# BUCKING TREES WITH DECAY

by

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## Abstract

The problem bucking of trees into logs is solved using dynamic programming. The state of the model is described by the physical dimensions of the tree, such as length, diameters and sweep. This thesis incorporates decay as a description of the state.

This thesis begins with a detailed analysis of decay morphology, obtaining the expected values and dispersion of key variables. The main goal of this thesis is to evaluate the decay information that could be gathered; this is done by incorporating different levels of information into the bucking algorithms. The first level assumes perfect information; in this case the algorithm is provided with the observed diameter of decay and its actual length. The second level uses an observed decay diameter and a length estimated based on the decay model. The third level also uses the observed decay diameter, but now the length is assumed to be a random variable, whose distribution parameters are based on the decay model. Furthermore, the models will be compared to the normal practices of forestry companies of British Columbia. A test of four hundred trees in four species, Spruce, Lodgepole Pine, Balsam Fir and Western Red Cedar was performed. Clear improvements were found when bucking with algorithms that consider decay. The value increased an average of 11.9%. One of the most relevant findings of this thesis is that this significant lift does not result from lower stumpage and transportation costs, but from higher recoveries. The stumpage and transportation costs are on average higher in the proposed algorithms as compared to the normal practices. This means that the use of bucking algorithms that incorporate decay translates into gains for the lumber companies as well as for the Provincial Government and the transportation industry.

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I would like to dedicate this thesis to my father, for teaching me the joys of learning.

# 1 INTRODUCTION

The forest products industry has become a very competitive sector of commerce. Marked with low profit margins and a large number of competitors, an improvement in raw material utilization might make the difference between bankruptcy and healthy profits.

The objective of any forest product company is to utilize the technology available today in order to get the most from each individual tree. No two trees are identical, but with the proper scanning system it is possible to gather enough information, in an economically and timely manner, to apply on-line optimization algorithms to each individual log. The improvements start with the optimal crosscutting of the tree into logs; this is referred as bucking. Usually, a log can have more than one use (sawlog, peeler or pulplog). There are physical limitations for each type of log; for example, a peeler has to have a given length, and it can not have more than a certain decay diameter exposed because the rotators might not hold it. The final use of the logs bucked from a tree does not have to be the same for one tree, so an individual tree can yield sawlogs, peelers and pulplogs.

The value of a pulplog is directly proportional to its volume. In the case of a peeler, the value is also determined by other variables such as taper or sweep, but is still a "smooth" function of these variables. The value of a sawlog is highly dependent on the number and dimension of boards cut from it. These dimensions are not continuous, thus, the value of sawlogs can not be considered as a smooth function of length, diameter, defect, sweep or taper. This makes the valuation of sawlogs somewhat complicated.

In the case of sawlogs, the longitudinal breakdown of each log into lumber can be improved by on-line systems, or lookup tables. These determine the position of the saws, log offsets and pattern to obtain the most from each sawlog. For peelers, the position of the rotators can also improve the recovery.

The optimal bucking solution for a tree is commonly found using dynamic programming In each step, a series of cuts are proposed at a certain distance from the starting point, normally the butt end of the tree. A log is produced from this cut and a remainder is left between the end of the segment and the end of the tree. The maximum value of the log plus the value of the corresponding remainder at each point is considered as the optimum value obtainable at that specific point, and the correspondent cuts that yield this value are considered the optimum policy. The algorithm is continued until the end of the tree is reached and the optimum policy found. A practical problem arises when having to evaluate the value of each individual segment. It can be either calculated with a specialized computer program or looked up in a table sorted by species, length, diameter and maybe taper, sweep and decay.

The problem can be graphically represented as a network problem. In it, the nodes represent all possible cutting points, and the arcs joining them represent the gain of a bucked segment limited by the adjacent nodes. Arcs of zero value are added to represent culled segments. The optimal bucking is given by the path joining the nodes at the butt and top ends of the log with the highest value.

The importance of optimal bucking had been realized even before the invention of proper mathematical techniques to solve it. Wackerman (1942) published an article on bucking. He proposed seven heuristic rules to improve the bucking; these early rules already anticipate the main ideas of analytical optimization, such as full utilization of tree, longbutting[1] ("jump-butting" in his paper) and grade cutting. Cobb (1958) realized that there is more to be done in the way

[1] Longbutting is the removal of a segment of less than merchantable length from a heavily decayed butt.

trees are bucked: "In recent years much time, thought and effort has gone into the search for more efficient timber harvesting and milling processes. Until recently, however, very little of this effort had been aimed at getting top quality from each tree as it is bucked into logs". At that time, operations research was booming. Mathematical techniques were being developed faster than the applications for them were being found. Cobb was also the first to correlate external indicators to internal defects, and apply this to improve bucking.

Bellman set the basis for dynamic programming in the early 1950's, but did not release a formal book until 1957, when he published "Dynamic Programming". His ideas were not implemented in the forest industry until the early 1970's. Pnevmaticos and Mann (1972) apply a dynamic programming algorithm to tree bucking for the first time. The basic approach is the same as used today: a recursive algorithm solved by backward induction. In the same paper, they propose a more elaborate algorithm where each segment is evaluated on the basis of its diameter and length, and the diameter of a point along the tree is determined from any other point assuming a constant taper throughout the tree.

Since then, dynamic programming algorithms for tree bucking have not evolved in form. The improvements have come in the way the segments are evaluated. The tendency is to assume real shaped logs, with taper, sweep, crook, non-circular sections, etc. instead of truncated cones. Multidimensional lookup tables are normally used to solve the problem, but with the increasing computer power, real-time and real-shape evaluation of segments should be the future tendency. Some more complicated variables have been integrated in the algorithms in the last years. Sessions (1988) gives an overall cost-benefit analysis for bucking, and in a latter paper, with Olsen and Garland (1989), includes volume-length restrictions on the logs. This is one of the first papers to integrate the bucking algorithms with the final breakdown of the log. These three authors, together with Pilkerton (1990), include block weight as a restrictive variable in the model.

Bucking is recognized as an integral part of lumber production. Some models have joined the bucking algorithms with the processing of the resulting logs using linear programming, for example Maness and Adams (1991).

In this thesis we go beyond past research on bucking by considering decay, or rot. Decay should be a fundamental variable in any bucking algorithm, and common practices on the field often over-simplify the way it is treated.

Decay is caused by a variety of fungi which break down and feed off the lignin or cellulose in the wood to the extent where the wood loses its mechanical properties and cannot be used to manufacture lumber. The fungus enters the tree through a root, broken branch, a damaged leader or a scarring of the stem.

The Ministry of Forests, BC, through the Resources Inventory Branch, has build a database consisting of data on about *80,000* trees from 16 species collected throughout British Columbia. The trees were measured in detail, and the diameters at several points along the tree were recorded. Destructive sampling was performed on each tree to determine the percentage of decay. External factors such as conks, scars, forks, frost cracks, etc., were recorded. A compilation of the database was published in 1976. In it, given the species, F.I.Z. (Forest Inventory Zone), age, DBH and risk group (determined by external indicators), the expected decay, waste and breakage factors can be read. The expected factors are averages for the given stand. The factors are then used to reduce gross volumes to realistic net volumes. The amount of deduction from these 3 factors is very significant; it often goes up to 20% or more, and rarely beneath 5%. Further description of this database, which in this thesis is refereed as the BCFS (British Columbia Forest Service) database, and its usage will follow.

Even though decay can account for a significant fraction of the trees usable volume, authors have ignored this factor in bucking algorithms. One reason for this might be that in order to include decay, a detailed analysis of the growth of decay on a tree by tree basis must be performed. To the best of this authors' knowledge, no such analysis has been performed so far. There are several papers that break down the average decay into a semi-continuous distribution (LeMay, Kozak and Marshall (1993), Hamilton and Brickell (1983)), but there is little work done on the morphology of decay. Another reason is that such algorithms could be hard to implement. Bucking with decay implies time in the case of manual bucking, and in the case of merchandisers, there would have to be a way to scan for decay, which is never easy.

In order to devise an optimal bucking policy, a decay model was developed in this thesis. This model estimates the expected length of the decay, as well as its physical shape.

This thesis is divided into two main parts: the bucking algorithm and the decay model. The main focus of the paper is on the bucking algorithm, leaving the decay model as mere support for it. Shall there be a better decay morphology analysis in the future, it should be easy to incorporate it to the bucking algorithm, providing a better set of optimal policies.

There are two main objectives in this thesis:

1. To evaluate the value of information that could be gathered about the decay. Three different bucking algorithms will be applied to the same set of sample trees. Each will have a different level of knowledge about the decay, and the unknown variables will be either assumed or calculated. The difference in solution value between the algorithms can be regarded as the added

value that a certain information would bring. These three algorithms will also be compared with common heuristic bucking techniques.

2. To find heuristic rules for longbutting. By analyzing the trends of the solutions, some heuristic might be found to serve as guides for simplified longbutting procedures.

Chapter 2, Current Practice, will provide an insight on the common logging practices and the standards, if any, stipulated by the Provincial Government of British Columbia. Chapter 3, Morphology, will explain the spread of decay into the tree and will analyze the physical shapes that such infection acquires. Chapter 4, Models, will propose three models, in addition to a common practices model, to solve the tree bucking problem. Chapter 5, Results, will analyze the results obtained from the models in Chapter 4.

# 2 CURRENT PRACTICE

This chapter will provide the background for understanding the ways decayed trees are handled and processed in common practice. Because these practices vary by province and company, an overview will be provided, with special emphasis on those stipulated by the Provincial Government of British Columbia (through the Ministry of Forests) and the industry standard (if any).

## 2.1 Scaling

The quantification of forest merchantable volumes is known as scaling. It serves the purpose of expressing measured quantities in known standards, so values can be assessed to timber stands in an objective manner. It starts with a competent person, a licensed scaler, inspecting the timber supply. Quantitative measures are taken to yield such numbers. These then have to be adjusted to account for such factors as decay, breakage or any other qualitative characteristics.

### 2.1.1 Decay Scaling

Decay is classified in scaling according to the way it occurs in the tree. Hence there is heart rot, sap rot, pocket rot, ring rot. These categories refer to the shape of the decay itself, and to some extent on its position on the stem. Although there are distinctions about how to handle the decay in terms of its cross-sectional shape, this work will concentrate on what is by far the most common type: the heart rot (a solid rot in the center of the log). Other forms of decay include:

- Ring rot: the decay has the cross-sectional shape of a ring with a center of sound wood from where lumber can be recovered.
- Sap rot: a pocket of decay concentrated in the sapwood.
- Cracks: includes checks (lengthwise cracks in the direction of the log radius) and shakes (lengthwise cracks along the rings). These cracks are often accompanied by decay.

As it will be explained in the next chapter, heart rot represents the most common case for high decay percentages.

When grading a log, the scaler must estimate the expected manufacturing losses that will occur due to the decay. Sound wood around the rot is lost for merchantable lumber because a sawyer must square the log around the rot. A trim allowance must be added to the defect dimension to compensate for this "squaring up" loss. The standard trim allowance is 2.0 cm (or 1 radius). This measure should be added on all sides of the decay, unless it is a sap decay or charred wood.

### 2.1.2 Log Scaling

Timber volumes are classified by grade within species to provide a more meaningful report for purchasers, sellers and managers. The lowest of these grades is the firmwood reject, by definition it means a log where:

(a) heart rot or a hole runs the whole length of the log being scaled and the residual collar of the firmwood constitutes less than 50 per cent of the gross scaled volume of the log,

(b) there is sap rot, charred wood, or catface and the residual firmwood is less than 10 cm in diameter at the butt end, or

(c) slabs or parts of slabs less than 10cm (5R) in thickness, or;

(d) there is rot and the net length estimated by the scaler is less than 1.2 m, and;

(e) includes the part of the log that is under 10cm (5R) in diameter.

(from Provincial Logging and Waste Measurement Procedures Manual)

A firmwood reject is considered not to be economically practical to manufacture, although this is closely related to the technology available, so one might find firmwood reject logs being brought in to be processed more often in the future.

The highest grade is called sawlog grade, it is defined as:

Logs and log segments 2.5 meters or more in length and 5R (10 cm) or more in small end diameter where the lumber quality and quantity meet or exceed the following criteria:

| | Length | Small End Diameter |
|---|---|---|
| Logs and Log Segments | 2.5m Interior<br>2.6m Coast | 5R |
| Slabs and Slab Segments | 2.5m Interior<br>2.6m Coast | 7.5R |
| Collars of Firmwood around Holes & Rot (if defect more than 20% of end diameter) | 2.5m | 7.5R |
| Collars of Firmwood around ring shake ring rot & pocket rot | 2.5m | 5R |
| Sound Hearts (includes charred wood & sap rot) | 2.5m | 5R |

Table 2-1: Minimum Gross Dimensions of Logs for Manufacture

(from Provincial Logging and Waste Measurement Procedures Manual)

There is another set of qualifications to be met by a Sawlog Grade that deals with knots in the wood. Nevertheless, since the main focus of this thesis is the handling of decay, those qualifications will be ignored.

A third grade of interest for this study is the Lumber Reject Grade. It is defined as:

Logs and slabs that are lower in grade than a sawlog but better than a firmwood reject.

(from Provincial Logging and Waste Measurement Procedures Manual)

There are 3 other grades for logs according to the Ministry of Forests of British Columbia: Dead/Dry Sawlogs, Dead/Dry Lumber Reject and Undersized Log Grade. However, these grades do not play any role in the longbutting or bucking procedures.

The sound wood that accompanies a firmwood reject is known as waste. This fiber, which because of its dimensions can not be turned into lumber, is often chipped and processed into pulp. Care must be taken to "shake off" the decayed portion so the chips are as clean as possible. This is often not a problem given that the decayed chips will practically pulverize and can be easily screened.

## 2.2 Longbutting

### 2.2.1 Definition

Longbutting is the first decision that a logger faces when a tree with decay has been felled. The decay treated here is commonly, but not exclusively, butt decay. It might very well be a middle decay that has expanded low enough to appear in the open face at the stump. The only consideration is that there is some decay visible in the exposed cut when the tree is felled.

Longbutting consist of removing a segment off the butt, with the purpose of handling the heavily decayed section independently. This decision is generally made at the roadside (in the field). It can be seen as a tradeoff between hauling decay to the mill site and leaving some valuable wood behind. This compromise will depend on the dimensions of the decayed section and the tree. Obviously, a section with a small decay in a large cross-section diameter is less likely to be longbutted than one with a large decay in a relatively small diameter. It should be clarified that the mentioned diameter is that measured at the same cross-section where the decay is exposed.

The relative dimensions of decay vs. diameter can be measured in two ways:

1. Rind: the rind is defined as the average thickness of clean wood outside the decayed section. Because one would like to have as much rind as possible, longbutting specifications in terms of rind will stipulate a minimum rind for the tree not to be longbutted. The logic behind this absolute measure is that it is relatively easy to define the rind dimensions necessary to recover lumber out of that segment. The problem is that it does not distinguish between a given rind from a small tree, in which case the decayed section is small, or a large tree, where the decayed section might be considerably larger. Therefore when dealing with rind specifications, it is possible to haul large volume segments with relatively poor recovery, especially on small logs. See Figure 2-1.
2. Relative measures: the ratio between decay and log diameter. In this case one would like to have this measure as low as possible, so the guidelines are specified in terms of a maximum ratio permitted so no longbutting is necessary. This relative measure will control better the recovery from a hauled segment.

### 2.2.2 Official Procedures

The Provincial Governments set the stipulations for a segment that can be left behind in terms of allowable rinds and diameter ratios. The government would like to see as much material as possible hauled (and thus paid for) out of the woods. Therefore, it declares the rind dimension as a maximum and the decay-diameter ratio as a minimum for a tree to be left behind; so any segment with a rind larger than the specification, or a diameter ratio smaller the specification, is to be hauled, or otherwise a penalty would apply. It should be noted that the capability of recovering lumber from a ring of wood depend on the diameter of this ring, as well as on its thickness (rind), so it is common to see these specifications as a function of the diameter. See Figure 2-1. The lumber industry can vary these specifications as long as they comply with the official ones; that is, they can set stricter rules, but never loosen them.

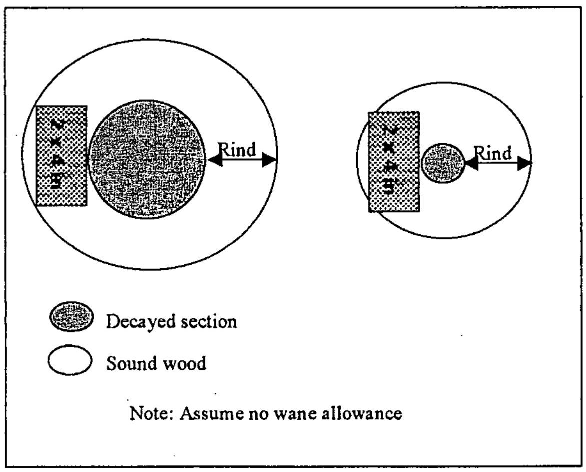



Figure 2-1: Importance of considering the tree diameter when applying the rind rule

The ways these rules are stipulated are as follows:

Where a hole or rot affecting the heartwood has a diameter which is 20% or less of the diameter of the log end in which it appears, trim allowance is added to the defect and the grade deduction is calculated.

Collar thickness is considered only when the diameter of the defect is greater than 20% of the diameter of the log end in which it appears. For logs where the collar thickness meets the minimum required to cut lumber the trim allowance is added and the grade deduction is calculated in the usual manner. Where the collar does not meet the minimum thickness required to produce lumber, the collar must be included as grade reduction.

(from Forest Service Scaling Manual)

The collar mentioned above corresponds to the 7.5R (15 cm) as indicated in Table 2-1. It should be clarified that the 15 cm is the width of a single side of the firmwood ring.

In British Columbia, once the harvest is completed, a Ministry of Forests residue surveyor cruises the field and determines the billing of logging residue and waste. The bases for this procedure are stipulated in the Provincial Logging Residue and Waste Measurement Procedures Manual.

Pieces showing rot or a hole running the whole length of the piece and with less than 50% firmwood are graded as a firmwood reject and are not required to be recorded.

If the long butt is more than 50% firmwood, the entire piece is classified and graded as avoidable sawlog waste.

If there is clear evidence that bucking was to raise the grade of the parent log from lumber reject to sawlog, then the long butt may be graded lumber reject.

The government stipulates that the longbutting should be done in 2 feet intervals. This 2-feet rule allows for frequent re-assessment of the decay, resulting in relatively low waste. However, the process is slow and thus costly for the logging companies.

The fines for lumber rejects are relatively low; for example, in 1996 the average stumpage price was \$ 30.00 /m$^3$, while the fines for lumber rejects were \$ 0.25 /m$^3$.

Although in practice it is difficult to assess a firmwood reject piece if the logger decides to haul it (perhaps to recover chips from the waste), for the purpose of this thesis it will be assumed that such piece would receive the same stumpage as a lumber reject.

## 2.3 Bucking

### 2.3.1 Woods Bucking

Even though the main purpose of bucking is to produce blocks of manufacturable length, there is another motive to buck. When transporting the logs from the woods to the mills, there is a maximum allowable length permitted for the trucks; so the load must be restricted in length to meet these specifications. This length depends on the nature of the road; a public road will usually have a lower maximum hauling length when compared to a private road. Logs must be bucked to meet these specifications.

Let us assume that there exists an optimum bucking pattern for a given log, that is, a set of lengths to be cut from that log. It is clear that a woods bucking cut must coincide with one of these cuts to maximize the value of the log. Obtaining an optimum bucking solution is not a trivial exercise; it often requires detailed scanning and many calculations. Equipment that performs such analysis is rarely found at roadside (where the woods-bucking is performed), so it is not uncommon for the actual woods-bucking cut to differ from the optimal set. The extent to which this lack of communication affects the value of a log is not easy to determine, and is an interesting field for further research.

The question remains as to what drives the woods bucking decision. Most of the time the operator follows predetermined rules, which together with experience yields a solution. Here is a compilation of some of these guidelines:

- Reduce decay: Longbutt
- Reduce sweep: Logs with high sweep are best cut into shorter segments.

- Avoid crooks: When possible, buck right before and after crooks.
- Meet hauling specifications.

Cases where logs might be directed to more than one mill can complicate the woods-bucking decision. When a company harvests a site to feed more than one mill (Lumber-Mill, Pulp-Mill or Veneer-Mill), a truckload will often be delivered to one given mill. Communication (log transportation) between mills might not exist. This means that the sort (haul) on which the woods-bucked segment is placed will determine its end use, and therefore its value. The operator must make the bucking decision with that in mind.

There are cases where all the bucking is made in the woods. These systems, called Cut-to-Length, have the advantage of easing the operations at the mill and provide the flexibility of being able to haul different sections of a log to different mills. The disadvantage is that the bucking decision is made, at least with the technology available today, without performing a complete scan of the log, thus optimization algorithms are not applicable. The systems base the decisions on heuristic bucking rules based on accessible information such as diameters and lengths.

