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50

The Effect of the Silviculture Survey Parameters on the Free-Growing Decision Probabilities and Projected Volume at Rotation

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Ministry of Forests
Forest Science Program

The Effect of the Silviculture Survey Parameters on the Free-Growing Decision Probabilities and Projected Volume at Rotation

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This handbook discusses the silviculture survey system used by the B.C. Ministry of Forests to assess stands for free-growing status. The silviculture survey system is reviewed, and the decision curve as a statistical tool to assess risk is explained. Decision curves are used to explore the effects of changes to survey parameters, as determined by a simulation study of homogeneous stem maps.

Projected volumes for homogeneous lodgepole pine stands (based on TASS, a growth and yield model) are also presented and discussed. The simulation study did not investigate the effects of disease, infestation, or brush competition on volume: all trees were assumed to be healthy and unimpeded by vegetation.

This work would not have been possible without the contributions of many people. First, I would like to thank Henry Benskin, Robin Brown, Lorne Bedford, and Ralph Winter for believing that this work shoud be done and for providing continuing support throughout and over the many years that this work has been ongoing. Ken Mitchell provided fundamental contributions because of his development and knowledge of the TASS model. Robert Macdonald of RamSoft Systems Ltd. developed the many simulation programs required and ran them to produce the fundamental simulation database. He was therefore instrumental to the success of this project.

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TABLES

FIGURES

A long-term goal of British Columbia's Ministry of Forests is to maintain sustainable forest harvests in the province. The silviculture survey system contributes to this goal by identifying those recently harvested and reforested strata that have not reached a free-growing state within a suitable time frame. Proper identification of these strata is important, since early remedial action will help them attain their potential yield at rotation.

The silviculture survey system is used by the Ministry of Forests and by industry to determine whether recently harvested strata have sufficiently regenerated and reached a free-growing state. Industry is required to maintain minimum stocking levels on these strata until they reach that free-growing state. Once that has been accomplished, they become the Crown's responsibility to maintain and develop.

1.1 Goals of the Silviculture Survey System

The objective of the free-growing silviculture survey is to make a decision[1] as to whether a stratum has attained a free-growing density of at least the minimum stocking standard (MSS) as specified in the Silviculture Prescription. As with any surveying methodology, there is always a risk of making an incorrect decision. Thus, a well-designed silviculture survey system will meet two goals:

1. maintain at an acceptable level the Ministry's risk of accepting strata as free-growing when they are not; and
2. minimize the licensee's risk of incorrectly rejecting strata that are truly free-growing.

1.2 Different Kinds of Density

Four kinds of density are referred to throughout this handbook, and it is important that their differences be understood.

There are two kinds of total density:

- *Total density*—the total number of acceptable trees regardless of their height.
- *Total free-growing density*—the total number of acceptable trees that meet a minimum height requirement. A minimum height of 2.0 m is used in the discussion in this handbook. Total free-growing density is expressed as trees per hectare (tph).

The two other types of density are:

- *Well-spaced density*—the number of acceptable trees (no height restrictions) that are a minimum inter-tree distance (MITD) apart. Unless otherwise specified in the following discussion, this distance is set at 2.0 m. Well-spaced density is expressed as well-spaced trees per hectare (wsph).
- *Free-growing density*—the well-spaced density of a stand that includes only those acceptable trees that have reached a minimum height. A minimum height of 2.0 m is used in the following discussion. Free-growing density can be low for young stands because many of the trees will not have reached the required minimum height. Free-growing density is expressed as free-growing trees per hectare (fgph).

Section 3.5 discusses these kinds of density in greater depth.

1.3 Silviculture Survey Methodology

The silviculture survey methodology used in British Columbia is described in the *Silviculture Surveys Guidebook* (available at <www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/silsurv/silsutoc.htm>).

Surveys are conducted within the strata (homogeneous areas) which have been identified within recently harvested cutblocks. In the first pass, the standard sample size is one 50 m^2 (1/200th ha) plot per hectare, with a minimum of 5 plots. If a second pass is necessary, then additional plots are added, up to an overall maximum of 1.5 plots per hectare. The statistical properties of the surveys discussed in this handbook assume that the plots are located randomly throughout the stratum. Operationally, though, plots are often laid out systematically with

1. Note that this objective is quite different from the objective of estimating the free-growing density of the stratum. Accordingly, the methods for calculating the results are different.

a random start location. In many circumstances the statistical properties for these two methods of locating plots are similar.

In each plot, only well-spaced acceptable trees count towards stocking. Acceptable free-growing trees must be of suitable species and of sufficient height, as well as meeting other criteria concerned with health and competing brush. "Well spaced" means that the trees are separated from other counted trees by a specific minimum inter-tree distance. As well, the resulting plot count is not allowed to exceed the M-value, a maximum plot count derived from the target stocking standard (TSS) density.

The mean and 90% confidence limits are determined using these capped counts. For example, if 9 acceptable well-spaced trees are found in a plot but the TSS is 1300 fgph (equivalent to 6.5 trees per plot), then a value of 6.5 is substituted for 9 during calculations for the sample mean[2] ($\bar{x}$), standard error, confidence interval (CI), and corresponding 90% confidence limits. The lower confidence limit (LCL) is equal to the mean minus the confidence interval (LCL = $\bar{x}$ – CI). The upper confidence limit (UCL) is equal to the mean plus the confidence interval (UCL = $\bar{x}$ + CI). The resulting sample statistics are used to decide if the stratum meets the minimum stocking standard according to the decision rules and procedure summarized in Tables 1 and 2.

TABLE 1 *Silviculture survey decision rules*

Mean Decision Rule		*Decision:*
If sample mean ($\bar{x}$) < MSS	then	Not-free-growing
If sample mean ($\bar{x}$) ≥ MSS	then	Free-growing
Lower Confidence Limit (LCL) Decision Rule		*Decision:*
If sample lower 90% confidence limit ($\bar{x}$ – CI) < MSS	then	Not-free-growing
If sample lower 90% confidence limit ($\bar{x}$ – CI) ≥ MSS	then	Free-growing

TABLE 2 *Silviculture survey decision procedure*

1) First pass with sample size of one plot per hectare with a minimum of five plots

Rules used:

- Mean decision rule for not-free-growing decision
- Lower Confidence Limit Decision Rule for free-growing decision
- If neither rule makes a clear decision ("Undecided") and the 90% confidence limits are within prescribed limits,[a] use the Mean Decision Rule to make both the not-free-growing and free-growing decisions. Otherwise, do a second pass by putting in additional plots up to a total of 1.5 plots per hectare.

2) Second pass with maximum sample size of 1.5 plots per hectare

Rule used:

- Mean Decision Rule for both the not-free-growing and free-growing decisions

[a] These limits are defined as follows: within ± 100 fgph if the sample mean is less than 1000 fgph; or within ± 10% of the sample mean if the sample mean is greater than 1000 fgph.

2. Because of the M-value, this sample mean provides a biased estimate of the free-growing density of the stratum.

A well-designed silviculture survey system will control the Ministry's risk of accepting as free-growing those strata which are not. Such control is achieved by using the lower 90% confidence limit as the decision rule within the survey system. Nevertheless, this known risk is modified, sometimes quite dramatically, by changes made to the survey system's parameters of minimum stocking standard, target stocking standard, or minimum inter-tree distance, or by using the mean as the decision rule when the first set of sample data does not result in a clear decision. A well-designed survey system must also consider the licensee's risk of having strata not accepted by the Ministry as free-growing when they are. The decision curve is a statistical tool that is used in this report to display these risks and show how they are affected by changes in the survey parameters.

2.1 Decision Curves

Decision curves provide a simple visual method of displaying how decision rules function. A decision curve is created by plotting the expected rate for making a decision against the "true" free-growing density. The curve shows how the chance of making that decision depends on the "true" free-growing density. The not-free-growing decision was used in this report along the left vertical axis for all decision curves.

Decision curves vary in shape and location. There are a number of reasons for this, including the use of different rules for making the not-free-growing decision and the choice of different values for the survey parameters (e.g., MSS, MITD, and the M-value). Three example decision curves are shown in Figure 1.

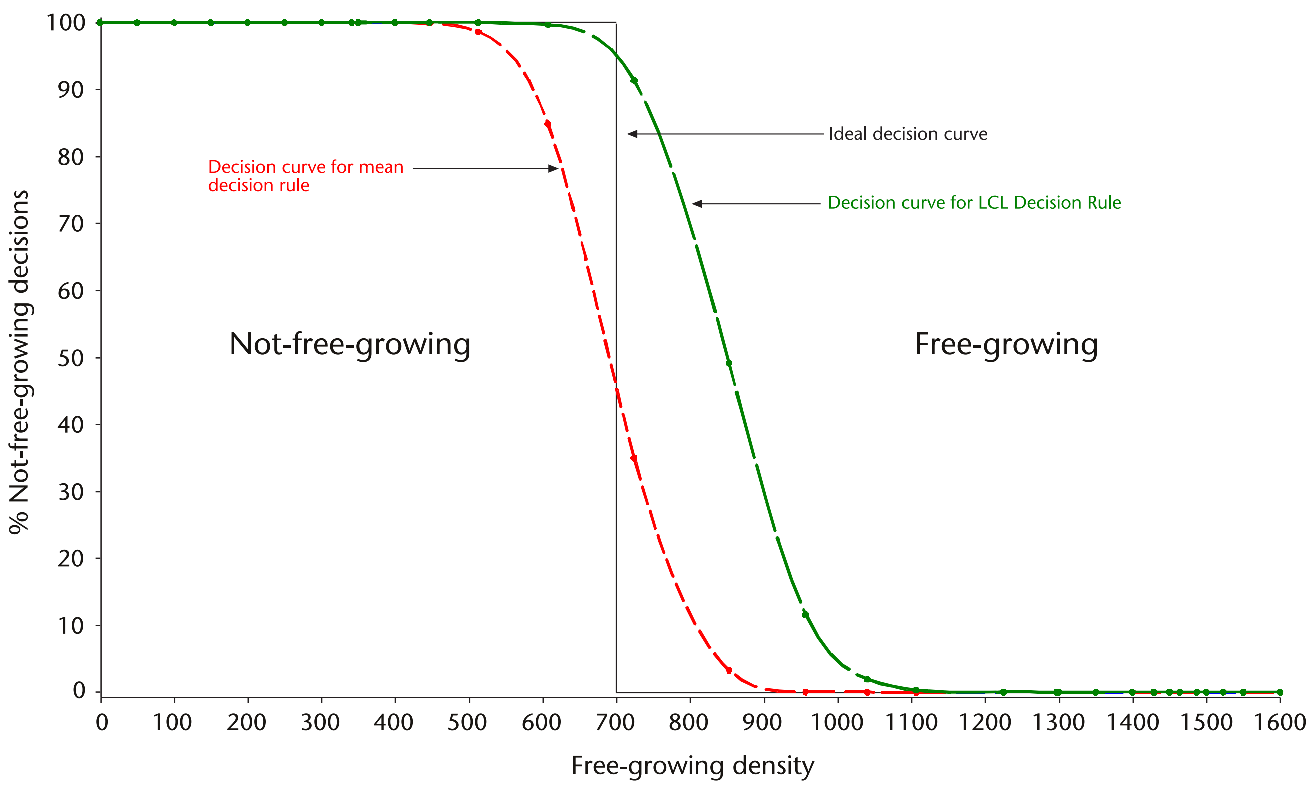


FIGURE 1 *Plots of the chance of making a not-free-growing decision as a function of free-growing density for the Mean Decision Rule and the Lower Confidence Limit Decision Rule. The ideal decision curve is also shown.*

For discussion purposes, let us suppose that the MSS is 700 free-growing trees per hectare. Ideally, all strata with densities less than 700 fgph would be correctly identified as not-free-growing all the time. Conversely, all those strata with densities greater than or equal to 700 fgph would always be identified as free-growing. This defines the ideal decision curve shown by the solid line in Figure 1.

