OPTIMAL BUCKING OF DOUGLAS FIR TAKING INTO CONSIDERATION EXTERNAL PROPERTIES AND WOOD DENSITY

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(Received for publication 12 August 2005; revision 11 January 2006)

ABSTRACT

During recent years niche markets have begun to demand forest products with specific characteristics. Traditionally markets required products with particular external log properties such as a specific diameter, length, and knot size. However, today's log markets are beginning to include new wood properties, such as basic density and stiffness. Although markets have not accompanied these new requirements with price incentives for producers to meet such demands, the new characteristics are nevertheless valued by these markets. An optimal bucking procedure, which included wood density, was developed. Four hypothetical market scenarios, covering a range of density specifications and price incentives, were evaluated, and results showed that in a density-constrained scenario the total revenue could be substantially less than in a scenario which did not specify density.

Keywords: optimal bucking; internal wood properties; basic density; value recovery.

INTRODUCTION

Forest harvesting has become increasingly mechanised during the last few decades. The drivers for this worldwide trend are the potential for improving productivity and reducing costs, as well as labour-related and safety issues. Mechanisation brings with it innovative communication and measurement systems, as well as introducing powerful on-board computers into the forest. These provide opportunities to:

- reduce the variability in product performance by sorting for niche uses;
- capture and store detailed descriptions of many stems within each stand;

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New Zealand Journal of Forestry Science 35(2): 139–152 (2005)

- reduce the variability in decision-making about which are the best markets to supply from each tree;
- and optimally control the bucking of logs at harvesting time (Murphy *et al.* 2004).

The objective of wood allocation from the forest owners' perspective is to maximise the economic return from the logs optimally bucked from each tree. The log buyers' objective is to obtain logs which can be optimally processed to yield maximum economic return and the best product performance based on solid wood and fibre qualities. The price the buyer is willing to pay depends on how well the supplier's logs meet his objectives.

Differences in tree architecture and chemistry within the stem of a tree and between trees and growth sites can result in different wood and fibre structure and product performance characteristics, leading to different economic returns for producers (Corson 2001). Industry has begun to incorporate these differences and specifications strategically to achieve optimal allocation and processing of the forest estate.

Each tree can be segmented for wood utilisation on the basis of stem quality, as determined by its macro-scale properties. Value recovery operations, therefore, must ensure the extraction of the more valuable solid wood grades. Poor attention to value recovery can result in substantial losses for the forest owner; value losses during bucking of 30% and higher have been reported (Geerts & Twaddle 1984; Sessions 1988; Haynes & Visser 2004; Boston & Murphy 2003; Murphy 2003). Separation into multiple log-sorts in-forest to meet market needs can have an impact on a range of harvesting production variables such as equipment requirements, value recovery, waste generation, productivity, cost, and landing size. These in turn can affect the overall economics of the operation.

The number of characteristics used to specify log-types is increasing. Traditionally, species, dimensions, and external quality characteristics such as branch size, sweep, scarring, and decay have been used to specify a particular log-type. However, today markets are beginning to include additional characteristics to specify the logs they require. For instance, consideration is now being given to such wood properties as stiffness, strength, density, spiral grain, extractives content, and consumption of energy for processing (Andrews 2002; So *et al.* 2002; Walker 2000; Young 2002).

Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) was selected for this study since it is of considerable economic importance, especially for the forest products industries of the United States, New Zealand, and some parts of Europe (Gartner *et al.* 2002) due to its primary uses as dimension lumber, piles, plywood, and pulp. Basic density was used since it is an internal property measure which is common to most markets as it provides an excellent means of predicting end-use characteristics of wood such as strength, stiffness, hardness, heating value, machinability, pulp yield, and paper-making quality (Jozsa & Brix 1989). Knowles *et al.* (2004) showed, for example, that outerwood density cores provided a reasonably accurate method for assessing breast height stiffness of individual standing Douglas fir trees. Although today there are no formal markets paying a differentiated price for logs with a determined basic density, they clearly prefer products with a higher density (Corson 2001). For this reason it was considered important to evaluate the economic consequences of hypothetical market scenarios which wood producers might face in coming years.