### 2.3.2 Mill Bucking

Mill Bucking is the final transverse cutting before processing the logs in the mill. It might or might not be driven by an optimizer. When performing mill bucking, it might be desirable to obtain a certain mix of log lengths. To best target this mix, the bucking rules (heuristic or optimized) should be evaluated by applying them (through a simulation) to the overall stem supply, thus calculating the expected log length distribution. This constraint might also affect the woods-bucking solution.

## 2.4 The BCFS Database

As mentioned earlier, the Ministry of Forests, BC, through the Resources Inventory Branch, has compiled a comprehensive database of the forests of British Columbia. The database was obtained in continuous text form and simple text manipulating procedures were developed to extract the necessary information. Each tree in the sample was cut, approximately every 0.30m at the butt end at fixed intervals; every 0.30m for the first 1.20m, at 2.30m, 4.50m and thereafter the cutting intervals were not fixed. At each of these cuts the diameter of the tree and of the decay, if any, were measured. From this data it was possible to reconstruct trees and their correspondent decays, when applicable. When decay was observed in a given section but not in the next one, it was assumed that it spread halfway into these two sections. The trees were used to test the bucking algorithms developed in this thesis. For consistency reasons every tree was reconstructed up to a 3.0-inch diameter and its corresponding length to this point was rounded to the nearest even-foot. Even though each reconstructed tree will consist of a series of diameters at given intervals, when calculating the value of a single-log this segment will be assumed to have constant taper; such taper will be calculated using the large-end and small-end diameters of the segment, as well as its length. For this thesis, 4 of the main commercial species of British Columbia were used: Lodgepole Pine *(Pinus contorta Dougl.)*, Balsam Fir (*Abies Balsamea L. Mill.*), Spruce (*Picea A. Dietr.*), and Western Red Cedar (*Thuja plicata Donn*). Each reconstructed tree carried a butt decay, the reconstruction of decays will be discussed in Section 3-5.

# 3 DECAY MORPHOLOGY

## 3.1 Motivation

In order to devise an optimal bucking policy for trees with decay, one must be able to predict what the decay will look like. Once a tree is felled, and a transversal face of the tree is exposed, a decayed section might show in this face. In such case, the size of the decayed section should give a rough idea of the extent of expansion of the decay into the tree.

When someone quotes an expected percentage of decay to be found in a given stand, the figure represents the volumetric proportion, from all trees, that is expected to be rotten. The provincial government of British Columbia compiled a set of tables in 1976 where for each species, Forest Inventory Zone, age, DBH and risk group, the expected percentage of decay can be found. The total volume of the stand, called Gross Merchantable Volume, is adjusted by this factor and the price paid for the stand is also revised.

Nevertheless, it is debatable if a x% of decay results in a x% of reduction in production. In the case of sawlogs, it is easy to visualize that the extent to which the decay will affect the recovery will depend, among other parameters, on the shape of the decay. In a cross-section with decay the sawyer must work around the rotten portion, with straight sawlines, so a cross-section with a circular decay zone is expected to lose approximately $\frac{4 * \text{decay area}}{\pi}$ off its area. See Figure 3-1. Also, the number of pieces that will be touched by a rotten portion will depend on the shape it follows as it spreads into the tree. The lumber lengths are discrete quantities, so a piece with decay must be trimmed-back to the nearest nominal length, losing more, in length proportion (real losses) than in volumetric proportion (percent of the decay in the piece), see Figure 3-2.

Figure 3-3 illustrates the importance of assuming the right shape of the decay when estimating the lumber losses it will provoke: on top, decay with a parabolic cross-section causes more lumber losses than one with a triangular cross-section, as shown on the bottom. This concept is of great importance and will be discussed later in this chapter.

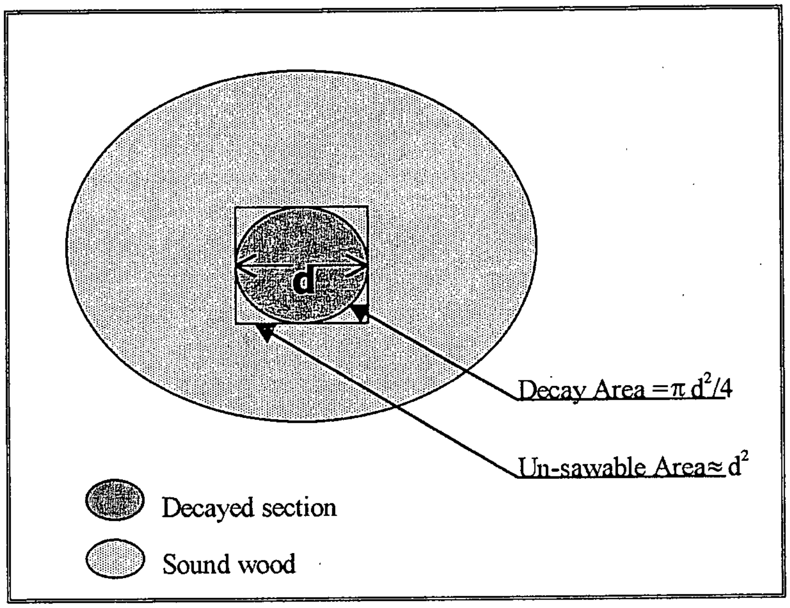
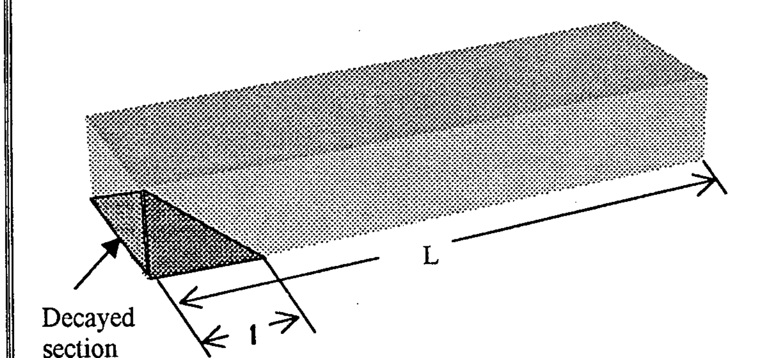



Figure 3-1: Real losses from sawing around the decayed area.




Longitudinal Proportion = 1 / L > Volumetric Proportion = 1 / 3L

Note: Assume triangular decay. The purpose is to show that the longitudinal proportion (real loses) will be larger than the volumetric (actual decay proportion). It should be clear that if one were to trim at nominal lengths the difference would be even larger.

Figure 3-2: Comparison of length and volumetric proportions.

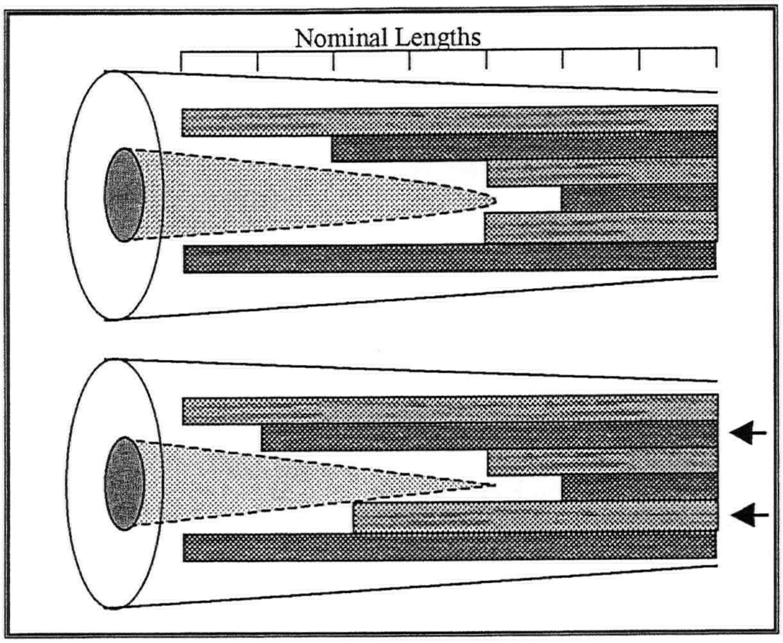



Figure 3-3: Difference in lumber losses when assuming a conic and a paraboloid decay.

## 3.2 Infection and Defense Mechanisms

Shingo (1979) explains the main mechanisms of decay growth. According to Shingo, the infected tree tries to encapsulate the decay. The tree is capable of building chemical barriers around the decay, which will prevent further expansion. There are 4 types of barriers:

1. Along the outmost layer of the sapwood. This layer will keep the decay from expanding to future rings, so if the tree is to survive the invasion, it will be able to grow healthy new layers. This is the most effective of all 4 barriers and the first one to develop.
2. Along the rays of the tree. This protection will prevent the decay to expand to a whole cross-section of the tree. Decayed wood is incapable of transporting nutrients, so if any one cross-section were completely infected throughout its sapwood, the tree would be unable of feeding above that section and would die. This is the second barrier to develop.

3. The third barrier is along the rings. Each ring in a tree consists of a *xylem* layer and another layer of protective tissue. The latest can form chemical compounds that can prevent the decay to expand to other rings.
4. The last barrier is formed by blocking the xylem of infected sections to prevent the decay from traveling up or down.

By these mechanisms the tree tries to encapsulate the decay in such a way that will prevent further invasion and will enable the tree to survive. It should be noted that the capability to develop each of these barriers could vary significantly from species to species, but all species are capable of developing these four mechanisms.

Another important factor in the spread of decay is the zone in which it develops. In a tree, the heartwood is dead tissue in the sense that it is incapable of transporting nutrients. Consisting of the oldest rings, this section contains high concentrations of chemicals that can prevent decay. Nevertheless, the tree is incapable of reacting in this zone; it cannot form any further defense mechanisms and must rely on the substances that it has deposited. So if the invading organism is capable of defeating the static barriers, it will spread with ease. Given that the heartwood is not involved in the nutrition of the tree, even if its is completely invaded, the tree can survive. For these two reasons, lack of resistance and no live threatening danger, if a tree has significant amounts of decay, chances are it will be in its center.

Within the sapwood, the tree can dynamically react to the spread of decay with the four mechanisms described above. The tissue itself does not contain the concentrated chemicals levels as the heartwood, but its reactivity allows the tree to fight better in this zone. This raises the important concept of point of entry. If the invading organism enters from a scar, broken branch or from any section of the tree where its first contact is with sapwood, the tree will have a good chance of containing it. If the entry point is a root, a deep frost crack, or any route that will give immediate access to the heartwood, the decay will be harder to contain.

We define butt decay as one that has entered from the lowest section of the tree, and expands mainly upward. Most butt decays are root entries and invade the heartwood. Middle decay by definition is one that has invaded from somewhere along the stem. The entry point is commonly a broken branch.

This thesis focuses on decay that is exposed when the tree is felled, so most of the time we will be talking about butt decays.

## 3.3 Variables

The key variables to be used throughout this thesis are defined below. For convenience, all variables related to the decay will be lower case and those related to the tree will be upper case.

| Decay Variables | | |
|---|---|---|
| Variable | Description | Units |
| $d_0$ | Diameter of the decay at the butt end of the tree | cm |
| $d_x$ | Diameter of the decay at a distance x from the butt of the tree | cm |
| $h_o$ | Total length of the decay, from the butt of the tree to the decay vertex | cm |
| $h_x$ | Remaining length of the decay measured from a distance x from the butt to the decay vertex | cm |

Table 3-1: Decay variables

| Tree Variables | | |
|---|---|---|
| Variable | Description | Units |
| $\{D_0, D_1, \ldots, D_T\}$ | Set of diameters of the tree | in |
| T | Total length of the tree | ft |

Table 3-2: Tree variables

Note that the variables $\{D_0, D_1, \ldots, D_T\}$ are sufficient to describe the shape of the tree. The initial set of diameters will be with those measured by the BCFS database. If a diameter is required at a point other than a measured section, it will be calculated by interpolating between its two adjacent sections assuming constant taper. In every case the trees have been assumed to have circular cross-sections.

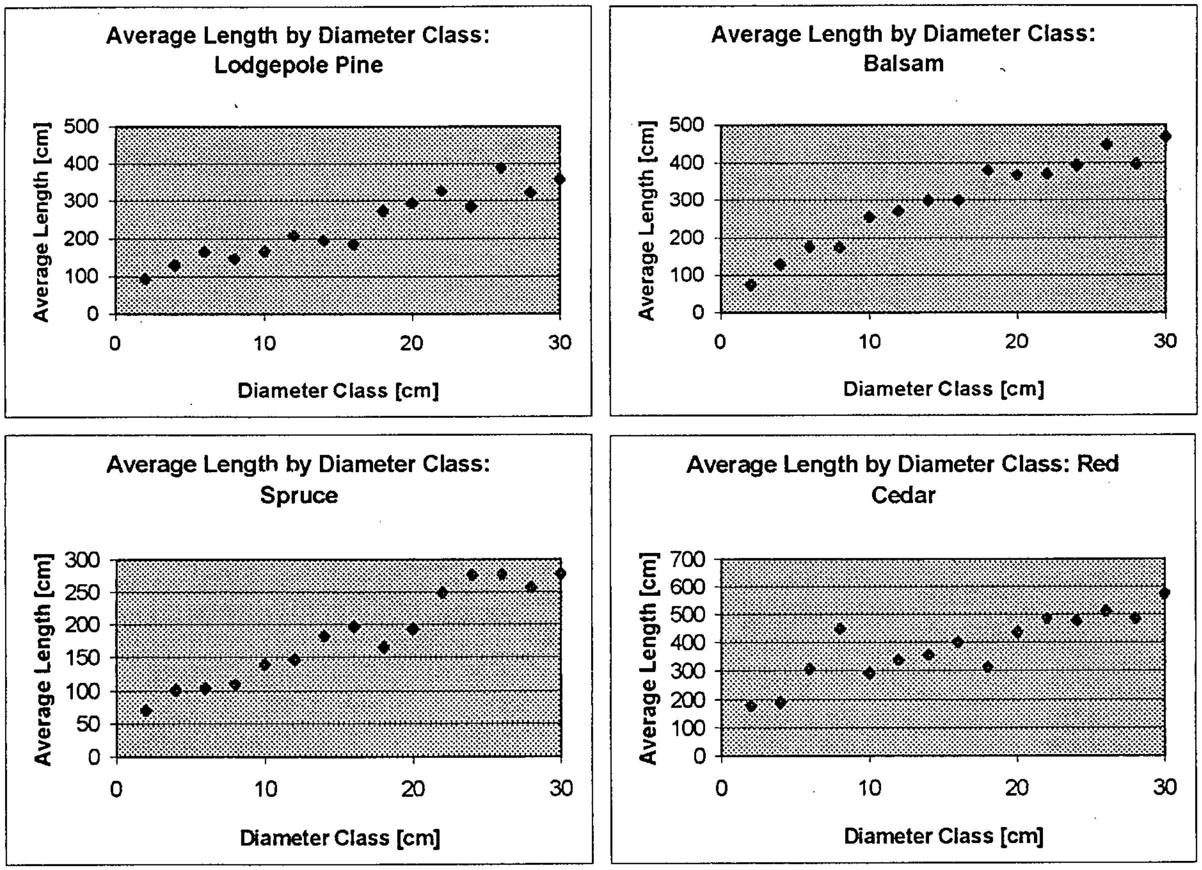
There will also be a set of variables related to the bucking itself; these will be defined when the algorithms are described. Notice that the decay variables are linked to a variable x measured from the butt end of the tree, while the tree variables are linked to a variable L measured from the top of the tree. The reason for the latter should be clear once the bucking algorithms are described. The reason for not measuring the decay using the same reference is simply that it expands in an upward direction (butt decays), so it is natural to describe decay using the butt end as reference.

The mixture of metric and imperial units in this thesis is due the nature of the variables. Tree variables are measured in imperial units because it is easier to relate them to lumber dimensions. Decay variables are measured in metric units to be consistent with the BCFS database.

### 3.4 Bucking Models

Looking ahead to the bucking problem, this thesis will analyze four different models. In all four models the diameter of the decay at the butt ($d_0$) is observed. Furthermore, the first model assumes that the length of the decay ($h_0$) is known; I will call this the *complete information model*. The second model will estimate the length of the decay ($h_0$) and will proceed as if this estimated length was correct, without updating the information after the bucking has commenced; we will call this the *estimation model*. The third model will estimate a probability distribution for the expected decay length ($h_0$); I will call this the *probability model*. The fourth model will simulate, as close as possible, the common practice of British Columbia logging companies, based on the procedures outlined by the Ministry of Forests; I will call this the *actual procedures model*. Detailed description of the models will follow.

Since two of the models use an estimate of the decay length, a procedure to predict this length must be developed. Common sense tells us that there should be a relation between the observed decay diameter (d) and its length (h); that is, h should be a function of d. It should be noted that when no explicit distinction is made in the decay variables d and h to identify a butt observation (subindex 0) or a mid-stem observation (subindex x) then these refer to either (butt or mid-stem). The d - h dependence should be closely linked to the way decay spreads in the tree (and of course the way the tree defends itself), so one can expect to see certain diameter-length patterns per species. In order to find a model for this relation the data was analyzed in a scatter plot, 1 for each species, of the diameter-length pairs. Such plots were too congested to devise any possible trends, so with the sole purpose of uncovering the nature of the diameter-length relation, if any, the decay diameters were grouped in 2-cm diameter classes (starting at 2.0 cm) and the average length for each group was calculated. These plots, which are shown below, uncover a definite diameter-length relation.




Figures 3-4 a,b,c,d: Average decay length by decay diameter class for Lodgepole Pine, Balsam, Spruce and Red Cedar

For a given species, suppose that the distribution of the length of the decay, h, for a given diameter d can be represented by the form:

$$h = Ad^{B}U \qquad \textbf{Equation 1}$$

where U is a random variable with a distribution which does not depend on d, and A and B are constants which also do not depend on d. Of course, A, B and U will be species dependent.

The most convenient distribution for U is lognormal. A brief description of the lognormal distribution can be found in Appendix 4. To fit the lognormal model to the data set, h was regressed on d in the equation

$$\ln(h) = \ln(A) + B\ln(d) + \ln(U) \qquad \textbf{Equation 2}$$

The units for d and h were centimeters. The regression provided the estimates for ln(A) and B. The following table shows the results of the regression, with the t-statistic of the coefficients.

| Species | ln(A) | B | t-stat ln(A) | t-stat B | $R^2$ |
|---|---|---|---|---|---|
| Lodgepole Pine | 3.524 | 0.596 | 39.86 | 15.89 | 0.211 |
| Balsam | 3.048 | 0.851 | 48.10 | 33.51 | 0.286 |
| Spruce | 2.991 | 0.727 | 65.83 | 44.34 | 0.405 |
| Red Cedar | 4.197 | 0.565 | 60.82 | 23.14 | 0.287 |

Table 3-3: Results of the regression

The high t-statistic shows that the coefficients have a significant role in the regression.

The error term of the regression is represented by ln(U). If U is assumed to have a lognormal distribution then ln(U) is expected to have a normal distribution. To learn if such assumption holds, the error term was plotted and compared to a normal distribution by performing a Chi-squared test. Devore (1982) gives an excellent description of this test.

To perform a Chi-squared test to test if a sample comes from a specified family of continuous distributions the data is divided into class intervals (cells). The number of data points that fall into each of these cells is compared to the number of data points that would fall into each cell for the theoretical distribution. The choice of cells is arbitrary; but to ensure that the chi-squared test is valid these have to be chosen independently of the sample observations. Once the cells are chosen, it is almost always quite difficult to estimate unspecified parameters (such as $\mu$

or $\sigma$ in the normal case) from the observed cell counts, so instead these are calculated from the full sample. For this test the probability space was divided into seven equiprobable class intervals. The seven class intervals for the standard normal distribution are $(-\infty, -1.07)$, $(-1.07, -0.57)$, $(-0.57, -0.18)$, $(-0.18, 0.18)$, $(0.18, 0.57)$, $(0.57, 1.07)$, $(1.07, \infty)$. In our case, the sample has mean zero but the standard deviation is different than one, so the endpoints of these class intervals must be multiplied by the standard deviation of the sample in question. The table with the standard deviation of ln(U) and sample count, for each species, will follow.

| Species | $\sigma$ | Sample size |
|---|---|---|
| Lodgepole Pine | 0.827 | 948 |
| Balsam | 0.874 | 1847 |
| Spruce | 0.620 | 2866 |
| Red Cedar | 0.602 | 1310 |

Table 3-4: Key statistics of ln(U)

The value of $\chi^2$ for the test is

$$\chi^2 = \sum_{all\ cells} \frac{(\text{observed} - \text{expected})^2}{\text{expected}}$$

where the observed is the number of data points that fall into each cell, and the expected, given that we use seven a priori equiprobable cells, is $\text{sample size}/7$.

