The value of timber inventory information for management planning

B.E. Borders, W.M. Harrison, M.L. Clutter, B.D. Shiver, and R.A. Souter

Abstract: Timber inventory data is the basis for many monetary transactions related to timber and timberland sale and (or) purchase as well as for development of timber management plans. The value of such data is well known and much appreciated for sale and (or) purchase of standing merchantable timber. Unfortunately, the value of timber inventory data for planning purposes is less well understood. We report on the results of a large simulation study that was undertaken to evaluate the utility and value of timber inventory data for timber management plan development for a typical timberland ownership in the southern United States. Our results indicate that timberland managers are likely producing management plans that do not maximize the profitability of their timberland holdings. Specifically, our results indicate it is likely that timber management organizations that develop timber management plans with stand level data that has a sampling error of 25% are experiencing expected losses in net present value in excess of 170 US$·ha^{-1} on a large proportion of the acreage found on typical timberland parcels in the southern United States.

Résumé : Les données d'inventaire de la matière ligneuse servent de base à plusieurs transactions monétaires reliées à l'achat et à la vente de bois et de terrains forestiers exploitables ainsi qu'à l'élaboration des plans d'aménagement de la matière ligneuse. La valeur de telles données est bien connue et très appréciée pour l'achat et la vente de bois marchand sur pied. Malheureusement, la valeur de l'information provenant de l'inventaire de la matière ligneuse pour la planification est moins bien comprise. Nous faisons état des résultats d'une vaste étude de simulation qui a été entreprise pour évaluer l'utilité et la valeur des données d'inventaire de la matière ligneuse pour l'élaboration d'un plan d'aménagement de la matière ligneuse pour une propriété forestière typique du sud-est des États-Unis. Nos résultats indiquent que les aménagistes forestiers produisent fort probablement des plans d'aménagement qui ne maximisent pas la profitabilité de leurs avoirs fonciers sous forme de terrains forestiers exploitables. De façon plus spécifique, nos résultats indiquent que dans le cas des organismes d'aménagement forestier qui élaborent des plans d'aménagement de la matière ligneuse avec des données à l'échelle du peuplement qui ont une erreur d'échantillonnage de 25 %, il est fort probable qu'ils connaissent des pertes présumées en valeur actualisée nette dépassant 170 US$·ha^{-1} sur une grande proportion de la superficie qu'on retrouve dans les parcelles typiques de terrain forestier exploitable du sud-est des États-Unis.

[Traduit par la Rédaction]

Introduction

Timber inventory is usually carried out using some type of probability sample design (Shiver and Borders 1996). All probability sample designs are subject to sampling error and nonsampling error. Probability samples are designed to help ensure that the structure of the sample is representative of the true underlying structure of the population of interest. If the resulting samples are representative of the population structure then sampling error should be small. Conversely, if the structure of the samples is not representative of the true underlying structure of the population then sample estimates are likely subject to large sampling error. Nonsampling error is associated with factors that include incorrect measurements, incorrect area determination, and incorrect identification of timber products. In practice, nonsampling error is often assumed to be minimal in timber inventory applications. Unfortunately this may not always be true. We do not address sources and impact of nonsampling error in this work; however, we will address it in detail in our future work.

A common use of timber inventory data is for the sale and (or) purchase of mature timber. For this application, sampling intensity (number of sample units per unit area) is usually relatively high. Of course the propensity to use a more intensive sample increases with the value of the timber.

Another common use of timber inventory data is for developing long term timber management plans. These plans make use of current estimates of standing timber inventory as a starting point for creating a management plan. For even-aged timber management, these plans typically include timing of various silvicultural treatments (e.g., vegetation control regimes, fertilization regimes), thinning ages and intensities, as well as final harvest ages and subsequent stand establishment procedures (e.g., planting density, choice of species, site preparation technique). In this type of long-term timber management planning, timber inventory data is used as input to growth and yield simulators that provide expected yields by product for each stand (i.e., management unit) at various points in time for the entire timberland par-

Received 2 November 2007. Accepted 30 May 2008. Published on the NRC Research Press Web site at cjfr.nrc.ca on 22 July 2008.

B.E. Borders,[1] W.M. Harrison, M.L. Clutter, and B.D. Shiver. Warnell School of Forestry and Natural Resources, The University of Georgia, Athens, GA 30602, USA.
R.A. Souter. USDA Forest Service, P.O. Box 227, Stoneville, MS 38776, USA.

