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Lucas Patrick Townsend

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HARVESTING FOREST BIOMASS IN THE US SOUTHERN ROCKY MOUNTAINS

By

LUCAS PATRICK TOWNSEND

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Thesis

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Approved by:

Scott Whittenburg, Dean of The Graduate School
Graduate School

Dr. Elizabeth Dodson, Chair
Department of Forest Management

Dr. John Goodburn
Department of Forest Management

Mr. Steve Hayes
Bureau of Business and Economic Research

Dr. Nathaniel Anderson
USDA Forest Service Rocky Mountain Research Station

Townsend, Lucas, Master of Science, August 2019 Forestry

Harvesting Forest Biomass in the US Southern Rocky Mountains

Chairperson: Dr. Elizabeth Dodson

Abstract

Ponderosa pine (*Pinus ponderosa*) and other mixed conifer forests of the United States southern Rocky Mountains (SRM) evolved under a low-severity, high-frequency fire regime. With the arrival of Euro-American colonists, fire was excluded from most forests, causing stands to grow dense and become prone to uncharacteristic high-severity crown fires. To combat wildfire threat, restoration treatments are frequently used to restore historic stand structure and function, effectively reducing high-severity fire risk. However, these treatments may be costly and little information is available regarding the forest operations used in the SRM.

In this thesis, five forest operations were studied in 2017 to quantify and benchmark cost and production rates. Individual contractors were then provided a set of suggestions to improve their operational efficiency, ranging from proper equipment use, to obtaining different types of machines and using different harvest systems. In 2018, we followed up with three of the five operations and observed their "improved" operations and calculated updated cost and production rates. In 2017, we found that the average cost of a forest operation was \$26.92 gt^{-1} (\$24.42/ton) of logs produced. If forest residues were comminuted as part of treatment, on average they cost \$9.17 gt^{-1} (\$8.32/ton) to produce. In 2018, after "improvements" had been implemented by contractors, we found that operations were on average 18% more cost effective. Biomass energy opportunities exist in this region as forest restoration efforts continue but current operations are largely restricted by market forces.

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This project would not have been possible without the contractors who offered their time and allowed us to study their operations, for which I am very grateful. Credit is also due to the U.S. Forest Service for conducting landscape-scale forest restoration and supporting the regional forest products economy.

Lastly, special thanks also go out to my family and partner D.T. for outstanding encouragement, patience, and support.

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1.0 Introduction and Literature Review to Harvesting Forest Biomass in the Southern Rocky Mountains

1.1 Background Information

The ponderosa pine (*Pinus ponderosa*) and mixed-conifer forests of the United States (US) southern Rocky Mountains (SRM) were historically characterized by a low-severity frequent-fire regime (3 to 6-year fire return interval) that supported low-density, open, park-like forest structures (Fulé et al. 1997). Compared to reference conditions, most stands have grown uncharacteristically dense and are more susceptible to high-severity crown fire from land-use changes caused by Euro-American colonization (Covington and Moore 1994). Human land-use practices have reduced the total amount of carbon ecosystems can store (Erb et al. 2018) and future high-severity wildfires in the SRM threaten forest regeneration in ponderosa pine forests due to a warming climate (Davis et al. 2019). Many of these forests do not support historic ecological functions and biodiversity has declined, resulting in consensus among scientists and managers that forest restoration in this region is a necessity (Allen et al. 2002). Restoration in this region can be achieved in several ways, one of which is mechanical treatments, often followed by prescribed fire (Allen et al. 2002; Reynolds et al 2013).

Mechanical restoration treatments are a common and practical method to restore stands to historic structures and reduce wildfire severity (Pollet and Omi 2002). Many land managers agree that mechanical treatments are necessary prior to implementing a prescribed fire regime, especially near places of development and outside of wilderness areas (Allen et al. 2002; Hampton et al. 2008). These mechanical restoration treatments have proven to be ecologically successful, quickly restoring stand structure (Larson and Churchill 2012), ecosystem function in both vegetation and soils (Falk 2006; Grady and Hart 2006), and species richness (Stoddard et al. 2011), all while providing future resilience to fire in a changing climate (Fulé 2008).

A restoration treatment in the context of this study is a silvicultural treatment that uses mechanical thinning to reduce stand density in a heterogenous fashion to promote historic ecosystem structure, function, and species richness based upon a reference condition. A fuels treatment is also a silvicultural treatment; however, the focus of a fuels treatment is to reduce stem density, surface fuels, and crown base height so that high-severity fire is less likely (Agee and Skinner 2005). While these two silvicultural treatments are identified separately, a restoration treatment can also function as a fuels treatment in fire-adapted forests because their historic structure naturally promotes resilience to high-severity fire. For example, a simulation study in northern Arizona showed that a spatially heterogenous restoration treatment required wind speeds twice as high to initiate crown fire compared to untreated stands, and that untreated stands would have experienced 48% more crown fire under severe fire-weather conditions (Fulé et al. 2001). The primary difference between a fuels treatment and a restoration treatment is that a restoration treatment is focused on a heterogenous pattern of residual individual trees, rather than even spacing that is typical of fuels treatments (Larson and Churchill 2012). The heterogenous spacing involves clumps of trees where individuals are in close proximity to each other in addition to wide gaps in the forest canopy that resemble a reference condition (Larson and Churchill 2012). While restoration treatments on the stand-scale are ecologically focused, large, landscape-scale projects like the Four Forests Restoration Initiative (4FRI) and White Mountain Stewardship Project also have economic intentions of stimulating forest product economies (Lucas et al. 2017; Neary and Zieroth 2007). These restoration treatments differ from conventional timber harvests as their goal is not to maximize volume harvested or profit, but to restore ecological functions and historic stand structures while using product revenue to offset treatment costs. In the SRM, this typically means leaving the largest, dominant trees standing and harvesting smaller-diameter stems and regeneration.

Executing restoration treatments from an operational perspective can be economically challenging due to the low-value stems cut during harvest. These small-diameter, low value products have challenged the regional forest products market. One outlet for these products is to utilize the wood for biomass energy (Hayes et al. in press). Forest operations and their role in harvesting forest biomass is an important component of the renewable energy sector. While forest biomass comprises only 0.6% of all electricity production in the US (EIA 2017), there are other forms of biomass energy such as wood pellets for home-heating and traditional fuelwood which many operations in the region frequently produce (Hayes et al. in press). Biomass energy products in the form of hog fuel for thermoelectric power, wood pellets, and fuel wood, along with products used for erosion control and animal bedding, now account for the highest sales by value in the SRM (Hayes et al. in press). Because biomass products are expensive to produce, optimizing forest operations is an important step towards the continued viability of biomass energy and regional forest restoration.

In 2016 Arizona produced 76.4 million board feet (MMBF), 63% of which came from National Forest System Lands, 35% from private and tribal lands, and 2% from other public lands (Hayes et al. in press). Harvest volume was up 7% from 2012 and 42% from 2007, however, this volume is still only 57% of what it was in 2002, demonstrating recovery in partial response to the White Mountain Stewardship Project (Hayes et al. in press). In 2016, New Mexico harvested 26.4 MMBF, 62% of which came from National Forest Systems Lands, 34%

from private and tribal lands, and 4% from other public lands (Hayes et al. in press). This is only 73% of the 2007 harvest, and 30% of the 1997 harvest (Hayes et al. in press). In 2016, 116.7 MMBF was harvested in Colorado, 65% of which came from National Forest System Lands, 29% from private lands, and 6% from other public lands (Hayes et al. in press). However, most of this harvested material is from the northern portion of the state and not considered part of the SRM. The two counties near the study area combined contributed 0.8% of the statewide volume produced in 2016. Volume produced from the entire state increased by 42% compared to the 2012 harvest and 35% from the 2007 harvest (Hayes et al. in press). Overall, this entire region has shown a considerable decrease in volume produced over the last two decades. Modern markets show that now sawlogs and other sawn materials only account for 35% of sales in the region, and other markets now account for the majority of sales (Figure 1.1)

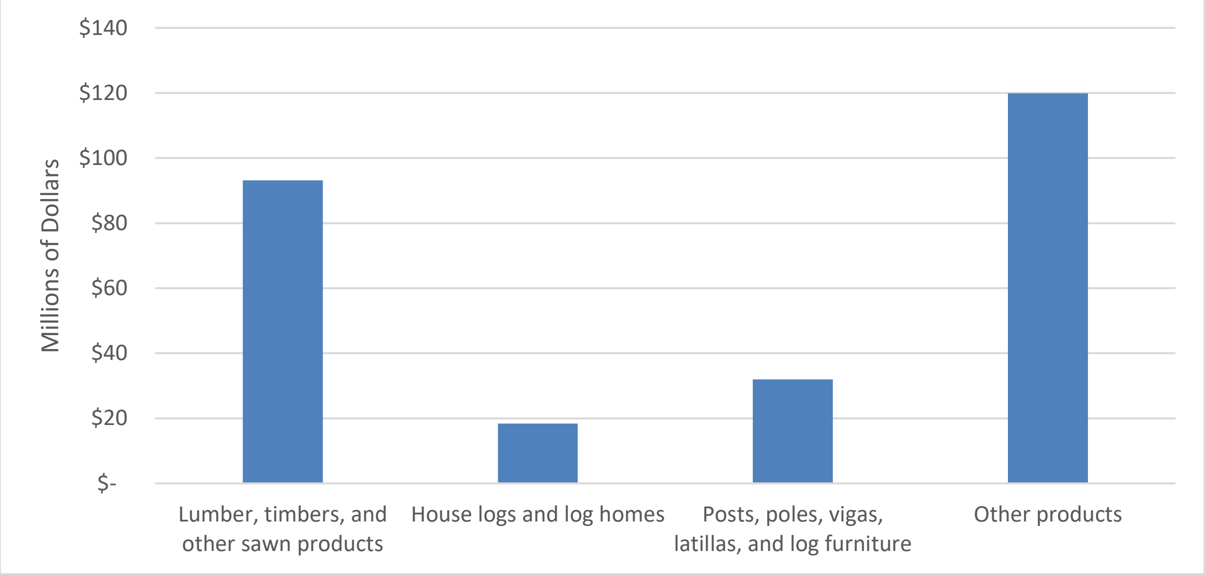

Figure 1.1 The Four-Corners regional timber market product mix by raw value and percent of sales. “Other products” are considered biomass material for electricity, shavings, firewood, fuel pellets, erosion control products, clean chips, mulch, animal bedding, utility poles, and mill residues.