Just as we never know for sure what the "true" free-growing density is for a stratum, neither can we ever obtain as sharp a decision curve as the ideal. Instead, survey results will perform more like one of the other two curves shown in Figure 1.[3] These curves correspond to the two decision rules described in Table 1. The Mean Decision Rule is the left-most rounded curve in Figure 1, while the LCL Decision Rule is the right-most curve. For the first pass of the Silviculture Survey Decision Procedure, these two curves divide the graph into three main areas:

1. all not-free-growing decisions are in the area to the left of the mean decision curve;
2. all free-growing decisions are in the area to the right of the LCL decision curve; and
3. the area between the two curves is the "Undecided" decision area where the confidence limits must be checked to determine if the Mean Decision Rule will be used with the current data or if a second pass will be necessary to collect more data.

2.2 Ministry's Risk

We define the Ministry's risk as the probability of not-free-growing strata being called free-growing.[4] This only occurs for strata with "true" free-growing densities less than the MSS. The three curves in Figure 1 show us what that risk is under three different situations.

For the curve representing the ideal situation, there is no risk at all because all not-free-growing strata are correctly identified as such. On the other hand, the mean decision curve carries the most risk and this risk is greatest at just below the MSS. This risk is measured by the vertical distance between the ideal curve and the mean decision curve. At 699 fgph, the correct not-free-growing decision will be made only about 50% of the time, as will the incorrect free-growing decision.

The LCL decision curve carries a more reasonable level of risk. At 699 fgph, the distance between the ideal and LCL decision curves is about 5%, so that a correct not-free-growing decision will be made at least 95% of the time.[5]

For strata that are not-free-growing, we can summarize the Ministry's risk for the two decision rules as follows:

1. The Mean Decision Rule will correctly identify non-free-growing (NFG) strata at least 50% of the time.
2. The LCL Decision Rule will correctly identify NFG strata at least 95% of the time.

The first statement is clearly weak, while the second statement gives assurance that the sampling procedure can correctly identify not-free-growing strata and will allow only a few not-free-growing strata to slip through the decision procedure.

Conclusion:
The Ministry directly controls its risk during the first pass by using the LCL Decision Rule to decide if strata are free-growing. In this case we can be confident that no more than 5% of the time will not-free-growing strata be called free-growing. If most strata are indeed being managed towards target densities and the survey is not conducted too early,[6] then the Mean Decision Rule would rarely be used.

The low and known risk associated with the LCL Decision Rule is increased by an unknown amount if the Mean Decision Rule is used in either the first or the second pass. How large the Ministry's risk can become has not been studied.

3. Values for the "true" free-growing density used along the horizontal axis for all graphs in this handbook were obtained via simulation and cannot be obtained from sample data. It would not be appropriate to plot the mean from sample data on the horizontal axis and then discuss the resulting decision rate obtained from the decision curve. Without exhaustive sampling or a stem map, we cannot know where to place a particular stratum on these graphs.
4. More precisely, the Ministry's risk is defined as the maximum probability of making a not-free-growing decision. This occurs just below the MSS. Unless otherwise stated, a value of 700 fgph will be assumed for the MSS.
5. Since only one tail of the two-tailed 90% confidence limits is used in the decision-making, the rate is about 95%.
6. "Too early" would be so soon after regeneration that many trees have not had a chance to reach the required minimum height.

Management Implications:
It is desirable that only the LCL Decision Rule be used for both the first and second sampling passes of the silviculture survey. If—as the current policy states—the Mean Decision Rule continues to be used during the second pass, then it should *only* be allowed during a second sampling pass *if* the first pass has returned an undecided decision. Thus, for example, it is not acceptable to start with 1.5 plots per hectare in order to skip the first pass—and the LCL Decision Rule—so that the Mean Decision Rule alone ends up being used to determine whether the stratum is free-growing. In this case, the Ministry's risk can be as high as 50%,[7] especially if strata are being managed towards minimum stocking densities.

2.3 Licensee's Risk

We define the licensee's risk as the probability of incorrectly identifying free-growing strata as not-free-growing. This risk can only occur for strata with "true" free-growing densities greater than the minimum stocking standard. Discussion of this risk can be simplified by selecting a specific point on the decision curve to represent the licensee's risk. We could, for instance, choose that free-growing density where the not-free-growing decision rate is, at most, 5%. Any free-growing density greater than that value will then be correctly identified as free-growing at least 95% of the time. For example, in Figure 1, the licensee's risk of 5% occurs at just under 850 fgph under the Mean Decision Rule and at about 1000 fgph for the LCL Decision Rule.

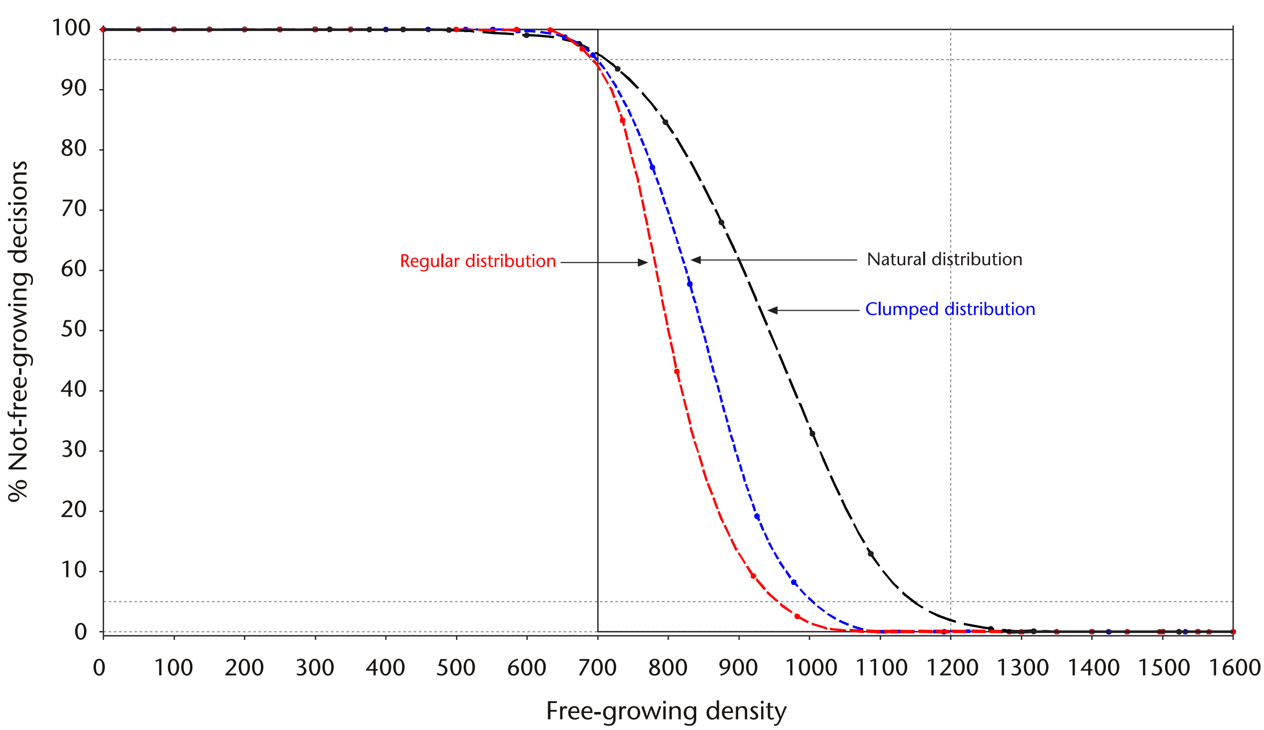


FIGURE 2 *Decision curves with the same Ministry risk but different licensee risks. Licensee risk changes because of the different spatial distributions of the trees.*

7. The two-pass decision procedure described in Table 2 requires using conditional probability to determine the final decision rates. Allowing the first step to be skipped can change the final probabilities substantially from what might otherwise be expected. How this works is explained in an example in Appendix 1.

On the other hand, a specific free-growing density could be chosen and the error rate at that density discussed. An obvious choice for that density would be the target stocking standard, because licensees are managing their stands to achieve this well-spaced density at free-growing. As an example, a TSS of 1200 fgph is often chosen when the MSS is 700 fgph. Thus, the silviculture survey could be designed to minimize the licensee's risk at this free-growing density.

Figure 2 shows how three different spatial distributions[8] can change the shape of the LCL decision curve. If this decision rule is used alone for making free-growing determinations, then the Ministry holds its risk constant at 5% for the MSS of 700 fgph. The licensee's risk, however, is different for each curve and can vary substantially. Nevertheless, at the TSS of 1200 fgph, the licensee's risk is negligible for the first two distributions and less than 5% for the third. A risk of 5% occurs at different free-growing densities depending on the spatial distribution. For the first curve, this occurs at about 950 fgph, at about 1000 fgph for the second, and at about 1150 for the third.

Conclusions:

The current silviculture survey system can use the LCL Decision Rule to control the Ministry's risk while not increasing the licensee's risk. Licensees can minimize their risk through careful management and adequate sampling.

Management Implications:

Since the licensee's risk can vary substantially depending on conditions, here are some suggestions for reducing that risk.

1. Properly stratify the area to be surveyed so that relatively homogeneous areas are sampled. This will reduce the standard error (and corresponding confidence limits), thus steepening the decision curve and thereby reducing the free-growing density at which a 5% risk occurs.
2. Aim for target stocking levels while managing the stand after harvest. In particular, manage the spatial distribution of the trees in the strata by looking for and correcting any substantial areas that are understocked. This is important to do because large areas containing few trees can substantially reduce average well-spaced and free-growing density for the strata and, correspondingly, reduce the expected volume at rotation for the stratum.
3. During the first pass when the LCL Decision Rule will be used, increase the survey sample size beyond the minimum. This would be especially valuable if the sample size were to be 8 or fewer plots. The larger sample size[9] will reduce the standard error and steepen the decision curve, thus reducing the free-growing density where the licensee's risk is 5% (see section 3.4). The extra cost of sampling with a few more plots may be more than offset by the cost of implementing unnecessary treatments or retaining the liability longer than necessary.

8. These are the regular, natural, and clumped distributions described in Appendix 2 and used in the simulations.
9. Nevertheless, sample sizes greater than 40 plots would not be expected to reduce the risk by much except, perhaps, for heterogeneous strata with trees arranged in an extremely clumped spatial distribution.

Small changes to some of the silviculture survey parameters can dramatically affect the Ministry's risk and potential volume loss. Changes to other parameters may produce little effect. For example, decreasing the MITD can dramatically increase the Ministry's risk while decreasing the licensee's risk by very little near the TSS. On the other hand, increasing the M-value when the MITD is 2.0 m may have little effect on either risk or potential loss in volume.

3.1 Simulating the Effects on Risk of Varying Parameter Values

Ministry staff often receive suggestions for changing the parameters of the silviculture survey. The following changes to the parameters increase the Ministry's risk.