[1]Corresponding author (e-mail: borders@warnell.uga.edu).

 doi:10.1139/X08-075

cel of interest. To identify "optimal" management regimes, an appropriate decision criterion is calculated for each alternative management regime for each stand in the forest. This decision criterion is then used to rank alternative management regimes for each stand. Often this decision criterion will be a financial value, such as the net present value (NPV) of the timber.

Based on our experience throughout the United States, foresters differentiate timber inventory data used for management planning from timber inventory data used for timber sale and (or) purchase. Specifically, forest managers in the southern United States typically refer to timber inventory for management planning as "management cruises." Management cruises are probability sample designs that are typically designed as very low intensity samples. Rather than using a sample design and (or) intensity that can provide estimates of various stand characteristics with a sampling error of ≤10%, it is common practice to have sampling error of 20%, 30%, or >30% at the stand level. The reasoning is that since the information will be used for planning purposes only and will not be used to buy and (or) sell stumpage, it is not as important to obtain precise and (or) accurate timber inventory data. Clearly, many rational individuals and organizations that understand the value of timber inventory data when used to buy and (or) sell stumpage fail to recognize the value of timber inventory data used for timber management planning purposes. In fact, our experience leads us to conclude that timber inventory data used in the planning process is often viewed simply as a cost center that has little inherent value.

Strategic and tactical timber management plans developed with the use of sophisticated growth and yield systems make use of available timber inventory data. Typically, in such planning exercises, various management regimes are evaluated for each management unit (i.e., stand) and the "optimal" regime is identified through evaluation of a decision criterion such as NPV. Logic tells us that if we provide poor quality timber inventory data as input to such tools, it is likely that the resulting plans will be less than optimal, since the inventory data are not representative of the population conditions found on the ground. This logic is consistent with the statement of Nelson (2003):

> "... our ability to formulate and run large-scale, long-term forecasting models often exceeds the scientific credibility of the data, especially for complex forest ecosystems. In the absence of critical thinking, such powerful models can become dangerous weapons."

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 (Duvemo and Lamas 2006). As Duvemo and Lamas (2006) point out, the work that has been carried out to address this question can be divided into two categories: analytical and simulation approaches.

In analytical approaches to this problem, the objective is usually to identify the optimal timber inventory sample intensity and (or) timing, often using the "cost-plus-loss theory" as described by Cochran (1963) and originally applied in the timber inventory context by Hamilton (1970). In this approach, cost refers to the cost of the inventory and loss refers to the loss in value associated with making less than optimal decisions about the resource. As discussed by Duvemo and Lamas (2006), authors who have published on this approach (Burkhart et al. 1978; Hamilton 1978, 1979; Stahl et al. 1994) have had to make very simplifying assumptions to carry out their work. Consequently, these studies leave many questions unanswered as to how their results may be useful for real world timber planning exercises.

Simulation approaches to investigating this problem have become more common as computing power has increased over the past 10–15 years. However, there are only a relatively small number of simulation studies that have been reported in the literature (Duvemo and Lamas 2006). 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 from timber data containing some level of error (Eid 2000; Holmstrom et al. 2003; Eid et al. 2004; Holopainen and Talvitie 2006; Duvemo et al. 2007). Eid (2000) evaluated the impact that timber inventory data errors had on optimal NPV for a timber property comprising 25 Norway spruce (*Picea abies* (L.) Karst.) stands in Norway. In this work, Eid found that with an error level of 15% in all inventory variables, the loss in NPV determined with a real discount rate of 3% varied from 64 to 1471 NOK (Norwegian Kroner)$\cdot$ha^{-1} for individual stands (equivalent to approximately 12–272 US\$$\cdot$ha^{-1}, using exchange rates in October 2007). Eid further pointed out that NPV losses were 243, 499, and 931 NOK·ha^{-1} (equivalent to approximately 45, 92, and 172 US\$·ha^{-1} using exchange rates in October 2007) for inventory variable error levels of 10%, 15%, and 20%, respectively. Holopainen and Talvitie (2006) studied the impact that various types of timber inventory data had on the expected NPV of approximately 700 ha of timber area in Helsinki, Finland. This area was primarily old-growth timber dominated by Norway spruce. In this study, Holopainen and Talvitie found that NPV loss due to less than optimal harvest timing decisions resulting from poor quality inventory data ranged from 498 to 1380 Euros (€)·ha^{-1} (equivalent to approximately 705 and 1955 \$US·ha^{-1} using exchange rates in October 2007) at a real discount rate of 5%. Duvemo et al. 2007 carried out a simulation study to evaluate the use of satellite-derived and ground-based inventory data for timber management planning for 64 stands in southern Sweden. Using cost-plus-loss analysis, they found that the ground-based inventory data resulted in much smaller expected loss than did the satellite-derived inventory data.