The null hypothesis for the test is that the sample follows a normal distribution. The test will be as follows:

if $\chi^2 \geq \chi^2_{\alpha,k-1}$, reject $H_o$

if $\chi^2 \leq \chi^2_{\alpha,k-1-m}$, Do not reject $H_o$

if $\chi^2_{\alpha,K-1-m} < \chi^2 < \chi^2_{\alpha,k-1}$, withhold judgement

In our case k = 7 (number of cells), m = 2 (number of distributions under comparison), and $\alpha$ will be taken at 0.05.

The plots for the errors and the results of the chi-squared test will follow.

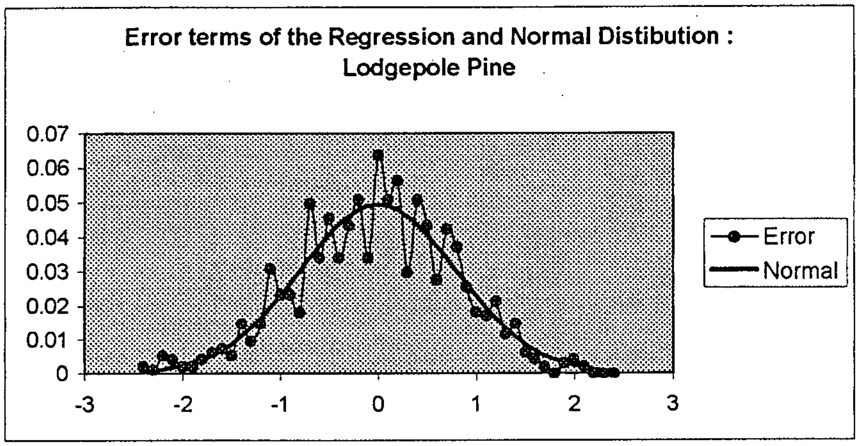



Figure 3-5a: Error terms of the Regression and fitted Normal Distribution for Lodgepole Pine

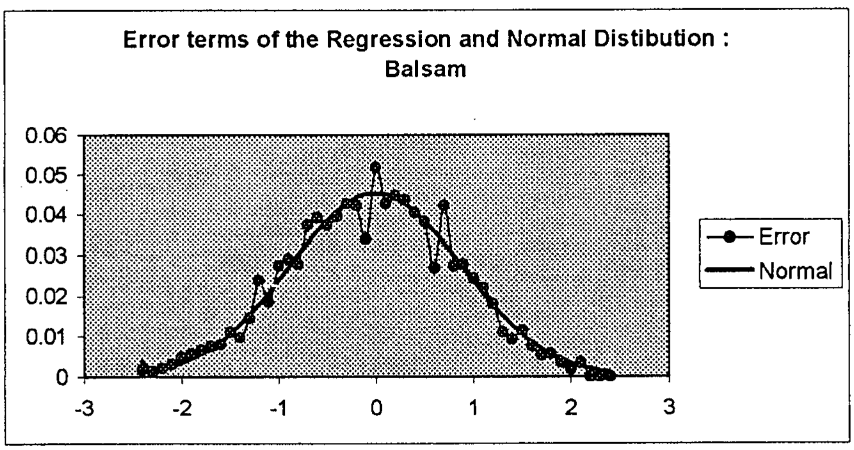



Figure 3-5b: Error terms of the Regression and fitted Normal Distribution for Balsam

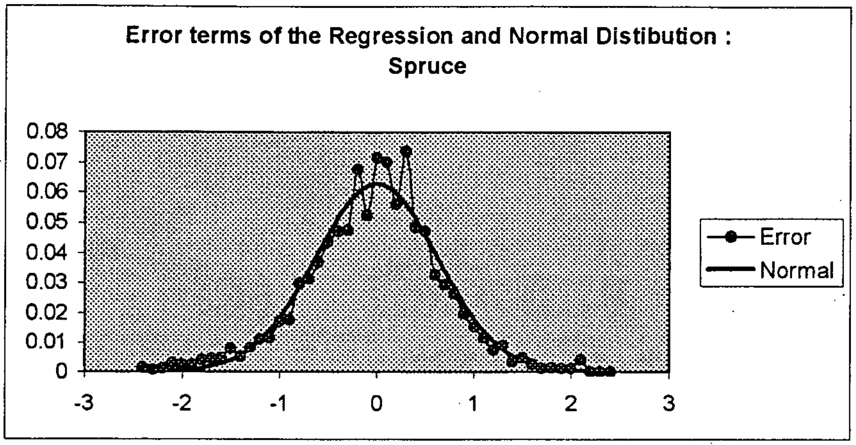



Figure 3-5c: Error terms of the Regression and fitted Normal Distribution for Spruce

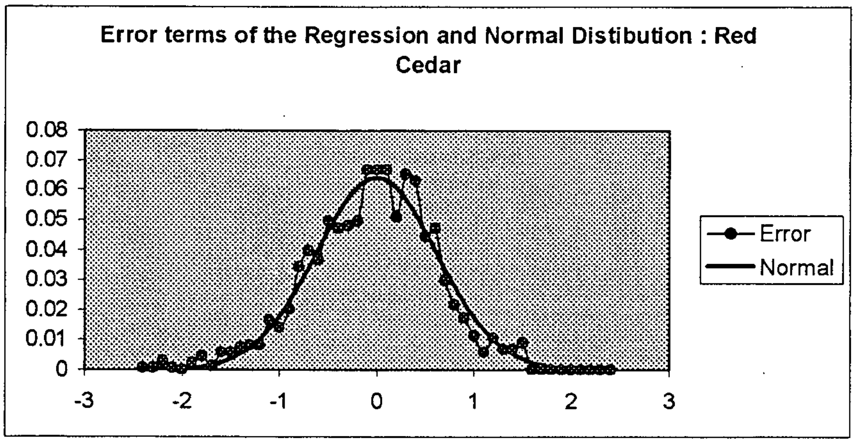



Figure 3-5d: Error terms of the Regression and fitted Normal Distribution for Red Cedar

| Species | Expected | $(-\infty, -1.07\sigma)$ | $(-1.07\sigma, -0.57\sigma)$ | $(-0.57\sigma, -0.18\sigma)$ | $(-0.18\sigma, 0.18\sigma)$ | $(0.18\sigma, 0.57\sigma)$ | $(0.57\sigma, 1.07\sigma)$ | $(1.07\sigma, \infty)$ |
|---|---|---|---|---|---|---|---|---|
| Lodgepole Pine | 135.4 | 135.0 | 122.0 | 127.0 | 144.0 | 152.0 | 145.0 | 123.0 |
| Balsam | 320.6 | 312.0 | 330.0 | 313.0 | 309.0 | 329.0 | 332.0 | 319.0 |
| Spruce | 409.4 | 428.0 | 370.0 | 381.0 | 388.0 | 437.0 | 439.0 | 423.0 |
| Red Cedar | 187.1 | 196.0 | 183.0 | 156.0 | 197.0 | 179.0 | 209.0 | 190.0 |

Table 3-5: Cell count for chi-squared test

The comparison values are:

$$\chi^2_{\alpha,k-1} = \chi^2_{0.05,6} = 12.592$$
$$\chi^2_{\alpha,\mathrm{k-1-m}} = \chi^2_{0.05,4} = 9.488$$

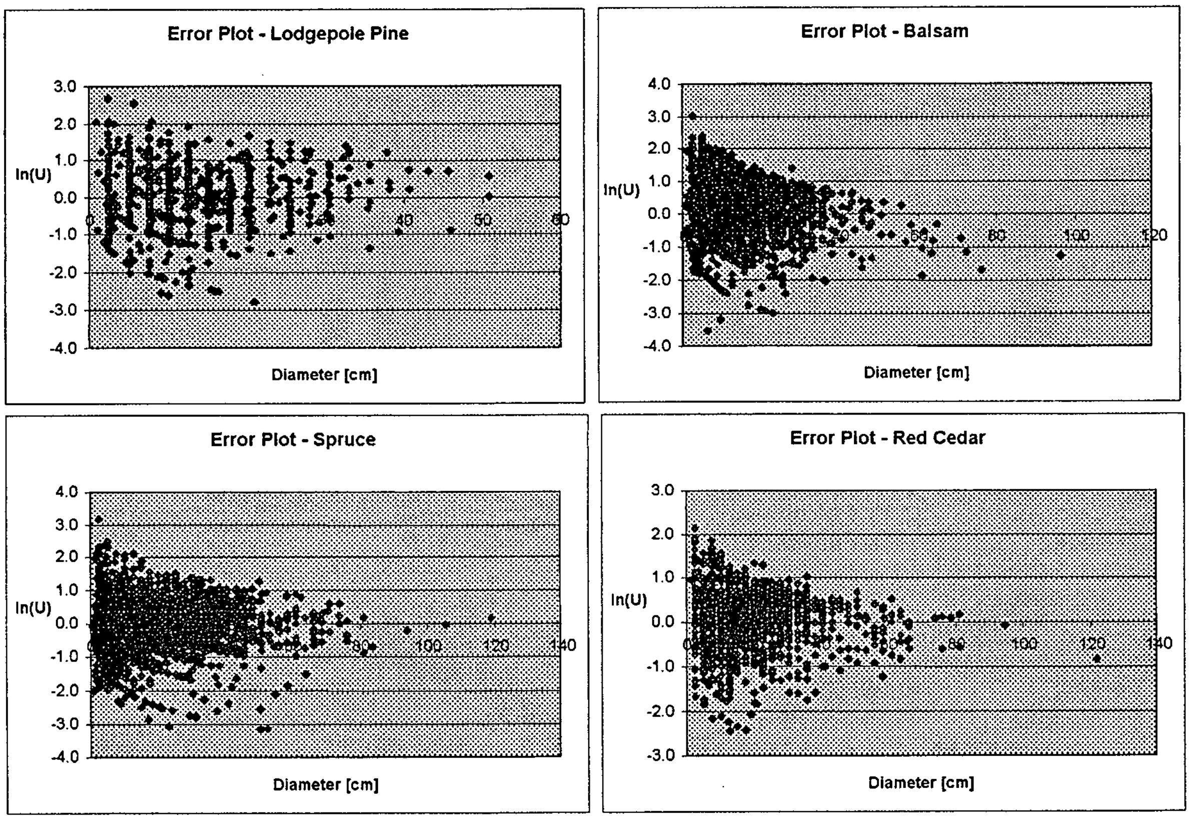
The results of the test are:

| Species | $\chi^2$ | Result |
|---|---|---|
| Lodgepole Pine | 6.245 | Do not reject $H_o$ |
| Balsam | 1.740 | Do not reject $H_o$ |
| Spruce | 12.177 | Withhold |
| Red Cedar | 8.736 | Do not reject $H_o$ |

Table 3-6: Chi-square test results

Given the values of t-statistic for both A and B we can conclude that there is strong evidence to infer that a relation of the form $\mathrm{h} = \mathrm{Ad}^{\mathrm{B}}U$ exists for all species. Furthermore, given the results of the chi-square test, U can be assumed to have a lognormal distribution for Lodgepole Pine, Balsam and Red Cedar. For simplicity reasons, and given that the chi-square test did not show completely negative results, Spruce will also be modeled by a lognormal distribution.

When plotting the errors of the regression as a function of the diameter of the decay, see Figures 3-6, these appeared to be heteroscedastic. This means that the variance of the errors is not independent to the diameter of the decay. The explanation for this is that a decay with a given diameter can only occur in a tree with at least that diameter, so a small decay diameter can occur in small and large trees while large decays will appear only in large trees. Given this, the expansion of a small diameter decay will be limited by the different ranges of tree diameters in which they present themselves, having more variability than large decay diameters which are limited by a more homogeneous range of diameters. This heteroscedasity will affect the models that use predictions and dispersion of decay (probabilistic models), by underestimating the variance of small diameter decays and overestimating the variance of large diameter decays. This variability did not interfere with the main objective of this thesis, for these models show clear improvements over the actual procedures model, as it will be shown in Chapter 5. Further discussion of how this variability affects the results will be presented in Chapter 5. The plots of the errors follow, notice the larger variability in the smaller diameters.




Figures 3-6 a,b,c,d: Error plots vs. decay diameter for Lodgepole Pine, Balsam, Spruce and Red Cedar

The expected value of a lognormal distribution, whose correspondent normal distribution has $\mu = 0$ and $\sigma > 0$, is greater than one[2]. This means that when calculating the expected length of a decay, given its diameter, the following equation will be used:

$$E[h|d] = Ad^B E[U]$$ **Equation 3**

This should not be a problem given the multiplicative nature of the model. This value will be the one used for the *estimation model.* The values for the mean and standard deviation of U, for each species, are shown in the following table.

| Species | $\mu$ | $\sigma$ |
|---|---|---|
| Lodgepole Pine | 1.381 | 1.261 |
| Balsam | 1.431 | 1.371 |
| Spruce | 1.279 | 1.116 |
| Red Cedar | 1.228 | 0.855 |

Table 3-7: Parameters for the lognormal distributions

Even though formulas which relate the mean and standard deviation of the lognormal distribution to its correspondent normal exist, the values in Table 3-7 were calculated directly from the sample by calculating the mean and standard deviation of the exponential of the error terms of the regression. Plots of the distribution of the exponential of the error terms of the regression and the assumed lognormal distribution for each species are shown below. These plots have the sole purpose of illustrating the distributions; there will be no statistical analysis on the

[2] Mathematically the expected value of a random variable U that follows a lognormal distribution, and whose correspondent normal distribution has parameters $\mu$ and $\sigma$ can be expressed as $E(U) = e^{\mu + \sigma^2/2}$. This is greater than one when $\mu + \sigma^2/2 > 0$. Since in our case $\mu \approx 0$ and $\sigma > 0$, E(U) > 1.

accuracy of the fit. The lognormal distributions have been scaled to match the count of the error terms.

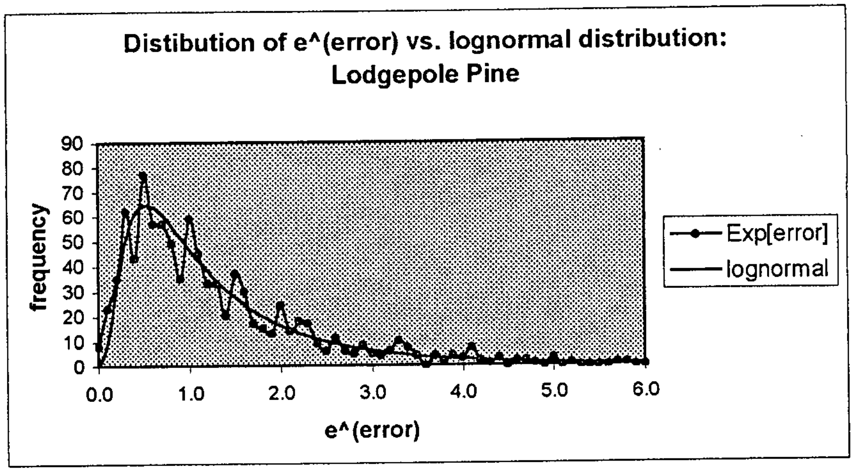



Figure 3-6a: Distribution of $e^{error}$ vs. lognormal distribution for Lodgepole Pine

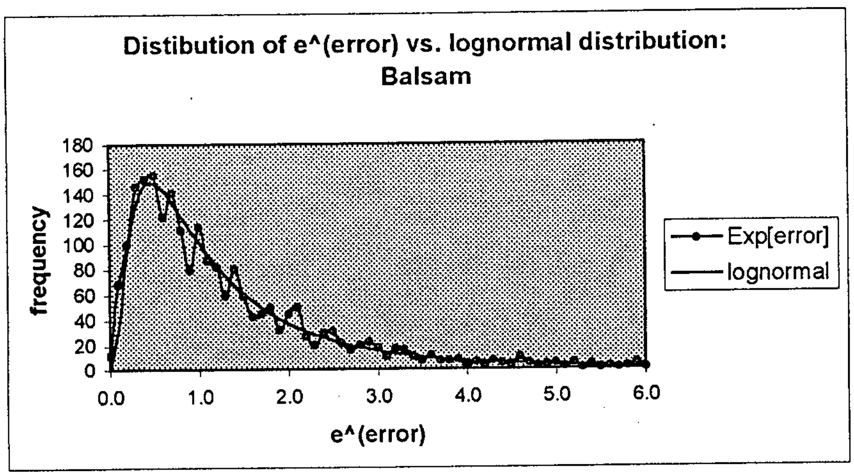



Figure 3-6b: Distribution of $e^{error}$ vs. lognormal distribution for Balsam

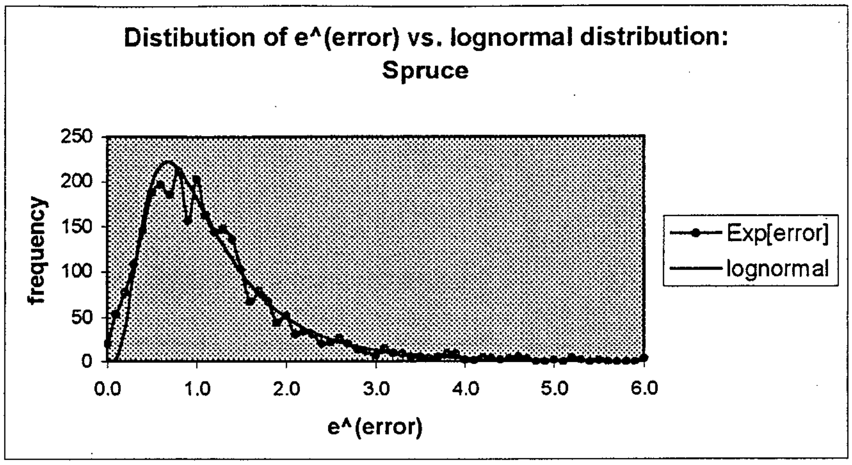



Figure 3-6c: Distribution of $e^{error}$ vs. lognormal distribution for Spruce

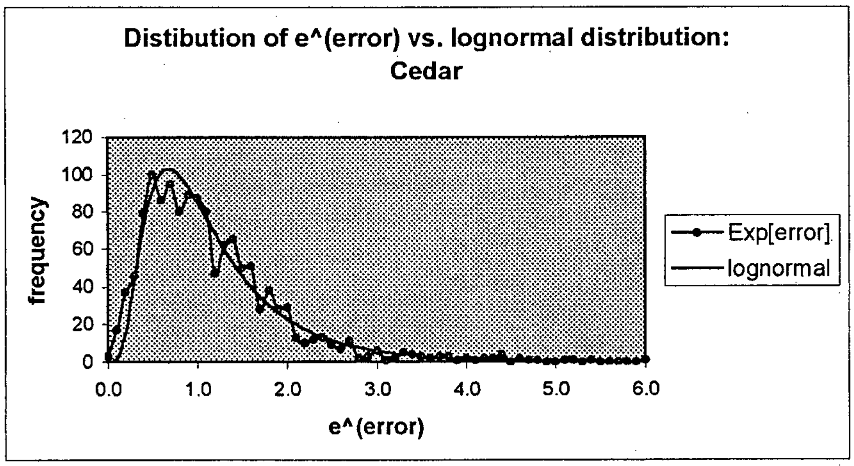



Figure 3-6d: Distribution of $e^{error}$ vs. lognormal distribution for Red Cedar

## 3.5 Morphology

As mentioned in Section 3.1, not only the length and diameter of the decay is necessary to calculate the value of a decayed log, but also its shape plays an important role. It is unrealistic to assume that all decay occurrences will follow the same geometric shape, but it should be clear that there is a need of finding an appropriate shape to define the contour of the decay with calculated dimensions d and h. In order to search for such a geometric shape, the BCFS database was used. For a given species, all the occurrences of butt decay were identified. The data obtained described the transversal dimensions of the decay from a given distance from the butt of the tree; this was enough information to rebuild the shape of the decay. For each species, about 2,000 butt decays were reconstructed. Plots for a few of these instances can be found in Appendix 1.

Even though common wisdom is that the shape of the decay follows the shape of a cone, the only author that explicitly mentions this is Basham (1991). After observing several decay shapes, as reconstructed from the BCFS database, the cone shape was questioned; nevertheless, for simplicity purposes, a well defined shape will be assumed throughout this thesis. A paraboloid (a parabola rotated around its axis) was considered. To determine which shape would best fit the data, a regression was performed for each reconstructed decay, in which the base diameter and the length of the decay were known (read from the database), and the intermediate points were estimated using the equations for the cone and the paraboloid.