- Increasing the M-value (maximum allowable tree count per plot) through increasing the target stocking standard
- Decreasing the minimum stocking standard
- Reducing the number of plots used for the survey (sample size)[10]
- Reducing the minimum inter-tree distance

To help the Ministry respond appropriately to these suggestions, it is valuable for staff to understand how changes to the survey parameters might affect the Ministry's risk. To demonstrate how the Ministry's and licensee's risks are affected when these survey parameter values are changed, a simulation study was performed and is reported here. Results were generated for the three familiar spatial distributions within TIPSY[11]: regular, natural, and clumped. Corresponding volumes for lodgepole pine were also projected using TASS.[12] The results are plotted as the ascending curves crossing the decision curves in Figures 3 through 8 (these projected volumes are discussed in sections 4 and 5). The methodology used is briefly described in Appendix 2. This section discusses the simulation results for the decision curves.[13]

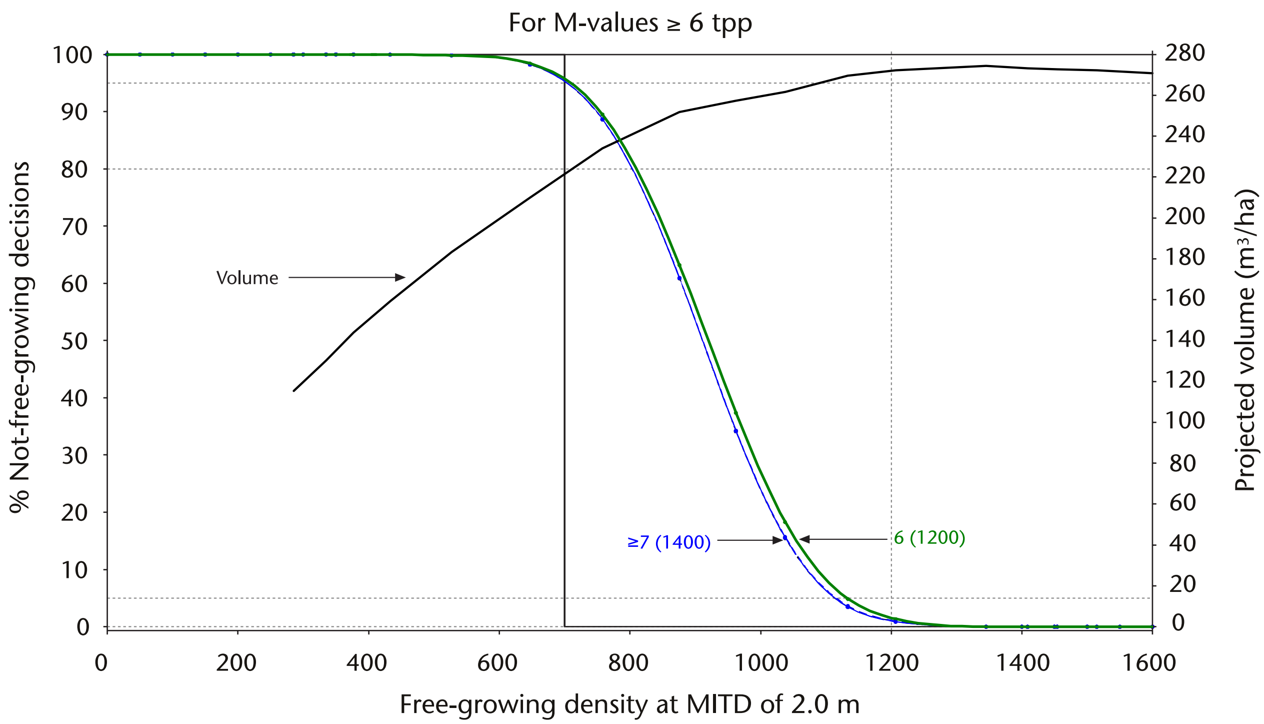
3.2 Changing the M-value

The maximum count or M-value is determined from the TSS assigned to the strata. Since the survey's 50-m^2 plots are 1/200th of a hectare in size, the TSS is divided by 200 to get the M-value. Thus, if the TSS were 1200 fgph, the M-value would be 6 trees per plot (tpp). Removing the M-value entirely from the sampling methodology is the same as increasing it to a relatively large number, as all counts are uncapped in the calculations.

The effect on risk of changing the M-value is shown in Figures 3 and 4 for the clumped distribution, using an MSS of 700 fgph (3.5 tpp) and TSS of 1200 fgph (6 tpp). For both figures, the upper graph shows the effect of increasing the M-value from 6 up to no cap, while the lower graph shows the effect of decreasing the M-value from 6 to 4 in 0.5 tpp steps. Figure 3 shows the effect of the M-value when the LCL Decision Rule is used; Figure 4 shows its effect when the Mean Decision Rule is used.

As the figures show, increasing the M-value from 6 changes the decision curves by very little. In particular, the Ministry's risk with the LCL Decision Rule is almost unchanged. On the other hand, reducing the M-value from 6 decreases the Ministry's risk but has the potential of increasing the licensee's risk substantially. When the Mean Decision Rule is used, the Ministry's risk can almost be returned to an acceptable level by reducing the M-value to 4 (corresponding to a TSS of 800 fgph).

10. This occurs because the silviculture survey system uses the Mean Decision Rule.
11. See <www.for.gov.bc.ca/research/gymodels/TIPSY/> for a description of this growth and yield model.
12. See <www.for.gov.bc.ca/research/gymodels/TASS/> for a description of this growth and yield model.
13. The curves in the figures presented in this handbook are based on a limited number of points (shown by small dots) and the spline fit may not provide a good fit for all values along the horizontal axis.
    Further, the curves in Figures 3 through 10 use a different set of simulation runs than was used in earlier drafts of this document. While the graphs are fundamentally the same, there are some small differences in appearance.



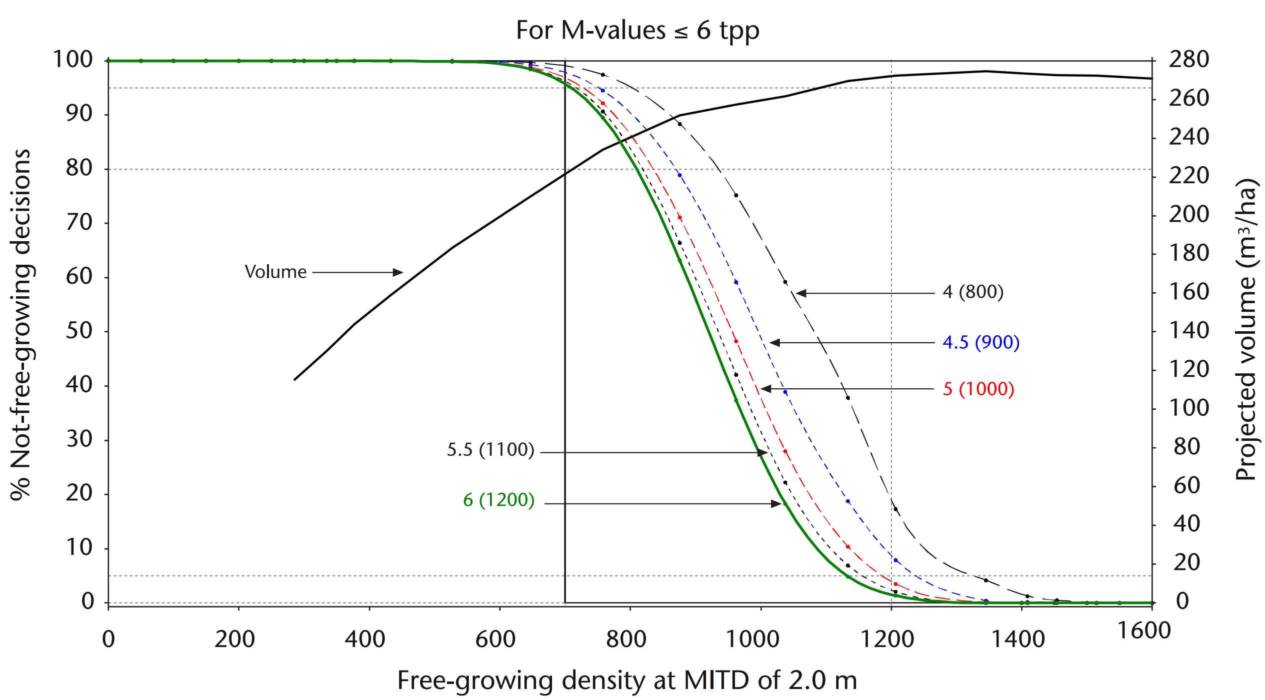
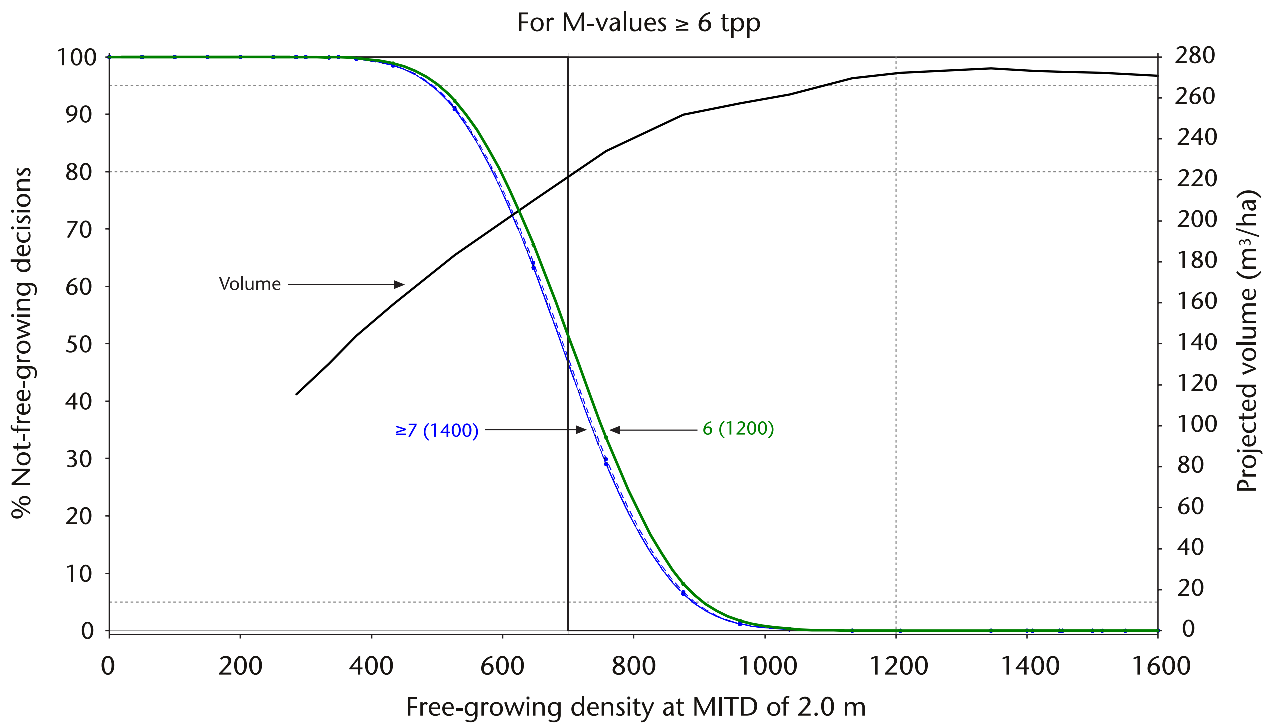


FIGURE 3 *Effect of changing the M-value on decision curves using the LCL Decision Rule for the clumped distribution, with MITD = 2.0 m.*