Clearly, relatively large NPV losses can result from the use of timber management plans developed with timber inventory data of poor quality. Just as obvious is the fact that not only timber inventory data quality contributes to the uncertain nature of financially optimal timber management plans. Factors such as fluctuation in stumpage prices, silvicultural costs, and quality of growth models used for forecasting tree and stand development can all have large influences on optimality of timber management plans. However, changes in stumpage prices and silvicultural costs are almost always beyond the control of timber management plan developers. Furthermore, most growth models are

Table 1. Area of timbered stands by stand type.

Stand type	No. of stands	Total area (ha)	Mean stand size (ha)	Percentage of total area
Premerchantable plantation loblolly pine	48	1192	24.8	29.4
Merchantable plantation loblolly pine	65	2016	31.0	49.8
Natural loblolly pine	18	442	24.6	10.9
Natural hardwood	19	397	51.6	9.8
Total	150	4047		100.0

developed independently of planning organizations, and at best timber management planning organizations simply evaluate alternative models for applicability to their situation and use the model that appears most appropriate. The quality of timber inventory data is the aspect of the planning enterprise over which timber managers have the most control. Thus, we believe it is important to try to quantify the potential value losses in the timber management planning enterprise that are associated with timber inventory data having different levels of sampling error.

Below we present a description and the results of a simulation study that was carried out for a realistically structured timberland ownership in the southern United States. In this work, we develop the true population and associated financially optimal (based on NPV) management plan at the stand level as well as the financially suboptimal management plans that result when various levels of error are introduced into important inventory variables. The objective is to evaluate the potential financial impact that timber inventory data can have on the value of a timberland ownership when plans are developed with timber inventory data with a range of sampling errors.

Methods

A hypothetical 4047 ha forest comprising 150 stands (i.e., management units) was developed for this study. Approximately 79% of the area is contained in 113 loblolly pine (*Pinus taeda* L.) plantations, with the remaining area divided among natural loblolly pine stands and natural hardwood stands (Table 1). In the loblolly pine plantation area, approximately 37% of timber is premerchantable (<12 years of age; Table 1) and the remaining area is distributed from 12 to 30 years of age, as shown in Fig. 1. There are a total of 18 natural loblolly pine stands and 19 natural hardwood stands with area distributed by 10 year age classes (Fig. 1). Clearly, the natural stands tend to be older than the merchantable pine plantations. Mean stand sizes were approximately 28 ha for plantatation pine, 25 ha for natural loblolly pine, and 21 ha for natural hardwood. This forest structure is typical of many ownerships currently found throughout the southern United States.