Cone:

$$d_x = d_0 \left(1 - \frac{x}{h_0}\right) \qquad (x \leq h_0) \qquad \textbf{Equation 4}$$

Paraboloid:

$$d_x = d_0 \left(1 - \frac{x}{h_o}\right)^{1/2} \qquad (x \leq h_0) \qquad \textbf{Equation 5}$$

For each decay instance, the sum of square errors (sse) of the difference between the calculated $d_x$ and the real diameter was calculated at each point of the reconstructed decay. Given that the base of the decay ($d_0$) and its length ($h_0$) were known, the error for the first point (base) and last will be zero, and thus can be excluded from the sse. Then, for each instance, the sse as calculated assuming a cone was compared to that calculated assuming a paraboloid. The following table shows the fraction of instances where the paraboloid had a lower sse than the cone. Also the average sse for both cases is presented.

| Species | sse paraboloid < sse cone | mean sse cone | mean sse paraboloid |
|---|---|---|---|
| Lodgepole pine | 89.5% | 18.42 | 8.85 |
| Balsam | 84.9% | 18.61 | 9.34 |
| Spruce | 87.8% | 34.32 | 15.76 |
| Red Cedar | 85.5% | 21.92 | 11.97 |

Table 3-8: Sum of squared errors comparison for conic and paraboloid shapes of decay

Based on this data, we conclude that the paraboloid provides a better fit for the shape of decay originating from the butt. Thus, in the bucking models, a decay with visible diameter d and length h will be assumed to follow the shape of a paraboloid with those dimensions.

When reconstructing the decays from the BCFS database, the only information carried to the models was the base of the decay and its length. The assumption of the parabolic shape will hold throughout this thesis.

# 4 MODEL

## 4.1 Dynamic Programming

Dynamic programming is a computational technique used in problems where a series of interrelated decisions are taken. It gives a systematic procedure to determine the optimal combination of decisions to be applied. This is the basic technique used to solve the bucking problem. Given that this work is partially directed to persons who might not be familiar with dynamic programming, a description of how the technique works is presented.

There is no one standard formulation for a dynamic programming problem; the technique can be thought as a general approach for solving such interrelated-decision problems. The following are basic characteristics that distinguish problems that can be solved using dynamic programming:

1. The problem can be divided in *stages*. These stages have a clear order; often the sequence corresponds to time.
2. Each stage has a set of *states* associated with it. These are the different possible conditions in which the system can be found at each stage. The number of states may not be finite.
3. At each stage and state, it is possible to take one or more *action*. The effect of the action is to transform the system from its actual state to an associated state in the next stage.
4. The transition from state to another can be solely determined by the action (*deterministic* case), or there can be randomness in the outcome of an action (*probabilistic* case).
5. A *policy* is a sequence of actions prescribed for every state and every stage.
6. The transition from one stage to another can be accompanied by a *reward*, or by a *cost*. This reward/cost is associated with the decision and is the driver of the whole problem. That is, the

total collection of rewards or penalties is what the dynamic programming algorithm is trying to maximize/minimize.

7. The solution procedure is designed to find an *optimal policy* for the problem as a whole; that is, a set of decisions for each possible state at every stage.
8. For any policy knowing the state and stage enables one to determine what action to undertake. Knowledge of how the state was reached is of no value.
9. The solution procedure begins by finding the optimal policy for the last stage. Dynamic programming starts with a small portion of the original problem (last stage) and finds a solution for this simple problem. Then it gradually enlarges the problem to include another stage defining a new sub-problem that has already a solution for its final stage, inherited from the previous sub-problem.
10. Given the optimal policy for stage n, an optimal policy for stage n - 1 is devised. This technique, called *backward induction*, is followed until the first stage is reached. At that point an optimal set of decisions for each stage has been uncovered.

Dynamic programming problems can be divided in two cases, depending on the evolution of the system from one period to the next:

*Deterministic dynamic programming*: in these problems, the stage in the following period is determined only by the actual state and decision.

*Probabilistic dynamic programming*: in these problems the next stage is determined by the actual state, decision and a probability distribution. This distribution is usually known to the decision maker. A different set of probabilities can be associated with each possible decision. These problems are more computationally intensive than deterministic problems.

Dynamic programming problems can also be categorized by the number of periods (finite vs. infinite), time interval between decisions (continuous and discrete), and some other characteristics.

As stated above the objective of the model is to find the optimal set of policies for the whole problem. The definition of optimal will depend on the scope of the problem; it might be a problem where the total cost of going through the stages needs to be minimized, or one where the total of rewards collected at each stage should be maximized.

## 4.2 The Tree Bucking Problem

The problem of cutting a tree into logs can be solved with dynamic programming. To do this, the stages, states, actions, rewards and state transitions should be identified. First, these variables will be defined for a simplified version of the problem, as first presented by Pnevmaticos and Mann (1972). Later, new descriptions of these variables will be incorporated yielding a more complete version.

*Stages*: the points where cuts can be made on the tree. We pass from one stage to the next when a cut is performed. The number of stages plays an important role in the accuracy of the solution and the computational effort needed. A tradeoff occurs between these two factors, and a compromise on the number of stages should be reached before solving the problem. For example, a model with possible cutting points every 10 feet will have little flexibility for finding combinations of lengths and thus might yield a poor solution; a model with possible cutting points every tenth of an inch will explore an immense set of solutions, many of which will have a relatively similar value and are not practical. The computational effort is a linear function of the number of cutting points. To find the right compromise between performance and time, one must keep in mind the context for which the problem is being solved; in an on-line system there will be little time to solve the problem, on the other hand a model can be built to construct sets of tables for bucking policies, in this case the model can be run off-line and more time would be available.

For the purpose of this thesis, the tree was divided into 2-foot segments; each of these being a possible cutting point. Because the length of the tree was rounded to the nearest even-foot (as explained in Chapter 2), the stages will cover the whole length of the tree, without any leftover segment after the last stage.

*States*: A state is defined as a set of physical characteristics that describe the portion of the tree that is yet to be cut. These variables are length, sweep and other qualitative characteristics. These are usually measurable and known to the decision maker. The extent to which meaningful variables are included or excluded from the model presents again a tradeoff between precision and effort. The main contribution of this thesis is the inclusion of decay to the state description. For this thesis, trees will be assumed to have no sweep, so the state will be entirely defined by the length of the portion of the tree to be cut, and in some cases by the diameter of decay present.

*Action*: the action consists of the decision of where to perform the next cut. Such cut will produce two logs, one of which can still be cut into subsequent segments. As explained above, this last log is the new stage of the system. The set of possible lengths must be finite. Again, the allowable set of lengths will determine the accuracy of the model. Discussion on this issue will follow.

*Rewards*: the typical tree-bucking problem collects a reward every time it cuts a segment. The reward is equal to the value of the cut segment. The problem as a whole can be seen as the maximization of the value of the whole tree by finding the optimal set of lengths to be cut from it. As explained earlier, in the case of sawlogs, the valuation is not simple. Once again, discussion on the evaluation of the rewards will follow. Given that the value of a sawlog is not a continuous function of its physical characteristics, it is not possible to determine the value of a segment by applying formulas based on these characteristics. Either a table is searched to find an approximate value, or a simulation-based procedure is performed to find an expected value for the piece. The table search has several disadvantages: it depends on lumber and byproducts market prices and on sawmill capabilities. The number of entries in these tables will depend on the level of detail of its variables. For example, a table with diameters from 6 to 40 inches (entries every 0.5 inch), lengths from 8 to 24 feet (entries every 2 feet), 5 levels of sweep and 5 levels of taper, would have over 30,000 entries. To construct a complete set of these tables is a considerable task, even if done off-line, and a new set would be needed every time market conditions change. The evaluation of segments throughout this thesis was done by a computer program developed specifically for this task.

*State transitions*: in the simplest case, when the state transitions are deterministic, the next state can always be predetermined because the properties of the tree can be observed for the whole tree.

### 4.2.1 The Simple Case: Bucking a tree without decay

The equations for a tree with deterministic transitions and no decay will follow. The following figure describes the quantities needed.

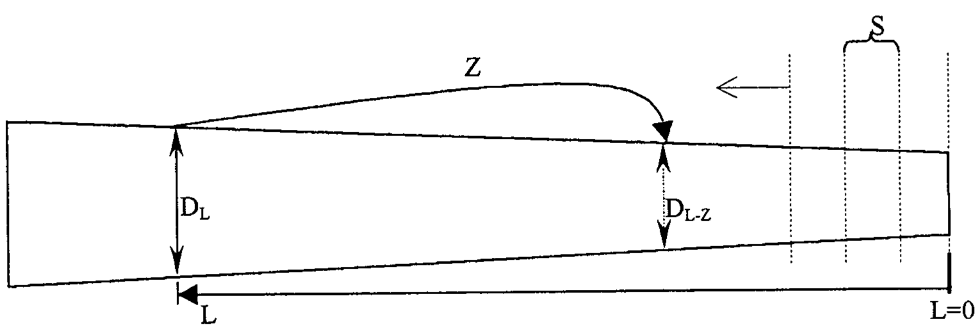



Figure 4-1: Scheme of a tree without decay

Given a tree with known diameters $\{D_0, D_1, \ldots, D_T\}$ and length T:

$$V(L) = \max_{Z = S, 2S, \ldots, L} \{ R(L, Z) + V(L - Z) \} \qquad \textbf{Equation 6}$$

$$V(0) = 0$$

Where:

L is the distance from the top of the tree. Notice that L is divided into segments of length S.

Z is the length of cut, from L and in direction to the top of the tree.

V(L) is the value of a segment with and length L and diameters $\{D_0, D_1, \ldots, D_L\}$. This segment might or might not be a single log.

R( L, Z ) is the reward of a segment of length Z, from a distance L from the top.

When calculating the reward of a segment, the taper has been defined as a constant, that is, a segment to be evaluated will be assumed to be a truncated cone with large-end and small-end diameters $D_L$ and $D_{L-Z}$.

4.2.2 The Backward Induction Algorithm:

Notice that the value of a segment where L=0 is zero. This is the starting point of the backward induction algorithm. In the next period, increase L by S and calculate the optimal policy for this stage. Here Z could only take the value of S, this would be the optimal policy and we would move back to 2S from the end of the tree. Now Z has 2 possible actions: Z=S and Z=2S. In the first case the total value of the segment (the last 2S of the tree) is the sum of 2 independent S's. In the second case the total value of the segment would be that of one unique 2S piece. Whichever results to be the optimal action is recorded and the algorithm moves back to 3S.

Equation 6 can be interpreted as follows: the value of a segment with a set of diameters $\{D_0, D_1, \ldots, D_L\}$ and length L equals the sum of the reward obtained from cutting a segment of length Z and the value of the remaining log, with length L – Z. The first reward is calculated through the procedure described in Appendix 2, while the later value is calculated at an earlier stage of the backward induction algorithm. Notice that the value of the second segment is zero when L = Z.

## 4.3 Models with Decay

This section presents new algorithms for solving the decayed-tree bucking problem. These models differ from the simple model without decay in that it has a more complex state definition. In addition to the variables declared above as determinant for the description of a state, decay will now be considered. At each stage, a visible decay might appear on the exposed cross-section, its diameter will be recorded and utilized as an additional state variable. Note that we are only concerned with the decay spreading from the exposed section to the top of the tree. This will comply with the memory-less property of the dynamic programming models; the actions depend merely on the actual conditions of the system, so if a decayed section is observed at a cross-section, it will not matter if there is any other decay exposed anywhere else.

As mentioned in the introduction, the main purpose of this work is to evaluate the information that can be gathered about the decay before implementing the bucking algorithm. The diameter of decay at the butt, and then at each exposed section after cutting off a log, will always be known. As mentioned in Chapter 3, the different levels of information will be related to the way the decay length is calculated. Hereinafter, the decay shape is assumed to be parabolic.

### 4.3.1 Complete Information Model

This model assumes that the actual length of the decay is known. Physically this can be determined by inserting a probe into the decay. This model requires intensive data collection and relatively simple calculation procedures for the bucking, because there is no decay estimation and the model is deterministic. See Figure 4-2.

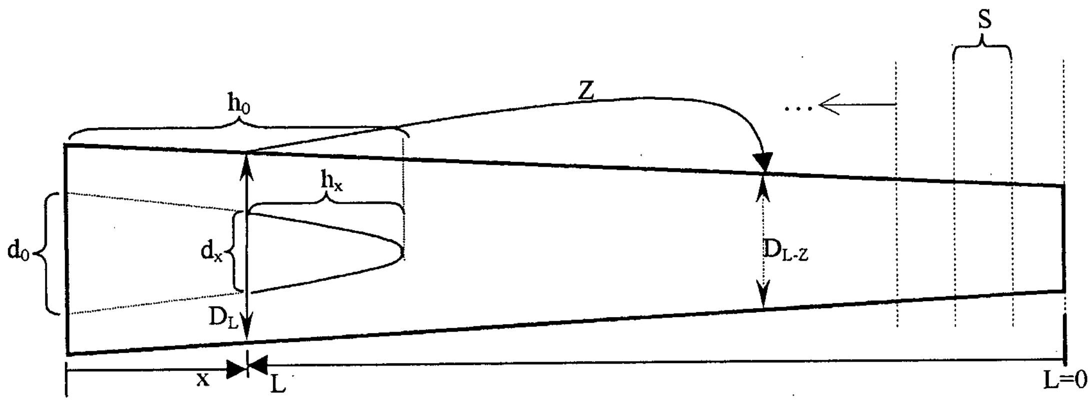



Figure 4-2: Scheme of a tree with decay

The equations for this model are the same as Equation 6, except that the initial parameters include the decay diameter $d_0$ and decay length $h_o$ apart from the diameters and length of the tree.

The decay parameters will not be explicitly defined in the dynamic equation. This is because given the initial parameters of the tree (T, $\{D_0, D_1, \ldots, D_T\}$, $d_0$, and $h_0$), and the variables involved in the dynamics of the backward induction (L and Z), $d_x$ and $h_x$ can be calculated at any point. Note that $L + x = T$. Namely, $d_{x+Z}$ can be estimated from $h_x$, $d_x$ and Z by the parabolid equation. Mathematically,

$$d_{x+Z} = \begin{cases} d_x\sqrt{1-\dfrac{Z}{h_x}} & h_x \geq Z \\ 0 & \text{Otherwise} \end{cases} \qquad \textbf{Equation 7}$$

In this case, the reward of the segment of length Z will account for the decay encountered in this segment.

It must be clear that the result of this, and the following models, is a set of lengths to be cut from the tree. Once these lengths are determined, the actual tree is bucked accordingly and each segment is evaluated by the procedure described in Appendix 2. In the case of the complete information model, given that all parameters are known, the decay values used by the algorithm will coincide with those observed once the tree is bucked. That might not be the case for the estimation or the probabilistic models. In these, the algorithm might be performed assuming a certain decay length that might not to be right; so when the bucking is performed, and the real decay parameters uncovered, the value of a segment can differ from the predicted one.

### 4.3.2 Estimation Model

The length of decay will be assumed to be equal to the mean decay given by Equation 3 of Chapter 3:

$$E[h|d] = Ad^{B}E[U]$$

This length will assumed to be correct and no updating will be done once the bucking has commenced. This model has simple data collection and simple calculation procedures, with an estimation stage and a deterministic algorithm. Apart from the tree variables, only the decay diameter at the butt ($d_0$) is required. However, the performance of this model will depend strongly on how well one can estimate the decay length. The equations for this model are the same as for the previous model but with a calculated $\tilde{h}_0$ instead of a given $h_0$, calculated by Equation 3. For this model not only the tree length T, diameters D, but also the value of A and B (from Chapter 3), and $\mu$ (U) will be needed as initial parameters.

### 4.3.3 Probability Model

The length of decay, and its distribution, will be calculated through the procedure described in Chapter 3. This model has simple data collection (same as previous model) and fairly complex calculation procedures. The diagram is basically the same as Figure 4-2. The equations differ in that there is now a probabilistic element representing the distribution of the length of the decay given an observed decay diameter. The dynamics of the algorithm are governed by this probability, so solutions are somehow weighted to obtain one that best solves the uncertain problem.

Given a tree with diameters D, decay parameters A, B, and $\mu$ and $\sigma$ of the lognormal distribution, as described in Chapter 3, and initial decay diameter and length $d_o$ and $h_0$:

$$V(L,d_x)=\max_{Z=S,2S,\ldots,L}\left\{\sum_{h_x=0}^{h_x=L}\left[\ R(L,Z,d_x,h_x)+V(L-Z,d_{x+Z})\ \right]P\left(h_x \mid d_x\right)\right\} \qquad \textbf{Equation 8}$$

$$V(0;)=0$$

There has been no attempt to nullify the effect of the heteroscedascity, but to do so one would have to add another dimension to the d – h relation. Given that Equation 8 already accounts for such relation, the addition would only mean a change in the probability function, but not on the structure of the equation itself.

It must be mentioned that the probabilistic model is not entirely consistent. The model used in the probabilistic case is not entirely consistent with the parabolic shape introduced in

Chapter 3. Note that the equation recalculates the parabolic shape at each stage where $d_x$ is greater than zero, yielding a shape that can be thought as a succession of parabolic segments instead of a single parabola. For example, a decay with diameter $d_0$ with expected distribution of lengths $h_0$ as described by Equation 1 ($h = Ad^B U$), will have an expected diameter $d_x$ at x from $d_0$ calculated from the parabolic equation $d_x = d_0 (1 - \frac{x}{h_o})^{1/2}$ . This $d_x$ will have its own corresponding distribution of $h_x$, again described by Equation 1. The distribution of $h_x$ should coincide with the distribution of $(h_0-x)$, but this is not the case. Nevertheless, the model presented in this section show clear improvements over the actual procedures model, as it will be shown in Chapter 5; this should be enough merit to prove its performance.

As explained before, the value of $d_{x+z}$ as predicted by the paraboloid equation will be assumed by

$$d_{x+Z} = \begin{cases} d_X\sqrt{1-\dfrac{Z}{h_X}} & h_X \geq Z \\ 0 & \text{Otherwise} \end{cases}$$

Equation 8 will span all the possible decay lengths from zero up to the remaining length L. For simplicity purposes the spanning will be done in discrete steps, instead of through a continuous method (integral). The step of this summation was set so that each interval would cover a probability of 0.10. This means that there will be 10 steps for the summation. Let these steps be identified as $k_i$ where i = 1 to 10, then the expected decay length ($h_x$) associated with each step is:

$h_x(k_i) = \text{Lognormal}^{-1}({}^{(i-0.5)}/_{10}, \mu, \sigma) * E[\text{length of decay}]$

Where,

$Lognormal^{-1}$ is the inverse of the cumulative lognormal probability density function

$\mu$, $\sigma$ are the parameters of the lognormal distribution as defined in Chapter 3, and

E[Length of decay] = $Ad_x^B$ E[U]

The i – 0.5 will make the length $h_x(k_I)$ correspond to that calculated at the midpoint of each interval (i, i+1). For example, let the E[length of decay]=1 the fourth step of the summation (k=4) will assume a decay length $h_x$ equal to $Lognormal^{-1}(0.35, \mu, \sigma)$.

### 4.3.4 Actual Procedures Model

In this case, the common practice of stem bucking was simulated. First, longbutting was performed according to the Ministry of Forest standards; there was no questioning whether or not to longbutt, if the observed parameters allowed it, the longbutting was performed. The longbutting step length was 2 feet. Then, the remaining length to a 10cm top was calculated and the bucking solution was found in a table. Such table can be found in Appendix 3.

## 4.4 Model Evaluation

The four models differ in data requirements and computational effort. The following table summarizes these characteristics:

| Model | Data Requirements | Computational Effort |
|---|---|---|
| Complete Information | High | Medium |
| Estimation | Low | Medium |
| Probabilistic | Low | High |
| Actual Procedures | Low | Low |

Table 4-1: Model evaluation

# 5 RESULTS

To analyze the performance of the four models, a test on one hundred stems in each of four different species was performed. The species were Lodegepole Pine, Balsam Fir, Spruce and Red Cedar. Stems with butt decay were randomly selected from the BCFS database. The stems were reconstructed down to a 3-inch top and the details of their correspondent decay (diameter at base and length) were also recorded. The stems were then longbutted and bucked using each of the four models. For each resulting segment, there was the choice of leaving it behind (in the forest), or hauling it into the mill; the appropriate stumpage and hauling costs were assumed for each case. Those logs that made it to the mill were simulated to be sawn in a mill configured by a Canter Twin, an Edger and a Trimmer. The details of the breakdown, as well as the stumpage, hauling and bucking costs, together with the lumber and chip prices used for the test, can be found in Appendix 2. Hauling was only permitted for segments of at least four feet in length. Segments left behind that had a large-end diameter smaller than 10 cm were not accounted for stumpage purposes. Those segments left behind were evaluated according to the Provincial Logging and Waste Procedures Manual. In the case of the actual procedures model, where the longbutting was performed following the same manual guidelines, the evaluation was simple. In the case of the three other models, the 2-feet rule was modified with the following criteria: if a longbutted segment measured more than 2 feet, then it was not accounted (for stumpage purposes) if it had less than 50% sound fibre, or if the rind rule applied in both ends of the segment. In these three models, if the longbutted segment measured 2 feet, or less, and provided that the longbutting specifications were met, then it was not accounted for stumpage purposes.