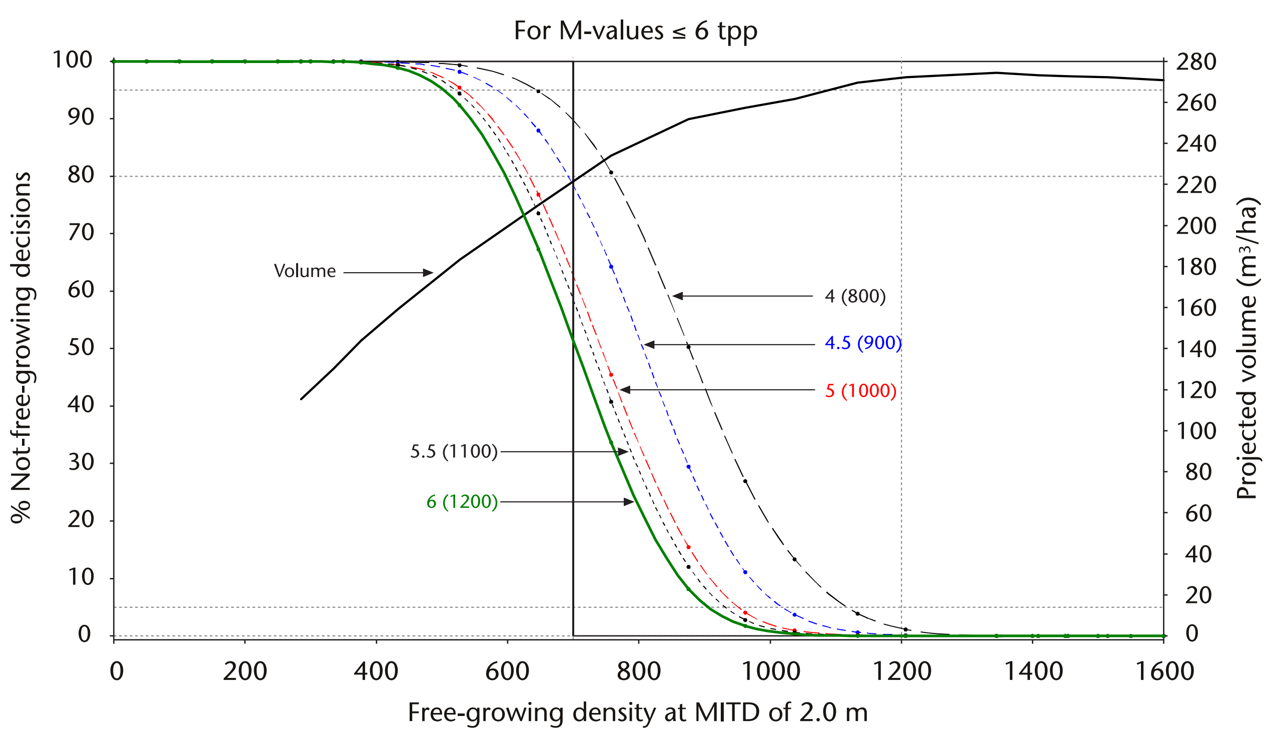


FIGURE 4 *Effect of changing the M-value on decision curves using the Mean Decision Rule for the clumped distribution, with MITD = 2.0 m.*

Capping the maximum allowable count (the M-value) may decrease the sample mean and the sample standard error[14] from what they would be without the cap. In turn, the corresponding decision curve can be severely affected if the M-value is very close in value to the MSS (when converted to units of trees per plot). On the other hand, increasing the value reduces the effect and, when the MITD is 2.0 m, all M-values greater than 3.5 tpp above the MSS (when converted to units of trees per plot) have a similar effect on the decision curve.

The effect of the M-value is complicated by its interaction with tree spatial distribution and MITD (graphs not shown). Changing the M-value affects the Ministry's risk more at a low MITD than at a higher MITD.

The current M-values being used by the Ministry, combined with an MITD of 2.0 m, safeguard against the unusually high count values that would be expected from extremely clumped distributions. The cap restricts the ability of the high counts to compensate for any low counts that might occur from holes or gaps present in a very clumped spatial distribution of trees.

Conclusions:
Current M-values have little effect on the decision curves for regular and natural distributions, but do control the Ministry's risk for very clumped distributions. Decreasing the M-value in the example given can reduce the Ministry's risk but greatly increase the licensee's risk. On the other hand, increasing the M-value from 6 trees per plot when the MITD is 2.0 m appears to have little effect. The effect of the M-value is more pronounced if the MITD is also reduced (results not shown). Thus, increases to the M-value should be carefully considered if the MITD is less than 2.0 m.

3.3 Changing the Minimum Stocking Standard

The LCL decision curves for a range of different MSS values (400–800 fgph) for the clumped distribution are shown in Figure 5. Decreasing the MSS simply shifts the curve to the left; the shape of the curve remains fundamentally the same.

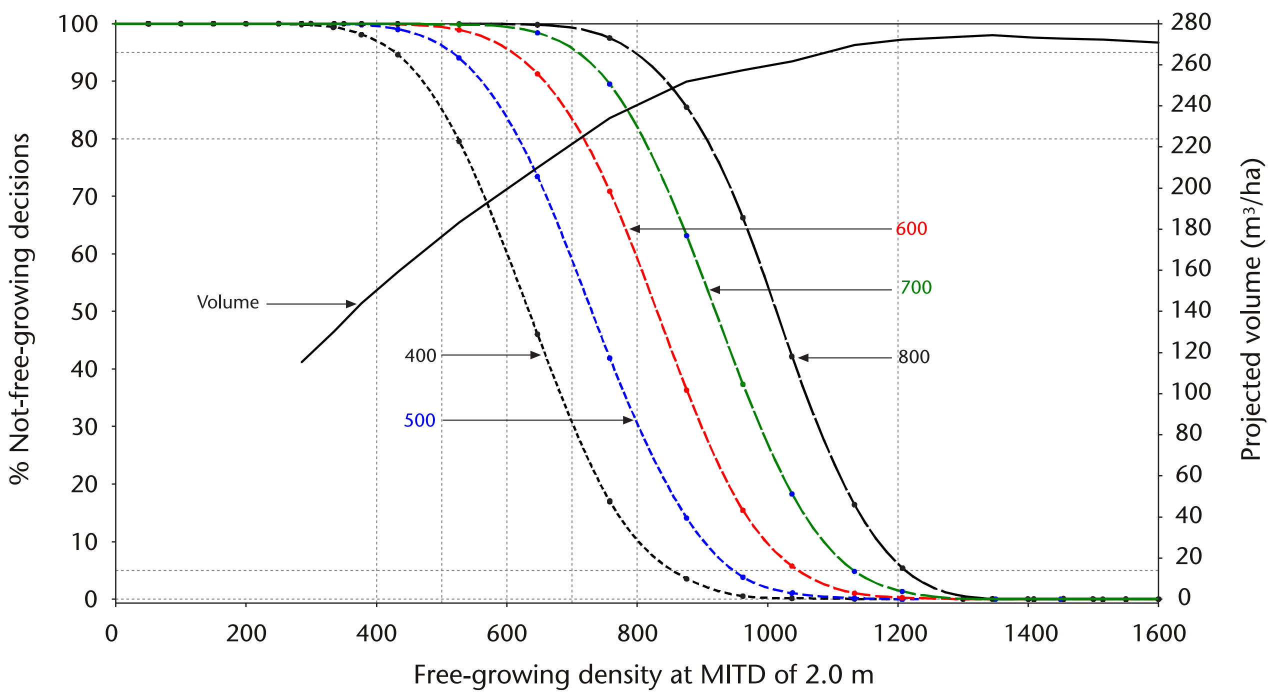


FIGURE 5 *Effect of changing the MSS on decision curves using the LCL Decision Rule for the clumped distribution, with MITD = 2.0 m. (The TSS for each curve was set to the MSS + 500 fgph.)*

14. If there are no observed counts greater than the M-value, the mean and standard error are not reduced.

Conclusions:
The basic shape of the decision curve is independent of the particular MSS value chosen. Clearly, if we were to change the MSS of the survey while still maintaining the definition of the Ministry's risk at 700 fgph, then decreasing the survey's MSS increases the Ministry's risk while increasing the survey's MSS decreases the Ministry's risk. Correspondingly, the licensee's risk changes in the opposite fashion. If other values of MSS are determined to be suitable for the free-growing survey, the behaviour of the decision curve about the new MSS remains the same.

3.4 Changing the Sample Size

The number of plots placed within a stratum, commonly known as the sample size, can affect both the Ministry's and licensee's risk by changing the steepness of the decision curve. Simulation results showing this are presented in Figures 6 and 7 for sample sizes of 5, 7, 8, 10, 15, 20, and 30.[15] These graphs show that decreasing the sample size flattens the decision curve while increasing the sample size steepens it. Fundamentally, this occurs because increasing the sample size decreases the standard error.

The Ministry's risk is held constant regardless of sample size when the LCL Decision Rule is used. This is shown in Figure 6. Increasing the sample size decreases the licensee's risk, while decreasing the sample size has the opposite effect. On the other hand, both risks change if the Mean Decision Rule is used as is shown in Figure 7. This is because the fixed point is now at about 50% at the MSS of 700 fgph. In this case, both the Ministry's and the licensee's risk increase with decreasing sample size and decrease with increasing sample size. This second fixed point provides little information about the effectiveness of the silviculture survey methodology.

In Figure 6, the licensee's risk of 5% for a sample size of 10 occurs at about 1000 fgph for the natural distribution and at about 1140 for the clumped distribution. When the sample size is decreased to 5 plots, this risk occurs at higher free-growing densities of about 1125 fgph and 1280 fgph for the natural and clumped distributions, respectively. If the sample size is increased, the licensee's risk of 5% will occur at lower free-growing densities. For the natural distribution, this risk occurs at about 925 fgph and 880 fgph for sample sizes of 20 and 30, respectively, while for the clumped distribution, this occurs at about 1020 fgph and 960 fgph, respectively.

It is important to recognize that the effect of sample size is independent of the proportion of the area sampled so long as this proportion is smaller than a tenth of the total area. Instead, it is more dependent upon the number of plots placed.

Conclusions:
The LCL Decision Rule controls the Minstry's risk regardless of sample size. Minimal sample sizes can greatly increase the licensee's risk while slightly larger sample sizes can substantially reduce this risk. Nevertheless, increasing sample sizes over 40 provides diminishing returns.

3.5 Changing the Minimum Inter-tree Distance

Well-spaced density is a key concept underlying the current silviculture surveys methodology. For instance, the stocking standards in the survey, both minimum and target, are not specified in terms of total density, but in terms of well-spaced density for regeneration surveys and free-growing density for free-growing surveys. (Section 4 shows that using free-growing density allows projections of total merchantable volume at rotation to be less dependent on the spatial distribution of trees than if total free-growing density were used.)