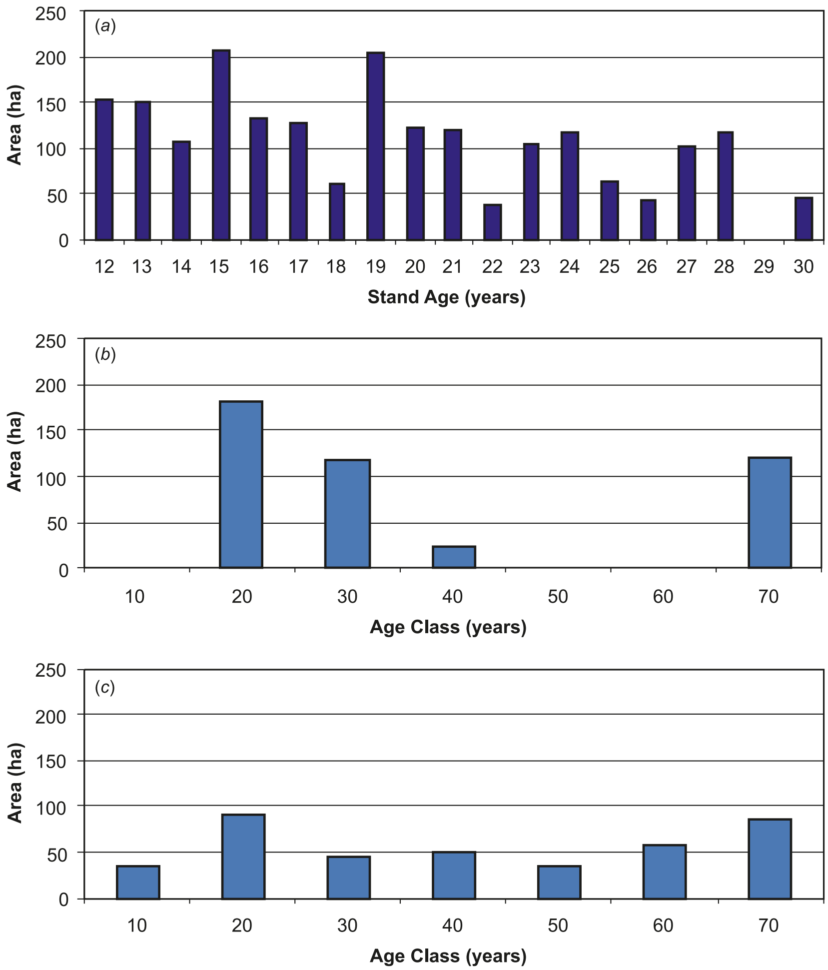
The forest was populated with whole stand estimates of age, site index (base age 25 for plantations, base age 50 for natural stands), stand dominant height, and number of surviving trees per hectare at current stand age for plantations. In addition to these variables, basal area per hectare was also assigned to each natural stand. Note that these stand characteristics were assigned by slightly modifying the stand characteristics of an actual property located in the southern United States. These variables are required input for the growth projection models used to develop expected yields at thinning and harvest points considered in development of optimal stand level management plans. These models are embedded within software known as SiMS_2006 (a software package developed for and used throughout the southern United States).[2]

For each individual stand an array of possible thinning timings and final harvest ages were considered and valued in $US and NPV was determined. The number of possible management regimes evaluated for a given stand varied by stand age and stand type. For plantations and natural loblolly pine stands, all possible two thin operations for a range of first thinning ages and second thinning ages separated by 4–10 years and followed by a final harvest were evaluated. For natural hardwood stands, only final harvest regimes were considered. Stumpage values were defined based on current markets. Real discount rates of 4%, 6%, and 8% were used in combination with sampling errors of 5%, 10%, 15%, and 25% in the pertinent input inventory variables (stand dominant height and number of surviving trees per hectare for plantations and stand dominant height, number of surviving tress per hectare and basal area per hectare for natural stands). Note that sampling error was introduced for each input variable simultaneously for a given level of error. There was no attempt to investigate the correlation structure among the input variables so as to account for such when generating error in the input variables. For each of the 12 possible combinations of discount rate and sampling error, 100 random iterations were simulated for each management regime on each stand in the forest. The number of regimes evaluated for each of the 12 combinations of discount rate and sampling error was 7 783 960. Thus, in total we evaluated >93 million regimes to develop the relationships shown and discussed below. Note that no forest level constraints were imposed in this work.

For each stand in the forest, the optimal management regime was identified using the population inventory data (i.e., error-free data) and its NPV per hectare (NPV_P) was determined. For each combination of stand, iteration, discount rate, and sampling error the optimal management regime was identified. This regime was then used to obtain the NPV for the stand using the error-free data, which is then referred to as NPV_E. Of course, the optimal NPV identified with inventory data having sampling error may be higher or lower than NPV_P. However, to determine expected NPV loss we must recognize that the error-free data represents the true conditions on the ground and that when a

[2] For those readers with interest in the specific models and model architecture please contact the corresponding author.

Fig. 1. (*a*) Area of merchantable loblolly pine plantations by 1 year age classes; (*b*) area of natural loblolly pine stands by 10 year age classes; (*c*) area of natural hardwood stands by 10 year age classes.



regime that is identified as optimal using data with error is applied to this true population, the result will be a NPV that is less than or equal to (equal when data with error identifies the identical optimal regime to that determined by error-free data) the optimal NPV identified with error-free data. The relationship between NPV_P and NPV_E is illustrated in Fig. 2. Using this logic, NPV loss per hectare (NPV_L) for a given stand *i*, random iteration *j*, and a given level of sampling error *k* at a given discount rate is then defined as

$$NPV_{Lijk} = NPV_{Pik} - NPV_{Eijk}$$

where *i* = 1, 2, 3, ..., 150 for the individual stands, *j* = 1, 2, 3, ..., 100 for the 100 random iterations, and *k* = 1, 2, 3, 4 for the four levels of sampling error.