Forest operations research is the study of harvesting wood fiber-based forest products through the examination of harvest productivity, costs, system design, implementation, and the associated factors required to address each of those topics (adapted from Heinimann 2007). Forest operations and engineering research has played an important role in understanding the costs of integrating sawlogs and biomass harvest, as is often the case in restoration and fuels treatments. For example, a study examining a fuels treatment in Oregon found that harvesting small diameter biomass stems during a fuels treatment as part of the commercial harvest cost 176% more than if the biomass material had been left untreated (Bolding et al. 2009). However, this study showed that the cost of removing that biomass material separately, independent of a sawlog harvest, would have been $968.96 more per acre than product revenue. Since both biomass and merchantable wood were harvested simultaneously, the cost of treatment was only $96.96 per acre more than product revenue. This study demonstrated that harvesting small diameter and non-merchantable material as part of one commercial harvest may be more economically efficient than conducting two separate entries for landowners seeking to treat small diameter stems, but that doing so may incur a net cost. In this context, biomass harvest may improve the financial outcome of a treatment or erode the profitability of a treatment depending on whether the baseline is a fuel treatment with high net costs or a timber harvest with high net revenue.

A study in northern California showed that using a feller-buncher to cut small diameter stems as part of a restoration treatment was particularly expensive, resulting in 71% of the total felling costs when 80% of the cut trees did not contain a sawlog (Vitorelo et al. 2011). Other sawlog harvesting functions in this study were not significantly influenced by harvesting biomass, as those same functions did not require extra steps to exclusively handle the biomass material. Another study from the same northern Californian region showed that harvesting biomass as part of sawlog harvest cost up to six times that of sawlog material alone (Harrill and Han 2012). When integrating stems less than 25 cm at DBH into harvest in southwestern Idaho, expensive harvest systems such as skyline and helicopter logging were found to be respectively three and six times more costly than ground-based harvesting systems when harvesting the same integrated products of sawlog and non-sawlog material (Han et al. 2004). This study also found that whole-tree harvest systems were the most efficient means to harvest small diameter stems compared to cut-to-length, skyline, and helicopter systems. Overall, many studies show that harvesting biomass as part of commercial timber harvest is possible, but much more costly to the contractor and that some financial incentive may be necessary in many cases to cover the harvest cost.

In the logging industry of the southeastern US, a study found that utilizing stems less than 13 cm in diameter for biomass energy via chipping cost \$18.97 gt^{-1} in 2018 dollars from stump to mill (Mitchell and Gallagher 2007). In this study, stump to truck harvest only consisted of 60% of the total cost, the remaining 40% was due to hauling, demonstrating that transportation costs represent significant operational expenses. In this region, wood chips were a marketable product, allowing the logging contractor to make \$4.77 gt^{-1} above the logging and transportation cost to compensate for overhead and provide profit. Another study that assessed commercial thinning in the southeast found that cutting small diameter material for wood chips did not provide any profit, and instead cost 28% more than the revenue (Hanzelka et al. 2016). These studies demonstrate that the same product can result in very different levels of profit and that biomass energy can be a potentially volatile market. Short rotation woody crops (SRWC) are another potential source of biomass in the US southeast (Santiago et al. 2018). However, these SRWC sources of biomass vary in economic feasibility, as one study found their profit could range from a loss of $1,397.47 to a profit of $1,588.36 per acre (Stanturf et al. 2017). This highly variable range is due to fluctuating site conditions experienced across the landscape. SRWC tend to require warm, moist climates and nutrient rich soils. As these studies show, small diameter stems have the potential to provide a reliable source of woody biomass for energy production, however, these stems are grown using agricultural methods and are engineered specifically to be profitable. Natural forests, especially those in need of fuel treatments, do not have this benefit, and therefore are unlikely to support profitable biomass harvesting as a stand-alone enterprise, but can still contribute to energy production and potentially offset all or a portion of the costs of harvest.

Similarly, other operations research has focused on finding ideal harvest systems for combined sawlog and biomass harvesting. In northern Idaho, two systems for harvesting biomass were compared on sites that were inaccessible to chip vans: one used on-site grinding into high-sided dump trucks that transported chips to a concentration site, the other used slash forwarding using fifth-wheel end-dump trailers to a concentration site where slash was directly ground into chip vans (Anderson et al. 2012). In this study, the forwarding of slash was approximately 4% more economically efficient as compared to chipping into high-sided dump trucks, however, if chip vans are accessible to a site, directly grinding into the chip vans is preferable because it eliminates an extra handling step and is more cost effective. Other research in the northern Rocky Mountain region examined the difference between cut-to-length and whole-tree harvest systems (Adebayo et al. 2007). Adebayo and others found that on average the whole-tree system produced volume 21% more economically efficient than the cut-to-length system when harvesting in a mixed-conifer stand in northern Idaho. The observation that a cut-to-length system was less productive and cost-efficient than a whole-tree system was supported by previous research from ponderosa pine stands in the western US (Hartsough et al. 1997). Operations that conduct fuel treatments and are required to cut biomass stems can use this information to help pick the most efficient method to harvest woody biomass.

While a great deal of information is available regarding cost and productivity estimates for many different regions, few studies have taken place in the SRM using empirical data. Work that has been conducted in the region has generally relied on modeled cost estimates rather than forest engineering methods based on time studies. Some of the work that has been done in the region focuses on the effects of different diameter restrictions and shows that implementing diameter caps significantly increases the cost of implementing fuels treatments. A modeling study by Larson and Mirth (2001) found that a full cutting restriction on trees 40 cm (16 in) at DBH resulted in harvesting costs of 5% to 19% more expensive than the same full cutting restriction on trees 56 cm (22 in) in DBH during restoration and fuels treatments, and contractor revenue declined 22% to 176% due to being excluded from large-diameter markets such as house logs. Another study suggests that western US modeled harvest costs for mechanical whole-tree harvest systems are 35% to 62% cheaper than other ground-based harvest methods but are yet to be verified by observational studies (Arriagada et al. 2008). A study by Lowell et al. (2008) in the SRM region used forest engineering methods to estimate cycle time but did not simultaneously quantify cost using the specific equipment observed and used a modeled approach instead. This study found that on average, whole-tree harvest systems were five times more profitable than cut to length systems when wood chips were part of harvest but only about twice as profitable when wood chips were not harvested. This study assumed that pallet stock was the primary sawn-wood product, a reasonable assumption for the SRM.

1.2 Thesis Layout

Because little information is available in the SRM to researchers, managers, and other forest operation contractors regarding harvest systems used, cost and productivity rates, and how biomass harvest is operationally improved, I seek to address the following questions:

1. What harvest systems are used and what are the baseline cost and production rates for sawlog and biomass harvest in this region?
2. How can timber and biomass harvesting systems be improved and what are the mechanisms behind improvement?

To answer these questions, I studied five forest operations with a detailed time study. Contractors were chosen by their willingness to participate in the study and had a steady line of forest restoration contracts in the SRM using equipment characteristic of the region. In 2017, the goal was to observe 10 operational days on each site and supply contractors with a set of recommendations to improve their operations. In 2018, the “improved” operations were observed for another 10 operational days and compared against the previous year’s data to assess change. Due to logistical challenges associated with fire season restrictions, only three of the five contractors were revisited in 2018.

This thesis is part of a larger project funded by the Biomass Research and Development Initiative (BRDI) of the U.S. Department of Agriculture, National Institute of Food and Agriculture award number 2016-10008-25636. The BRDI project examines ways to improve biomass energy utilization and identifies the current barriers to producing biomass energy from forest restoration treatments in the SRM. The BRDI project is a large project encompassing the domains of forest operations, economics, silviculture, forest ecology, and fire sciences. My specific role in this project is to analyze and identify ways to improve the forest operations used in the SRM.

In this thesis, Chapter 2 provides the 2017 baseline cost and production rates, and identifies the best operational practices observed in the first year. This second chapter has been published in the *International Journal of Forest Engineering* in a special issue from the 41st annual meeting of the Council on Forest Engineering (Townsend et al. 2019). Chapter 3 details the suggested changes to operations and the analysis leading to my recommendations. Chapter 4 analyzes the "improved" operations in 2018 and supplies updated cost and production rates based on those recommendations. The discussion to this thesis, Chapter 5, identifies areas requiring further research due to noise in our own data or lack of available information, includes observations made in the field worth noting but not included in other chapters, and emphasizes the importance of understanding forest operations to managers who design harvest units. Lastly, Chapter 6 provides a conclusion and summary of the key findings from this research.

Information from this thesis will help forest operations contractors, land managers, and other researchers better understand the costs of producing forest biomass in the SRM. Information I produce about individual harvests will be compared by other researchers to the environmental effects observed on each site. Given that restoration treatments are driven by their ability to improve forest health and promote historic forest structure and function, identifying practices that may be environmentally damaging or environmentally beneficial is an important task in developing best management practices (BMPs).

Cost data from this thesis will be used by other researchers to model region-wide biomass energy production and compare its benefits against those of fossil fuels. Results presented here will allow other BRDI researchers and economists to assess the benefits of forest restoration compared to harvesting costs. Harvesting costs detailing specific harvest systems, such as whole-tree versus cut-to-length, will also help other researchers and land managers determine the most cost-effective ways to meet restoration goals and objectives.

Overall, generating baseline cost and production rates and identifying how to improve operational cost efficiency and productivity has significant implications for multiple fields. Whether the results are used to determine ideal silvicultural prescriptions, model regional energy production, or assess the value of restoration against its costs, understanding the role of forest operations and how operations can be improved is central to understanding biomass harvest in the SRM.