The distribution of basic density of Douglas fir from Canada, the United States, Europe, and New Zealand tends to be bell-shaped, with a mean between 400 and 500 kg/m^3. Density for individual trees in the Western United States ranges between 330 and 570 kg/m^3 (Anon 1965). Understanding the sources of variability of properties such as density will allow industry to better match wood to markets. In 1959, Knigge (1962, cited in Anon. 1965), selected five trees from each of 51 second-growth (< 100 years old) Douglas fir stands situated between the Canadian border and northern California and from the Coast Range to the western slopes of the Cascades. In general, density increased with age, improved with site class, increased with average growing season temperature, and decreased with increasing growing season precipitation and increasing elevation. However, only 34% of the variation between individual trees could be accounted for. Acuna & Murphy (in press) studied the spatial variation of density for Douglas fir in Western Oregon, and found that the only statistically significant variable (albeit weakly significant) was the height within the tree. Silvicultural management (e.g., pruning and spacing) has also been shown to affect density in some trees (Megraw 1986a, b).

Bucking individual Douglas fir stems into logs based on wood density will require tools for rapidly assessing density in the forest. Near-infrared spectroscopy is one of the emerging technologies that shows promising potential for this task (Acuna & Murphy unpubl. data A; So *et al.* 2004).

Bucking Algorithms

One of the most important processes during harvesting is bucking. The reasons for bucking a tree into sections are reduction of weight, segregation of defects and unmerchantable portions of the bole, adaptation to method of transportation and manufacture, and adaptation to market requirements (Conway 1982). Not all parts of a tree stem are merchantable. Therefore a key decision is how to cut the tree stem into different sections, which are commonly referred to as logs.

The process of producing logs from tree stems which achieves the highest value is known as bucking optimisation (Pickens *et al.* 1997). Bucking optimisation problems may occur at the stem level, at the stand level, and at the forest level. At the stem level, the bucking pattern that maximises the individual stem value is determined. At the stand level, the best pattern for each stem and class is established (e.g., based on diameter at breast height), and the aggregate production value is maximised (Arce *et al.* 2002). At a forest level, the bucking pattern for each stand which maximizes global profit is established. A second segregation of problems (models) is referred to as buck-to-value and buck-to-order. The former deals with the optimal bucking of an individual tree, whereas the latter solves the problem of bucking multiple trees subject to demand constraints (Kivinen & Uusitalo 2002; Marshall 2005).

Most solutions for bucking optimisation at the stem level are based on the use of techniques such as dynamic programming (DP), network programming, simulation, and integer-linear programming (Briggs 1980; Nasberg 1985; Sessions 1988). Among these, dynamic programming is the mathematical technique most employed by researchers. The first detailed and published description of the algorithm appeared in a paper by Pnevmaticos & Mann in 1972. In New Zealand, Geerts & Twaddle (1984) developed a dynamic programming algorithm which was implemented in a software package called AVIS (Assessment of Value by Individual Stems). Their formulation considered stem quality deterministically, and each potential log was checked to make sure that the stem qualities did not violate the required log type quality.

Published studies on optimal bucking, which have incorporated internal (or non-traditional) variables in the bucking decisions, are difficult to find, but wood density has been included in at least one commercial bucking system (Atlas 2006). Given the changing market requirements for forest products, it is important that the economic impact of a wider range of variables be evaluated.

In the early 1990s value recovery audits of 10 logging crews were undertaken for a New Zealand forest company. One of the sawmills supplied by the forest company would not accept sawlogs from stem heights above 20 m in each stem because of concerns about low-density wood occurring above this height. The 20-m breakpoint for density was incorporated into the value recovery audits based on optimal bucking (G. Murphy pers. comm.).

Objective of the Study

The objective of this study was to determine the effect of density specifications on volume by log-type, as well as total volume and revenue. The study used hypothetical scenarios with different market requirements for density of the log-types in order to see the potential impact of density on decision-making and on the economics of the forest operation.

METHODS

Field Site and Tree Data Set

The data used in this study were collected from a dominant industrial Douglas fir stand in the Pacific Northwest (Washington State). The site was selected based on logistics (location, and crew willingness to be studied) and the number of log-types being cut. Net stocked area of the stand was 12.18 ha, with an average stocking of 273 stems/ha. It was on mainly flat ground with an access road through the middle, and was clearfelled. The estimated average tree size was 2.35 m^3, and average diameter at breast height (dbh) was 46 cm based on field measurements made in 1997 and grown-on using tree growth models to give the stand parameters at time of harvesting (Marshall 2005).