Note that it is possible to identify an optimal regime for data with error that is actually infeasible when the regime is evaluated with error-free data. For example, the optimal regime for stand data with error may require a commercial thinning at a given age but when this regime is evaluated against the error-free data for this stand the thinning cannot be performed, since a required minimum removal cannot be met. Thus, for each set of 100 random iterations some proportion of the regimes will be infeasible when evaluated against the true conditions on the ground. Therefore, for a given discount rate, the expected NPV_L for stand *i* at a given level of sampling error *k* is defined as

$$NPV_{Lik} = \frac{\left(\sum_{j=1}^{n} NPV_{Lijk}\right)}{n}$$

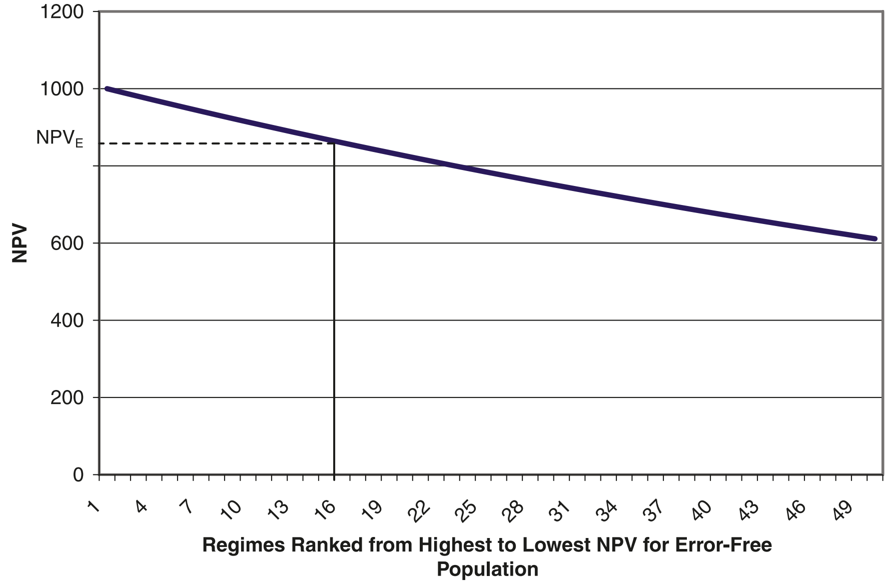
where *n* in the number of feasible regimes identified using data with error.

Clearly, identification of infeasible regimes as optimal is problematic for decision makers and thus they should be recognized as such. However, since there is no way to identify what an appropriate NPV loss is for such an infeasible regime, they are not represented in the expected NPV loss for the stand. To more fully recognize the impact of such infeasible regimes in the decision-making process, the percentage of infeasible regimes identified as optimal is determined for each discount rate and level of sampling error.

Results

Expected NPV loss varied by stand type, level of sampling error, and discount rate (Table 2). Expected NPV loss increases with sampling error, and as discount rate increases expected NPV loss decreases. The largest expected NPV

Fig. 2. Relationship between NPV_P and NPV_E (in currency units) when the optimal regime identified using data with error (regime 16 in this case) is different than the optimal regime identified using error-free population data.



losses occur for premerchantable plantation loblolly pine, followed by merchantable plantation loblolly pine, natural loblolly pine, and natural hardwood stands (Table 2). For premerchantable loblolly pine plantations, the range in expected NPV loss for a discount rate of 6% goes from 19.89 US$·ha^{-1} for sampling error of 5% to 172.97 US$·ha^{-1} for sampling error of 25%. Expected NPV loss as a percentage of optimal NPV for the error-free population shows similar trends to expected NPV loss (Table 3). For premerchantable loblolly pine plantations, the range in the percentage of NPV loss for a discount rate of 6% goes from 0.74% for sampling error of 5% to 5.22% for sampling error of 25%, whereas for merchantable loblolly pine plantations the range is 0.10% for sampling error of 5% to 1.82% for sampling error of 25%.

