The true robust solution is different from the deterministic solution.
Full Citation	Murphy G and Stander HC (2007) Robust Optimisation of forest transportation networks: a case study. Southern Hemisphere Forestry Journal 69(2).
Other Interesting References	• Kouvelis P and Yu G (1997) Robust discrete Optimisation and its application. Kluwer Academic Publishers. Boston

	• Bai D, Carpenter T and Mulvey J (1997) Making a case for robust optimisation models. Management Science 43: 895-907.

Reference	**Eriksson 2006**
Title	Planning under uncertainty at the forest level: A systems approach
Interesting Information from Introduction	• Dynamic Programming can deal with uncertainty at an individual stand planning level, but dealing with uncertainty at a forest or estate level is significantly more difficult. • The standard model 1 formulation used in all of the well-established forest planning systems splits the operation of the often complex stand projection system from the LP-based planning model. • Due to the wide scale used of this formulation and its versatility, it would make sense to develop tools for analysis of stochastic phenomena using the same platform.
Objective	Allow for the modelling of uncertainty in the standard forest planning model 1 formulation.
Approach	• The paper outlines the formulation that allows for "recourse". "A stochastic programme with recourse requires that management can be adapted to new information as events unfold" (p 112). • This requires the ability to make decisions in each period for each stand. Please refer to the paper for details of the formulation. • A small example is given showing how the formulation can be applied. The example shows how the stochastic effect of weather on growth can be modelled into a traditional LP model.
Results	• This paper shows how stochastic programming can be integrated in the standard model 1 LP formation used in forest planning. • The application of this technique is limited to situations where the scenario probabilities are unaffected by management actions. • Another limitation is problem size – the stochastic model will always be larger than the corresponding deterministic model.
Full Citation	Eriksson L O (2006) Planning under uncertainty at the forest level: A systems approach. Scandinavian Journal of Forest Research. 21 (Suppl 7): 111-117
Other Interesting References	

AN INDUSTRY PERSPECTIVE ON THE IMPACT OF FOREST DATA QUALITY ON PLANNING PROCESSES

The following information was collected during discussions with staff members who are directly involved in forest planning and inventory from a number of forest management companies. These discussions were carried out as an unstructured interview; although a series of questions was used to help direct the discussion they were not asked directly and hence neither the questions nor the answers have been provided in this paper. A bullet point summary from each discussion is provided.

The goals of these discussions were to understand how the New Zealand forest industry perceives uncertainty in yield information and how it can impact on forest planning. The discussions also provided a mechanism to inform the industry of the research topic and gain guidance on the direction of future research efforts.

Company	**1**
Size	Large
General Comments	• The current levels of inventory intensity have been developed from years of trial and error. They are confident that current inventory intensities are correct for their requirements. • In terms of financial projection (valuation) there is far more uncertainty in the log prices than in the resource information and predictions. • It seems that the resource team still gets questioned about the quality of their predictions. • They do not have a formal way of presenting the underlying data uncertainty in forest management plans. • They run an extensive reconciliation program for yields and have found that their predictions are within five percent of the actual yields. This close alignment between the predicted and actual yields gives management confidence in their yield prediction and the plans produced from them. • They are constantly using the reconciliation program results to review they inventory program looking for ways they can improve they predictions. • They believe that for planning purposes their current inventory levels are higher than required, but this intensity is required for reporting to investors. • Their main issues are around predicting pruned and structural quality. However there is currently very little way of predicting structural quality using field-based measurement.
General Comments on research topic	
Interesting point for research project	• The value of reducing uncertainty for stumpage sales. • The value of taking density cores for structural segregation of the stands.

Company	**2**
Size	Large
General Comments	• Current inventory intensity is probably higher than would be

	required for planning. • Company 2 does a lot of the planning work for the purpose of managing the expectations of the forest owners. • Company 2 is currently trying to implement better harvest unit level reconciliation, which may require an even higher intensity for forest inventory. • At the strategic level, the scale of Company 2's estate means that planning modelling is reasonably robust. • Company 2 requires a high degree of accuracy from its forest inventory for harvesting reconciliation. It is important to monitor the harvesting crew performance with high accuracy. • The estate is reasonably consistent in terms of yield and quality and has been well croptyped. • Company 2 carries out a MRI (Mid-rotation inventory) at 14-15 years which is at a low intensity with the inventory plan not being based on target PLE. • The PHI is done the year prior to harvest and the inventory design is based on a target of 10% PLE by stand. • Company 2's tactical planning models seem robust. • Currently they are seemingly putting a real focus on improving sales and operational planning.
General Comments on research topic	• Stumpage sales are one area where the precision inventory is not well understood.
Interesting point for research project	• Company 2 is interested the new Timberline inventory systems.

Company	**3**
Size	Large
General Comments	• Current inventory intensity is probably higher than would be required for planning in most areas. • It is hypothesised that they could reduce the age of their MRI from age of 20 which could improve their overall resource description. • Company 3's Woodstock models are based on harvest units/stands. • In some regions, improvements in yield prediction perhaps can be made through improved inventory. • There is currently no formal way of expressing the level of underlying input data uncertainty in the results of the Company 3 planning models. • The company tends to be a reactive business as opposed to proactive. They have been managing the current resource for only three years so are in a "bit of a catch up" mode. • In regions where there is some concern over the level of certainty in the inventory yield estimate they would be willing to pay extra to reduce that uncertainty. • Currently inventory decisions would be cost driven. • It is believed that probably bigger improvements can be made by improving log making than improving inventory. • They do not see major shifts in the planned management of a stand/harvest unit from when the plan was generated using the MRI-based yield tables to PHI-based yield tables. They did indicate that they do see some shift in the planned

	management, moving from the generic yield tables created by Forecaster to the MRI based yield tables.
General Comments on research topic	• Overall positive
Interesting point for research project	• It suggested that one area for improvement is the young age stands (5-10 years old) inventory. This is an area where LIDAR or tree counting could be beneficial. • The optimal time for MRI inventory is another area that could be explored.