One hundred stems were used for testing the bucking procedure which was based on both external and internal properties. Detailed measurements were recorded in the field to characterise each stem (Marshall 2005). The variables used in the bucking model were height, diameter, volume, quality, and density. These were assessed at intervals of 0.1 m along the stem because log lengths were in multiples of 0.1 m.

Density was not measured by Marshall (2005). Basic density was, therefore, estimated for each 0.1-m section of the stem by using a regression equation obtained from 391 wood samples of trees (Douglas fir) located in 17 young growth stands in the Coastal and Cascade Ranges of Oregon (Acuna & Murphy in press). The density equation used was as follows:

$$\text{DENSITY} = 427.1 - 3.3 * \text{HEIGHT} \qquad (R^2 = 0.26)$$

where, DENSITY = basic density (kg/m^3) for the outer portion of the tree.
HEIGHT = height above the base of the tree (m)

This density function should not be taken as being representative of all Douglas fir stands.

Market Requirements

The same market requirements (product specifications) were applied to all the stems (Table 1). Ten log-types plus waste were included in the analysis. Nine of the log-types included multiple lengths of 0.6 m. Fibre included multiple lengths of 0.1 m. A total of 122 log lengths were included in the analysis. Supply-constrained markets were assumed — this meant that production of any particular log-type was not limited by demand. The log supplier could, therefore, cut as much of each log-type as required to maximise his value recovery. The quality required for each type of log was assessed by the bucking model. The log-types included were sawlogs for export (log-types ES1, ES2, ES3, ES4), and sawlogs and chipsaw logs

TABLE 1–Market requirements and constraints for the test stems.

Log-type	Lengths (m)	Minimum small-end diameters (mm)	Relative market prices* ($/m^3)	Quality required
ES1	8.0 to 9.8	305	149	A
ES2	11.0 to 12.2	305	132	A
ES3	8.0 to 9.8	305	125	ABC
ES4	9.8 to 11.0	229	93	A
DS1	4.9 to 7.3	305	104	ABC
DS2	11.0 to 12.2	305	97	ABCD
DS3	4.9 to 7.3	203	77	ABCD
CNS1	4.9 to 7.3	127	68	ABCDE
CNS2	7.3 to 9.1	127	68	ABCDE
FIBER	3.7 to 12.2	127	22	ABCDE

* Prices reflect market conditions as of late 2002.

for domestic markets (log-types DS1, DS2, DS3, CNS1, and CNS2). Pulpwood was included in the analysis (log-type FIBER).

The quality codes in Table 1 relate mainly to the size of knots (Table 2).

TABLE 2–Quality codes and their characteristics

Code	Knot size (cm)	Code	Knot size (cm)
A	< 3.8	D	> 6.3 and < 7.6
B	> 3.8 and < 5.1	E	> 7.6
C	> 5.1 and < 6.3	W	Waste

Density Scenarios

Density could be specified in at least three different ways: the minimum density found at any point along the length of a log, the average density found for a series of measurements along the length of a log, and the average density weighted by volume for a series of measurements along a log (which most closely relates to weight scaling of logs). The density scenarios used in this paper refer to average basic density weighted by volume.

Four different scenarios were used to model the impact of density on volume recovery by log-type and on total value recovery (Table 3). These were chosen to reflect a range of possible market conditions and are by no means exhaustive.

The first scenario was the control scenario — no density requirements were imposed (current situation for traditional bucking procedures). The second scenario specified the highest densities. Each log-type required a high density to meet the constraints imposed by the market especially for the most valuable products,

TABLE 3–Scenarios for density requirements used in the analysis

Logs	*Scenario 1 minimum density required (kg/m^3)	Scenario 2 minimum density required (kg/m^3)	Scenarios 3 & 4 minimum density required (kg/m^3)
ES1	0	450	450
ES2	0	450	400
ES3	0	450	400
ES4	0	400	350
DS1	0	400	350
DS2	0	400	300
DS3	0	350	300
CNS1	0	350	300
CNS2	0	300	300
FIBER	0	300	300

* Control scenario.

domestic and export sawlogs. No price premiums were specifically allocated to higher density logs. The third scenario could be considered one with average density requirements and was less constrained than the second scenario. Again no price premiums for density were included in the third scenario.

Scenario 4, however, did use a differential price for each log-type, according to the wood density of logs. For this purpose, three density classes were established with corresponding prices for each log-type. These prices are shown in Table 4 and are based on expected product yields, revenues, and processing costs for each log-type. A more detailed description of how the prices were calculated is reported by Acuna & Murphy (unpubl. data B).