The maximum NPV loss was also identified for each stand type, level of sampling error, and discount rate (Table 4). These values follow the same trends as expected NPV loss. However, as expected, the magnitude of these values is much larger than the values for expected NPV losses. For example, for premerchantable loblolly pine plantations the range in maximum NPV loss for a discount rate of 6% goes from 116.19 US$·ha^{-1} for sampling error of 5% to 474.24 US$·ha^{-1} for sampling error of 25%.

The mean percentage of infeasible management regimes varies by stand type and sampling error but not by discount rate (Table 5). For premerchantable loblolly pine plantations, the mean percentage of infeasible management regimes varies from approximately 10% for sampling error of 5% to 22% for sampling error of 25%. Note that since there were no thinning options considered for the hardwood stands there were no infeasible regimes identified as optimal. It is interesting that the percentage of infeasible regimes is not sensitive to discount rate. Thus, even though discount rate can impact choice and value of a regime, the likelihood of selecting an infeasible regime is similar, regardless of discount rate.

Table 2. Expected net present value (NPV) loss (US$·ha^{-1}) by stand type, sampling error, and discount rate.

	NPV loss (US$·ha^{-1})		
Sampling error (%)	4% discount rate	6% discount rate	8% discount rate
Premerchantable plantation loblolly pine			
5	26.46	19.89	11.19
10	92.34	60.69	30.10
15	181.65	100.03	45.74
25	381.75	172.97	67.98
Merchantable plantation loblolly pine			
5	5.71	5.78	5.31
10	19.30	19.55	17.15
15	37.86	43.61	33.21
25	113.37	108.58	67.93
Natural loblolly pine			
5	0.02	0.00	0.00
10	2.50	3.81	4.74
15	5.04	6.18	7.64
25	16.01	15.89	16.01
Natural hardwood			
5	0.00	0.00	0.00
10	0.10	0.17	0.00
15	0.00	0.00	0.00
25	0.15	0.10	0.15

Discussion

It is clear that timber inventory data quality can have a large impact on the expected financial returns associated with timber management planning. In this study, we introduced error into individual stand characteristics that are typically used as input to growth models for southern United States timberland ownerships. As discussed above, these

Table 3. Expected NPV loss as a percentage of the optimal NPV of the error-free population for premerchantable and merchantable loblolly pine plantations by sampling error and discount rate.

	Expected NPV loss (%)		
Sampling error (%)	4% discount rate	6% discount rate	8% discount rate
Premerchantable plantation loblolly pine			
5	0.79	0.74	0.46
10	2.77	2.06	1.18
15	5.04	3.25	1.75
25	9.43	5.22	2.52
Merchantable plantation loblolly pine			
5	0.07	0.10	0.12
10	0.23	0.35	0.36
15	0.46	0.75	0.70
25	1.44	1.82	1.39

Table 4. Maximum NPV loss (US$·ha^{-1}) by stand type, sampling error, and discount rate.

	Max. NPV loss (US$·ha^{-1})		
Sampling error (%)	4% discount rate	6% discount rate	8% discount rate
Premerchantable plantation loblolly pine			
5	95.23	116.19	56.17
10	225.34	237.76	106.06
15	400.19	310.59	150.71
25	801.49	474.24	228.45
Merchantable plantation loblolly pine			
5	42.01	35.63	29.97
10	64.54	72.99	63.48
15	101.98	119.48	114.73
25	371.70	257.36	206.98
Natural loblolly pine			
5	0.40	0.00	0.00
10	38.05	66.00	85.47
15	57.85	99.01	128.10
25	129.95	128.37	163.83
Natural hardwood			
5	0.00	0.00	0.00
10	1.98	3.48	0.00
15	0.00	0.00	0.00
25	1.04	1.85	2.64

errors have different impacts on expected NPV losses in various stand types and stand ages. Specifically, this work indicates that inventory sampling error in older stands has less influence on expected NPV loss than in younger stands. This is logical, since errors at young ages will be magnified by long-range growth projections which will, in turn, have more influence on thinning and final harvest timing decisions. Further, errors in fast growing relatively intensively managed loblolly pine plantations have more influence on expected NPV loss than errors in more slowly growing natural loblolly pine stands and extensively managed hardwood stands.

Table 5. Mean percentage of infeasible management regimes by stand type, sampling error, and discount rate.