2.0 Harvesting forest biomass in the U.S. southern Rocky Mountains: cost and production rates of five ground-based forest operations

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2.1 Abstract

The forests of the southern Rocky Mountains of North America have experienced substantial change since European colonization. High-grade logging, forest grazing practices, and fire suppression have altered once park-like ponderosa pine-dominated ecosystems into dense forests in need of restoration treatments, but such treatments are challenged by the low-value wood products removed during treatment. This study aims to understand and evaluate restoration harvest practices in the southern Rocky Mountains in terms of equipment used, production rates, and costs under both observed and modeled site and stand conditions across the region. During the summer of 2017 we observed five ground-based harvest operations of varying size and capacity across the region and analyzed their characteristics using detailed time study data. Observed stump-to-truck harvest rates ranged from \$19.11 to \$43.25 (USD) gt^{-1} with an average of \$29.70 gt^{-1}, and modeled costs based on standardized variables from \$19.95 to \$33.39 gt^{-1} with an average of \$26.19 gt^{-1}. Observed average productivity rates for felling, skidding, processing, loading, and biomass grinding were respectively 22.9, 16.0, 20.7, 27.8 and 49.8 tonnes per scheduled machine hour (SMH^{-1}). Under modeled conditions for the same functions except grinding, productivity averaged 25.4, 18.6, 23.1, and 28.2 tonnes SMH^{-1}. Results from this study will be used as a benchmark for efficiency and costs and to model region-wide biomass production.

Key words: Forest operations, restoration, biomass, cost, productivity, Ponderosa pine

2.2 Introduction

Ponderosa pine forests of the southern Rocky Mountains evolved under a low-severity frequent fire regime which routinely consumed fuels and maintained low regeneration densities. Most forests were open, dominated by large trees with a grass understory (Covington and Moore 1994; Reynolds et al. 2013). With the arrival of European settlers, the process of fire was excluded from the landscape resulting in higher stem densities and increased risk of stand replacing, high-severity wildfire. Over the past century, environmentally harmful practices such as high-grade logging and grazing cattle in forested areas have amplified the negative effects of fire exclusion (Allen et al. 2002). In recent times, land managers have been working to restore historic forest conditions and the role of fire in the southern Rocky Mountains. Because of this change in stand structure, mechanical treatments are often necessary before reintroduction of frequent low-severity fire (Hampton et al. 2008). These restoration treatments differ from conventional timber harvests in that their primary goal is to improve ecological function through recreation of historic stand structures, therefore the largest and most economically valuable trees are often retained while subdominant, smaller, and less economically valuable trees are removed. In response to forest change and increased risk of severe wildfire, public land managers have created landscape-scale projects like the Four Forests Restoration Initiative (4FRI) in the state of Arizona to both restore historic forest conditions and stimulate local and regional forest product economies (Lucas et al. 2017). The large volume of small diameter, low-grade, and low value wood from restoration treatments has challenged existing regional markets, and the industry is struggling to adapt. One way the industry has adapted is by investing in various forms of biomass energy such as whole-tree chips for thermoelectric power, pellets for wood stoves, and traditional fuelwood for heating (Sorensen et al. 2016). Biomass energy and other markets such as animal bedding and erosion control products now account for the highest sales by value in the region, deviating from historic products of lumber, timbers, and other sawn wood (Sorensen et al. 2016). While information is available regarding the wood products industry in the southern Rocky Mountains, little information is available to land managers, logging contractors, and researchers about logging systems and their associated costs and production rates when used on restoration treatments that include biomass harvest. In other regions, such as the northern Rocky Mountains, biomass harvesting costs have been calculated and the challenges with low-value wood have been explored (Bell et al. 2017; Anderson et al. 2012; Kim et al. 2017). Furthermore, other regions outside of the U.S. Rocky Mountains which utilize biomass have been studied and their operations quantified (Belbo and Vivestad 2018; Di Fulvio et al. 2017; Han et al. 2004; Hanzelka et al. 2016; Santiago et al. 2018; Vitorelo et al. 2011).

The objective of this study is to understand the current state of forest operations in the southern Rocky Mountains in terms of equipment used, structure of harvest systems, stump-to-truck logging costs, and production rates, with the goal of improving future operations and expanding biomass utilization in the region. This study is part of a broader project aimed at also understanding: the effects of biomass harvest on forest ecosystems; ways to improve the environmental performance of logging practices; and the public health impacts of woody biomass energy compared to fossil fuels.

2.3 Materials and methods

2.3.1 Contractor and site selection

Contractors were selected in January of 2017 based on their willingness to participate in the study, use of operations and equipment characteristic of the region, and a steady workflow of forest restoration-focused contracts. Two of the selected contractors were based in central-eastern Arizona, two in northwestern New Mexico, and one in south-central Colorado. Our goal was to observe 10 consecutive operational days for each operation and use the results to develop recommendations for each operation to improve efficiencies and decrease costs.

Forest restoration-focused contracts already held by the participating contractors were selected as field study sites. Four of the five contractors were operating on United States (U.S.) Forest Service projects, with the fifth operating on a restoration-focused project on a state wildlife management area (Figure 2.1). Pre-treatment site information was collected for all sites using fixed-radius 0.04 ha plots (0.1 acre) for mature trees (diameter at breast height, DBH ≥ 13 cm), with data collected for tree diameter, species, and height. For saplings (DBH < 13 cm, height > 1.4 m), a 0.004 ha (0.01 acre) fixed radius plot using the same plot center was used to collect the same information as for mature trees. To collect seedling information, three 0.001 ha (0.003 acre) plots were used to sample species composition and average height. The density of small trees was highly variable by site with varying levels of treatment required. On all sites ponderosa pine (*Pinus ponderosa*) was the dominant species, with Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), Gambel oak (*Quercus gambelii*), and quaking aspen (*Populus tremuloides*) as secondary cohabitants (Table 2.1).

2.3.2 Field data collection

Detailed time study methods (Olsen and Kellogg 1983) were used to evaluate all harvesting functions within each operation (Table 2.2). Because hot saws operated too quickly for accurate data collection by activity, activity sampling was used periodically, approximately every 45 minutes, to describe the proportion of time spent on individual activities within a cycle. All tree and log diameters were ocular estimates, while distance was estimated with the aid of a laser-rangefinder. Delays were recorded but were not used to develop utilization rates because the recording of "long delays", defined as delays longer than 30 minutes, were not consistently targeted and recorded.

2.3.3 Logging system descriptions

All operations utilized ground-based harvesting systems, four of which were fully mechanized (Appendix 2.1). Operations 1 and 2 used rubber-tired feller-bunchers followed by rubber-tired grapple skidders and roadside processing with dangle-head processors. Both of these operations had hog fuel markets available to them. After slash piles air dried, horizontal grinders were used to comminute slash directly into chip vans. Operation 3 was a hybrid cut-to-length system using a harvester to fell and process stems in the woods, which provided an even distribution of fuel for a later broadcast burn, followed by a grapple skidder bringing processed logs to the landing. Log trucks were loaded using a dangle-head processor. Operation 4 used a tracked, leveling feller-buncher due to steep slopes, a rubber-tired grapple skidder, and roadside processing with a dangle-head processor. All feller-bunchers used hot saws (also known as rotary disk saws). Operation 5 was a semi-conventional system with hand-felling, tree-length skidding using a rubber-tired grapple skidder, and roadside processing using a trailer-mounted pull-through delimber.

2.3.4 Products produced

Operation 1 and 2 produced the same two sawlog sorts: "large" logs which were 40 cm (16 in) or greater large-end diameter, and "small" logs less than 40 cm (16 in) large end diameter to a 11 cm (4.5 in) top. Preferred sawlog lengths were 4.9 m (16 ft), with 0.61-meter (2-foot) multiples accepted. Operation 1 also produced a chip log with a small end diameter of 5 cm (2.5 in) for a pellet mill producing bagged pellets for home heating. Both Operations 1 and 2 produced hog fuel from whole trees and slash for commercial electricity production. Operation 3 produced one sort of logs with small-end diameter down to 11 cm (4.5 in) and lengths of 0.6-meter (2-foot) multiples starting at a minimum of 2.4 m (8 ft). Operation 4 had one sort of logs with diameter 6 cm (2.5 in) and greater starting at 2.4 m (8 ft), but preferred lengths of 7.6, 8.2, and 8.8 m (25, 27, 29 ft). These logs were primarily hauled to two integrated mills that produced multiple products such as pellets, dimensional lumber, rough-hewn timbers (vigas), firewood, posts, and rails. Logs were also hauled to other sawmills producing green dimensional lumber for export. Operation 5 produced one sort of tree length logs down to a 10 cm (4-inch) top, which were hauled to a lumber mill with post and pole and pellet facilities.

2.3.5 Cost and productivity analysis

This study examined productivity and cost in two different scenarios: one is based on the observed stand and site conditions for each operation; the other is based on modeled productivity and costs assuming a standard set of stand and site conditions, such as skidding distance and stem diameter. The modeled analysis was used to directly compare operations without site-specific variables influencing productivity and costs.

To estimate machine productivity from cycle time data, ordinary least squares linear regression models were constructed to predict delay-free cycle time based on variables that are easily observed and measured in the field. Models were refined using backwards stepwise selection. For specific operational functions where regression models could not be constructed, summary statistics were used to describe the range of possible values for cycle time. Any model developed that represented multiple operations used randomly selected balanced samples so that each operation was equally represented in the model. Each model, cost, and productivity estimate is given on a per machine basis rather than in aggregate, as some operations had multiple machines performing the same function.

Both observed and modeled costs and productivity estimates were calculated assuming a standard 23.6 tonne (U.S. 26 ton) payload per log truck. Based on this payload and piece counts per load, we estimated a weight per piece for each sort. Allometric equations were used to estimate weights for trees with large end diameters less than 10 cm (4 in) (Jenkins et al. 2003). Machine rates were calculated using purchase prices for new machines in each class of equipment (USFS Machine rate calculator) and standard costing assumptions (Table 2.3). Any cost data compared from earlier studies was adjusted for inflation (BLS 2018).

2.3.5.1 Modeling assumptions

A diameter of 21 cm (8.2 in) was assumed for all modeled felling and processing estimates. Hot saw cycles assumed 2.5 trees at 21 cm in diameter, plus 2.5 trees with diameters less than 10 cm (4 in) per bunch. An average travel distance of 4.3 m per cycle was used to model tracked hot saw cycle time. The harvester model assumed 1.1 stems per cycle with 1.3 logs produced per tree, and a travel distance of 2.4 m (8 ft) per cycle. An average skid distance of 300 m (985 ft) with two bunches assembled containing 10.3 trees per bunch was assumed. Loading was modeled assuming an average of 38 grapple swings required to fully load a truck using the “large” sort of logs.