Again, it is stressed that Scenarios 2, 3, and 4 are not based on real markets. They were selected only for demonstration purposes.

TABLE 4–Scenario 4 log prices ($/m^3) by basic density class and log-type

Log-type	Lower class (300–399 kg/m^3)	Middle class (400–499 kg/m^3)	Upper class (500–600 kg/m^3)
ES1	136.0	149.0	154.5
ES2	120.3	131.7	136.5
ES3	114.7	125.4	129.9
ES4	85.2	93.2	96.6
DS1	94.2	103.5	107.4
DS2	88.0	96.8	100.5
DS3	70.0	76.6	79.4
FIBER	15.7	21.9	28.7

Dynamic Programming Algorithm

A dynamic programming algorithm was implemented in a system called IP-BUCK (bucking with internal properties) which was developed by the first author of this paper in the programming language Visual C++™. The outputs given by the system correspond to the volume and number of logs by each log-type, as well as the total volume and value produced after optimally bucking a set of stems.

Two different files are required to run the dynamic programming algorithm: the stem file and the log specification file. For each stem, the stem file contains information on height, diameter, volume, quality, and density. The log specification file contains requirements for each log-type to be produced — normally, the small- and large-end diameters (SED, LED), relative market prices, lengths, quality, and density (*see* Table 1). This file also includes the possible lengths of each product (multiple lengths) which correspond to the different stages in the DP algorithm. The basic steps of the algorithm can be summarised as follows:

(1) Starting from the butt of the stem (stage = 0), look at all feasible next lengths for each log-type.

(2) Move to the minimum stage (given by the smallest multiple length of the set of log-types).

(3) For each log-type check SED and LED within bounds given by the list.

(4) From the last stage to the current location, read and check Quality and Density.

(5) Calculate cumulative value to current stage and keep the highest solution.

(6) Repeat steps 1–5 with the rest of the stages until the whole stem is analysed.

RESULTS

The effect of density on the volume per log-type is shown in Fig. 1. There were large variations for the four scenarios. In the control scenario more than half of the total volume (54%) was assigned to ES1, and another 15% to pulpwood (FIBER). The waste in this scenario was relatively low at 7% of the total volume.

In Scenario 2, the export sawlogs (ES1, ES2, and ES3) required a basic density of at least 450 kg/m^3 which was not met by any log. Hence, the volume was concentrated in domestic sawlogs DS2 (56% of the total volume). Also, there was a substantial increase in the volume of pulpwood (FIBER) compared to the first scenario,increasing from 15% to 31%. The waste volume remained the same as for the first scenario.

In Scenario 3, volume was distributed across more products than the previous scenarios. Although most volume was concentrated in the export sawlog grade (ES2 (42%), there were other products with a high share of volume, such as ES3, DS1, and FIBER with 12%, 14%, and 17%, respectively. This means that there

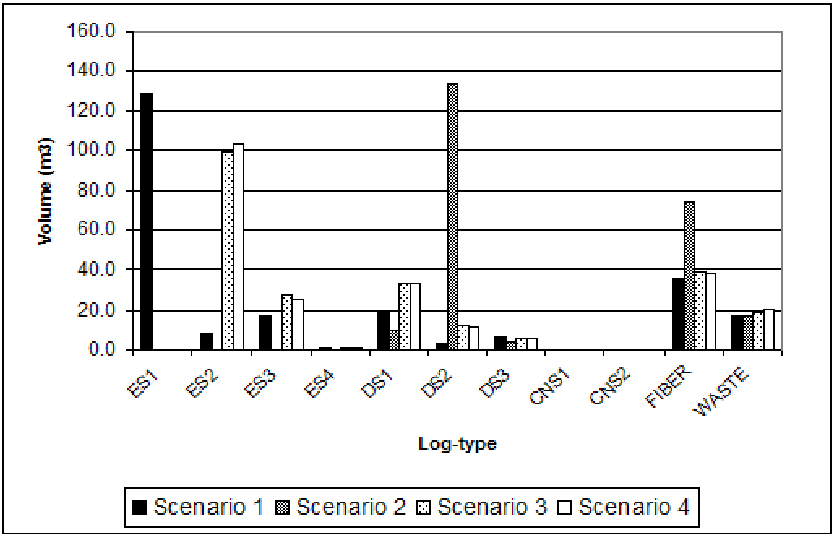

FIG. 1–Effect of density on volume per log-type

were logs which could meet a basic density requirement of 400 kg/m^3, but not of 450 kg/m^3. Also it is important to mention that, in this scenario, there was a reduction in the pulpwood (FIBER) volume compared to the second scenario (from 31% to 17%) and a slight increase in the waste (from 7% to 8%).