While there are many different definitions or ideas about what a well-spaced stand is, a clear and precise definition is required for operational work. The silviculture survey methodology uses the following definitions:

- *Well-spaced density* is the count of trees separated by a minimum distance (often 2.0 m) within a 50-m^2 plot. This count is converted to well-spaced trees per hectare (wsph).
- *Free-growing density* is defined in the same way as well-spaced density is, with the added proviso that the trees counted must meet a minimum height requirement. The resulting count is

15. All other decision curves presented in this handbook use a sample size of 10 plots.

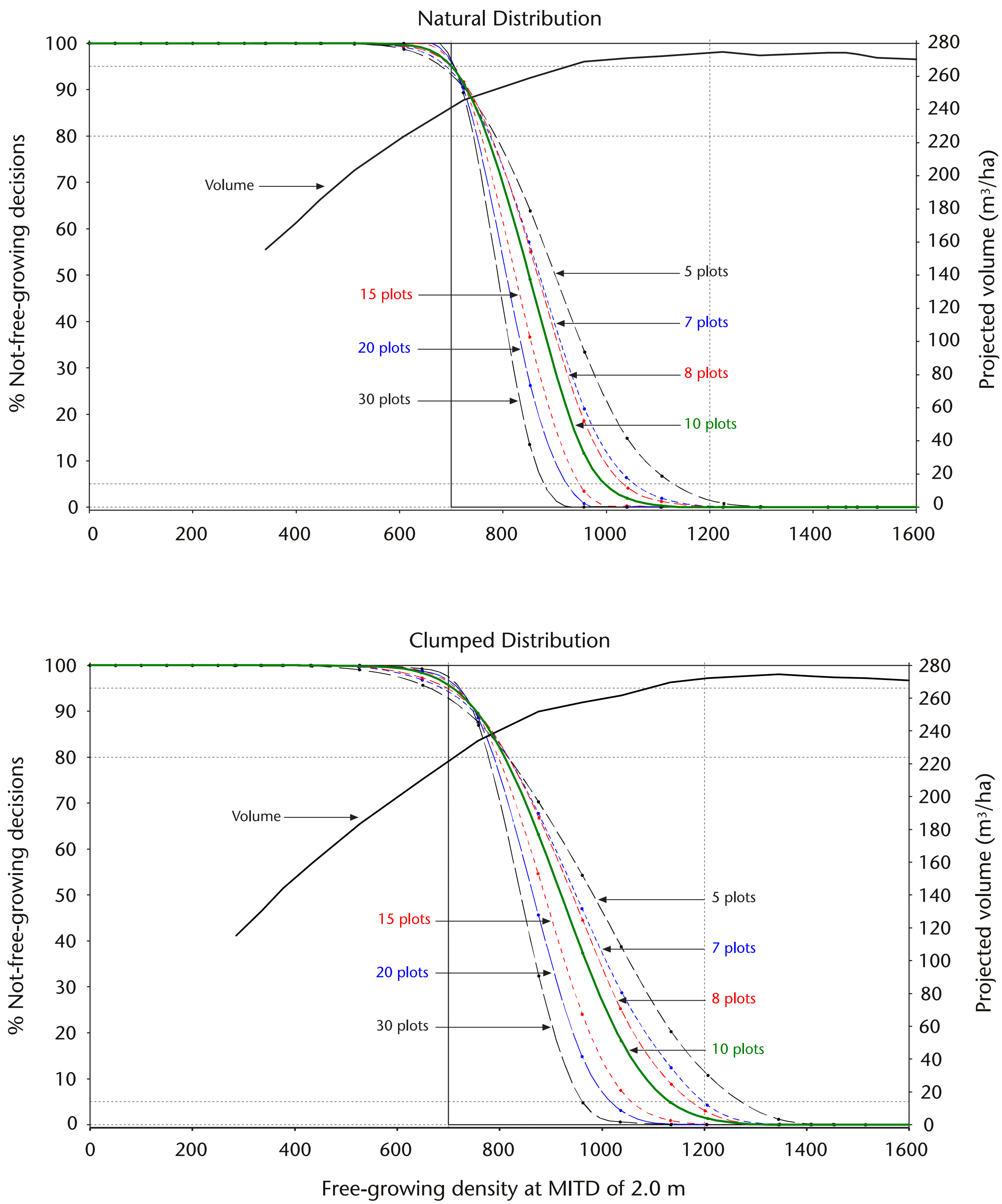
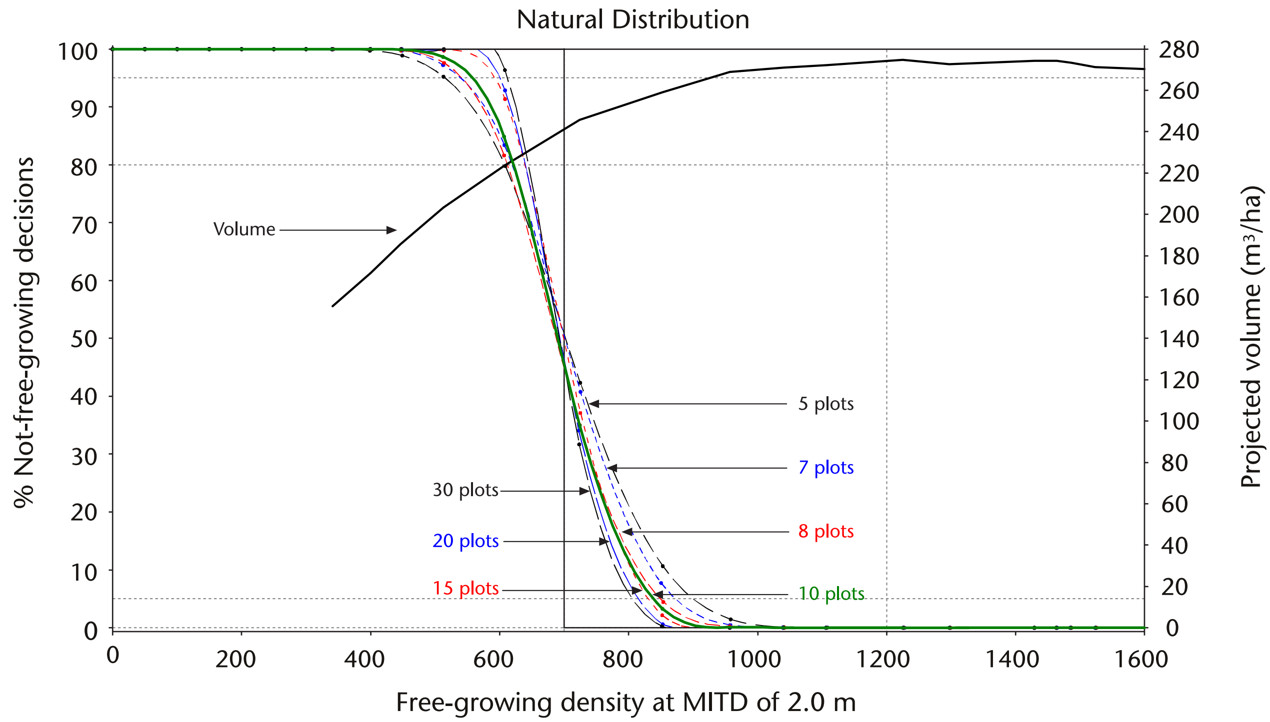


FIGURE 6 *Effect of changing the sample size on decision curves using the LCL Decision Rule for the natural and clumped distributions. The horizontal axes use an MITD of 2.0 m as the definition of free-growing. Samples sizes of 5, 7, 8, 10, 15, 20, and 30 are shown.*



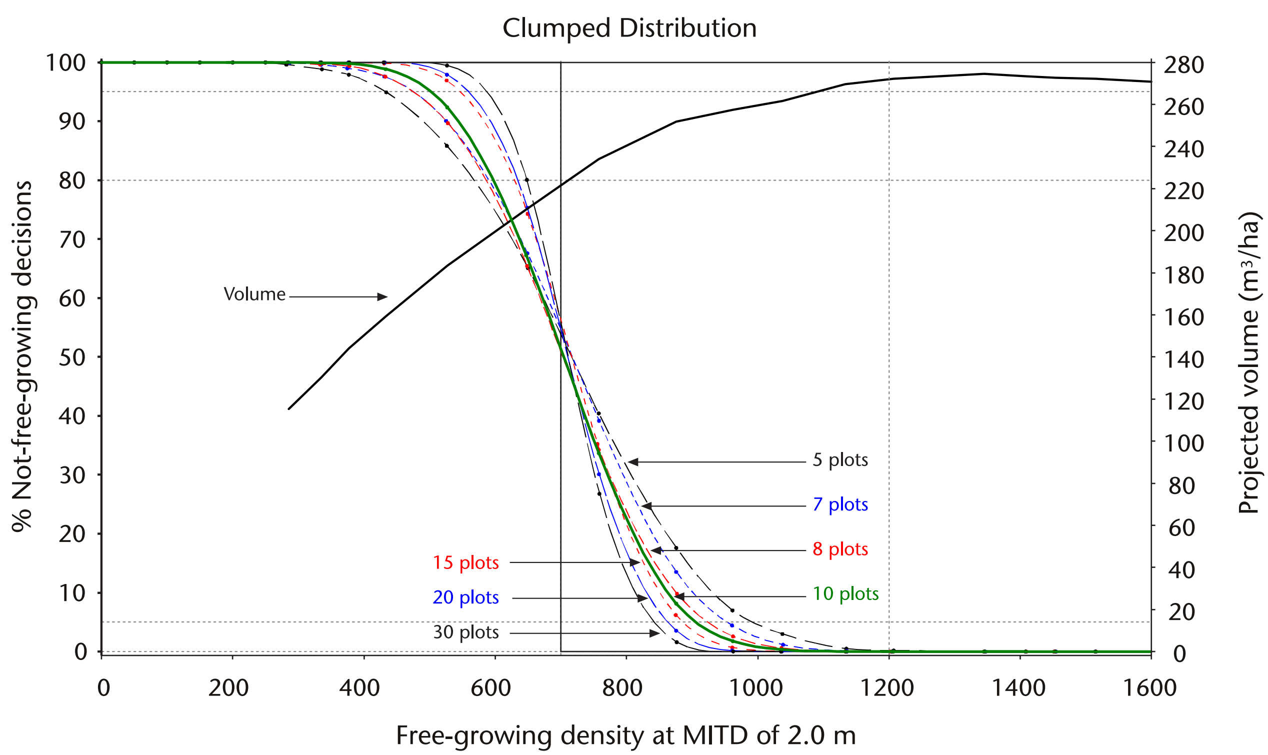


FIGURE 7 *Effect of changing the sample size on decision curves using the Mean Decision Rule for the natural and clumped distributions. The horizontal axes use an MITD of 2.0 m as the definition of free-growing. Samples sizes of 5, 7, 8, 10, 15, 20, and 30 are shown.*

converted to units of free-growing trees per hectare. It is important to note that free-growing density depends on the stand age and height at time of sampling, while well-spaced density does not. Thus, free-growing density is much smaller than the corresponding well-spaced density at very young stand ages (e.g., the free-growing density might be zero just after planting or regeneration, when the well-spaced density might be 1400 wsph). Free-growing density steadily increases and approaches the corresponding well-spaced density as the trees grow and meet the minimum height requirement.[16]

Note that these definitions of density do *not* include the capping M-value.

The Silviculture Prescription for a particular stratum defines the well-spaced density for that stratum by specifying a value for the MITD. This value is used in subsequent stocking (well-spaced) and free-growing surveys. So far in this discussion, both well-spaced density and free-growing density have been defined with MITD = 2.0 m. All graphs in this report (except for Figures 10 and 11) use this definition along the horizontal axis. To examine the effect of changing the MITD, let us suppose that different values were used in the survey. The effect on LCL decision curves of using MITDs of 0.0, 1.0, 1.5, and 2.0 m are shown in Figure 8 for the natural and clumped distributions.

These figures show that as the survey MITD value is decreased, the Ministry's risk can increase by a great deal. Perhaps surprisingly, this is more so for the natural distribution than for the clumped distribution used in this simulation study.[17] If the MITD is decreased from 2.0 m to 1.5 m, then the Ministry's risk increases from 5% to about 20% for the natural, and from 5% to about 13% for the clumped distribution. If the MITD is decreased further to 1.0 m, then the risk increases from 5% to about 45% (natural) and about 20% (clumped). And for no MITD, the risk increases from 5% to more than 60% (natural) and about 30% (clumped). Thus, decreasing the MITD can dramatically increase the Ministry's risk of incorrectly classifying as free-growing stands with less than 700 fgph. This occurs because more of the trees within clumps are counted. Using a lower MITD increases the mean, thus reducing the impact of low counts from holes or gaps. Of course, the licensee's risk decreases with decreasing MITD, but does so less dramatically than the Ministry's risk increases.