	Mean percentage of infeasible management regimes		
Sampling error (%)	4% discount rate	6% discount rate	8% discount rate
Premerchantable plantation loblolly pine			
5	10.0	9.6	11.1
10	15.1	14.6	15.3
15	18.2	17.9	18.4
25	21.9	21.5	22.3
Merchantable plantation loblolly pine			
5	0.0	0.2	0.0
10	0.0	0.2	0.0
15	0.1	0.4	0.3
25	0.2	0.4	0.1
Natural loblolly pine			
5	0.6	0.4	0.4
10	3.1	2.1	2.0
15	4.9	3.6	3.2
25	8.8	7.1	6.1

It should be noted that many timber management organizations in the southern United States view the need for high quality timber inventory data in young plantations as a low priority. In fact, it is not unusual for timber management planning organizations to have stand-level inventory data in young plantations that exhibit >25% estimated sampling error for standing volume, which often indicates that sampling error in characteristics such as dominant height and trees per hectare is even larger. Based on the results reported here, it is quite likely that owing to the use of imprecise inventory data many of these organizations are experiencing significant reduction in return on investment through development of management plans that preclude the opportunity to maximize profit from timber management activities. Of course, new inventory information and new plans will be developed on a predefined schedule. The NPV losses identified in our work may or may not be realized, depending on the precision of the most recently available timber inventory data used in the most recent planning effort.

In addition to the potential to develop management plans that reduce the value of a timberland asset by a large dollar amount, inventory error also produces problems in plan implementation, as indicated by the rather large percentage of infeasible management regimes produced by inventory data with sampling error ≥10%. The type of infeasibility identified in this work was associated with the minimum thinning removals required for commercial thinning operations. This type of problem is routinely encountered by field personnel who implement the "optimal" plans developed with strategic and (or) tactical planning systems. Clearly, this can lead to the field personnel losing confidence in plans that are created by technical planning groups. As such, there is a high likelihood that field personnel will begin to ignore such plans and manage according to their own wishes. Obviously, when this occurs there is a total breakdown in the planning and (or) implementation process.

It should be noted that the results of this study indicate the expected NPV loss is relatively minor for slow growing natural loblolly pine and natural hardwood stands that tend to be older than 20–30 years of age. This is because most of these stands are at an age that eliminates thinning options from the management regimes considered. Consequently, optimization for such stands was merely to identify the age of final harvest. Once this final harvest age was determined with inventory data containing sampling error, the value of this suboptimal harvest age was determined using the error-free data as described above. Thus, there is not much opportunity to substantially reduce NPV. In reality, however, stumpage is often sold by sealed bid procedures. Therefore, simply looking at expected NPV loss underestimates the potential loss in value for these older stands.

As demonstrated above, timber inventory data should be viewed as an asset that is crucial for maximizing the value of the timber asset. To more precisely demonstrate the value of the inventory information we can look at the cost of inventory information relative to expected NPV loss. Assume that all stand types in our hypothetical forest will be sampled with a sample unit that costs US$25 to locate, measure, and analyze. The variable cost per sample unit will be assumed as 25% of total cost or US$6.25 per sample unit. A baseline inventory cost can easily be established for a forest level inventory that results in a 25% level of sampling error (allowable error) for all stands. To do this calculation we assume the coefficients of variation for premerchantable plantation loblolly pine, merchantable plantation loblolly pine, natural loblolly pine, and natural hardwood are 45%, 60%, 80%, and 100%, respectively. Calculating the required number of sample units to achieve 25% sampling error in each stand and using the infinite population sample size formula for simple random sampling with z/t (z is a standard normal variate and t is the variate from Student's t distribution) value set at 2 (to approximate 95% confidence), we find the required sample sizes per stand to be 13, 23, 41, and 64 sample units for each stand for each of the four stand types. Multiplying these required sample sizes by total cost per sample unit and number of stands of each stand type results in a total inventory cost of US$101 824. Based on our expected NPV_L results, it appears that we can significantly lower expected NPV loss in our forest by decreasing sampling error to 10% in premerchantable plantation loblolly pine and to 15% in merchantable plantation loblolly pine. These precision targets require 81 and 64 sample units per stand for premerchantable and merchantable plantation loblolly pine stands, respectively. Assume that the fixed cost of US$25 456 for the original inventory will remain constant regardless of sampling intensity within a stand. We can then determine that the variable cost for the more intensive inventory will increase to US$187 524, resulting in a total inventory cost (fixed plus variable costs) of US$212 980. Thus, we have increased inventory cost by US$111 156. Next, we can determine the expected total forest NPV loss by multiplying the expected NPV_L by number of hectares of each stand type. When sampling error is 25% in all stand types, expected total forest NPV loss (6% discount rate) is US$432 141. By reducing sampling error in the planted stands as described above, we find that expected total forest NPV loss (6% discount rate) is US$167 323. Thus, expected NPV loss has been reduced by US$264 817 by increasing sampling intensity in the planted stands. Clearly, since the additional inventory cost was US$111 156, significant value will be realized by improving the precision of inventory estimates in the planted loblolly pine stands. Of course, additional benefits of having fewer infeasible regimes will also be associated with improved inventory precision.