2.4 Results

2.4.1 Productivity Models by Function

2.4.1.1 Felling

Hot saw cycle times and bunch compositions varied between operations. Despite major differences between stem sizes in bunch compositions among operations (Figure 2.2), average cycles were close to one minute and typically resulted in approximately 5 stems cut per cycle (Table 2.4). Bunch compositions averaged 2.5 stems per cycle with diameters less than 10 cm (4 in), plus 2.5 stems per cycle with diameters greater than 10 cm (4 in). Wheeled hot saws spent similar time in each activity of the cycle, while the tracked hot saw spent less time moving between trees and a greater proportion of time cutting and bunching (Figure 2.3). On average, the tracked hot saw cut stems at an observed rate 36% faster than the wheeled hot saws. Observed productivity for all hot saws averaged 32.1 tonnes SMH^{-1}, varying from 91% to 155% of the mean (Table 2.4). Total delay-free cycle time for wheeled hot saws could be modeled based on the total number of stems cut, regardless of stem diameter. Predicting delay-free cycle time for the tracked hot saw was also dependent on the total number of stems cut in addition to the total distance traveled per cycle (Table 2.5). When modeled, hot saw productivity averaged 32.9 tonnes SMH^{-1}, varying from 89% to 118% of the mean.

On Operation 3, where felling and processing were completed with a harvester, the average cut tree diameter was small and included the treatment of regeneration. On average only 0.7 logs per tree were produced. Thirty-two percent of our observations were on trees less than 15 cm at the large-end diameter. Because of the small diameter trees, the harvester produced an average of 13.9 tonnes SMH^{-1}. Delay-free cycle time was best correlated with the distance traveled, cut stem diameter, the number of stems cut and processed, and the number of logs produced (Table 2.5). Modeling harvester productivity based on the larger standardized diameter resulted in a productivity rate of 23.6 tonnes SMH^{-1} (Table 2.4).

Hand-felling resulted in the lowest productivity rate of all felling methods, producing 4.4 tonnes SMH^{-1}under observed conditions (Table 2.4). Hand-felling was best modeled by the diameter of the stem being cut (Table 2.5). When using the standardized diameter of 21 cm, productivity was estimated to 4.6 tonnes SMH^{-1} (Table 2.4).

2.4.1.2 Skidding

Although skidder size and capacity varied among operations, all machines served the same function and therefore are directly comparable. Operations differed in the average number of bunches assembled, the number of pieces per bunch, and round trip distance (Table 2.6). Under observed conditions, skidding averaged 16 tonnes SMH^{-1}, and varied by operation from 56% to 192% of the mean (Table 2.6). Operation 4 occasionally processed trees at in-woods landings for slash dispersal purposes, requiring logs to be re-skid to a roadside landing after processing. Although this practice was thought to make slash dispersal more efficient, cycle times that involved re-skidding of slash from a roadside landing were not significantly different than cycles that did not involve return skidding of slash ($p=0.78$). Skidding that followed hand-felling was significantly slower over the same distances as compared to other operations ($p = 0.02$), therefore it was left out of the combined model. For all operations, delay-free cycle time was estimated based on the total distance traveled and the number of bunches or pieces (in the case of unbunched stems) assembled (Table 2.7). When modeled, average skidding production was 16.1 tonnes SMH^{-1}, and varied from 67% to 132% of the mean.

2.4.1.3 Processing

Dangle-head processors were the most common processing equipment and had a mean observed productivity rate of 22.9 tonnes SMH^{-1}and varied from 92% to 110% of the mean (Table 2.8). Delay-free processing time with dangle-head processors was based on the large end diameter of the tree, number and sort of logs produced (Table 2.9). Because processing time depended on log sorts produced and sorts were not consistent between operations, a combined processing model could not be developed. With diameter standardized, an average of 23.5 tonnes SMH^{-1}was modeled. Modeled productivity rates ranged from 93% to 107% of this mean. The pull-through delimber had a broken topping saw, so topping was completed by breaking the stem. This resulted in an observed productivity of 7.2 tonnes SMH^{-1}, 32% of the productivity of a dangle-head processor (Table 2.8). Meaningful predictive models could not be developed with the data collected.

2.4.1.4 Loading

Between operations there were large differences in loading cycle times and productivity rates. Observed conditions resulted in an average productivity rate of 27.8 tonnes SMH^{-1} and varied from 63% to 160% of the mean, with the lower bound attributed to loading with a dangle-head processor (Table 2.10). For Operations 1, 2, and 3 predictive models were based on the number of grapple swings to load the truck and log sort (Table 2.11). Operations 1 through 3 were standardized by using a modeled time given 38 swings assuming the large log sort for all operations. Because statistically-significant models could not be generated for Operations 4 and 5, averages were used. The modeled productivity average for all loading machines was 27.7 tonnes SMH^{-1} and varied from 81% to 125% of the mean.

2.4.1.5 Grinding

Biomass grinding only occurred on Operations 1 and 2. For both operations, grinding was separated in time from other harvesting activities in order to allow slash to air dry, which improves its energy content per unit value. Operation 2 owned two grinders, one of which worked independently on the same site as Operation 1 (labeled in the table as “Operation 2 (Site 1)”). Although two different grinder sizes and makes were used, they had similar delay-free cycle times and productivity. The average productivity from all grinders was 49.8 tonnes SMH^{-1} (Table 2.12). Averages were used to estimate productivity and costs in both the observed and modeled analyses.

2.4.2 Stump to truck costs

The most efficient felling was completed by hot saws in both observed and modeled conditions. Under observed conditions, hot saws cost an average of \$5.35 gt^{-1} and under modeled conditions \$5.23 gt^{-1}. While the machine rate was more expensive for the tracked hot saw than the wheeled hot saw, the tracked hot saw had the lowest cost per tonne under observed conditions. After standardization, the wheeled hot saw on Operation 1 was the most cost-efficient machine (Table 2.13). The least efficient felling method was hand-felling, resulting in an observed cost 300% of the mean hot saw felling cost. Under modeled costs the result was similar, with hand-felling 298% of the mean hot saw cost per tonne (Table 2.13).

Skidding costs were highly variable with an average cost of \$10.79 per tonne with costs ranging from 43% to 160% of the mean cost. The high observed skidding cost for Operation 2 was because bunches of small material less than 10 cm in diameter were skid separately from the larger merchantable logs and accounted for a large proportion of bunches skid. The mean modeled skidding cost was \$9.17 gt^{-1}. Costs ranged from 73% to 127% of the mean modeled skidding cost. Operation 2 under modeled conditions cost 102% of the mean, indicating near average skidding costs when biomass material was not skid separately from whole trees.

Processing costs were less variable than both felling and skidding costs. The observed average processing cost for dangle-head processors was \$7.02 gt^{-1}. Operations varied from 84% to 111% of the mean (Table 2.13). Processing costs were generally dependent on processing intensity. Tree length processing and the handling of longer logs were more efficient from a processing perspective. Once diameter was standardized in processing models, the mean average cost \$7.28 gt^{-1}. Average costs per tonne varied from 89% to 108% of the mean under modeled conditions. Under modeled conditions, the pull-though delimber on Operation 5 cost 111% of the mean cost per tonne when compared to dangle-head processors (Table 2.13).

Loading was the least expensive function in operations when a loader was used. For knuckle-boom loaders the average observed loading cost was \$3.62 gt^{-1}. Operations ranged from 70% to 129% of this observed average cost per tonne (Table 2.13). Operation 3 which used a processor to load, cost 259% of the observed average cost per tonne for knuckle-boom loaders. Under modeled conditions, the average loading cost for knuckle-boom loaders was \$3.68 gt^{-1}. Operations ranged from 89% to 127% of the modeled average cost per tonne (Table 2.13). The processor loading on operation 3 maintained a high relative cost to knuckle-boom loaders, costing 198% of the average modeled cost per tonne.

Grinding costs were similar despite the range in size of grinders, averaging \$9.17 gt^{-1}. Grinding costs only varied around this mean from 96% to 106% of the average cost (Table 2.13). Both grinding operations worked to directly fill 40-foot long trucks and did not grind into piles for later loading.

Total round wood harvesting costs exhibited a wide range in both observed and modeled conditions. The observed average round wood harvest cost was \$30.40 gt^{-1}. Costs varied from 62% to 131% of this average under observed conditions (Table 2.13). Under modeled conditions, the average round wood cost was \$26.92 gt^{-1}. Costs varied from 81% to 143% of the average modeled cost (Table 2.13). The high-end outlier in the range of costs was Operation 5. This is attributed to the high cost of hand-felling, which was not used in other operations. Biomass grinding for Operations 1 and 2 added 32% to round wood production costs under observed conditions, and 39% more under modeled conditions. While grinding biomass increased operational costs, it provided a source of revenue as well.

2.6 Discussion

2.6.1 Best Practices

The most efficient felling practices were those that considered the skidding operations that followed. Typically, these operators had previous experience operating a skidder and were able to create optimal bunch sizes so that a skidder could achieve a full payload with a single bunch, and seldom needed to assemble a second bunch, or break apart a bunch that was too large for a single cycle. Good felling practices were most evident on Operation 1, where on average the skidder operator had to assemble a second bunch only once every four cycles (Table 2.6).

The harvester and skidder combination working closely together on Operation 3 made for inefficient skidding but could be preferable for operations that are required to distribute slash throughout the unit for later prescribed burning or for nutrient cycling. Though forwarders are often used in this situation, they are not common in the study area and there is no reference in this region as to what it would cost to use forwarders in restoration treatments. However, we do speculate it would significantly increase production efficiency if one were used in this situation (Becker et al. 2006). Alternatively, a whole-tree system with return skidding of slash could be used to accomplish this same task, although the distribution of slash between the two methods may not be the same (Han et al. 2009). While there were a limited number of observed cycles (n=9), our results indicate that there was no statistical difference between skidding cycles with an empty back haul and those returning slash to the unit on the back haul. Skidder cycles devoted specifically to dispersing slash without moving any merchantable product would increase costs but may be necessary in some cases.

Hand-felling that did not consistently use directional felling techniques resulted in inefficient skidding (Table 2.13). The skidder operator was required to assemble multiple stems to create a single turn (Table 2.6). This resulted in slower cycle times, lower productivity levels, and more costly skidding.

Experienced skidder operators (Operation 1) alternated short and long distance cycles when working directly with the processor to maintain balance and minimize operational delays. This is in contrast to operations that started assembling the bunches nearest to the landing and worked outward, resulting in frequent operational delays in skidding for short skids, and processor delays with longer skids.