Given that the primary breakdown system assumed (Canter Twin) is normally used to process small to medium logs, care was taken to choose logs with a butt diameter between 8.0

and 13.0 inches; furthermore, for each butt diameter inch interval (8.0 – 9.0 in, 9.0 – 10.0 in, etc.) exactly 20 logs were selected.

The evaluation of the logs was performed by a Visual Basic application written specifically for this thesis. The program communicated with Microsoft Excel which was used as front-end.

Because the processing of trees is a practice that involves different players with different interests, the evaluation of the models is not a simple task. The most obvious objective is to maximize the revenue of the operations, that is to maximize the value of lumber and chips,minus the harvesting, hauling and stumpage costs. This criteria is of interest to the companies exploiting the resources. On the other hand, several parties, like the Provincial Government or environmental groups, would like to see as little waste as possible. It should be noted that even though the reduction of waste was analyzed throughout the models, the main objective of this thesis was to maximize the revenues of the operations.

A table summarizing the dimensions of each tree, and its correspondent decay, used for this test can be found in Appendix 5.

## 5.1 Comparison of Value

The results of the runs have been summarized in the following tables. Here, the average value per log in each of the five diameter classes studied for each species is presented for each model. The value of a segment equals the revenues from lumber and chips minus the stumpage, transport and cutting costs. To provide an insight on where the gains or losses come from, similar tables for all the components of income, except for cutting cost which is practically irrelevant, are presented. All prices are in Canadian Dollars.

| Total Value (Average per Log) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Complete Information | 29.11 | 24.31 | 24.08 | 11.09 |
| Probabilistic | 28.21 | 23.39 | 23.27 | 10.13 |
| Estimation | 27.18 | 22.36 | 22.88 | 8.80 |
| Actual Procedures | 26.52 | 21.67 | 22.04 | 8.93 |

Table 5-1: Average total value per log

| Lumber Value (Average per Log) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Complete Information | 39.66 | 33.38 | 33.27 | 16.40 |
| Probabilistic | 39.04 | 32.84 | 32.89 | 16.20 |
| Estimation | 37.81 | 31.52 | 32.13 | 14.35 |
| Actual Procedures | 37.11 | 30.98 | 31.23 | 14.75 |

Table 5-2: Average value of lumber per log

| Chip Value (Average per Log) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Complete Information | 8.55 | 7.90 | 7.52 | 6.33 |
| Probabilistic | 8.51 | 7.52 | 7.82 | 6.68 |
| Estimation | 8.71 | 8.15 | 7.73 | 6.72 |
| Actual Procedures | 8.21 | 7.79 | 7.20 | 5.77 |

Table 5-3: Average value of chips per log

| Stumpage Cost (Average per Log) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Complete Information | 11.69 | 10.36 | 10.24 | 6.71 |
| Probabilistic | 12.01 | 10.44 | 10.84 | 7.73 |
| Estimation | 11.95 | 10.64 | 10.44 | 7.28 |
| Actual Procedures | 11.69 | 10.57 | 10.05 | 6.96 |

Table 5-4: Average stumpage cost per log

| Transport Cost (Average per Log) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Complete Information | 6.28 | 5.60 | 5.42 | 4.01 |
| Probabilistic | 6.20 | 5.34 | 5.59 | 4.18 |
| Estimation | 6.22 | 5.61 | 5.48 | 4.08 |
| Actual Procedures | 5.95 | 5.43 | 5.11 | 3.59 |

Table 5-5: Average transport cost per log

The results will be analyzed in two ways. First, the results of the actual, probabilistic and estimation models will be compared to the complete information model. These results will provide an insight on what percentage of the potential maximum revenue can be obtained by using non-optimum models. The second analysis will compare the results of the probabilistic, estimation and complete information models to those of the actual procedures model. The results will show how much the revenue can be increased by using models that use more complex bucking algorithms. In essence, both analyses are equivalent, but each provides a different insight.

| Total Value (as % of Complete Information) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Probabilistic | 96.9% | 96.2% | 96.7% | 91.3% |
| Estimation | 93.4% | 92.0% | 95.0% | 79.3% |
| Actual Procedures | 91.1% | 89.1% | 91.5% | 80.5% |

Table 5-6: Average total value per log as percentage of Complete Information model

| Lumber Value (as % of Complete Information) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Probabilistic | 98.4% | 98.4% | 98.8% | 98.8% |
| Estimation | 95.3% | 94.4% | 96.6% | 87.5% |
| Actual Procedures | 93.6% | 92.8% | 93.9% | 90.0% |

Table 5-7: Average lumber value per log as percentage of Complete Information model

| Chip Value (as % of Complete Information) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Probabilistic | 99.6% | 95.1% | 104.0% | 105.6% |
| Estimation | 101.9% | 103.2% | 102.8% | 106.1% |
| Actual Procedures | 96.1% | 98.6% | 95.7% | 91.2% |

Table 5-8: Average chip value per log as percentage of Complete Information model

| Stumpage Cost (as % of Complete Information) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Probabilistic | 102.7% | 100.8% | 105.8% | 115.1% |
| Estimation | 102.2% | 102.7% | 101.9% | 108.4% |
| Actual Procedures | 100.0% | 102.1% | 98.1% | 103.6% |

Table 5-9: Average stumpage cost per log as percentage of Complete Information model

| Transport Cost (as % of Complete Information) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Probabilistic | 98.7% | 95.3% | 103.2% | 104.3% |
| Estimation | 99.0% | 100.3% | 101.0% | 101.6% |
| Actual Procedures | 94.8% | 97.1% | 94.3% | 89.6% |

Table 5-10: Average transport cost per log as percentage of Complete Information model

Comparing to the actual procedures model:

| Total Value (as % of Actual Procedures) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Complete Information | 109.7% | 112.2% | 109.2% | 124.3% |
| Probabilistic | 106.4% | 108.0% | 105.6% | 113.5% |
| Estimation | 102.5% | 103.2% | 103.8% | 98.6% |

Table 5-11: Average total value per log as percentage of Actual Procedures model

| Lumber Value (as % of Actual Procedures) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Complete Information | 106.9% | 107.8% | 106.5% | 111.2% |
| Probabilistic | 105.2% | 106.0% | 105.3% | 109.8% |
| Estimation | 101.9% | 101.8% | 102.9% | 97.3% |

Table 5-12: Average lumber value per log as percentage of Actual Procedures model

| Chip Value (as % of Actual Procedures) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Complete Information | 104.1% | 101.4% | 104.5% | 109.7% |
| Probabilistic | 103.7% | 96.5% | 108.6% | 115.8% |
| Estimation | 106.1% | 104.6% | 107.4% | 116.4% |

Table 5-13: Average chip value per log as percentage of Actual Procedures model

| Stumpage Cost (as % of Actual Procedures) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Complete Information | 100.0% | 98.0% | 101.9% | 96.5% |
| Probabilistic | 102.7% | 98.8% | 107.9% | 111.1% |
| Estimation | 102.2% | 100.7% | 103.9% | 104.6% |

Table 5-14: Average stumpage cost per log as percentage of Actual Procedures model

| Transport Cost (as % of Actual Procedures) | Lodgepole Pine | Balsam | Spruce | Red Cedar |
|---|---|---|---|---|
| Complete Information | 105.5% | 103.0% | 106.1% | 111.6% |
| Probabilistic | 104.2% | 98.2% | 109.5% | 116.4% |
| Estimation | 104.5% | 103.3% | 107.2% | 113.4% |

Table 5-15: Average transport cost per log as percentage of Actual Procedures model

Interpreting the results, comparing the actual procedures model with the complete information model, there is an average potential gain of 11.9% in value, for all diameter classes and species. This gain comes from a 7.6% increase in lumber revenues, 4.6% increase in revenues from chips, and a 0.7% decrease in stumpage. The transportation costs increase by 6.1%.

When using the probabilistic model, there is an average gain of 7.4% in value, for all diameter classes and species compared to the actual procedures model. This gain comes from a 6.0% increase in lumber revenues, 5.4% increase in revenues from chips. Stumpage and transportation costs increase by 4.5% and 6.1% respectively.

When using the estimation model, there is an average gain of 2.6% in value, for all diameter classes and species compared to the actual procedures model. This gain comes from a 1.5% increase in lumber revenues, 8.1% increase in revenues from chips. Stumpage and transportation costs increase by 2.6% and 6.5% respectively.

Compared to the complete information model, the Probabilistic model shows the next best performance recovering 96.0% of the potential maximum gain, for all diameter classes and all species. Next is the Estimation model, recovering 91.7% of the potential. Finally, the Actual model shows an average value of 89.4% of the potential maximum.

This thesis is focused on the potential value increase of small logs with butt decay. To best interpret the magnitude of the potential gains, it is important to determine what percentage of the tree population, of the same diameter range, presents butt decay. The following table shows the percentage of trees with butt decay, by species, on the diameter range of 8.0 to 13.0 inches at the butt, as calculated from the BCFS database.

| Species | Fraction of 8-13" Butt Diameter trees with Butt Decay |
|---|---|
| Logepole Pine | 0.093 |
| Balsam | 0.157 |
| Spruce | 0.208 |
| Red Cedar | 0.267 |

Table 5-16: Fraction of trees with 8" to 13" Butt Diameter and Butt Decay

By weighting the results of table 5-1 by the fractions of trees with butt decay, the average potential gain in value, for the four species over all trees in the diameter range of 8.0 to 13.0 inches at the butt, is approximately 2.8%. To emphasize this result, assume an average value per tree of $25.00, then, the average gain per tree would be about $0.70. Assuming now a company with an annual allowable cut of 1,000,000 (one million) cubic meters, from which 200,000 comes from trees within the 8.0 – 13.0 inch diameter range. Assuming an average volume per tree of 0.250 $m^3$, this company would process 800,000 trees within the 8.0 – 13.0 inch diameter range per year. This translates into a potential gain of $560,000 per year. Applying the same logic to the probabilistic model, the expected gain per year would be about $350,000. As for the estimation model, the expected gain would be about $120,000 per year.

There is an interesting result that must not be overlooked. The results show a clear revenue improvement when bucking with algorithms that consider decay. However, these gains do not come at the expense of lower stumpage or transport costs, they are a consequence of higher lumber recoveries. The stumpage and transportation costs are higher on average for all the three models that include decay than for the actual procedures model. A higher value per tree, and higher stumpage and transportation payoffs mean gains for all the parties involved in the forestry practice (forest products industry, Provincial Government and transport industry); so it is in the best interest of all parties involved to implement these improved algorithms.

## 5.2 Comparison of Waste

As mentioned in Chapter 2, waste is defined as the sound fiber that is left behind in the woods. This fiber is usually accompanied by substantial amounts of decay, to the extent that it is not economically feasible to haul it for processing. At least that is the common wisdom.

The waste was recorded for each of the trees processed by each of the models. The following table shows the average waste per tree, in $dm^3$, for all species and all diameters.

| Model | Waste [$dm^3$] (Average per tree) |
|---|---|
| Complete Information | 7.42 |
| Probabilistic | 9.40 |
| Estimation | 4.49 |
| Actual Procedures | 16.45 |

Table 5-17: Average waste by model

Table 5-17 shows that the actual procedures model leads to considerably more waste than the other three models.

## 5.3 Longbutting

The percentage of trees, of all species and diameter classes, that were longbutted in each of the four models is shown in the following table.

| Model | % of trees longbutted |
|---|---|
| Complete Information | 20.3% |
| Probabilistic | 19.8% |
| Estimation | 11.5% |
| Actual Procedures | 46.3% |

Table 5-18: Percentage of trees longbutted by model

Table 5-18 shows that the actual procedures model tends to be more aggressive in longbutting. The whole set of trees was analyzed to look for possible patterns in the longbutting. These patterns would ideally provide heuristics for better longbutting procedures. Nevertheless, there was no apparent pattern; some trees were longbutted even with a moderate amount of decay while others that had considerably amounts of decay were bucked for lumber. Further discussion will follow.

## 5.4 Conclusions

Section 5-2 indicates that there is a clear improvement to be made by applying bucking models that consider decay. The actual procedures model tends to haul less wood (and consequently pay less stumpage and transport), and has the poorest performance in value recovered. This indicates that the longbutting rules, together with the grading procedures, stipulated by the Provincial Government of British Columbia, result in losses for all the parties involved.

The better performance of the probabilistic model, compared to the estimation model, indicates that the procedure developed to estimate the expected length of decays is not accurate enough, and that the allowance for errors (as the probabilistic model does), translates in better results.

The discussion of how each of these models would be implemented is left open. The requirements of each of these models should be clear from Table 4-1. With the increasing power of computers, the tendency is to move towards solutions that rely more on heavy computations and away from those relying on manual or mechanical procedures. With this in mind, the insertion of a probe might someday be economically infeasible for the time that has to be spent, as compared to the time needed to solve a probabilistic dynamic problem. With the technology available today it would be possible to apply the estimation and the complete information models in the field. The probabilistic model takes longer to solve, but with more powerful computers, or a logistic system that can recognize a log after it has been scanned (bar codes are an option), this model is definitely applicable.

It is obvious that longbutting on a log-by-log basis will always yield better solutions than fixed sets of rules, which are not even clear and whose application may result in considerable losses.

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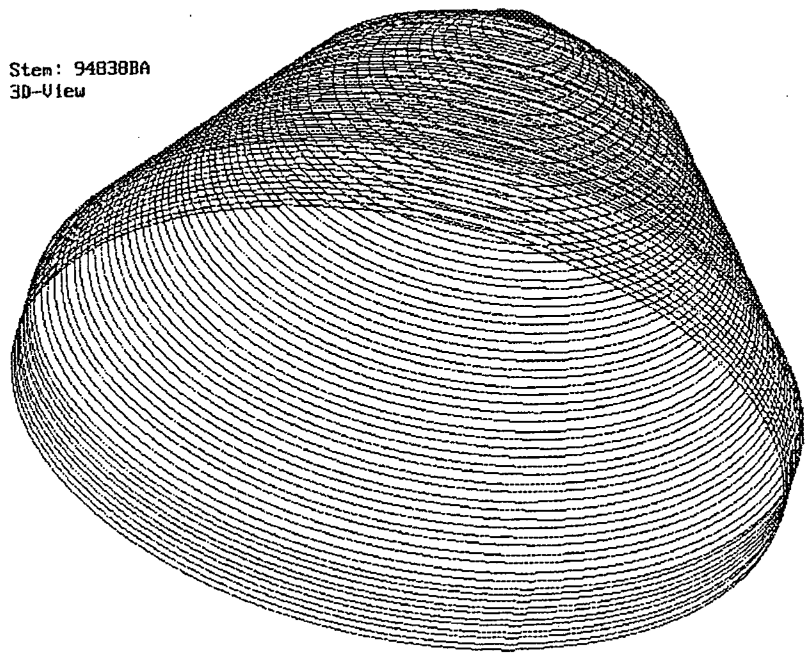
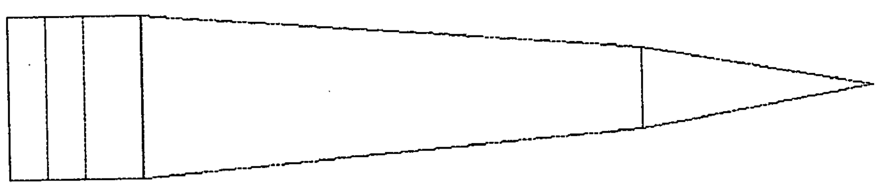
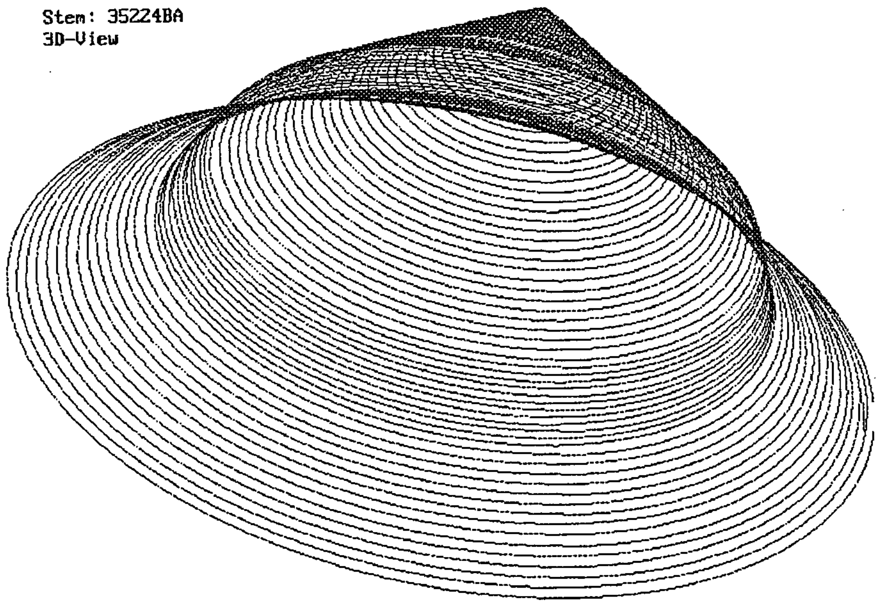
## Appendix 1: Decay Shapes