Conclusion:
Changing the MITD can greatly increase the Ministry's risk while changing the licensee's risk at the target of 1200 fgph by a small or negligible amount. This effect is discussed further in Section 5. Changes to the MITD should be carefully thought out before implementation.

16. It is interesting to note that while we might expect the free-growing density to be no greater in value than the well-spaced density, which individual trees are actually counted in a specific survey plot may be quite different for the two different measures of density. This is because the surveyor maximizes the tree count differently for the different survey objectives.

17. As we might expect, decreasing the MITD shifts the decision curves a little more to the left for the clumped than for the natural distribution (look at where the curves cross the 95% horizontal line). But the Ministry's risk increases more for the natural distribution because the decision curves are steeper for the natural than for the clumped distribution (look at where the curves cross the vertical line at MSS = 700 fgph).

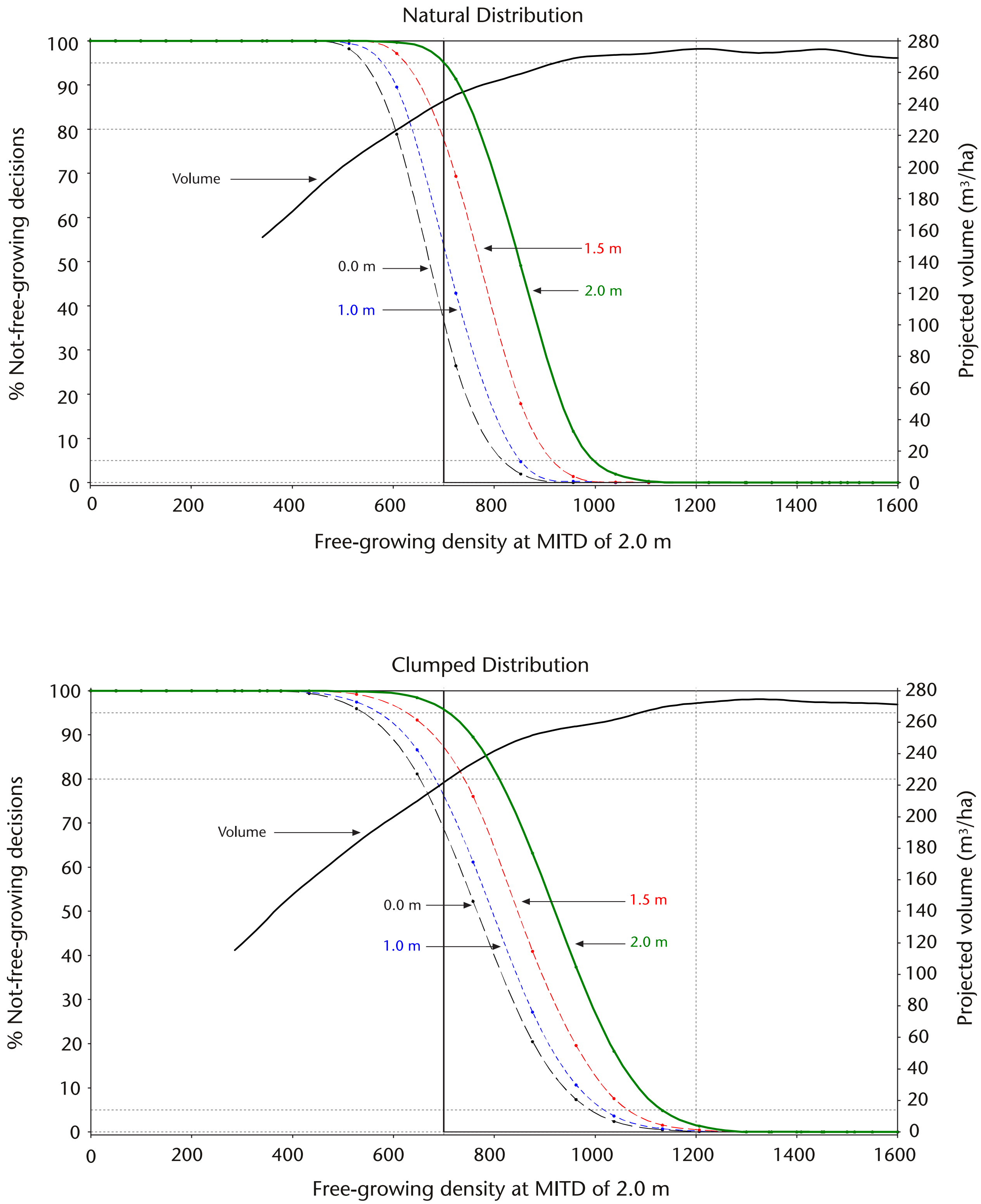


FIGURE 8 *Effect of changing the MITD on decision curves using the LCL Decision Rule for the natural and clumped distributions. The horizontal axes use an MITD of 2.0 m as the definition of free-growing.*

The parameters of the silviculture survey should be designed so that those strata not likely to attain their potential yield at rotation can be correctly identified as such. This allows those strata to be closely examined and appropriate action taken. In the work described here, the Ministry's tree-growth model, TASS*, was used to project the potential volume of lodgepole pine stands with a wide range of "true" free-growing densities arranged according to three different spatial distributions.*

4.1 Projected Volume Curves

Stands that meet the minimum stocking requirement should also produce acceptable minimum yields at rotation. To study this feature of the silviculture survey system, TASS was used to project the yield as measured by the total merchantable volume (12.5 cm+ DBH, 10.0 cm top dib, 30 cm stump) at 20-m site height (67 years). Values were determined for a range of densities of lodgepole pine stands with a site index of 18 and for the three standard spatial distributions within TIPSY: regular, natural, and clumped. A 100% potential volume was set at 280 m^3/ha, since this was about the maximum potential volume observed in this simulation study. Note that these volumes are projected for the whole stand—that is, for all trees whether or not they would have been counted at the time of the survey. These projections also assume that all trees are healthy, free of disease, and unimpeded by vegetation.

4.2 Free-Growing Density with MITD = 2.0 m and Minimum Height = 2.0 m

The relationship between projected volume at 20-m site height and free-growing density for the three spatial distributions at the simulated age of 15 or 16 years is shown in Figure 9. The projected volume is about the same for the regular and natural distributions, with the clumped distribution falling slightly below. Around the minimum stocking standard of 700 fgph, the yield for the clumped distribution is about 8% less than for the regular

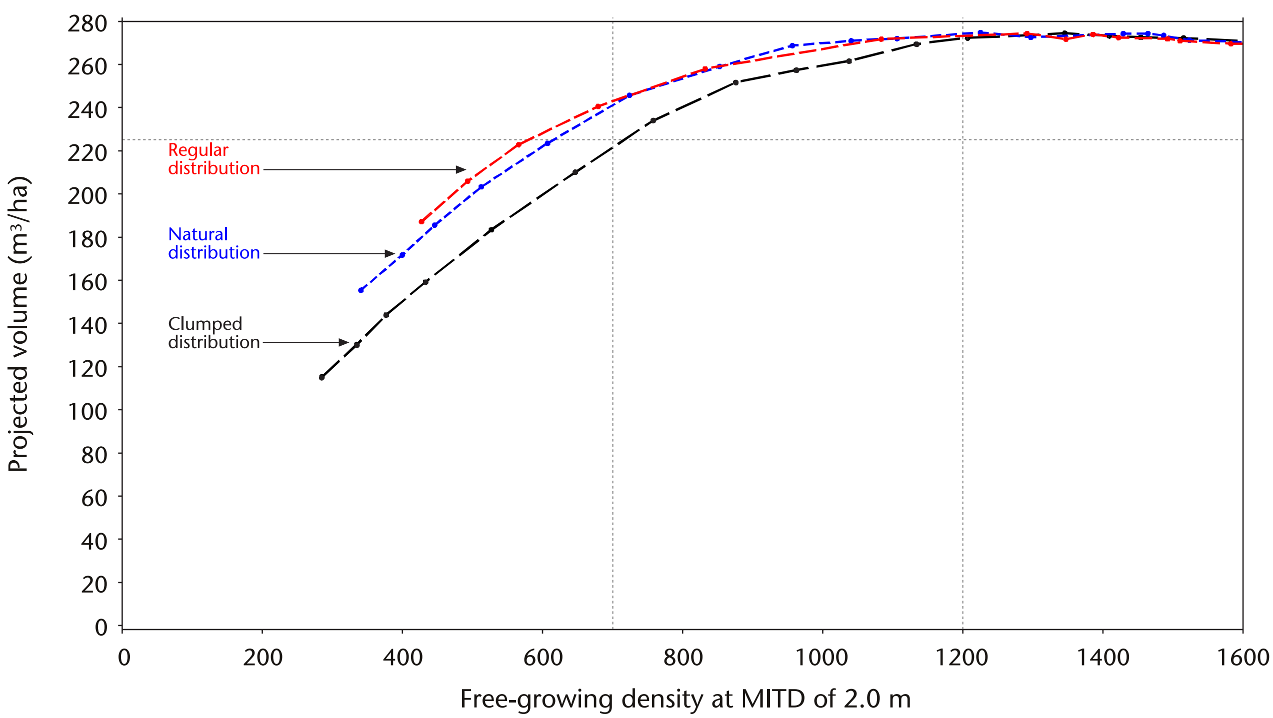


FIGURE 9 *Projected merchantable volume (at 20-m site height and 12.5+ cm DBH) for free-growing density at three different spatial distributions.*

or natural distributions. This difference diminishes with increasing density until it is negligible at about 1300 fgph. At just over 800 fgph, the clumped distribution attains the same projected volume as the regular and natural do at 700 fgph.

For this modelling situation, even with a regular distribution of stems, the projected merchantable volume at the MSS of 700 fgph is about 13% less than the potential that the site could yield at higher densities. This potential is just attained at the target stocking of 1200 fgph.

4.3 Total Density with No MITD and No Minimum Height

As just illustrated in Figure 9, the free-growing density (defined with an MITD of 2.0 m and a minimum height of 2.0 m) predicts projected volumes of similar value regardless of the spatial distribution of the trees, although moderately or severely clumped spatial distributions will reduce the projected volume for the lower densities. This independence of spatial distribution does not hold for total density where, as Figure 10 shows, the relationship between projected volume and total density is quite different. At total densities below 1600 tph, there is about a 10% difference in projected volume between the three spatial distributions, with the clumped distribution showing about 20% less volume than the regular distribution. However, this difference in spatial distribution becomes negligible when total density is greater than 3500 tph.