Dangle-head processors exhibited the most efficient processing. For tree length processing though, the cost of a pull-through delimber was high but comparable to dangle-head processors (Table 2.13). If the topping saw on the pull-through delimber had not broken, it may have been more productive and therefore more cost-efficient. While the cost per tonne to operate a pull-through delimber was similar to dangle-head processors, it was significantly less productive and may not be appropriate for higher productivity operations.

The most efficient loading practices used a knuckle-boom log loader and worked from decks that were well-sorted. The least efficient loading was completed by a dangle-head processor which experienced frequent delays from sorting and was limited to fewer logs per swing, thus requiring more swings per load on a more expensive machine (Table 2.8, Table 2.13). This is widely understood by most contractors, but the practice is sometimes resorted to when a dedicated loader is not available.

Grinding results indicate that the delay-free cycle time to fill a 12.2-meter (40-foot) chip van was not statistically different between a 765 horsepower and 1050 horsepower grinder, resulting in similar levels of productivity. The primary difference in observed total load time was the average delay per truck. Operators that kept grinders fed with a constant stream of biomass made up of smaller, more frequent grapple swings resulted in shorter, less frequent delays than operators who relied on fewer grapple loads with more material. Not only was this trend exhibited between different machines, it was also observed between different operators on the same machine (Table 2.12). At face value this result implies that contractors could achieve the same level of grinding productivity with a smaller, potentially less costly machine but because this study did not collect data on long-term repair and maintenance costs it cannot make a fair comparison regarding long-term costs.

2.6.2 Comparison and limitations

Operation 3 was a modified cut-to-length operation. Compared to other studies, the southern Rocky Mountains share similarities with the northern Rocky Mountains regarding the use of a harvester. When operating under conditions with trees greater than 21 cm in diameter that do not involve the treatment of regeneration or small diameter stems, cut-to-length systems can be equally cost-efficient as the whole-tree operations observed in this study. Other studies have also shown that cut-to-length systems and whole-tree systems have similar costs when stand conditions are standardized (Adebayo et al. 2007). Some prescriptions may limit the amount of slash that can be left on the unit, and therefore require pile burning or biomass utilization, making cut-to-length a difficult and expensive system to use.

The cost data in this study indicate that hand-felling is not an efficient felling method and should be replaced by mechanized felling in cases where site conditions are appropriate (Table 2.13). For individual operators, hand-felling may be used because it represents very low capital investment, but it is also less productive, and in this case is more costly on a per unit basis.

In fuels treatments in other parts of the western U.S., biomass harvest of small diameter stems is frequently paired with sawlog removal and results in more costly harvesting as almost the same work is needed to cut trees regardless of their size and value (Han et al. 2004; Vitorelo et al. 2011). Biomass opportunities may exist in forest restoration operations, but the operational costs tend to outweigh the associated market value of the biomass, especially when they are not a byproduct of sawlog production. However, wildfires that occur in fuel treatments tend to be smaller and offer potential savings up to 17% in fire suppression costs compared to if the same stand burned without treatment (Thompson et al. 2017; Thompson et al. 2013), though this relationship is complex (Thompson and Anderson 2015). In other regions, such as the southeastern U.S. where forest biomass is a marketable product associated with commercial timber harvest, cutting small diameter stems in thinning operations or coppice plantations for biomass energy may be profitable depending on market conditions (Santiago et al. 2018; Stanturf et al. 2017).

In-woods biomass grinding observed in this study is comparable to chipping operations in northern Europe (Belbo and Vivestad 2018). Chipping or grinding of biomass represent significant costs in both cases and needs to be as efficient as possible for biomass to be considered an economically efficient energy source. In this study, improper use of equipment was a significant source of mechanical delays.

A study in the southeastern U.S. that involved cutting small diameter pine trees exclusively for biomass energy found that the cost of harvesting biomass was 52% lower in the southeast than what was modeled on the most efficient operation (Operation 1) in the southern Rocky Mountains (Hanzelka et al. 2016). These treatments were clearcutting prescriptions, which are simpler and more efficient to carry out than restoration treatments. The individual felling, skidding, and grinding costs in that study were all less expensive than the average observed and modeled costs in this region. Another study that examined felling costs showed the costs of felling in the southern Rocky Mountain region fit into the range of felling costs experienced in other countries (Di Fulvio et al. 2017).

A limitation of this study is that the costs presented here are only direct stump-to-truck costs and do not include the cost of overhead, administration, transportation to market, or subsequent slash treatment. Some variables not included here, such as trucking costs, play a large role in determining stump-to-gate cost and economic feasiblity (Reddish et al. 2011), often ranging from 33% to 60% of the total stump-to-market expenses (Grebner et al. 2005; Hanzelka et al. 2016).

The lack of markets for small diameter logs from the treatment of stands dominated by small, often non-merchantable trees is a major challenge in the southern Rocky Mountains. Other regions such as the Pacific Northwest U.S. and the southeastern U.S. already have well-developed biomass energy markets because of their short rotation lengths for higher-value forest products and their well-established timber economies that include large-scale co-generation of heat and power at forest industry facilities (Zamora-Cristales et al. 2015; Stanturf et al. 2017). Much of the biomass harvested in this study was used for medium-scale (<30 MW) power production for the electrical grid. Additional facilities of this type and scale could stimulate markets for biomass harvested from restoration treatments. Because the southern Rocky Mountains region does not have a strong timber economy or large-scale biomass facilities, expanding biomass harvest to improve the economic viability of restoration treatments will be challenging.

2.7 Conclusion

This study improves land managers' understanding of challenges and costs associated with restoration harvests in the southern Rocky Mountains. Forest contractors now have a reference to compare logging systems they may use in the future and can benchmark their operations using these results.

2.8 References

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2.9 Appendices

Appendix 2.1

Appendix 2.1. Harvesting system descriptions.

Operation	Felling	Skidding	Processing	Loading	Grinding	Trucking
1	Rubber-tired hot saw (Tigercat 726G)	Rubber-tired grapple skidder (CAT 525 B)	Dangle-head processor (CAT 320 D with Waratah 623 C)	knuckle-boom loader (John Deere 2154 D)	Horizontal grinder, loader (Peterson 4710 B, CAT 320 D)	Log trucks with fixed-length trailers, Chip vans for biomass
2	Rubber-tired hot saws (John Deere 843 L (2) and CAT 573 C)	Rubber-tired grapple skidders (John Deere 948 L (2), John Deere 648 H (2), CAT 555D)	Dangle-head processors (John Deere 2454 D with Waratah 623 C, CAT 324 D with Waratah 623 C)	knuckle-boom loader (John Deere 2156 G)	Horizontal grinder, loader (Terex-Ecotec 680 (2), CAT 250 D)	Log trucks with fixed-length trailers, 12.2-meter (40-foot) Chip vans for biomass
3	Harvester (John Deere 240D with Logmax 7000 XT)	Rubber-tired grapple skidder (John Deere 748 H)	N/A	Dangle-head processor (John Deere 2054 with Waratah HTH 628)	N/A	Stinger-steered and flatbed log trucks
4	Tracked Hot saw (TimberPro TL735 B)	Rubber-tired grapple skidder (Tigercat 610)	Dangle-head processor (Doosan DX225LL with Waratah 622 B)	Truck-mounted loader (Prentice 280)	N/A	Stinger-steered and self-loading log trucks
5	Chainsaw (Husqvarna 372 XP)	Rubber-tired grapple skidder (John Deere 548 E)	Pull-through delimber (CTR 450)	Trailer-mounted loader attached to delimber (Prentice 310)	N/A	Log truck with fixed-length trailer

2.10 Table Captions

Table 2.1. Pre-treatment stand conditions. Species key: PIPO = *Pinus ponderosa*, PSME = *Pseudotsuga menziesii*, ABCO = *Abies concolor*, QUGA = *Quercus gambelii*, POTR = *Populus tremuloides*

Table 2.2. Cycle descriptions for each function and machine type.

Table 2.3. Assumed purchase prices, utilization rates, and machine rates used for evaluation.

Footnotes:

[a] The following assumptions were held constant: 1500 hours worked per year; 5-year machine life; salvage value 20%; interest rate 6.5%, insurance rate 1.3%; taxes 2%; fuel use 13.35 L/kW-hr (2.63 gal/hp-hr); repair and maintenance at 100% of depreciation; operator wage of $20 per hour; benefits 50% of wage; hand-felling wage $35 per hour; hand-felling benefits 100% of wage; rubber tire replacement 1500 machine hours at $20,000 per set.

Utilization rates were assumed to be different for each function and were sourced from literature ([b]Adebayo et al. 2007; [c]Anderson et al. 2012; [d]Brinker et al. 2002; [e]Dodson et al. 2015; [f]Miyata 1980).

Table 2.4. Felling summary statistics with observed and modeled productivity.

Table 2.5. Prediction models for delay-free cycle time for all felling.

Table 2.6. Summary statistics and production rates for skidders.

Table 2.7. Skidding models to predict delay-free cycle times.

Footnote:

[a] Combined model represents Operations 1-4.

Table 2.8. Processing summary statistics for all processing. The harvester in Operation 3 is included, but cycle time also includes felling.