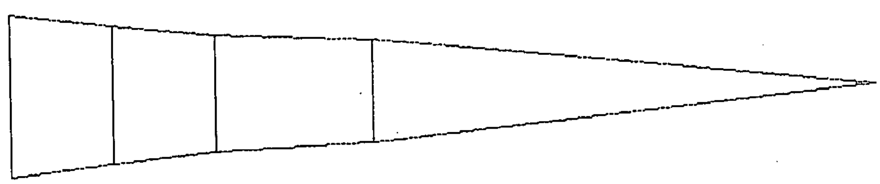


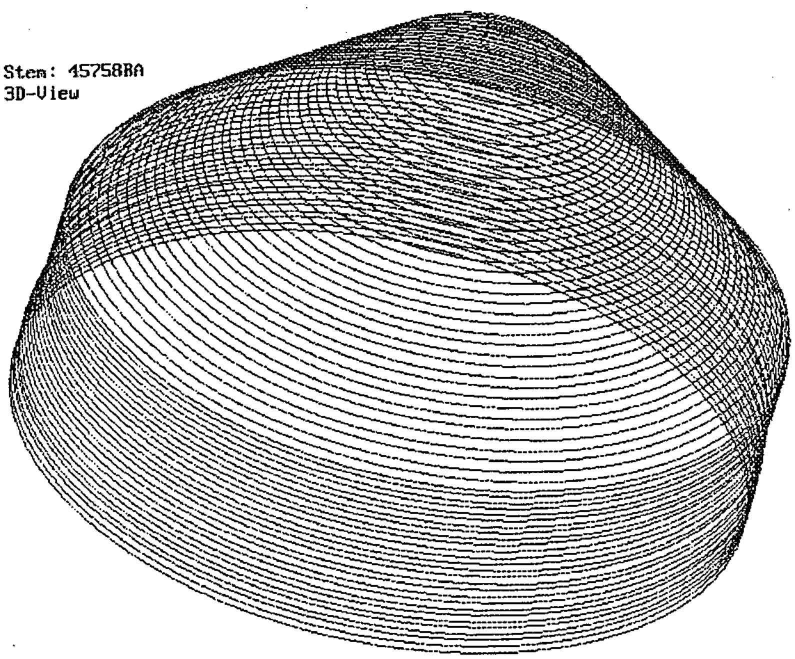
Stem: 35224BA
3D-View



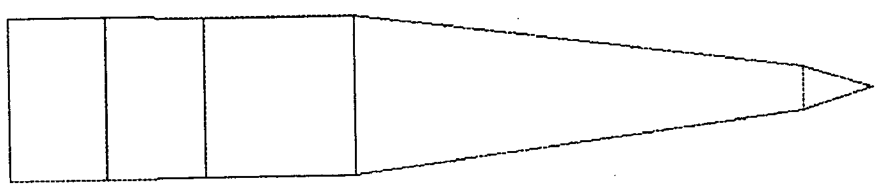
Stem: 35224BA
Top Plan



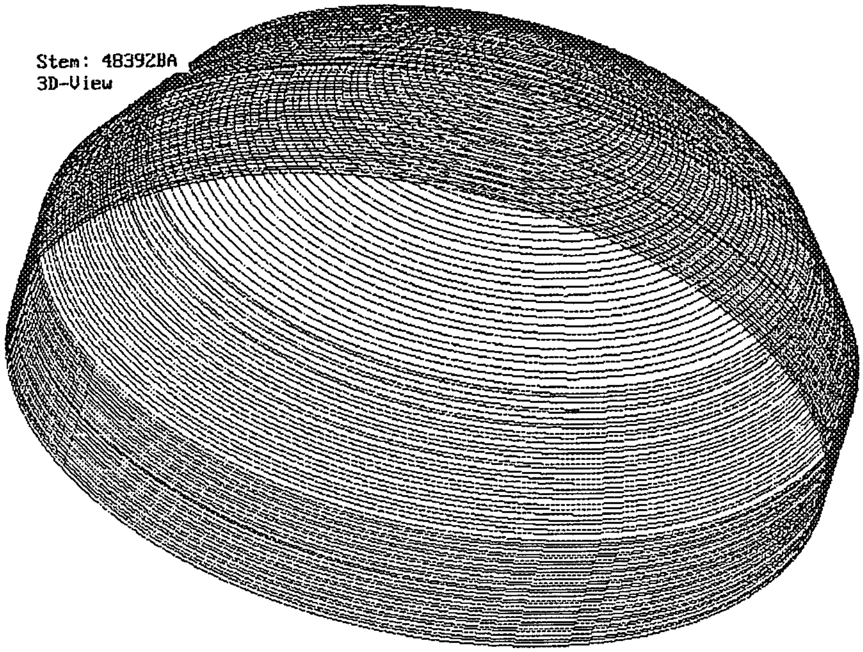
Stem: 45758BA
3D-View



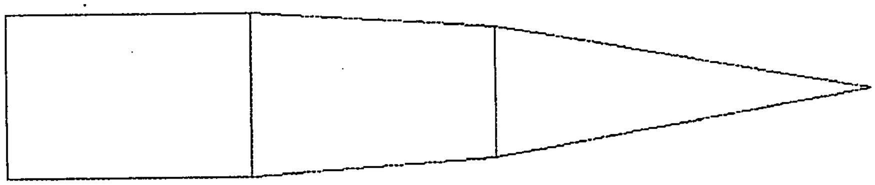
Stem: 45758BA
Top Plan



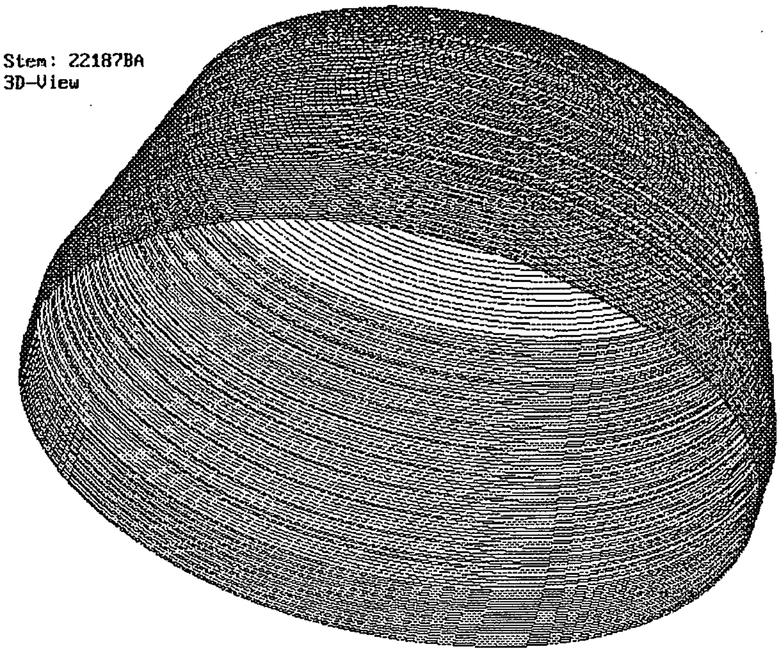
Stem: 48392BA
3D-View



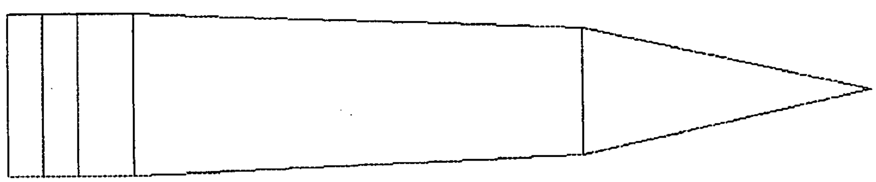
Stem: 48392BA
Top Plan



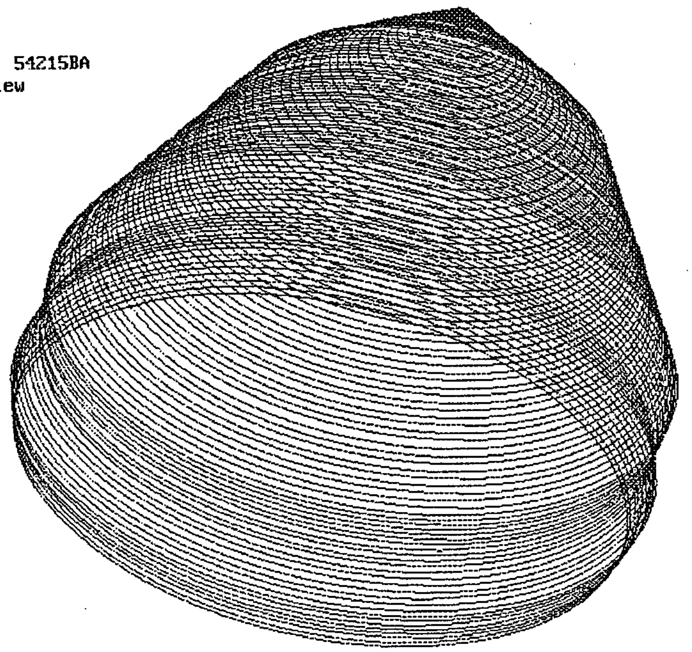
Stem: 22187BA
3D-View



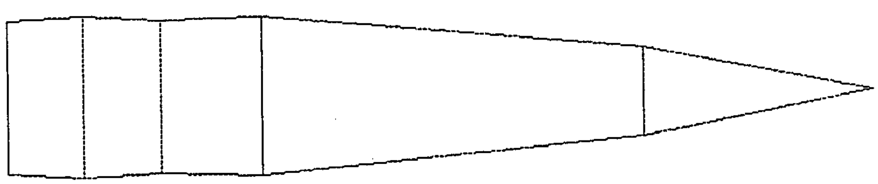
Stem: 22187BA
Top Plan



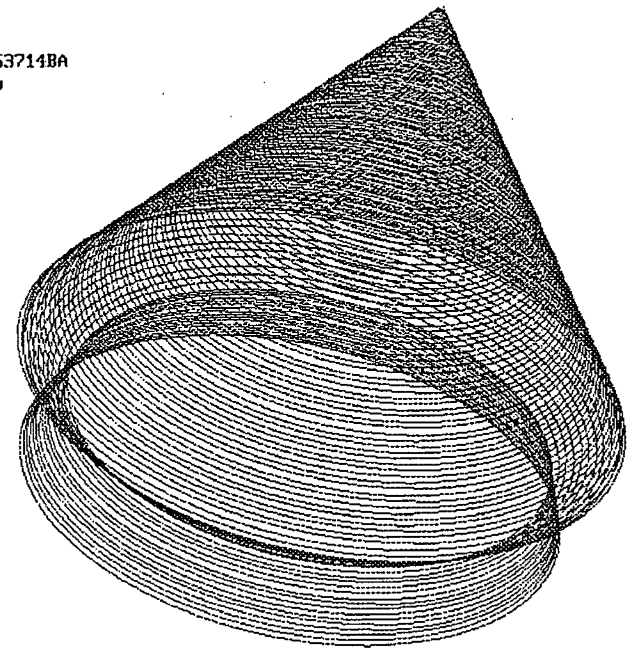
Stem: 54215BA
3D-View



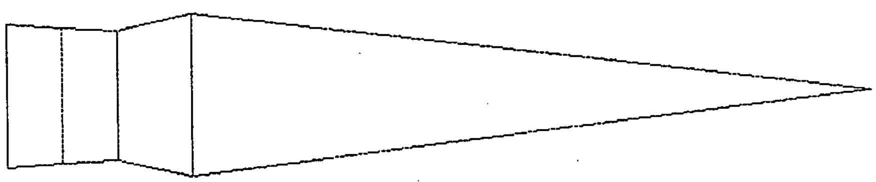
Stem: 54215BA
Top Plan



Stem: 53714BA
3D-View



Stem: 53714BA
Top Plan



Appendix 2: Sawing Details

The logs have been assumed to be processed in a mill consisting of a Canter-Twin chip-n-saw, a gang, an edger and a trimmer. For those not familiar with this machinery, the Canter-Twin receives a log and cuts a cant out of its center and chips the outmost face of the sides. Figure A2-1 shows the process seen from the end-view of the log.

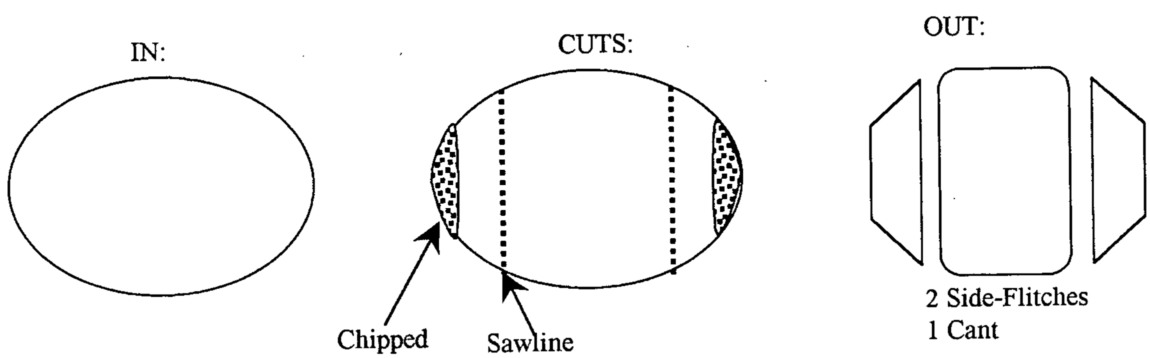



Figure A2-1: Input and Output of the Canter-twin

The cant width is cut at a pre-determined size to produce lumber of a given width. The side-flitches thickness is also set to produce lumber of a given thickness. The cant is later "sliced" in a gang. The gang has saws spaced at intervals equal to the desired lumber thickness. Each individual piece, from the gang or direct from the Twin (the flitches) is then passed on to the edger which squares the sides, see Figure A2-2. The edger is also set to cut at predetermined widths. The pieces are then passed to a trimmer that cuts the ends off in order to produce lumber of nominal lengths. All the nominal lengths, widths and thickness can be found in Table A2-1 later in this appendix.

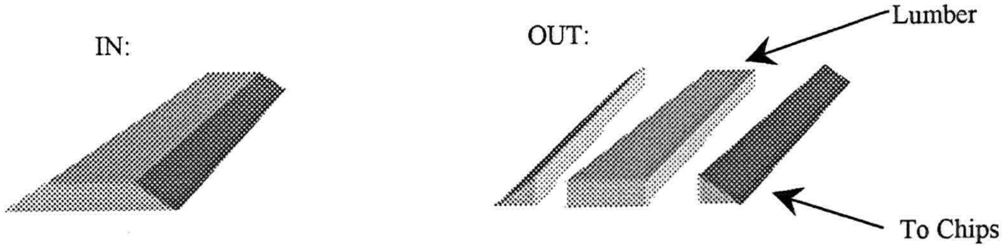



Figure A2-1: Input and Output of the Edger

Depending on the grade of lumber being produced, the pieces are allowed to have round (non-square) edges up to a certain degree, this is known as wane allowance. For the purpose of this thesis the pieces will have to be square (i.e. no wane allowed).

For this thesis, there were five lumber widths considered: 3, 4, 6, 8 and 10-inches, seven lengths: 8, 10, 12, 14, 16, 18 and 20-foot, and one thickness: 2-inches. The actual dimensions of lumber often differ from their nominal sizes, the following tables shows the actual dimensions of lumber.

| Lumber Thickness | |
|---|---|
| Nominal [inches] | Actual [inches] |
| 2 | 1.5625 |

| Lumber Width | |
|---|---|
| Nominal [inches] | Actual [inches] |
| 3 | 2.5625 |
| 4 | 3.5625 |
| 6 | 5.6250 |
| 8 | 7.5000 |
| 10 | 9.5000 |

Table A2-1: Nominal and Actual lumber sizes

In the case of lengths, the actual dimensions were assumed to equal the nominals. The saw kerf was assumed to be 0.150 inches, for all machines. No kerf was assumed for the bucking cuts. No allowance for shrinkage was assumed.

To calculate the lumber prices to be used, the Madison's Canadian Lumber Report[3] was used. The prices for the last week of each month for 1996 were averaged and this numbers were used for the sawing calculations. Table A2-2 shows these prices, all in Canadian Dollars.

Lumber Prices [$/Mbf]

| Thickness = 2in | | Lumber Width | | | | |
|---|---|---|---|---|---|---|
| | | 3 | 4 | 6 | 8 | 10 |
| Lumber Length | 8 | 215.90 | 287.90 | 308.70 | 313.10 | 318.10 |
| | 10 | 231.80 | 309.00 | 342.00 | 312.50 | 299.40 |
| | 12 | 252.30 | 336.30 | 335.00 | 383.90 | 418.70 |
| | 14 | 282.50 | 376.70 | 356.00 | 354.90 | 517.40 |
| | 16 | 324.70 | 432.90 | 401.80 | 407.90 | 491.90 |
| | 18 | 298.80 | 398.30 | 436.30 | 441.40 | 488.80 |
| | 20 | 327.10 | 436.10 | 447.90 | 443.30 | 483.70 |

Table A2-2: Lumber prices

The price for chips was assumed as $100 per Bone-Dry Unit (BDU). A common conversion factor of 100 $ft^3/BDU$ for all species was assumed. For simplicity purposes it was assumed that no sawdust was produced, instead, any part of the log not converted into lumber was assumed to produce chips.

The stumpage rate was assumed as the average for 1996, as determined by the Ministry of Forests of British Columbia; the used rate was 30 dollars per cubic meter. The transportation cost was assumed as 15 dollars per cubic meter. It should be noted that the stumpage is paid on the net volume (excluding decay), while the transport rate is paid on the gross volume (including decay). A cost of 30 cents was assumed for each cut performed.

[3] Madison's is a weekly report for Canadian and U.S. lumber and panel prices.

Appendix 3: Bucking table for Actual case.

The Actual case used a table-driven procedure to compute the bucking solution. The only input for this table is the length of the remaining segment. For the first cut, the length to a 4-inch diameter was used. The length of cut in the table refers to the cut to be performed at the large-end of the log. The length refers to the length of the remaining segment; this has been defined every 2-feet, the defined length being the lower limit of the interval.

| Length [ft] | Length of cut [ft] |
|---|---|
| 8 | 8 |
| 10 | 10 |
| 12 | 12 |
| 14 | 14 |
| 16 | 16 |
| 18 | 18 |
| 20 | 20 |
| 22 | 12 |
| 24 | 12 |
| 26 | 16 |
| 28 | 16 |
| 30 | 20 |
| 32 | 16 |
| 34 | 18 |
| 36 | 20 |
| 38 | 20 |
| 40 | 20 |
| 42 | 16 |
| 44 | 16 |
| 46 | 20 |
| 48 | 16 |
| 50 | 20 |
| 52 | 20 |
| 54 | 20 |
| 56 | 20 |
| 58 | 16 |
| 60 | 20 |
| 62 | 20 |
| 64 | 16 |

| | |
|---|---|
| 66 | 20 |
| 68 | 20 |
| 70 | 20 |
| 72 | 20 |
| 74 | 20 |
| 76 | 20 |
| 78 | 20 |
| 80 | 20 |
| 82 | 20 |
| 84 | 20 |
| 86 | 20 |
| 88 | 20 |
| 90 | 20 |

Table A3-1: Bucking table for Actual case

For example, a 80-foot stem (reconstructed to a 3-inch top) that measures 74 feet to a 4-inch top would first cut a 20-foot segment, leaving 54 feet, it would then cut another 20-foot segment, leaving 34 feet; it would then cut a 18-foot segment, leaving 16 feet. This last segment would be cut as long as possible, that is it will either be a 20-foot segment or a segment measuring the resulting length of subtracting the lengths of the previously bucked segments from the total length. In our example, after bucking two 20-footers and one 18-foot log, the remaining length (to 80 feet) is 22 feet, so the last segment would messure 20 feet.

## Appendix 4: Lognormal distribution

A nonnegative random variable X is said to have a lognormal distribution if the random variable Y = ln(X) has a normal distribution. The resulting probability density function of a lognormal random variable when ln(X) is normally distributed with parameters $\mu$ and $\sigma$ is

$$f(x;\mu,\sigma)=\begin{cases}\dfrac{1}{\sqrt{2\pi}\sigma x}e^{-\frac{1}{2\sigma^2}[\ln(x)-\mu]^2} & x\geq 0\\ 0 & x<0\end{cases}$$

Appendix 5: Details of tress processed

Herewith is a brief summary of the trees processed. The first column, TreeID corresponds to the Identification number of the BCFS database. The second column is the code given for easier identification, the first two letters of this code identify the species: BA for Balsam, PL for Lodgepole Pine, SP for Spruce, and RC for Red Cedar. The last column shows the value of the length of decay as calculated by Equation 3.

| TreeID | Tree Code | Length [ft] | Butt Diameter [in] | decay length [cm] | decay diameter [cm] | Estimated decay length [cm] |
|---|---|---|---|---|---|---|
| 54215 | BA-8-1 | 30.0 | 8.15 | 355.0 | 10.3 | 218.2 |
| 8176 | BA-8-2 | 40.0 | 8.11 | 75.0 | 10.2 | 217.3 |
| 46943 | BA-8-3 | 38.0 | 8.70 | 215.0 | 6.0 | 138.4 |
| 49807 | BA-8-4 | 28.0 | 8.11 | 100.0 | 12.4 | 256.6 |
| 924259 | BA-8-5 | 32.0 | 8.19 | 136.0 | 15.2 | 305.1 |
| 931600 | BA-8-6 | 32.0 | 8.19 | 167.0 | 7.6 | 169.2 |
| 53307 | BA-8-7 | 50.0 | 8.82 | 144.0 | 6.5 | 148.1 |
| 45743 | BA-8-8 | 36.0 | 8.70 | 60.0 | 2.7 | 69.1 |
| 58610 | BA-8-9 | 32.0 | 8.35 | 140.0 | 7.5 | 166.4 |
| 44234 | BA-8-10 | 44.0 | 8.82 | 416.0 | 12.3 | 254.8 |
| 46602 | BA-9-1 | 36.0 | 9.80 | 99.0 | 11.4 | 238.9 |
| 44178 | BA-9-2 | 36.0 | 9.61 | 502.0 | 15.6 | 311.9 |
| 43846 | BA-9-3 | 46.0 | 9.80 | 27.0 | 2.6 | 66.8 |
| 933510 | BA-9-4 | 48.0 | 9.69 | 167.0 | 5.1 | 120.5 |
| 51625 | BA-9-5 | 50.0 | 9.45 | 95.0 | 11.0 | 231.7 |
| 914926 | BA-9-6 | 44.0 | 9.49 | 136.0 | 10.2 | 217.3 |
| 50204 | BA-9-7 | 26.0 | 9.02 | 279.0 | 5.5 | 128.5 |
| 935979 | BA-9-8 | 48.0 | 9.80 | 105.0 | 15.2 | 305.1 |
| 924481 | BA-9-9 | 36.0 | 9.21 | 197.0 | 2.5 | 65.7 |
| 17727 | BA-9-10 | 30.0 | 9.29 | 93.0 | 7.6 | 169.2 |
| 35283 | BA-10-1 | 66.0 | 10.98 | 328.0 | 10.2 | 217.3 |
| 35129 | BA-10-2 | 34.0 | 10.12 | 167.0 | 11.4 | 238.9 |
| 9093 | BA-10-3 | 50.0 | 10.00 | 133.0 | 10.2 | 217.3 |
| 56404 | BA-10-4 | 42.0 | 10.20 | 60.0 | 6.0 | 138.4 |
| 931064 | BA-10-5 | 48.0 | 10.79 | 75.0 | 10.2 | 217.3 |
| 48457 | BA-10-6 | 48.0 | 10.20 | 60.0 | 2.8 | 71.3 |
| 51947 | BA-10-7 | 42.0 | 10.20 | 60.0 | 4.3 | 103.2 |
| 922179 | BA-10-8 | 28.0 | 10.20 | 75.0 | 2.5 | 65.7 |
| 45670 | BA-10-9 | 52.0 | 10.98 | 51.0 | 4.6 | 110.4 |
| 948378 | BA-10-10 | 58.0 | 10.98 | 761.0 | 10.2 | 217.3 |
| 931023 | BA-11-1 | 54.0 | 11.81 | 151.0 | 5.1 | 120.5 |
| 54414 | BA-11-2 | 70.0 | 11.26 | 75.0 | 9.5 | 204.6 |
| 924543 | BA-11-3 | 30.0 | 11.61 | 45.0 | 5.1 | 120.5 |
| 800906 | BA-11-4 | 74.0 | 11.42 | 109.0 | 17.8 | 349.0 |
| 48018 | BA-11-5 | 54.0 | 11.93 | 66.0 | 10.2 | 216.4 |
| 6263 | BA-11-6 | 78.0 | 11.42 | 69.0 | 7.6 | 169.2 |