Company	**4**
Size	Medium

General Comments	• Four sources of variation in monthly planning:
	    o Actual inventory yield mix
	    o Production rate
	    o Timing of crew shift (actual vs planned)
	    o Work in progress inventory
	• Company 4 carry out their pre-harvest inventory at age 22-24 years; the inventoried stands are then grown on for use in their tactical and monthly planning models.
	• They have found that projecting forward 22-24 year old PHI is robust enough and see no need to do PHI any later.
	• The yield tables for stands younger than 22 years are generated by Forecaster using information from old stands with similar growth and form.
	• Company 4 sources wood from their own forest for which they have good inventory-based yield information as well as woodlots which normally have no yield information. This has in the past caused significant problems, particularly with crew scheduling.
	• Company 4 has thought about MRI for the purpose of yield matching, probably just on a subset of stands for validation of the Forecaster yield tables.
	• They would be interested in any research or new inventory systems that can deliver a reduction in inventory cost for the same level of accuracy. They have been interested in new Timberline pre-harvest inventory systems and have been involved in the early trials.
	• They are interested in methods of communicating underlying uncertainty in input data through into wood flow forecasts.
	• Strategies and tactical planning is main driver for determining the number of plots that need to be installed.
	• Harvest reconciliation is not really done for crew performance monitoring at Company 4.

General Comments on research topic	• Positive
Interesting point for research project	• The impact of mixed source wood – i.e. from source with inventory (i.e. own forest) and from sources without inventory (woodlots).

DISCUSSION

The New Zealand forestry industry spends a significant amount of money each year collecting information about the state of its forest estate. The exact spend by individual companies could be easily calculated, as the cost per plot is well known. This forest inventory information has very little value until it is used to assist decision making. At that point the value of the information is the value difference between the projected value of decisions made with and without the information less the cost of acquiring that data (Kangas 2010). In forestry, inventory data are collected for a large number of reasons, not just planning, so it is important that the value assigned to any information is the sum of its uses.

The review of the international research shows that the most popular method for trying to value forest inventory information is the cost-plus-loss methodology (Kangas 2010, Holmström *et al*. 2003, Duvemo *et. al*. 2007 etc). Nearly all the papers reviewed on this topic commented that obtaining an accurate estimate of the cost of data acquisition is substantially easier than calculating the loss due to incorrect decision making as a result of using low quality input data. Most used simulation approaches to calculate the difference in NPV between using a reference data set and the data from a particular inventory system. The difference in NPV becomes the loss in the cost-plus-loss equation. Kangas (2010) demonstrated that Bayesian decision theory could also be used to place a value on inventory data. The author suggested that the main advantage of this approach over cost-plus-loss was that this Bayesian methodology can take into account prior information such as historical inventory data. There were no instances in the literature of either of these approaches being used in New Zealand. However, the results from the international studies would indicate that research in the area could be used to determine the appropriate timing and inventory intensities for New Zealand's plantation forests.

From discussions with industry practitioners it appears that the tactical and strategic planning models used in New Zealand are relatively robust to uncertainty in yield data. Planning staff consistently noted that management plans developed using yield prediction based on low intensity mid-rotation inventories change little when more accurate yield prediction are integrated into the planning model, although there is no evidence in the small amount of the research literature that exists to support the above premise (Border *et al.* 2008, Murphy and Stander 2007). One of the objectives of future research in this area should be repeating the work carried out by Border *et al.* (2008) in the New Zealand context. Most of the companies contacted believed that their individual companies are probably doing too much inventory for planning purposes citing harvesting reconciliation and reporting as the main reason for maintaining their current levels of measurement.

It is clear from the industry discussion that although all the companies involved carry out forest inventory using the "MARVL" style methodology, the frequency and timing of the inventories vary from company to company. Trying to determine the optimal timing for inventory is another potential area of research where a valuation technique such as cost-plus-loss could be utilised. Haara (2005) states that the costs of traditional stand-level inventory are fairly high, but its accuracy is still considered to be fairly low. The goals of future research into forest inventory must be to improve accuracy while reducing costs. Unfortunately often with new inventory techniques it is difficult to achieve both of these goals. During the discussions undertaken as part of this paper it has been determined that the industry practitioners involved do not have a good understanding of which should be considered more important, cost or accuracy.

To date there has been very little research work in New Zealand on trying to determine the value of forest inventory data. The cost of collecting forest inventory information is well known but there is no formal way of measuring the value of this inventory information in relation to effective decision making. Robust sampling strategies are generally utilised which allow the calculation of confidence levels around yield estimates, but there are insufficient tools to communicate this uncertainty through planning systems to decision makers. The future research in this project should aim to better the understanding of the value of reducing uncertainty, determine how sensitive decision support systems are to uncertainty and develop ways to communicate a measure of uncertainty through to decision makers to help make more informed and effective decisions.

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