In Scenario 4 the percentage values were similar to those of Scenario 3 in terms of volume per log-type. Where there were differences, they were minimal: the export sawlog grade ES2 represented 43% of the total volume in Scenario 4 and 42% in Scenario 3, log-type ES3 represented 11% in Scenario 4 and 12% in Scenario 3, and FIBER represented 16% in Scenario 4 and 17% in Scenario 3. Waste constituted 8% in both scenarios.

The effect of density on the distribution of the number of logs per log-type is shown in Fig. 2. In the control scenario the number of logs was concentrated in basically three products, ES1, DS1, and FIBER with 27%, 10%, and 31% of the total number of logs produced, respectively. The number of pieces assessed as waste in this scenario was about 19% of the total number of logs (348 pieces).

In the second scenario, half of the total number of logs produced were pulp logs (FIBER, 149 logs), and 23% of the logs were concentrated in the product DS2. There was a reduction in the total number of logs compared to the first scenario (from 348 to 301 logs). The proportion of pieces assessed as waste in this scenario remained the same as in the first scenario (19%).

In Scenario 3 more logs were distributed across more products than in the previous two scenarios. The highest percentages of logs were found in products ES2 (17%),

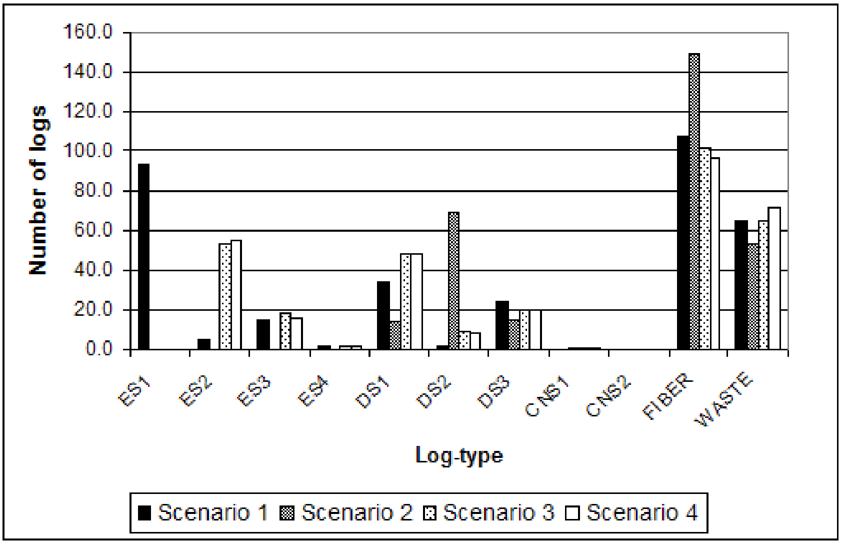

FIG. 2–Effect of density on the number of logs per log-type

DS1 (15%), and FIBER (32%). There was an increase in the total number of logs compared to the second scenario (from 301 to 317 logs), and an increase in percentage of pulpwood (FIBER) from 18% to 21%.

In Scenario 4, only the percentage in log-type FIBER was different from that in Scenario 3, decreasing from 32% (Scenario 3) to 30% (Scenario 4). Conversely, waste increased 1% from Scenario 3 (21%) to Scenario 4 (22%). Although the total number of logs produced in Scenarios 3 and 4 was the same (317 logs), the distribution by log-type presented some changes. The most important variation was in log-type FIBER, with the number of logs reducing from 101 (Scenario 3) to 96 (Scenario 4). This difference was due to the variation in price for logs with different wood density. In Scenario 3 just one price was used, which corresponded to the price associated with the middle class (400–499 kg/m^3) of Scenario 4. However, as the density market requirement for this FIBER was 300 kg/m^3 or greater, most logs that barely met this requirement received the price for the lower density class (<400 kg/m^3), which was considerably lower than that of the middle class (\$21.9/m^3 *vs* \$15.7/m^3). This explains the reduction in the number of logs in log-type FIBER, and the increase in other log-types, such as ES2 which increased from 53 (Scenario 3) to 55 (Scenario 4).