| TreeID | Tree Code | Length [ft] | Butt Diameter [in] | decay length [cm] | decay diameter [cm] | Estimated decay length [cm] |
|---|---|---|---|---|---|---|
| 904713 | BA-11-7 | 46.0 | 11.61 | 410.0 | 7.6 | 169.2 |
| 16072 | BA-11-8 | 68.0 | 11.50 | 563.0 | 25.4 | 472.2 |
| 54059 | BA-11-9 | 62.0 | 11.38 | 459.0 | 11.8 | 245.1 |
| 58596 | BA-11-10 | 48.0 | 11.46 | 95.0 | 7.0 | 157.8 |
| 14296 | BA-12-1 | 60.0 | 12.40 | 246.0 | 15.2 | 305.1 |
| 907690 | BA-12-2 | 66.0 | 12.60 | 90.0 | 7.6 | 169.2 |
| 49883 | BA-12-3 | 54.0 | 12.32 | 622.0 | 25.8 | 477.7 |
| 35002 | BA-12-4 | 40.0 | 12.52 | 228.0 | 11.4 | 238.9 |
| 15095 | BA-12-5 | 66.0 | 12.40 | 219.0 | 20.3 | 390.2 |
| 803017 | BA-12-6 | 68.0 | 12.28 | 54.0 | 2.5 | 65.7 |
| 801015 | BA-12-7 | 56.0 | 12.01 | 167.0 | 7.6 | 169.2 |
| 912568 | BA-12-8 | 70.0 | 12.20 | 395.0 | 12.7 | 261.9 |
| 52887 | BA-12-9 | 62.0 | 12.80 | 338.0 | 10.5 | 222.7 |
| 48047 | BA-12-10 | 64.0 | 12.80 | 95.0 | 2.9 | 74.6 |
| 41482 | BA-8-11 | 42.0 | 8.11 | 246.0 | 10.2 | 217.3 |
| 58524 | BA-8-12 | 28.0 | 8.03 | 30.0 | 4.4 | 105.3 |
| 32295 | BA-8-13 | 28.0 | 8.31 | 60.0 | 7.0 | 157.8 |
| 46177 | BA-8-14 | 50.0 | 8.46 | 202.0 | 10.1 | 214.6 |
| 917902 | BA-8-15 | 26.0 | 8.31 | 288.0 | 5.1 | 120.5 |
| 48484 | BA-8-16 | 34.0 | 8.90 | 112.0 | 11.4 | 238.9 |
| 802983 | BA-8-17 | 42.0 | 8.19 | 167.0 | 7.6 | 169.2 |
| 928971 | BA-8-18 | 44.0 | 8.19 | 136.0 | 15.2 | 305.1 |
| 29301 | BA-8-19 | 40.0 | 8.58 | 90.0 | 15.2 | 305.1 |
| 46134 | BA-8-20 | 32.0 | 8.03 | 30.0 | 4.5 | 108.3 |
| 53297 | BA-9-11 | 52.0 | 9.25 | 149.0 | 5.3 | 124.5 |
| 54017 | BA-9-12 | 44.0 | 9.25 | 196.0 | 8.0 | 176.8 |
| 30046 | BA-9-13 | 38.0 | 9.21 | 18.0 | 6.4 | 146.2 |
| 931618 | BA-9-14 | 32.0 | 9.61 | 136.0 | 5.1 | 120.5 |
| 931070 | BA-9-15 | 50.0 | 9.88 | 197.0 | 5.1 | 120.5 |
| 934748 | BA-9-16 | 46.0 | 9.69 | 410.0 | 10.2 | 217.3 |
| 936211 | BA-9-17 | 30.0 | 9.21 | 75.0 | 7.6 | 169.2 |
| 930761 | BA-9-18 | 34.0 | 9.02 | 167.0 | 10.2 | 217.3 |
| 8196 | BA-9-19 | 42.0 | 9.61 | 75.0 | 12.7 | 261.9 |
| 58716 | BA-9-20 | 44.0 | 9.13 | 490.0 | 6.0 | 138.4 |
| 948392 | BA-10-11 | 56.0 | 10.98 | 121.0 | 12.7 | 261.9 |
| 35224 | BA-10-12 | 56.0 | 10.31 | 267.0 | 17.8 | 349.0 |
| 53996 | BA-10-13 | 42.0 | 10.12 | 220.0 | 15.4 | 307.7 |
| 43847 | BA-10-14 | 46.0 | 10.59 | 72.0 | 9.2 | 198.1 |
| 46164 | BA-10-15 | 52.0 | 10.67 | 213.0 | 9.4 | 201.8 |
| 45758 | BA-10-16 | 48.0 | 10.59 | 279.0 | 13.1 | 268.0 |
| 45701 | BA-10-17 | 52.0 | 10.31 | 75.0 | 14.6 | 294.8 |
| 35204 | BA-10-18 | 56.0 | 10.79 | 90.0 | 2.5 | 65.7 |
| 48468 | BA-10-19 | 46.0 | 10.59 | 60.0 | 7.5 | 166.4 |
| 58735 | BA-10-20 | 32.0 | 10.39 | 60.0 | 12.6 | 260.1 |
| 46178 | BA-11-11 | 56.0 | 11.57 | 277.0 | 26.7 | 491.9 |
| 49589 | BA-11-12 | 62.0 | 11.54 | 95.0 | 17.5 | 344.0 |
| 58695 | BA-11-13 | 54.0 | 11.85 | 30.0 | 3.9 | 95.9 |

| TreeID | Tree Code | Length [ft] | Butt Diameter [in] | decay length [cm] | decay diameter [cm] | Estimated decay length [cm] |
|---|---|---|---|---|---|---|
| 35927 | BA-11-14 | 42.0 | 11.61 | 231.0 | 15.2 | 305.1 |
| 36005 | BA-11-15 | 56.0 | 11.10 | 54.0 | 7.6 | 169.2 |
| 22187 | BA-11-16 | 58.0 | 11.42 | 746.0 | 22.9 | 432.4 |
| 51058 | BA-11-17 | 32.0 | 11.30 | 30.0 | 3.0 | 76.7 |
| 800913 | BA-11-18 | 60.0 | 11.61 | 502.0 | 7.6 | 169.2 |
| 924574 | BA-11-19 | 38.0 | 11.18 | 136.0 | 10.2 | 217.3 |
| 56434 | BA-11-20 | 28.0 | 11.06 | 30.0 | 4.9 | 115.5 |
| 4602 | BA-12-11 | 70.0 | 12.09 | 532.0 | 5.1 | 120.5 |
| 35202 | BA-12-12 | 64.0 | 12.72 | 99.0 | 8.9 | 193.5 |
| 29295 | BA-12-13 | 46.0 | 12.91 | 87.0 | 10.2 | 217.3 |
| 61820 | BA-12-14 | 88.0 | 12.13 | 60.0 | 3.6 | 89.6 |
| 58678 | BA-12-15 | 48.0 | 12.48 | 301.0 | 14.0 | 284.5 |
| 904716 | BA-12-16 | 84.0 | 12.99 | 75.0 | 5.1 | 120.5 |
| 43928 | BA-12-17 | 48.0 | 12.01 | 36.0 | 16.6 | 328.0 |
| 948381 | BA-12-18 | 48.0 | 12.01 | 700.0 | 10.2 | 217.3 |
| 806434 | BA-12-19 | 74.0 | 12.99 | 319.0 | 10.2 | 217.3 |
| 53714 | BA-12-20 | 66.0 | 12.01 | 480.0 | 9.8 | 209.1 |
| 807120 | PL-8-1 | 44.0 | 8.11 | 105.0 | 7.6 | 157.0 |
| 807761 | PL-8-2 | 46.0 | 8.19 | 349.0 | 5.1 | 123.7 |
| 807775 | PL-8-3 | 40.0 | 8.31 | 105.0 | 5.1 | 123.7 |
| 1241 | PL-8-4 | 50.0 | 8.58 | 319.0 | 10.2 | 187.1 |
| 807454 | PL-8-5 | 48.0 | 8.58 | 121.0 | 2.5 | 80.9 |
| 1794 | PL-8-6 | 28.0 | 8.70 | 30.0 | 2.5 | 80.9 |
| 31690 | PL-8-7 | 72.0 | 8.70 | 203.0 | 17.5 | 258.1 |
| 922798 | PL-8-8 | 46.0 | 8.70 | 196.0 | 2.5 | 80.9 |
| 1827 | PL-8-9 | 30.0 | 8.82 | 179.0 | 2.5 | 80.9 |
| 1273 | PL-8-10 | 48.0 | 8.82 | 130.0 | 5.1 | 123.7 |
| 922818 | PL-9-1 | 46.0 | 9.02 | 45.0 | 2.5 | 80.9 |
| 2357 | PL-9-2 | 44.0 | 9.09 | 33.0 | 5.1 | 123.7 |
| 1140 | PL-9-3 | 50.0 | 9.09 | 57.0 | 12.7 | 213.2 |
| 922880 | PL-9-4 | 46.0 | 9.09 | 136.0 | 12.7 | 213.2 |
| 47491 | PL-9-5 | 50.0 | 9.29 | 30.0 | 12.7 | 213.2 |
| 42918 | PL-9-6 | 46.0 | 9.29 | 96.0 | 16.4 | 248.3 |
| 39879 | PL-9-7 | 42.0 | 9.41 | 145.0 | 10.7 | 192.5 |
| 925356 | PL-9-8 | 40.0 | 9.41 | 319.0 | 17.8 | 260.7 |
| 922861 | PL-9-9 | 50.0 | 9.41 | 136.0 | 5.1 | 123.7 |
| 45259 | PL-9-10 | 52.0 | 9.69 | 413.0 | 16.3 | 246.9 |
| 49351 | PL-10-1 | 66.0 | 10.28 | 195.0 | 8.0 | 161.8 |
| 933738 | PL-10-2 | 60.0 | 10.39 | 167.0 | 17.8 | 260.7 |
| 49583 | PL-10-3 | 52.0 | 10.55 | 30.0 | 9.5 | 179.3 |
| 2097 | PL-10-4 | 48.0 | 10.59 | 63.0 | 22.9 | 303.0 |
| 807093 | PL-10-5 | 48.0 | 10.59 | 105.0 | 5.1 | 123.7 |
| 1197 | PL-10-6 | 64.0 | 10.79 | 69.0 | 7.6 | 157.0 |
| 904026 | PL-10-7 | 52.0 | 10.79 | 75.0 | 12.7 | 213.2 |
| 807092 | PL-10-8 | 60.0 | 10.79 | 868.0 | 2.5 | 80.9 |
| 1513 | PL-10-9 | 42.0 | 10.91 | 66.0 | 10.2 | 187.1 |
| 933723 | PL-10-10 | 62.0 | 10.91 | 75.0 | 10.2 | 187.1 |

| TreeID | Tree Code | Length [ft] | Butt Diameter [in] | decay length [cm] | decay diameter [cm] | Estimated decay length [cm] |
|---|---|---|---|---|---|---|
| 807080 | PL-11-1 | 48.0 | 11.10 | 105.0 | 12.7 | 213.2 |
| 1650 | PL-11-2 | 50.0 | 11.10 | 69.0 | 2.5 | 80.9 |
| 45220 | PL-11-3 | 64.0 | 11.18 | 416.0 | 12.5 | 210.7 |
| 807448 | PL-11-4 | 58.0 | 11.18 | 105.0 | 10.2 | 187.1 |
| 807802 | PL-11-5 | 50.0 | 11.30 | 105.0 | 7.6 | 157.0 |
| 807472 | PL-11-6 | 56.0 | 11.50 | 75.0 | 15.2 | 237.3 |
| 49293 | PL-11-7 | 68.0 | 11.57 | 60.0 | 7.4 | 154.5 |
| 806013 | PL-11-8 | 80.0 | 11.61 | 136.0 | 12.7 | 213.2 |
| 1642 | PL-11-9 | 36.0 | 11.81 | 243.0 | 7.6 | 157.0 |
| 807440 | PL-11-10 | 48.0 | 11.89 | 121.0 | 15.2 | 237.3 |
| 932397 | PL-12-1 | 82.0 | 12.01 | 212.0 | 20.3 | 282.0 |
| 53194 | PL-12-2 | 72.0 | 12.28 | 141.0 | 18.0 | 262.4 |
| 1689 | PL-12-3 | 40.0 | 12.28 | 93.0 | 12.7 | 213.2 |
| 34758 | PL-12-4 | 66.0 | 12.40 | 273.0 | 8.9 | 172.5 |
| 30300 | PL-12-5 | 42.0 | 12.40 | 81.0 | 8.1 | 163.0 |
| 806138 | PL-12-6 | 52.0 | 12.40 | 228.0 | 17.8 | 260.7 |
| 806143 | PL-12-7 | 70.0 | 12.52 | 410.0 | 7.6 | 157.0 |
| 922944 | PL-12-8 | 52.0 | 12.60 | 1093.0 | 20.3 | 282.0 |
| 919521 | PL-12-9 | 46.0 | 12.72 | 197.0 | 22.9 | 303.0 |
| 49398 | PL-12-10 | 80.0 | 12.76 | 60.0 | 4.1 | 108.6 |
| 933887 | PL-8-11 | 44.0 | 8.11 | 136.0 | 2.5 | 80.9 |
| 1766 | PL-8-12 | 36.0 | 8.70 | 96.0 | 5.1 | 123.7 |
| 807646 | PL-8-13 | 44.0 | 8.31 | 167.0 | 10.2 | 187.1 |
| 914963 | PL-8-14 | 44.0 | 8.11 | 380.0 | 7.6 | 157.0 |
| 933828 | PL-8-15 | 42.0 | 8.11 | 105.0 | 12.7 | 213.2 |
| 34273 | PL-8-16 | 34.0 | 8.11 | 197.0 | 2.5 | 80.9 |
| 49134 | PL-8-17 | 42.0 | 8.27 | 349.0 | 13.6 | 221.6 |
| 1765 | PL-8-18 | 32.0 | 8.50 | 380.0 | 10.2 | 187.1 |
| 807688 | PL-8-19 | 42.0 | 8.70 | 75.0 | 5.1 | 123.7 |
| 1795 | PL-8-20 | 34.0 | 8.90 | 151.0 | 2.5 | 80.9 |
| 906328 | PL-9-11 | 48.0 | 9.61 | 167.0 | 12.7 | 213.2 |
| 31959 | PL-9-12 | 58.0 | 9.41 | 45.0 | 3.3 | 95.5 |
| 807256 | PL-9-13 | 42.0 | 9.29 | 121.0 | 10.2 | 187.1 |
| 807077 | PL-9-14 | 30.0 | 9.21 | 121.0 | 12.7 | 213.2 |
| 906364 | PL-9-15 | 40.0 | 9.41 | 45.0 | 5.1 | 123.7 |
| 933916 | PL-9-16 | 50.0 | 9.49 | 167.0 | 10.2 | 187.1 |
| 49375 | PL-9-17 | 70.0 | 9.57 | 95.0 | 14.5 | 230.7 |
| 1514 | PL-9-18 | 36.0 | 9.61 | 441.0 | 7.6 | 157.0 |
| 41663 | PL-9-19 | 36.0 | 9.61 | 57.0 | 18.8 | 269.3 |
| 904022 | PL-9-20 | 54.0 | 9.69 | 45.0 | 5.1 | 123.7 |
| 807464 | PL-10-11 | 48.0 | 10.20 | 167.0 | 10.2 | 187.1 |
| 933842 | PL-10-12 | 48.0 | 10.20 | 167.0 | 15.2 | 237.3 |
| 1844 | PL-10-13 | 46.0 | 10.20 | 185.0 | 10.2 | 187.1 |
| 806222 | PL-10-14 | 78.0 | 10.31 | 136.0 | 17.8 | 260.7 |
| 807145 | PL-10-15 | 44.0 | 10.51 | 105.0 | 7.6 | 157.0 |
| 1505 | PL-10-16 | 44.0 | 10.71 | 69.0 | 10.2 | 187.1 |
| 807262 | PL-10-17 | 38.0 | 10.71 | 121.0 | 12.7 | 213.2 |

| TreeID | Tree Code | Length [ft] | Butt Diameter [in] | decay length [cm] | decay diameter [cm] | Estimated decay length [cm] |
|---|---|---|---|---|---|---|
| 908728 | PL-10-18 | 66.0 | 10.79 | 212.0 | 20.3 | 282.0 |
| 807782 | PL-10-19 | 48.0 | 10.91 | 837.0 | 15.2 | 237.3 |
| 1657 | PL-10-10 | 42.0 | 10.98 | 96.0 | 10.2 | 187.1 |
| 935356 | PL-11-11 | 88.0 | 11.10 | 75.0 | 2.5 | 80.9 |
| 1698 | PL-11-12 | 50.0 | 11.42 | 33.0 | 7.6 | 157.0 |
| 36512 | PL-11-13 | 56.0 | 11.42 | 225.0 | 8.9 | 172.5 |
| 29521 | PL-11-14 | 76.0 | 11.50 | 60.0 | 7.6 | 157.0 |
| 1702 | PL-11-15 | 54.0 | 11.61 | 624.0 | 10.2 | 187.1 |
| 29528 | PL-11-16 | 70.0 | 11.61 | 66.0 | 10.2 | 187.1 |
| 1288 | PL-11-17 | 56.0 | 11.81 | 410.0 | 24.9 | 318.5 |
| 1687 | PL-11-18 | 54.0 | 11.81 | 30.0 | 5.1 | 123.7 |
| 1574 | PL-11-19 | 38.0 | 11.89 | 340.0 | 17.8 | 260.7 |
| 5358 | PL-11-20 | 78.0 | 11.85 | 99.0 | 20.3 | 282.0 |
| 800162 | PL-12-11 | 86.0 | 12.01 | 45.0 | 5.1 | 123.7 |
| 2255 | PL-12-12 | 34.0 | 12.01 | 155.0 | 17.8 | 260.7 |
| 1515 | PL-12-13 | 46.0 | 12.20 | 286.0 | 7.6 | 157.0 |
| 55544 | PL-12-14 | 68.0 | 12.24 | 30.0 | 7.5 | 155.7 |
| 1658 | PL-12-15 | 46.0 | 12.28 | 155.0 | 12.7 | 213.2 |
| 1633 | PL-12-16 | 38.0 | 12.28 | 182.0 | 7.6 | 157.0 |
| 1674 | PL-12-17 | 56.0 | 12.52 | 27.0 | 5.1 | 123.7 |
| 54686 | PL-12-18 | 76.0 | 12.60 | 295.0 | 15.0 | 235.4 |
| 50003 | PL-12-19 | 66.0 | 12.64 | 30.0 | 1.2 | 50.9 |
| 49342 | PL-12-20 | 68.0 | 12.68 | 248.0 | 20.2 | 281.1 |
| 932013 | SP-8-1 | 46.0 | 8.82 | 136.0 | 2.5 | 49.6 |
| 43349 | SP-8-2 | 28.0 | 8.39 | 21.0 | 2.6 | 50.3 |
| 938435 | SP-8-3 | 48.0 | 8.58 | 228.0 | 12.7 | 161.6 |
| 40524 | SP-8-4 | 28.0 | 8.58 | 194.0 | 6.4 | 98.2 |
| 908015 | SP-8-5 | 28.0 | 8.82 | 167.0 | 15.2 | 184.1 |
| 41104 | SP-8-6 | 44.0 | 8.50 | 30.0 | 3.3 | 60.7 |
| 30930 | SP-8-7 | 42.0 | 8.19 | 90.0 | 6.6 | 100.4 |
| 31558 | SP-8-8 | 34.0 | 8.19 | 167.0 | 15.2 | 184.1 |
| 42762 | SP-8-9 | 48.0 | 8.19 | 209.0 | 14.6 | 178.8 |
| 41094 | SP-8-10 | 32.0 | 8.11 | 33.0 | 3.3 | 60.7 |
| 42385 | SP-9-1 | 32.0 | 9.80 | 96.0 | 18.2 | 209.5 |
| 51062 | SP-9-2 | 40.0 | 9.57 | 60.0 | 7.1 | 105.9 |
| 42367 | SP-9-3 | 32.0 | 9.21 | 60.0 | 18.5 | 212.4 |
| 30650 | SP-9-4 | 42.0 | 9.49 | 90.0 | 10.2 | 137.8 |
| 47844 | SP-9-5 | 40.0 | 9.69 | 94.0 | 12.4 | 158.8 |
| 39044 | SP-9-6 | 50.0 | 9.61 | 36.0 | 3.5 | 62.7 |
| 936445 | SP-9-7 | 40.0 | 9.69 | 167.0 | 12.7 | 161.6 |
| 43302 | SP-9-8 | 44.0 | 9.41 | 148.0 | 6.5 | 99.3 |
| 39437 | SP-9-9 | 38.0 | 9.49 | 158.0 | 12.7 | 161.6 |
| 41908 | SP-9-10 | 26.0 | 9.09 | 139.0 | 14.4 | 176.6 |
| 34440 | SP-10-1 | 36.0 | 10.79 | 45.0 | 7.6 | 111.3 |
| 39458 | SP-10-2 | 34.0 | 10.20 | 63.0 | 10.2 | 137.8 |
| 39682 | SP-10-3 | 66.0 | 10.39 | 60.0 | 3.8 | 67.2 |
| 39374 | SP-10-4 | 58.0 | 10.79 | 145.0 | 25.7 | 269.7 |