Tables

Table 2.1

Operation	**Slope (%)**	**TPH < 10 cm**	**TPH > 10 cm**	**BA > 10 cm (m^2/ha)**	**QMD > 10 cm**	**Avg Ht (m) > 10 cm**	**Species Composition (% by basal area)**				
							PI PO	PS ME	AB CO	QU GA	PO TR
1	8	638	715	29.4	22.9	12.1	92.5	0	0	7.5	0
2	7	618	404	29.9	30.7	14.3	97.3	0.2	0.1	2.4	0
3	7	41	315	19.0	27.7	12.4	100	0	0	0	0
4	15	2801	694	30.0	23.5	15.3	96.5	1.4	2.1	0	0
5	9	21	299	19.6	28.9	12.8	79.6	17	3	0	0.4

Table 2.2

Machine type	Timed cycle elements	Independent variables
Felling		
Wheeled hot saw	Total time to build and lay down one bunch	Tally of trees cut per 10 cm size class
Tracked hot saw	Total time to build and lay down one bunch	Tally of trees cut per 10 cm size class, distance traveled (feet)
Harvester	Travel to tree, cut, process	Distance traveled (feet), large-end diameter to 5 cm size class, number of stems cut at once, total number of logs produced
Hand-felling	Travel to tree, pre-limbing, face cut, back cut, delimbing	Distance traveled to tree, tree species, large-end diameter
Skidding		
Rubber-tired grapple skidder	Travel empty, assemble turn, travel loaded, decking/piling	Distance traveling empty (feet), distance traveling between each bunch (feet), tally of bunches assembled, distance traveling loaded (feet)
Processing		
Dangle-head processor	Limb and buck, slash management	Large-end diameter to 5 cm size class, tally of logs produced by sort
Pull-through delimber	Positioning tree in delimber, delimbing, topping, decking	Large-end diameter to 5 cm size class
Loading		
Log loader/Dangle-head processor	Time per swing of logs loaded onto truck	Number of logs in each swing
Biomass grinding		
Horizontal grinder	Time per swing of biomass material into grinder	Categorization of material in each swing (slash, logs, mix, or fines)

Table 2.3

Machine	Horsepower	Purchase Price (USD)	Utilization rate (%)	Cost USD/SMH[a]
Felling				
Wheeled hot saws	270-285	287,000	60[d]	$133
Tracked hot saw	300	525,000	60[e]	$187
Harvester	177	540,000	70[b]	$183
Hand-felling	5.5	900	50[f]	$71
Skidding				
Rubber-tired grapple skidder	115	300,000	65[e]	$125
	203-263	330,000	65[e]	$143
	300	370,000	65[e]	$156
Processing				
Dangle-head processor	139-166	475,000	75[c]	$164
	190-194	540,000	75[c]	$183
Pull-through delimber	150	65,000	65[d]	$57
Loading				
Trailer-mounted loader	150	175,000	65[e]	$86
Truck-mounted loader	145	250,000	65[e]	$105
Knuckle-boom loader	164-188	277,000	65[e]	$113
Biomass grinding				
Horizontal Grinder (including loader)	765	800,000	85[c]	$421
	1050	900,000	85[c]	$473

Table 2.4

Factor	Units	Mean Values, by operation				
		1	2	3	4	5
Observed delay-free cycle time	Minutes	0.98	1.14	0.55	0.78	1.84
Diameter	Centimeters	18	10	18	11	22
Distance	Meters	NA	NA	2.4	4.3	6.4
≤ 10 cm	Stems/bunch	0.86	3.54	NA	3.02	NA
> 10 cm	Stems/bunch	4.12	1.76	NA	1.73	NA
Observed Delay	Minutes	0.16	0.2	0.23	0.14	0.78
Total stems	Stems/cycle	4.98	5.3	1.1	4.75	1
Productivity observed	Tonnes/SMH	29.3	17.2	13.9	49.8	4.4
Productivity modeled	Tonnes/SHM	30.7	29.3	23.6	38.7	4.6

Table 2.5

Operation	Intercept	β_1 Number of stems cut	β_2 Distance (meters)	β_3 Diameter (cm)	β_4 Number of logs	R^2
1	0.2709	0.1415	NA	NA	NA	0.52
2	0.5170	0.1079	NA	NA	NA	0.51
Combined wheeled	0.4415	0.1204	NA	NA	NA	0.51
3	-0.2274	0.1442	0.0347	0.0228	0.1883	0.48
4	0.3864	0.0644	0.2060	NA	NA	0.54
5	-2.2070	NA	NA	0.1822	NA	0.50

Table 2.6

Factor	Units	Mean Values, by operation				
		1	2	3	4	5
Observed delay-free cycle time	Minutes	4.50	7.60	6.63	6.08	6.80
Number of bunches		1.3	1.7	3.0	1.4	2.5
Number of pieces		12.7	17.1	8.7	5.5	8.0
Total distance	meters	384	455	257	206	202
Observed delay	Minutes/ cycle	1.34	0.55	0.89	1.16	0.23
Productivity observed	Tonnes/ SMH	17.6	9.0	12.6	30.8	10.0
Productivity modeled	Tonnes/ SMH	21.3	16.6	16.8	14.9	10.7

Table 2.7

Operation	Intercept	β1 Distance (100's of meters)	β2 Number of bunches	R^2
1	0.2202	0.5264	1.4310	0.63
2	-0.2528	0.9310	1.7108	0.61
3	0.1099	1.5003	0.6030	0.85
4	0.3626	1.1940	1.3302	0.79
5	-1.1524	2.8313	0.9026	0.65
[a]Combined model	0.1761	0.8924	1.2311	0.65

Table 2.8

Factor	Units	Mean Values, by operation				
		1	**2**	**3**	**4**	**5**
Observed delay-free cycle time	Minutes	0.41	0.58	0.55	1.08	1.46
Large-end diameter	cm	22	22	18	21	22
Large logs produced	Logs/ cycle	1.17	0.18	0.77	0.94	1
Small logs produced	Logs/ cycle	0.74	2.21	NA	0.52	NA
Delay	Minutes/ cycle	0.11	0.15	0.23	0.50	0.40
Productivity observed	Tonnes/ SMH	21.0	22.5	13.9	25.3	7.2
Productivity modeled	Tonnes/ SMH	21.8	23.4	23.6	25.2	NA

Table 2.9

Operation	Intercept	β_1 Diameter (cm)	β_2 (Number of large sawlogs)	β_2 (Number of small sawlogs)	R^2
1	0.0466	0.0093	0.1140	0.0383	0.64
2	0.0401	0.0185	0.3812	0.0361	0.47
4	-0.2703	0.0403	0.4331	0.2196	0.47

Table 2.10

Factor	Units	Mean Values, by operation				
		1	2	3	4	5
Observed delay-free cycle time	Minutes	31.39	20.70	52.64	40.75	36.58
Number of grapple swings		41	25	51	35	36.7
Total pieces		223	144	96	56	87.3
Delay	Minutes	4.66	4.10	10.54	2.96	16.08
Productivity observed	Tonnes/ SMH	29.3	44.4	17.5	22.6	25.1
Productivity standardized	Tonnes/ SMH	33.6	34.6	22.5	N/A	N/A

Table 2.11

Operation	Intercept	β_1 Number of swings	β_2 Short log sort	R^2
1	9.7446	0.4639	7.8852	0.59
2	9.6940	0.3680	2.2493	0.59
3	5.7078	0.9258	N/A	0.46
Combined model	-2.6417	0.9730	N/A	0.72

Table 2.12

Factor	Units	Mean Values, by operation		
		1	**2 (Site 1)**	**2 (Site 2)**
Observed delay-free cycle time	Minutes/truck	23.37	20.21	22.44
Total grapple	Swings/truck	73	53.8	36.8
Delay/truck	Minutes	4.44	4.94	8.11
Productivity observed	Tonnes/SMH	46.7	48.6	54.0

Table 2.13

	Operation				
Function	**1**	**2**	**3**	**4**	**5**
	Observed Costs ($ gt^{-1})				
Felling	$4.54	$7.74	$13.17	$3.76	$16.06
Skidding	$8.13	$17.31	$11.37	$4.65	$12.47
Processing	$7.80	$7.38	NA	$5.89	$7.87
Loading	$3.86	$2.54	$9.38	$4.65	$3.42
Grinding	$9.02	$9.24	N/A	N/A	N/A
Round wood cost	$24.34	$34.97	$33.93	$18.94	$39.83
Round wood with biomass cost	$33.36	$44.21	N/A	N/A	N/A
	Modeled Costs ($ gt^{-1})				
Felling	$4.33	$4.54	$7.74	$4.84	$15.58
Skidding	$6.72	$9.38	$8.50	$9.59	$11.68
Processing	$7.51	$7.83	NA	$6.51	$7.87
Loading	$3.36	$3.27	$7.29	$4.65	$3.42
Grinding	$9.02	$9.24	N/A	N/A	N/A
Round wood cost	$21.92	$25.02	$23.53	$25.58	$38.55
Round wood with biomass cost	$30.94	$34.26	N/A	N/A	N/A

Figure Captions

Figure 2.1. Map of study site locations.

Figure 2.2 Average number of stems per hot saw bunch by diameter class by operation.

Figure 2.3. The proportion of time devoted to each potential cycle activity (left) and average time per hot saw cycle in minutes (right) by operation. Operation 1 and 2 are wheeled felling operations, whereas Operation 4 is tracked.

Figure 2.4. Modeled total cycle time by number of stems cut for hot saws with observed data points. Time for the tracked hot saw is estimated using an average of 4.3 meters traveled.

Figure 2.5. Modeled total cycle time by distance assuming 2 bunches were assembled for operations 1-4 with observed data points, with the thick black line representing the combined skidding model.