The effect of density on the total value recovered is shown in Fig. 3. Total value recovered decreased as the density became more constrained. However, what is important to evaluate is the magnitude of these changes. When Scenario 2 is compared with the control scenario, there is a reductionof 40% in the total revenue (from \$25,890 to \$15,550). This is in response to the high density constraints which

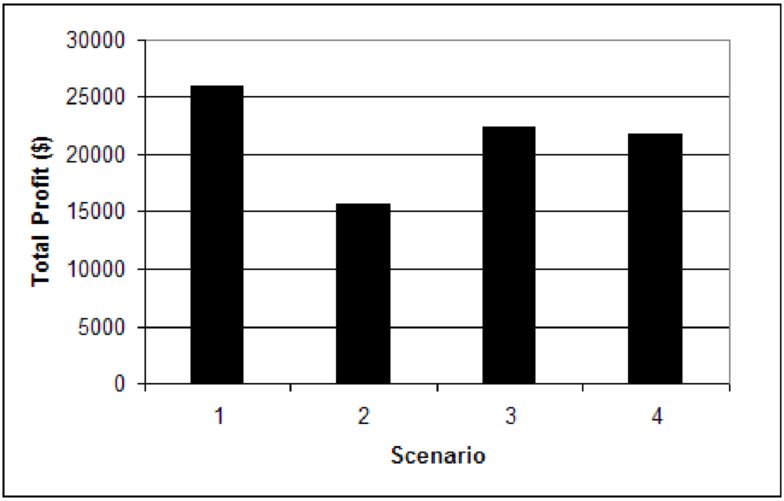

FIG. 3–Effect of density on total value recovery

did not allow the production of the most profitable log-types (sawlogs for export). Pulpwood became the predominant log-type in this scenario. Similarly, comparing the first with the third and fourth scenarios, the total value recovered decreased 13.5% and 15.7%, respectively. These results are very sensitive to the assumed market density requirements and to the density equation used.

DISCUSSION AND CONCLUSIONS

Bucking and sorting based on density could be expected to improve mill economic recoveries. This study showed that optimal bucking algorithms can be easily modified to include internal wood properties such as density, but the inclusion of this property could be expected to change the distribution of the number of logs as well as the merchantable volume of each log-type. This has implications for log handling costs. In addition, optimally bucking stems based on basic density may reduce the total value recovered by the forest owner, unless appropriate premiums are paid for additional properties. Assuming no increase in price for higher density wood, the result could be value losses as high as 40% for the forest owner. We repeat, however, that this change in recovered value is very sensitive to the density requirements we assumed and to the tree characteristics we modelled.

There are limitations associated with this study, which affected the results and our conclusions: only one stand was used, only two sets of market conditions were evaluated (one with and one without premiums for log-types meeting a specific density requirement), hypothetical density classes (scenarios) were used, and a density function was used rather than actual densities, to calculate the density at each segment of a stem.

A particular limitation which requires additional comment, is that the maximum density that could be predicted by the density model used in the study was 427 kg/m^3. This was below the 450 kg/m^3 limit for the most valuable log types used in the analyses. It was also well below the upper limit reported for Douglas fir density for individual stems (~570 kg/m^3) (Anon 1965). Use of an alternative density model, or real density measurements, could result in a different set of changes in log product yields and value recovery.

Future research should cover a number of topics. These include:

- The effect of a wider range of stand conditions and market scenarios on log product yields and value recovery when density is included as a log quality attribute.
- The impact of inaccurate density measurements or predictions on optimal bucking and value recovery.
- The effect on revenue of including density in demand-constrained markets.
- The impact of wood properties, other than density, in increasingly competitive markets.
- The effect of the new requirements on the cost of log production. We observed that there were different distributions of products and a tendency for a reduced number of logs when using a constrained-density scenario. Generally, as the number of logs increases the bucking cost increases and the value-recovery diminishes. Studies indicate that an increase in the complexity of the decision-making by adding more log-types can result in a drop in actual value-recovery (Parker *et al.* 1995; Murphy *et al.* 2003).

Log producers should expect the evolution of log markets with new requirements and be prepared for such changes. Although the scenarios (markets) evaluated here were hypothetical, the results presented gave an indication of the potential impacts of the new market requirements on log product yields and value recovery from the forest owner's perspective, and demonstrated how internal properties could be included in optimal bucking systems.

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