For timberland managers developing management plans in the southern United States, our work indicates that consideration should be given to reducing stand level sampling error in planted stands to ≤15%. For other regions, similar analyses can be carried out to estimate expected NPV_L. Forest managers can then compare expected gain in NPV with the increased inventory costs associated with decreasing stand level sampling error. Of course, all available technologies should be considered for obtaining inventory information so as to obtain highly precise, unbiased inventory data at the most reasonable cost possible.

It should be noted that loblolly pine plantations in the southern United States are routinely managed quite intensively with various combinations of vegetation control and fertilization regimes in addition to simply scheduling thinnings and final harvests. In this work, we did not evaluate the expected NPV loss associated with scheduling of these cultural treatments in less than optimal fashion, since doing so would have increased the size of the problem substantially. Consequently, it is important to quantify expected NPV loss when these types of intensive silvicultural treatments are scheduled in less than optimal fashion. Experience with such intensively managed stands indicates that when vegetation control and (or) fertilization are (is) prescribed incorrectly the costs to the timberland owner can be significant.

In this study, error was introduced into all the important inventory variables that drive growth projections simultaneously. Future work in this area should address the influence that errors in individual inventory variables have on expected NPV loss in a fashion similar to Eid (2000). Note that in this work no forest level constraints were imposed. In future work, it will be instructive to evaluate NPV loss in timber value when realistic forest level constraints are imposed. Finally, it should also be noted that timber management plans may become less than optimal when scheduled silvicultural treatments, thinnings, and final harvests are not performed as scheduled. The influence that such deviations have on expected NPV loss is also an area of study that should be addressed, although we have not done so in this work.

References

Burkhart, H.E., Stuck, R.D., Leuschner, W.A., and Reynolds, M.R. 1978. Allocating inventory resources for multiple-use planning. Can. J. For. Res. **8**: 100–110. doi:10.1139/x78-017.

Cochran, W.G. 1963. Sampling techniques. John Wiley, New York.

Duvemo, K., and Lamas, T. 2006. The influence of forest data quality on planning processes in forestry. Scand. J. For. Res. **21**: 327–339. doi:10.1080/02827580600761645.

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. doi:10.1139/X07-069.

Eid, T. 2000. Use of uncertain inventory data in forestry scenario models and consequential incorrect harvest decisions. Silva Fenn. **34**: 89–100.

Eid, T., Gobakken, T., and Naesset, E. 2004. Comparing stand inventories for large areas based on photo-interpretation and laser scanning by means of cost-plus-loss analyses. Scand. J. For. Res. **19**: 512–523. doi:10.1080/02827580410019463.

Hamilton, D.A. 1970. Precision requirements for some information in timber management decisions. Ph.D. Dissertation. Iowa State University, Ames, Iowa.

Hamilton, D.A. 1978. Specifying precision in natural resource inventories. *In* Proceedings of Integrated Inventories of Renewable Natural Resources. USDA For. Serv., Tuscon, Ariz.

Hamilton, D.A. 1979. Setting precision for resource inventories — the manager and the mensurationist. J. For. **77**: 667–670.

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.

Holopainen, M., and Talvitie, M. 2006. Effect of data acquisition accuracy on timing of stand harvests and expected net present value. Silva Fenn. **40**: 531–543.

Nelson, J. 2003. Forest-level models and challenges for their successful application. Can. J. For. Res. **33**: 422–429. doi:10.1139/x02-212.

Shiver, B.D., and Borders, B.E. 1996. Sampling techniques for forest resource inventory. Wiley Publishing, New York.

Stahl, G., Carlsson, D., and Bondesson, L. 1994. A method to determine optimal stand data acquisition policies. For. Sci. **40**: 630–649.