| TreeID | Tree Code | Length [ft] | Butt Diameter [in] | decay length [cm] | decay diameter [cm] | Estimated decay length [cm] |
|---|---|---|---|---|---|---|
| 42769 | SP-10-5 | 52.0 | 10.51 | 237.0 | 17.4 | 203.2 |
| 39799 | SP-10-6 | 44.0 | 10.98 | 93.0 | 2.0 | 42.2 |
| 932139 | SP-10-7 | 46.0 | 10.98 | 258.0 | 17.8 | 206.5 |
| 905689 | SP-10-8 | 44.0 | 10.39 | 197.0 | 17.8 | 206.5 |
| 39617 | SP-10-9 | 56.0 | 10.12 | 81.0 | 5.1 | 83.3 |
| 40093 | SP-10-10 | 56.0 | 10.59 | 60.0 | 7.0 | 104.8 |
| 922473 | SP-11-1 | 36.0 | 11.42 | 136.0 | 17.3 | 202.3 |
| 39669 | SP-11-2 | 66.0 | 11.69 | 179.0 | 7.7 | 111.8 |
| 924887 | SP-11-3 | 78.0 | 11.30 | 75.0 | 7.6 | 111.3 |
| 908316 | SP-11-4 | 78.0 | 11.10 | 440.0 | 22.9 | 248.0 |
| 29875 | SP-11-5 | 56.0 | 11.81 | 63.0 | 5.1 | 83.3 |
| 41625 | SP-11-6 | 28.0 | 11.30 | 161.0 | 10.4 | 139.7 |
| 905739 | SP-11-7 | 60.0 | 11.61 | 258.0 | 22.9 | 248.0 |
| 29335 | SP-11-8 | 60.0 | 11.10 | 191.0 | 17.8 | 206.5 |
| 934960 | SP-11-9 | 88.0 | 11.42 | 258.0 | 15.2 | 184.1 |
| 41880 | SP-11-10 | 50.0 | 11.61 | 54.0 | 18.7 | 213.7 |
| 35119 | SP-12-1 | 44.0 | 12.72 | 45.0 | 6.4 | 98.2 |
| 917976 | SP-12-2 | 82.0 | 12.91 | 517.0 | 30.5 | 305.5 |
| 41953 | SP-12-3 | 48.0 | 12.01 | 158.0 | 19.2 | 218.2 |
| 29543 | SP-12-4 | 56.0 | 12.20 | 30.0 | 2.5 | 49.6 |
| 948949 | SP-12-5 | 58.0 | 12.28 | 121.0 | 12.7 | 161.6 |
| 41743 | SP-12-6 | 52.0 | 12.80 | 462.0 | 15.2 | 184.1 |
| 41431 | SP-12-7 | 36.0 | 12.28 | 231.0 | 25.4 | 267.5 |
| 803477 | SP-12-8 | 90.0 | 12.09 | 75.0 | 7.6 | 111.3 |
| 948968 | SP-12-9 | 72.0 | 12.52 | 121.0 | 12.7 | 161.6 |
| 39625 | SP-12-10 | 70.0 | 12.91 | 258.0 | 17.5 | 204.0 |
| 908509 | SP-8-11 | 44.0 | 8.82 | 410.0 | 7.6 | 111.3 |
| 41096 | SP-8-12 | 36.0 | 8.11 | 105.0 | 8.0 | 115.5 |
| 35819 | SP-8-13 | 28.0 | 8.50 | 111.0 | 8.9 | 124.8 |
| 931715 | SP-8-14 | 42.0 | 8.50 | 167.0 | 7.6 | 111.3 |
| 43335 | SP-8-15 | 40.0 | 8.82 | 148.0 | 13.5 | 168.9 |
| 922388 | SP-8-16 | 48.0 | 8.90 | 105.0 | 15.2 | 184.1 |
| 40566 | SP-8-17 | 32.0 | 8.50 | 182.0 | 15.5 | 186.8 |
| 42658 | SP-8-18 | 46.0 | 8.90 | 99.0 | 17.5 | 204.0 |
| 40668 | SP-8-19 | 40.0 | 8.70 | 60.0 | 12.7 | 161.6 |
| 908511 | SP-8-20 | 22.0 | 8.19 | 319.0 | 12.7 | 161.6 |
| 908513 | SP-9-11 | 38.0 | 9.80 | 136.0 | 12.7 | 161.6 |
| 938576 | SP-9-12 | 48.0 | 9.21 | 75.0 | 2.5 | 49.6 |
| 911868 | SP-9-13 | 50.0 | 9.80 | 151.0 | 10.2 | 137.8 |
| 924736 | SP-9-14 | 40.0 | 9.29 | 471.0 | 17.8 | 206.5 |
| 38094 | SP-9-15 | 42.0 | 9.09 | 112.0 | 6.4 | 98.2 |
| 29733 | SP-9-16 | 48.0 | 9.80 | 60.0 | 7.6 | 111.3 |
| 34873 | SP-9-17 | 48.0 | 9.88 | 105.0 | 3.6 | 64.6 |
| 39406 | SP-9-18 | 42.0 | 9.41 | 60.0 | 4.1 | 71.0 |
| 40428 | SP-9-19 | 36.0 | 9.02 | 30.0 | 5.3 | 85.6 |
| 43364 | SP-9-20 | 36.0 | 9.02 | 130.0 | 7.5 | 110.2 |
| 924726 | SP-10-11 | 40.0 | 10.51 | 228.0 | 17.8 | 206.5 |

| TreeID | Tree Code | Length [ft] | Butt Diameter [in] | decay length [cm] | decay diameter [cm] | Estimated decay length [cm] |
|---|---|---|---|---|---|---|
| 50545 | SP-10-12 | 44.0 | 10.04 | 130.0 | 15.0 | 182.4 |
| 938482 | SP-10-13 | 46.0 | 10.39 | 105.0 | 7.6 | 111.3 |
| 40127 | SP-10-14 | 36.0 | 10.79 | 105.0 | 14.3 | 175.7 |
| 40070 | SP-10-15 | 50.0 | 10.51 | 30.0 | 3.6 | 64.0 |
| 39298 | SP-10-16 | 60.0 | 10.51 | 63.0 | 11.4 | 149.4 |
| 42777 | SP-10-17 | 40.0 | 10.39 | 234.0 | 12.2 | 156.9 |
| 908039 | SP-10-18 | 32.0 | 10.91 | 471.0 | 17.8 | 206.5 |
| 42633 | SP-10-19 | 42.0 | 10.71 | 63.0 | 13.1 | 165.3 |
| 931861 | SP-10-20 | 88.0 | 10.91 | 197.0 | 12.7 | 161.6 |
| 30690 | SP-11-11 | 58.0 | 11.42 | 66.0 | 5.8 | 91.4 |
| 35883 | SP-11-12 | 56.0 | 11.30 | 167.0 | 15.2 | 184.1 |
| 936546 | SP-11-13 | 52.0 | 11.61 | 45.0 | 17.8 | 206.5 |
| 939378 | SP-11-14 | 60.0 | 11.30 | 75.0 | 5.1 | 83.3 |
| 29319 | SP-11-15 | 52.0 | 11.30 | 42.0 | 2.5 | 49.6 |
| 41891 | SP-11-16 | 46.0 | 11.50 | 243.0 | 19.1 | 217.0 |
| 938485 | SP-11-17 | 50.0 | 11.50 | 105.0 | 5.1 | 83.3 |
| 38357 | SP-11-18 | 38.0 | 11.10 | 99.0 | 15.2 | 184.1 |
| 39660 | SP-11-19 | 64.0 | 11.42 | 90.0 | 15.2 | 184.1 |
| 34606 | SP-11-20 | 64.0 | 11.50 | 75.0 | 12.7 | 161.6 |
| 29899 | SP-12-11 | 78.0 | 12.28 | 33.0 | 2.5 | 49.6 |
| 45769 | SP-12-12 | 58.0 | 12.60 | 39.0 | 9.3 | 128.8 |
| 932070 | SP-12-13 | 74.0 | 12.80 | 167.0 | 10.2 | 137.8 |
| 42370 | SP-12-14 | 38.0 | 12.60 | 96.0 | 17.8 | 206.5 |
| 939358 | SP-12-15 | 76.0 | 12.72 | 105.0 | 7.6 | 111.3 |
| 47649 | SP-12-16 | 84.0 | 12.01 | 237.0 | 24.1 | 257.4 |
| 917973 | SP-12-17 | 76.0 | 12.09 | 136.0 | 28.2 | 288.6 |
| 47645 | SP-12-18 | 80.0 | 12.72 | 243.0 | 20.9 | 231.7 |
| 39381 | SP-12-19 | 54.0 | 12.72 | 158.0 | 19.3 | 219.0 |
| 37865 | SP-12-20 | 62.0 | 12.20 | 45.2 | 5.1 | 83.3 |
| 905376 | RC-8-1 | 42.0 | 8.90 | 90.2 | 2.5 | 136.9 |
| 915428 | RC-8-2 | 40.0 | 8.11 | 151.2 | 5.1 | 204.8 |
| 907647 | RC-8-3 | 30.0 | 8.31 | 182.2 | 5.1 | 204.8 |
| 910228 | RC-8-4 | 22.0 | 8.19 | 364.2 | 15.2 | 379.4 |
| 905403 | RC-8-5 | 32.0 | 8.11 | 90.2 | 7.6 | 256.5 |
| 915420 | RC-8-6 | 46.0 | 8.19 | 90.2 | 12.7 | 342.8 |
| 928266 | RC-8-7 | 22.0 | 8.19 | 243.2 | 5.1 | 204.8 |
| 913216 | RC-8-8 | 18.0 | 8.39 | 304.2 | 10.2 | 302.9 |
| 921835 | RC-8-9 | 16.0 | 8.90 | 722.2 | 17.8 | 414.8 |
| 915438 | RC-8-10 | 30.0 | 8.31 | 151.2 | 12.7 | 342.8 |
| 907468 | RC-8-11 | 32.0 | 8.70 | 151.2 | 2.5 | 136.9 |
| 9934 | RC-8-12 | 44.0 | 8.58 | 334.2 | 5.1 | 204.8 |
| 8094 | RC-8-13 | 24.0 | 8.11 | 395.2 | 5.1 | 204.8 |
| 907493 | RC-8-14 | 30.0 | 8.58 | 120.2 | 5.1 | 204.8 |
| 915906 | RC-8-15 | 40.0 | 8.31 | 151.2 | 2.5 | 136.9 |
| 8978 | RC-8-16 | 26.0 | 8.19 | 93.2 | 12.7 | 342.8 |
| 915920 | RC-8-17 | 22.0 | 8.31 | 243.2 | 15.2 | 379.4 |
| 910144 | RC-8-18 | 32.0 | 8.19 | 273.2 | 12.7 | 342.8 |

| TreeID | Tree Code | Length [ft] | Butt Diameter [in] | decay length [cm] | decay diameter [cm] | Estimated decay length [cm] |
|---|---|---|---|---|---|---|
| 9926 | RC-8-19 | 28.0 | 8.50 | 392.2 | 10.2 | 302.9 |
| 801503 | RC-8-20 | 34.0 | 8.31 | 127.2 | 7.6 | 256.5 |
| 24238 | RC-9-1 | 30.0 | 9.69 | 486.2 | 15.2 | 379.4 |
| 28357 | RC-9-2 | 42.0 | 9.69 | 102.2 | 7.6 | 256.5 |
| 53822 | RC-9-3 | 28.0 | 9.33 | 445.2 | 4.5 | 190.8 |
| 37217 | RC-9-4 | 30.0 | 9.09 | 303.2 | 3.3 | 160.2 |
| 907446 | RC-9-5 | 32.0 | 9.49 | 120.2 | 17.8 | 414.8 |
| 910182 | RC-9-6 | 32.0 | 9.49 | 151.2 | 10.2 | 302.9 |
| 920752 | RC-9-7 | 40.0 | 9.49 | 120.2 | 2.5 | 136.9 |
| 915396 | RC-9-8 | 48.0 | 9.88 | 395.2 | 17.8 | 414.8 |
| 21034 | RC-9-9 | 30.0 | 9.41 | 160.2 | 7.6 | 256.5 |
| 902990 | RC-9-10 | 36.0 | 9.49 | 151.2 | 10.2 | 302.9 |
| 928280 | RC-9-11 | 24.0 | 9.80 | 212.2 | 12.7 | 342.8 |
| 9021 | RC-9-12 | 30.0 | 9.02 | 386.2 | 15.2 | 379.4 |
| 25738 | RC-9-13 | 34.0 | 9.02 | 145.2 | 10.2 | 302.9 |
| 9023 | RC-9-14 | 32.0 | 9.02 | 340.2 | 17.8 | 414.8 |
| 801986 | RC-9-15 | 34.0 | 9.80 | 364.2 | 10.2 | 302.9 |
| 8987 | RC-9-16 | 32.0 | 9.69 | 435.2 | 10.2 | 302.9 |
| 24598 | RC-9-17 | 32.0 | 9.80 | 243.2 | 10.2 | 302.9 |
| 905377 | RC-9-18 | 38.0 | 9.88 | 182.2 | 12.7 | 342.8 |
| 905372 | RC-9-19 | 30.0 | 9.29 | 303.2 | 17.8 | 414.8 |
| 913215 | RC-9-20 | 36.0 | 9.29 | 90.2 | 21.1 | 456.6 |
| 920735 | RC-10-1 | 30.0 | 10.98 | 90.2 | 2.5 | 136.9 |
| 9941 | RC-10-2 | 46.0 | 10.39 | 453.2 | 7.6 | 256.5 |
| 905379 | RC-10-3 | 46.0 | 10.31 | 273.2 | 17.8 | 414.8 |
| 915446 | RC-10-4 | 46.0 | 10.91 | 364.2 | 20.3 | 446.7 |
| 913251 | RC-10-5 | 24.0 | 10.79 | 90.2 | 2.5 | 136.9 |
| 9906 | RC-10-6 | 46.0 | 10.98 | 243.2 | 17.8 | 414.8 |
| 920776 | RC-10-7 | 48.0 | 10.12 | 151.2 | 7.6 | 256.5 |
| 24181 | RC-10-8 | 34.0 | 10.39 | 130.2 | 7.6 | 256.5 |
| 913249 | RC-10-9 | 36.0 | 10.31 | 151.2 | 5.1 | 204.8 |
| 9476 | RC-10-10 | 34.0 | 10.79 | 364.2 | 12.7 | 342.8 |
| 914047 | RC-10-11 | 38.0 | 10.51 | 151.2 | 10.2 | 302.9 |
| 25786 | RC-10-12 | 44.0 | 10.71 | 364.2 | 15.2 | 379.4 |
| 920719 | RC-10-13 | 48.0 | 10.00 | 166.2 | 7.6 | 256.5 |
| 33992 | RC-10-14 | 44.0 | 10.71 | 425.2 | 20.3 | 446.7 |
| 23987 | RC-10-15 | 44.0 | 10.51 | 486.2 | 10.2 | 302.9 |
| 915414 | RC-10-16 | 32.0 | 10.31 | 303.2 | 15.2 | 379.4 |
| 906135 | RC-10-17 | 42.0 | 10.71 | 151.2 | 5.1 | 204.8 |
| 43728 | RC-10-18 | 44.0 | 10.59 | 227.2 | 1.3 | 94.7 |
| 914022 | RC-10-19 | 34.0 | 10.12 | 151.2 | 5.1 | 204.8 |
| 27902 | RC-10-20 | 28.0 | 10.20 | 249.2 | 12.7 | 342.8 |
| 801941 | RC-11-1 | 38.0 | 11.18 | 151.2 | 2.5 | 136.9 |
| 9480 | RC-11-2 | 46.0 | 11.10 | 87.2 | 12.7 | 342.8 |
| 28261 | RC-11-3 | 30.0 | 11.50 | 303.2 | 7.6 | 256.5 |
| 33712 | RC-11-4 | 32.0 | 11.81 | 191.2 | 2.5 | 136.9 |
| 37392 | RC-11-5 | 42.0 | 11.30 | 364.2 | 13.0 | 347.3 |

| TreeID | Tree Code | Length [ft] | Butt Diameter [in] | decay length [cm] | decay diameter [cm] | Estimated decay length [cm] |
|---|---|---|---|---|---|---|
| 43734 | RC-11-6 | 40.0 | 11.18 | 185.2 | 13.4 | 352.6 |
| 907680 | RC-11-7 | 36.0 | 11.30 | 151.2 | 7.6 | 256.5 |
| 33715 | RC-11-8 | 36.0 | 11.81 | 364.2 | 15.2 | 379.4 |
| 21829 | RC-11-9 | 32.0 | 11.61 | 303.2 | 12.7 | 342.8 |
| 915603 | RC-11-10 | 44.0 | 11.30 | 243.2 | 12.7 | 342.8 |
| 915409 | RC-11-11 | 42.0 | 11.89 | 243.2 | 20.3 | 446.7 |
| 905387 | RC-11-12 | 46.0 | 11.42 | 151.2 | 12.7 | 342.8 |
| 915427 | RC-11-13 | 46.0 | 11.61 | 120.2 | 12.7 | 342.8 |
| 915445 | RC-11-14 | 46.0 | 11.18 | 182.2 | 15.2 | 379.4 |
| 804440 | RC-11-15 | 38.0 | 11.10 | 240.2 | 15.2 | 379.4 |
| 903358 | RC-11-16 | 48.0 | 11.81 | 182.2 | 10.2 | 302.9 |
| 52588 | RC-11-17 | 50.0 | 11.89 | 339.2 | 12.0 | 332.0 |
| 905381 | RC-11-18 | 38.0 | 11.89 | 212.2 | 22.9 | 478.2 |
| 907469 | RC-11-19 | 42.0 | 11.81 | 151.2 | 2.5 | 136.9 |
| 947208 | RC-12-1 | 54.0 | 11.42 | 304.2 | 10.2 | 302.9 |
| 913183 | RC-12-2 | 34.0 | 12.52 | 288.2 | 22.9 | 478.2 |
| 37382 | RC-12-3 | 62.0 | 12.72 | 234.2 | 11.9 | 330.4 |
| 5084 | RC-12-4 | 56.0 | 12.52 | 694.2 | 20.3 | 446.7 |
| 54872 | RC-12-5 | 46.0 | 12.13 | 172.2 | 14.0 | 362.2 |
| 24036 | RC-12-6 | 40.0 | 12.28 | 425.2 | 22.9 | 478.2 |
| 913255 | RC-12-7 | 36.0 | 12.80 | 243.2 | 20.3 | 446.7 |
| 915410 | RC-12-8 | 48.0 | 12.72 | 273.2 | 12.7 | 342.8 |
| 928342 | RC-12-9 | 44.0 | 12.01 | 105.2 | 2.5 | 136.9 |
| 9922 | RC-12-10 | 64.0 | 12.52 | 243.2 | 20.3 | 446.7 |
| 910195 | RC-11-20 | 36.0 | 12.72 | 624.2 | 20.3 | 446.7 |
| 947205 | RC-12-11 | 62.0 | 12.99 | 426.2 | 22.9 | 478.2 |
| 6689 | RC-12-12 | 60.0 | 12.80 | 352.2 | 12.7 | 342.8 |
| 19317 | RC-12-13 | 48.0 | 12.80 | 310.2 | 5.1 | 204.8 |
| 8997 | RC-12-14 | 38.0 | 12.01 | 273.2 | 10.2 | 302.9 |
| 32690 | RC-12-15 | 30.0 | 12.40 | 264.2 | 10.2 | 302.9 |
| 907565 | RC-12-16 | 42.0 | 12.40 | 395.2 | 17.8 | 414.8 |
| 915365 | RC-12-17 | 40.0 | 12.80 | 90.2 | 2.5 | 136.9 |
| 947182 | RC-12-18 | 40.0 | 12.99 | 334.2 | 17.8 | 414.8 |
| 22592 | RC-12-19 | 46.0 | 12.91 | 303.2 | 7.6 | 256.5 |
| 22544 | RC-12-20 | 52.0 | 12.80 | 395.2 | 12.7 | 342.8 |