4.4 Free-Growing Density with Different MITDs and Minimum Height = 2.0 m

Figure 11 shows the effect of changing the definition of free-growing density by using different values of MITD and with or without applying the height restriction for the case with no MITD. Points at the same height (same projected volume) but on different curves are from the same simulated stand, but have been plotted against different definitions of free-growing density. As the MITD decreases from 2.0 m (fewer trees counted) to 0 (all trees counted), the projected volume curve is shifted to the right. The amount of sideways shift depends on the MITD and is greater with increasing density. Removing the height restriction has a similar effect

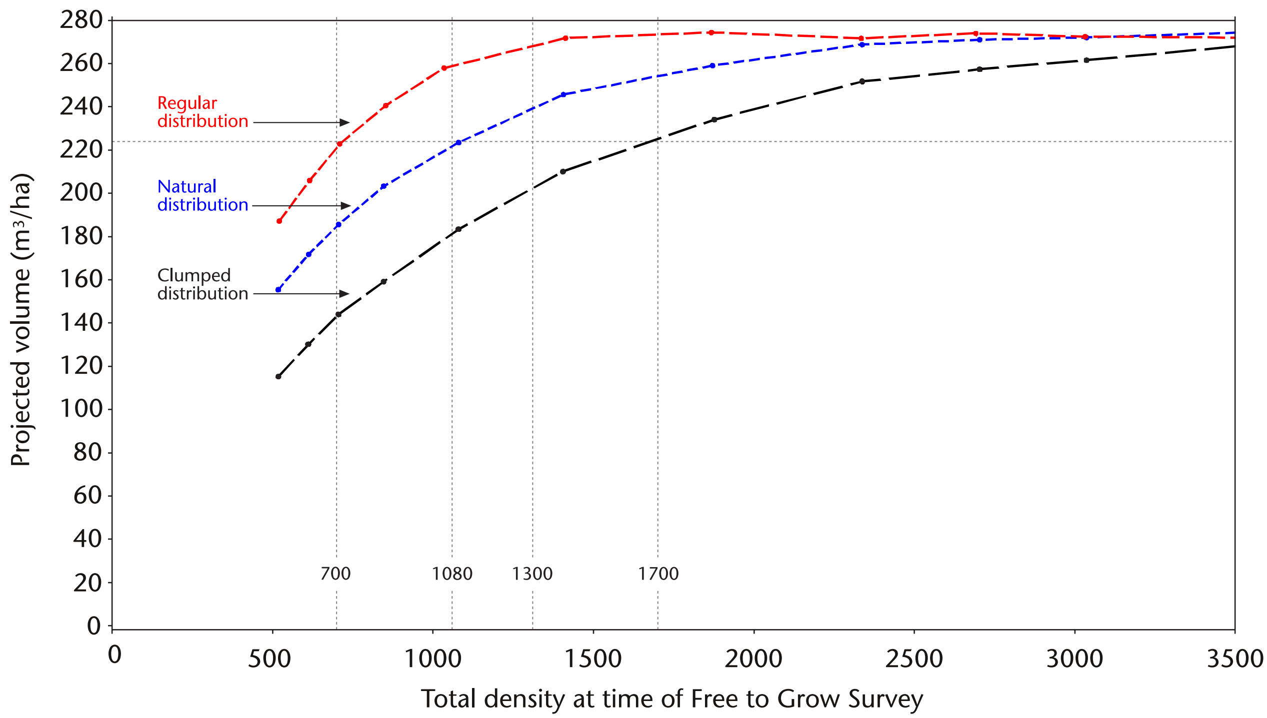


FIGURE 10 *Projected merchantable volume (at 20-m site height and 12.5+ cm DBH) for total density at three different spatial distributions.*

as reducing the MITD: the curve is shifted further to the right.

In Figure 11, the curve for 2.0 m is the same as that for the clumped distribution in Figure 9, although the horizontal scale is different. The curve for 0.0 m is the same as the one for the clumped distribution in Figure 10. The gradual transition between these two volume curves as the height restriction is added and the MITD increased is shown by the intermediate curves.

Now consider the five volume projections at the TSS of 1200 fgph. The top four points represent different simulated stands with different total free-growing densities. The lowest two points are from the same simulated stand, one with the height restriction and one without. The lowest point shows a volume projection of about 190 m^3/ha. If the height restriction is included, while leaving the MITD at 0, then the volume projection increases to about 225 m^3/ha. When an MITD of 1.0 m is added to the height restriction, the projected volume is about 245 m^3/ha. For an MITD of 1.5 m the projected volume is about 260 m^3/ha; for 2.0 m it is about 270 m^3/ha.

We can estimate the corresponding total free-growing density for each of these stands by sliding the point of interest horizontally to the MITD = 0.0 m curve and noting which total free-growing density this corresponds to on the horizontal axis. The results are about 1450 tph for 1.0 m; about 1900 tph for 1.5 m; and at about 3000 tph for 2.0 m. Thus, stands with the same "true" free-growing density value of 1200, but with actual densities that have been defined using different MITDs, represent stands with quite different total free-growing densities and correspondingly different projected volumes. Recall that these projections include the volume from all the trees at the site, and not just those that are counted during the survey.

These volume curves will not be as widely separated for less clumpy spatial distributions (such as the regular and natural), but could be even more widely separated for more extremely clumped spatial distributions.

Conclusion:

It may be easier to project volume at rotation using well-spaced density or free-growing density at a high MITD rather than total free-growing density, since projected yields are less dependent on the

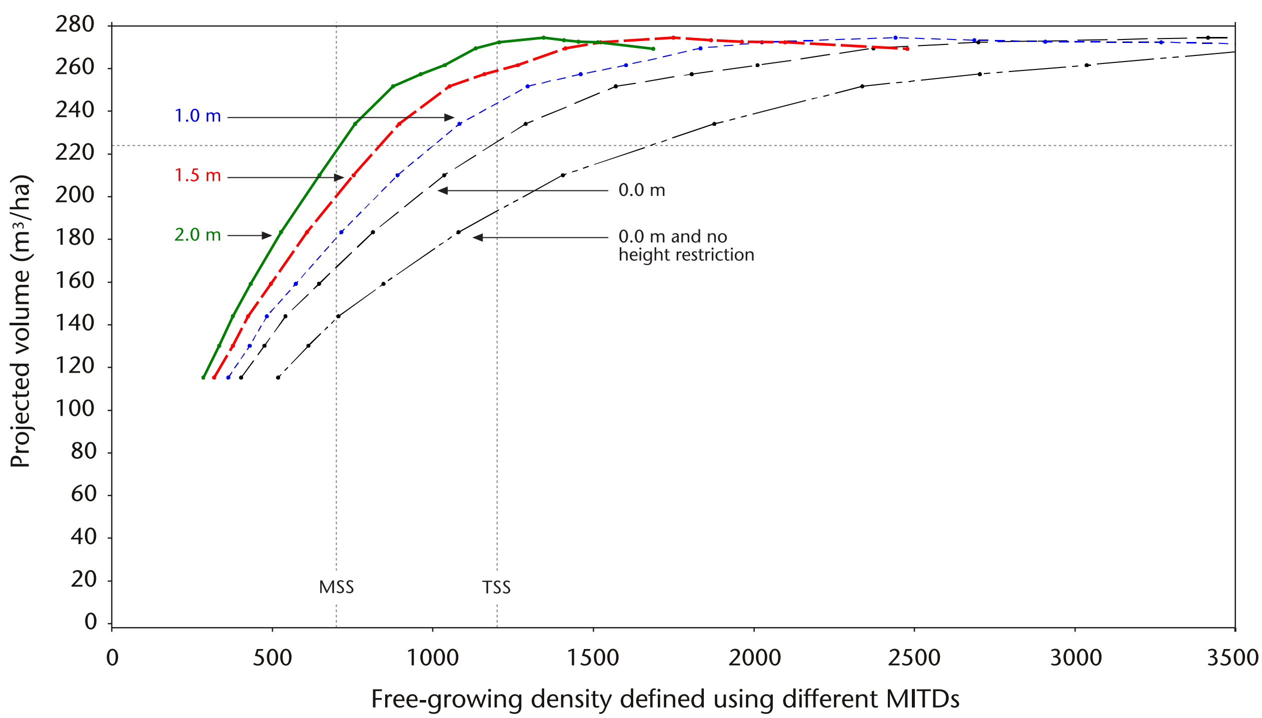


FIGURE 11 *Projected merchantable volume (at 20-m site height and 12.5+ cm DBH) for the clumped distribution, using different MITDs to define free-growing density, all with a 2.0-m height restriction. A curve for total density with no height restriction and an MITD of 0.0 m is also included.*

spatial distribution of the trees. Except for strata with regularly spaced trees, stands with the same free-growing density estimates, but defined using different MITDs, will have different projected volumes at rotation, with the higher volumes corresponding to higher values of MITD. The result is that density estimates based on different MITD values are not comparable.

5 USING THE DECISION AND PROJECTED VOLUME CURVES TOGETHER

The decision and projected volume curves can be used together to answer specific questions about the effects on projected volume of changing a particular silviculture survey parameter. As an example, a particularly interesting question to ask is: How does the projected volume at the Ministry's risk of 5% change as the MITD is decreased?

To help answer this question, portions of the two graphs in Figure 8 are enlarged in Figure 12 to show the potential impacts of changing the MITD. The four descending curves show how the decision curve shifts left as the MITD is decreased from 2.0 m to 1.5 m to 1.0 m and finally to 0.0 m. The ascending solid curve is the projected potential volume. It is important to recall that this projected volume is an estimate of the maximum volume achievable—an amount that is usually reduced by disease, pest damage, brush competition, and other factors.

For an MITD of 2.0 m, the Ministry's risk is about 5% at 700 fgph for both the natural and clumped distributions. These points are shown on the graphs by the dots at the intersection of the horizontal 95% not-free-growing line and the 2.0 m decision curve. Follow the arrow from that point down to the volume curve where another dot has been placed in Figure 12. The height of this second dot, as measured along the projected volume axis on the right, is the estimated projected volume. The resulting values are about 240 m^3/ha for the natural distribution and 222 m^3/ha for the clumped. Recall that the maximum potential volume was set at 280 m^3/ha.

However, if surveys were conducted using an MITD of 1.5 m instead of 2.0 m, the Ministry's risk of 5% would now occur at about 625 fgph for the natural distribution and about 630 fgph for the clumped distribution (shown by the dots at the intersection of the 95% not-free-growing line and the 1.5 m decision curves). The reason for this is that we can only be 95% certain of correctly identifying not-free-growing strata whose "true" means are less than these new values. Strata with "true" means between 625 or 630 fgph and 700 fgph will have a lower than 95% chance of being correctly identified as not-free-growing.

The resulting projected potential volumes are determined as before: by following the arrow from the new dots to the projected volume curve. For the natural distribution, the potential volume is reduced a further 4% to about 228 m^3/ha; for the clumped distribution, it is reduced an additional 5% to about 206 m^3/ha. The values for all four MITD values discussed here are summarized in Table 3.

At the MSS value of 700 fgph defined with an MITD of 2.0 m, strata are predicted to produce only 80–85% of their potential volume simply because there are not enough trees growing on the site. The current survey methodology, with an MITD of 2.0 m and a TSS of 1200 fgph, offers surveyors at least a 95% chance of correctly identifying all those stands that are projected to produce even less volume. If surveys are conducted with smaller MITDs, this percentage will be reduced by an unknown amount. Correspondingly, the chances of misidentifying strata projected to produce less than 80–85% of the potential volume and allowed to grow without remedial action will increase by an unknown amount.

While the simulated results allow us to put specific numbers into Table 3, in general, these numbers will be unknown. Thus, the numbers in this table should be understood as showing the trends, but not the specific magnitudes for any particular situation. Similar tables could be constructed for other survey parameters to see the impact on projected volume.

TABLE 3 *Minimum free-growing density values for which the Ministry's risk is 5%, for MITD values of 0.0, 1.0, 1.5, and 2.0 m, and the resulting projected potential volumes*

	Natural Distribution			Clumped Distribution		
MITD (m)	Minimum free-growing density	Volume (m^3/ha)	Percent of Maximum[a]	Minimum free-growing density	Volume (m^3/ha)	Percent of Maximum[a]
2.0	700	240	86	700	222	79
1.5	625	228	81	630	206	73
1.0	580	215	78	570	192	69
0.0	550	210	75	540	187	66

[a] The maximum potential volume was set at 280 m^3/ha. These numbers only show trends; the values indicated would not necessarily be realized for any specific stratum.