Figures

Figure 2.1

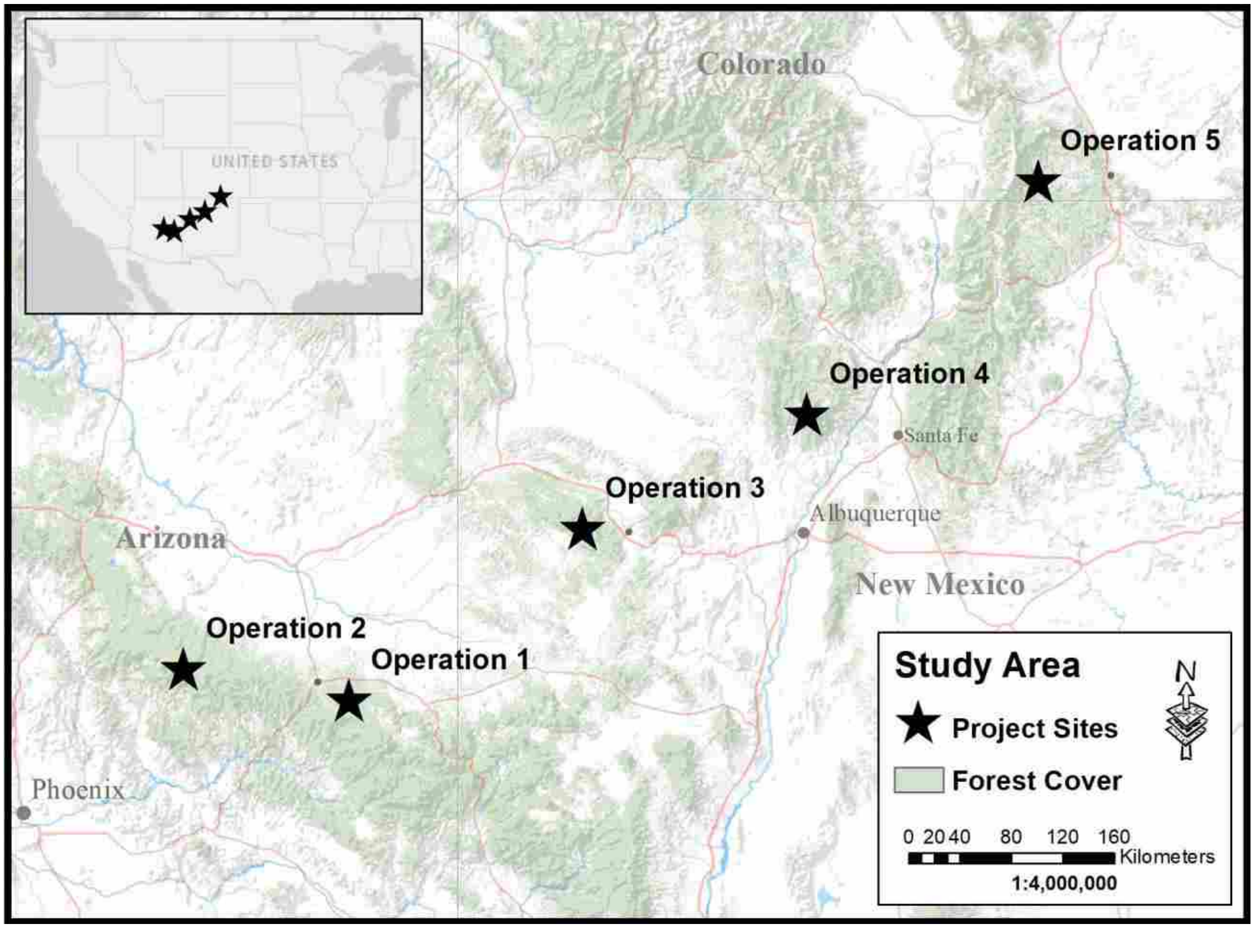


Figure 2.2

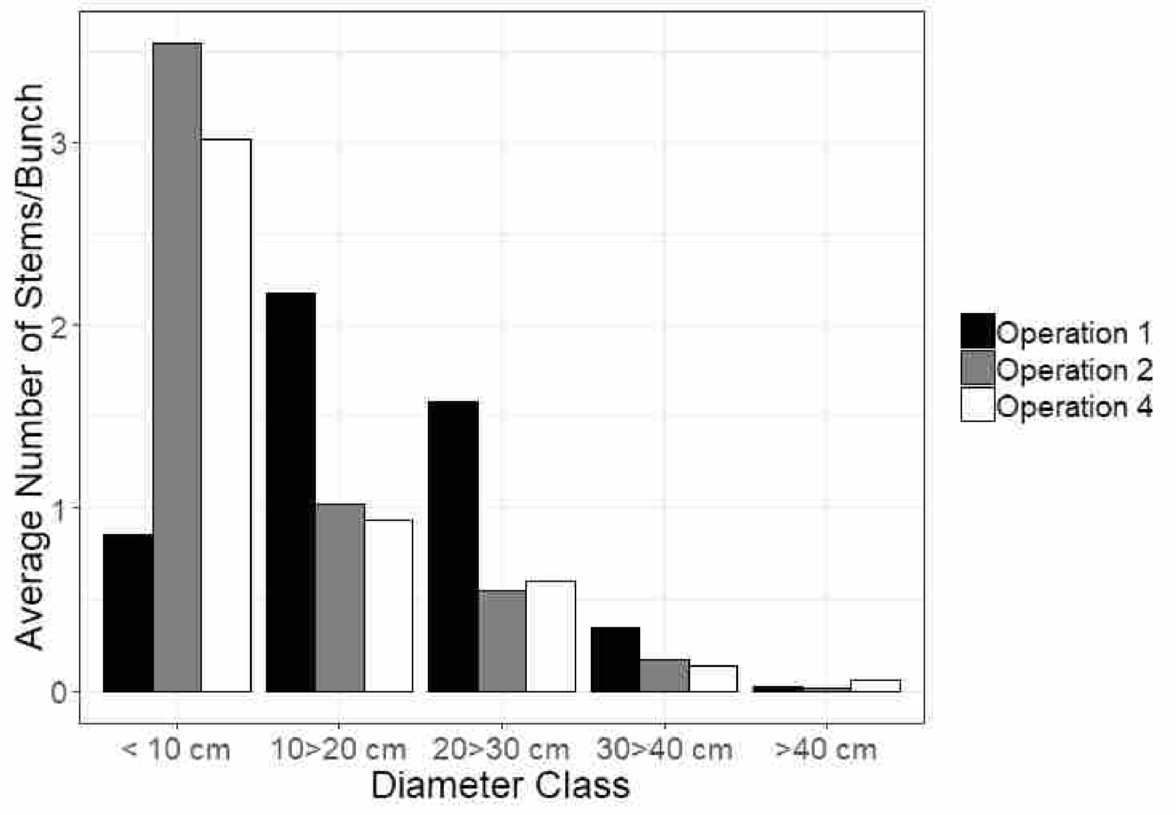
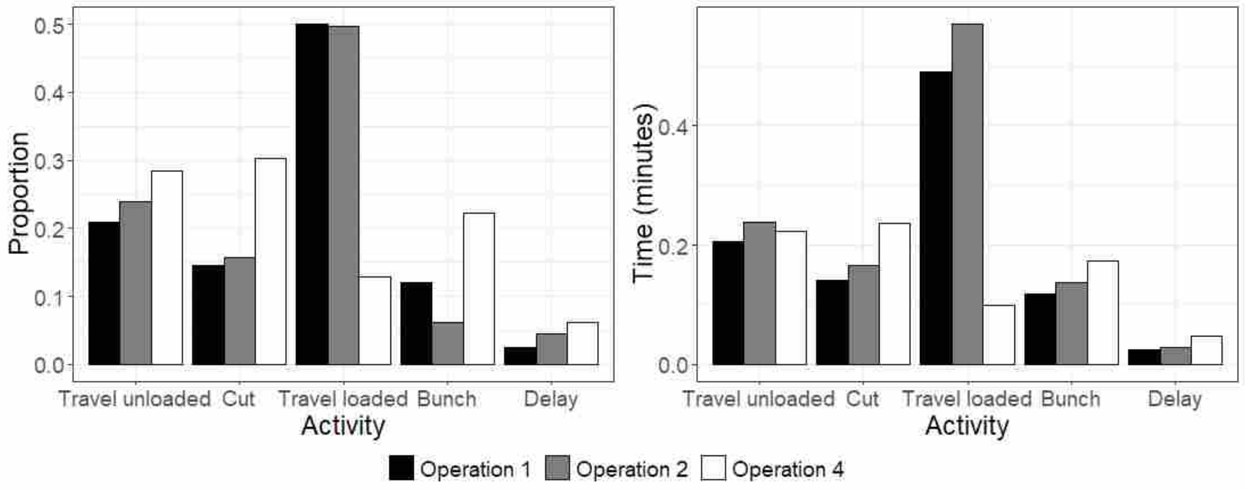

Average Number of Stems/Bunch
0
1
2
3
< 10 cm
10>20 cm
20>30 cm
30>40 cm
>40 cm
Diameter Class
Operation 1
Operation 2
Operation 4

Figure 2.3



0.5
0.4
0.3
0.2
0.1
0.0
Proportion
Travel unloaded
Cut
Travel loaded
Bunch
Delay
Activity
0.4
0.2
0.0
Time (minutes)
Travel unloaded
Cut
Travel loaded
Bunch
Delay
Activity
Operation 1
Operation 2
Operation 4