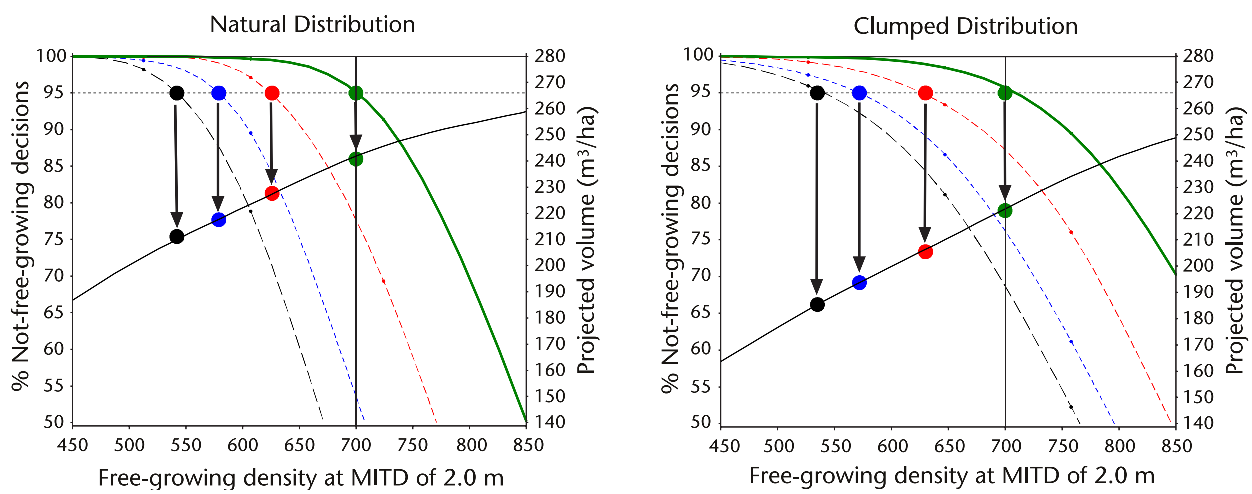


FIGURE 12 *Decreases in projected volume corresponding to decreases in MITD when the Ministry's risk is kept constant*

A well-designed silviculture survey system can help the Ministry control its risk of not detecting not-free-growing stands. The long-term cost[18] of failing to do so can be high, since undetected not-free-growing stands remain untreated and thus less productive at rotation than they could have been. As modelled for lodgepole pine in this report (Appendix 2), the current survey system is designed to accept stands with between 80 and 100% of potential volume at 20 m site height at least 95% of the time. Presumably, the possible 20% reduction in potential volume for clumped lodgepole pine stands with densities near the minimum stocking standard is acceptable for future harvests.

When the Mean Decision Rule is used, the Ministry's risk can be quite high. This risk gets even higher if the first pass is skipped. This greater risk means that there is an increased chance that not-free-growing stands will remain undetected, untreated, and less productive than they could have been. However, if the LCL Decision Rule was always used and the second pass eliminated, then no more that 5% of stands with less volume would be incorrectly identified.

Licensees will also want to minimize their risk in order to avoid incurring the immediate costs of possible remedial action and continuing liability. Section 2.3 presented some suggestions for reducing this risk, including the use of larger than minimum sample sizes in the first pass when the LCL Decision Rule will be used. This might be particularly cost-effective for strata with clumpy spatial distributions.

The MITD specified in the Silviculture Prescription for a stratum effectively defines the free-growing density to be used for that stratum. This handbook has only presented results for a definition using 2.0 m. Accepting a lower value for the MITD is equivalent to reducing the MSS and allowing strata with lower potential volumes a greater chance to be declared free-growing. Also important to remember is that density estimates using different MITD values are not comparable, and that density values specified without the defining MITD are meaningless.

The results discussed here may differ for other species and other measures of yield. Keep in mind that the volumes discussed are optimistic because the TASS projections did not include any growth impediments due to vegetation competition, forest health problems, the presence of small swamps and boulder fields, or other factors that would reduce the projected volume for a stratum.

18. The Ministry's risk could also be called the long-term risk, since the consequences of an incorrect decision may not be realized until harvest. Correspondingly, the licensee's risk could be called the short-term risk, since the costs of an incorrect decision are more immediate.

The probability of incorrectly accepting as free-growing a stand that is not-free-growing depends on how the decision rules are used. If the Mean Decision Rule is used only after the first pass has an "undecided" outcome, the Ministry's risk will be lower than if the first pass is skipped so that the Mean Decision Rule is used directly on all the sample data.

Fundamentally, this is a question of how to assign the "undecided" probability in Figure 1 to the not-free-growing and free-growing decision probabilities. When the first pass is skipped, all of the undecided probability is, *de facto*, assigned to the free-growing decision. This greatly increases the Ministry's risk. When the first pass is not skipped, the undecided probability is divided between the not-free-growing and free-growing decisions so that the Ministry's risk is not increased so greatly. An example may help illustrate how this works.

Suppose that the "true" free-growing density is 699 fgph and estimates of the probabilities for the Mean Decision Rule and Lower Confidence Limit Decision Rule are shown in the following table (numbers were read from the curves in Figure 1).

The first column shows the values for using the Mean Decision Rule after the first pass is skipped (assumed to be the same as using the Mean Decision Rule at the first pass). The second column shows the probabilities of the sample producing one of three possible outcomes during the first pass. The arrows between these first two columns show how all of the undecided probability of the first pass is added to the free-growing probability to obtain the probability of a free-growing decision using the Mean Decision Rule.

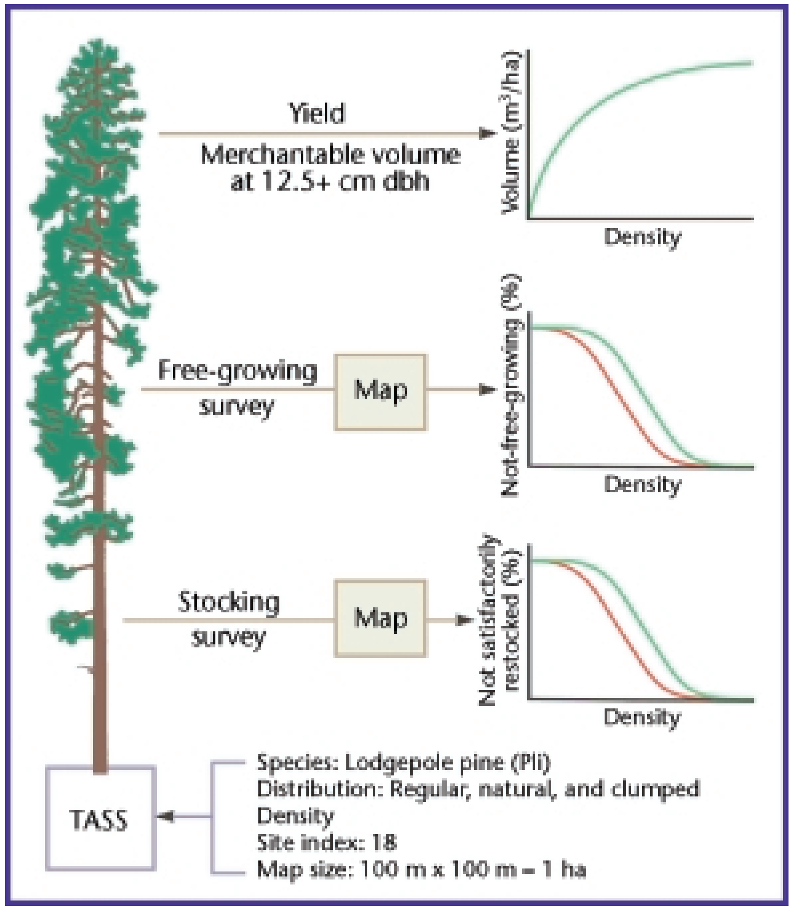
The probabilities for the outcomes of the second pass require calculating the conditional probabilities. Instead of putting all of the undecided probability into the free-growing decision, the conditional probability splits it and gives a piece to each of the not-free-growing and free-growing decision probabilities. The split is determined by the ratio of the not-free-growing/free-growing probabilities resulting from the Mean Decision Rule, since it is the rule used for the second pass. Thus, the conditional probability of obtaining a not-free-growing decision during the second pass is the probability of obtaining a not-free-growing outcome during the first pass (0.48) plus a 48% share of the undecided probability (0.47) from the first pass. Similarly, the conditional probability of obtaining a free-growing decision during the second pass is the probability of obtaining a free-growing outcome during the first pass (0.05) plus a 52% share of the probability of the undecided probability (0.47) from the first pass. Final values are shown in the last column.[19]

In summary then, using the Mean Decision Rule after skipping the first pass adds all of the first pass's undecided probability into the free-growing decision probability. On the other hand, the conditional probability splits this undecided probability between the two possible decisions according to the proportions of the Mean Decision Rule probabilities. For this example, the Ministry's risk is 52% when the Mean Decision Rule is used after skipping the first pass, but only 29% if the proper method is followed.

Decision	Second pass probabilities if first pass skipped[a]		First pass probabilities		Calculations for second pass conditional probabilities	Second pass conditional probabilities
Not-free-growing	0.48	←	0.48	→	= 0.48 + 48% of 0.47	= 0.71
Undecided	N/A	↙	0.47	↗ ↘	N/A	N/A
Free-growing	0.52	←	0.05	→	= 0.05 + 52% of 0.47	= 0.29
Total	1.00		1.00			1.00

[a] Taken from the first pass Mean Decision Rule and so assumes that the increased sample size has a negligible effect.

19. It is interesting to note that if the LCL Decision Rule were used for the second pass, the Ministry's risk would also increase, though not by much. For the example, the resulting conditional probability would be calculated to be about 7% instead of 5% (i.e., 0.05 + 5% of 0.47 = 0.074).



The growth and yield model TASS was used to project virtual lodgepole pine stands through time. Merchantable volume data were collected when the stands were projected to reach a harvestable age. This was chosen to be at 67 years of age for a site index of 18. Simulations were run on ten maps for each of a range of nominal densities. The three distributions are described below.

Tree maps complete with individual tree information were extracted for first pass regeneration and free-growing surveys at 2 or 4 years and 15 or 16 years. Surveys with a range of sample sizes were simulated 1000 times on each of these TASS-generated tree maps. Target stocking, minimum stocking, and minimum inter-tree distance parameters were varied when calculating the frequency of free-growing and not-free-growing decisions. These frequencies provide the estimated risk decision rates presented on the vertical axis of many of the figures throughout this report. Free-growing density for the corresponding horizontal axes was estimated by the average count of trees at least 2.0 m tall and at least 2.0 m apart from all 10 000 simulated 50-m^2 plots for the runs with a sample size of ten.

Simulated Distributions

1. Regular: Trees are arranged in a square spacing pattern with some variation allowed about the intended locations. This distribution is also called the square or planted distribution within TIPSY. Few plantations would be able to maintain this relatively uniform distribution even if successfully planted in so regular a fashion. Rather, this distribution provides an extreme for comparison purposes.
2. Natural: Trees are assigned at random to locations within the map. This distribution is also called the random distribution within TIPSY, since it is based on the random or Poisson distribution. Natural distributions may adequately represent actual spatial patterns for a wide variety of circumstances.
3. Clumped: Clump centres are randomly located on the map. Trees are then randomly assigned to a clump centre and located a random distance and direction from the centre. This provides a moderately clumped distribution and is used by TIPSY as another variation of a natural tree distribution.