Figure 2.4

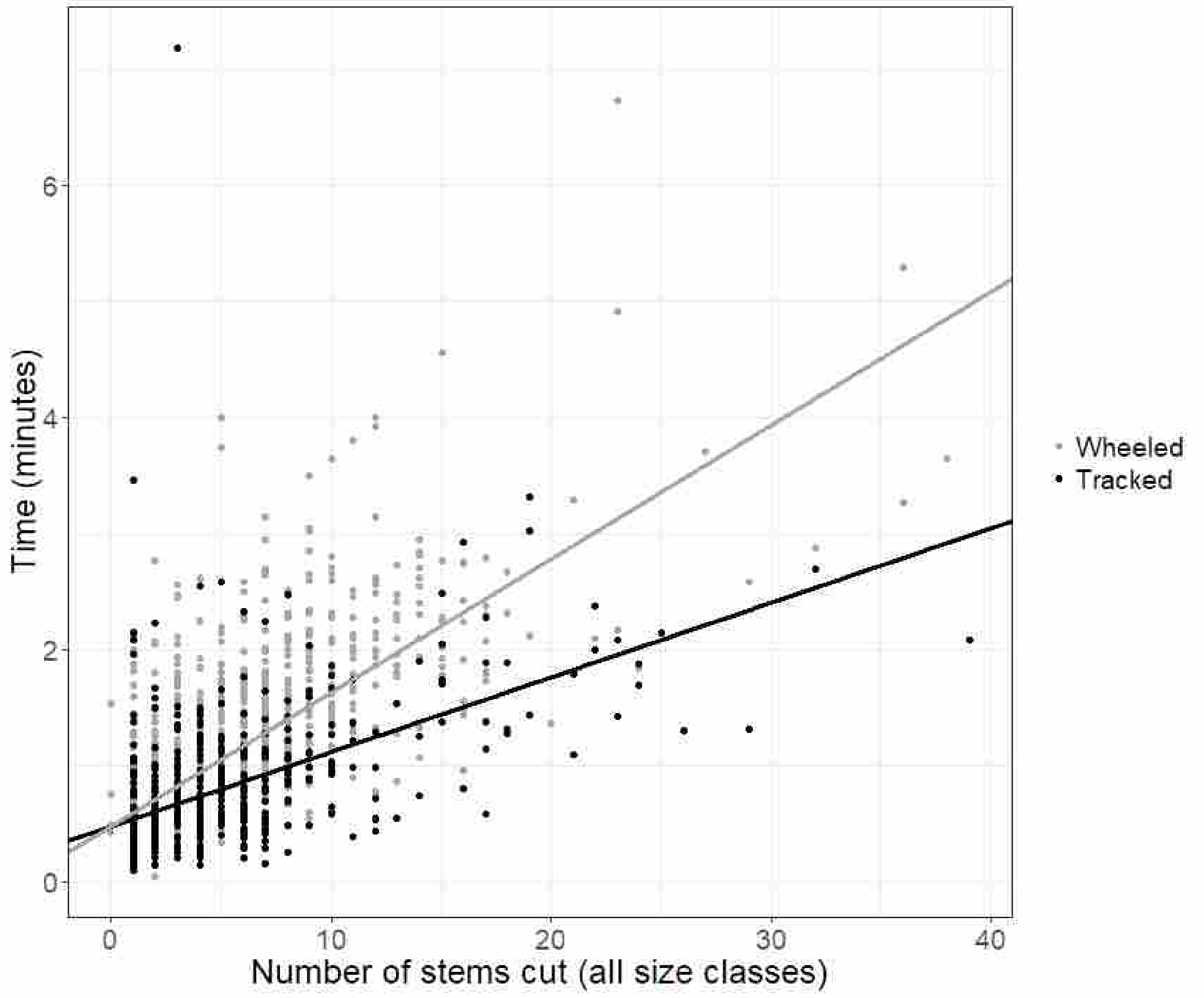
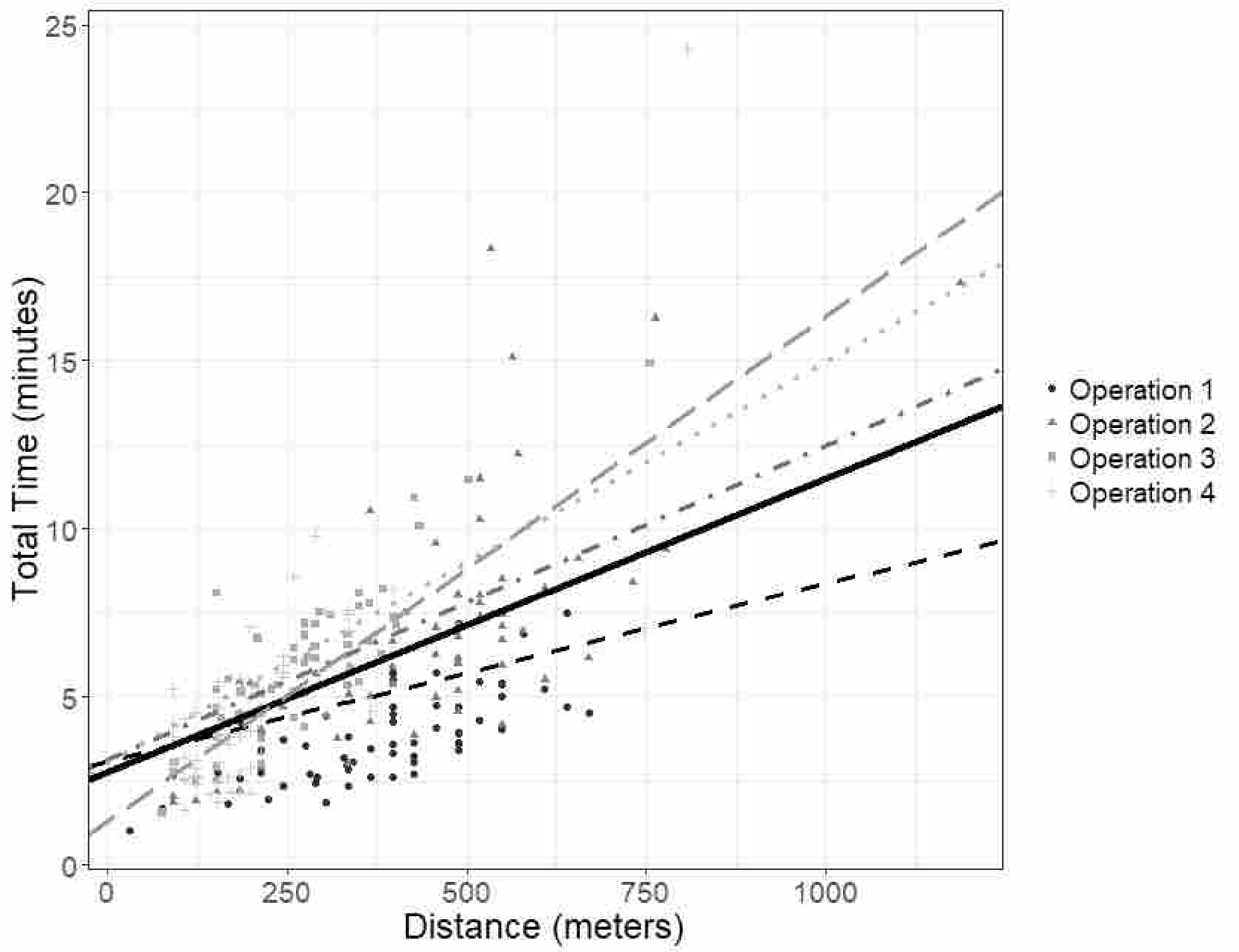

Time (minutes)
0
2
4
6
0
10
20
30
40
Number of stems cut (all size classes)
Wheeled
Tracked

Figure 2.5



25
20
15
10
5
0
Total Time (minutes)
0
250
500
750
1000
Distance (meters)
● Operation 1
▲ Operation 2
■ Operation 3
+ Operation 4

3.0 Recommendations to Operators After the 2017 Field Season

3.1 Overview

After data had been analyzed from the 2017 field season, a set of recommendations was delivered to each operation based on analysis questions developed in the field and discussions with contractors. This chapter details those specific recommendations. Recommendations were made with the intention of increasing operational productivity and efficiency. Operations displayed a wide range of opportunities for suggestions. Some operations, such as Operation 1, had little to improve upon from our observations while others, such as Operation 5, had major suggested changes. Each report discussed with operators involved the same benchmarking information and figures that were presented in Chapter 2 and therefore will not be presented again here.

Delay is a concept frequently referenced throughout the next chapters and is defined as time when a machine does not perform its intended function directly related to its productivity. Delay could be operational in that a task needed to be done, such as a skidder moving slash, however, moving slash does not directly contribute to bringing sawlogs to the landing. Delay could also be mechanical, relating to problems with the machine, and personal, such as a break to smoke a cigarette where no productive tasks are accomplished. These categories are not referenced throughout this document, however, they are understood as different from each other and that some can be adjusted, such as skidder wait times, and others cannot, such as lunch.

3.2 Operation 1

Operation 1 was the most efficient operation we studied. The hot saw operator worked to create optimal size bunches that allowed the skidder to assemble a full turn from a single hot saw bunch. On average, only once in every four cycles was the skidder required to assemble a second bunch to create a full turn. This operation also alternated short and long skid distances so that interaction delays, delays from waiting on the other machine at the landing for both the skidder and processor were minimized. This allowed Operation 1 to have optimal system balance. System balance is here defined as when the production of each function or machine within an operation is relatively equal to the production of others. In contrast to a balanced system as seen on Operation 1, an unbalanced system may be one that has a hot saw that can cut twice the amount of wood that a skidder can transport back to the landing in a single shift.

Our only suggestion was that Operation 1 consider some additional method of sorting, creating separate decks for standard and large sawlogs at the landing for faster loading cycles. These separate decks of large sawlogs may be placed behind the bigger decks of standard sawlogs for later loading or the loader can reach over standard sawlog deck when it is time to load them. However, sorting often took place between trucks when the loader was waiting, effectively utilizing downtime. Sorting on this operation was important because each of the three log sorts, small sawlogs, large sawlogs, and chip logs, were being sent to different facilities and could not be combined in the same truck load. Unfortunately, during data collection on this operation, sorting was not specifically recorded as a delay or quantified between trucks and is not possible with our data to determine the increase in cost efficiency from this practice. This operation did sort stems within the same deck, placing small chip logs at the bottom of the deck, followed by both small and large sawlogs. Large sawlogs were placed so that they protruded about one foot from the rest of the deck, making them stand out from the small sawlogs that were the main sort by volume.

3.3 Operation 2

During our observational period in 2017 we noticed issues relating to span of control and identified practices that would potentially improve their efficiency. Span of control issues were related to the large number of different operators working at one time, small number of experienced operators available for work in the region, and the combined management of both sawlog and biomass harvest operations. This operation frequently used three hot saws, five skidders, two processors, one loader, and one large biomass grinder. Depending on harvest system, an additional loader was also used and a total of 12 machines may be operating at a given time, not including truck drivers, service truck, and supervisor.

3.3.1 At what point does it pay to separate the processing and skidding (referring to the cold-decking system briefly observed)?

We observed two skidding/processing systems: hot-decking, where the skidder brought turns directly to the processor and they worked together at the same landing; and cold-decking, where the skidder brought turns to a landing where a knuckle-boom loader was waiting to sort out biomass stems for later grinding and separately deck the stems containing sawlogs. The processor then worked on these pre-decked stems. Ideally with this cold-decking system, the processor would be processing decks at a separate landing where skidding was complete to minimize the amount of equipment working at a given landing. More often, however, the processor worked at the same landing as the loader and skidder and occasionally waited for the loader to deliver trees to process. The motivation for cold-decking was to minimize interaction between the skidder and processor.

In our observations of hot-decking, we did not observe skidding delays from waiting on the processor. When all skidding delays were included in the analysis between the two systems, a

0.25 minute, 66% longer average delay, was found for hot decking as compared to cold decking (Table 3.1). Because more cycles, and therefore, more delays, were recorded for the hot-decking system than the cold-decking system, all delays were included in the analysis of delays rather than excluding any. However, delay by type was quantified to show the differences between the two systems. Hot-decking skidding delays were on average 30% (0.25 minutes per cycle) longer, largely due to more observed mechanical delays (Table 3.1). Operational skidding delays only accounted for 1% of all delay time in the cold-decking system and were not observed in the hot decking system (Figure 3.1). We did not observe any delays relating to the skidder waiting on the processor during hot-decking.

Table 3.1. Total delay time and percent of delay time in parentheses by machine for cold-decking and hot-decking systems.

Mean Values (Minutes)	**Cold-Decking**	**Hot-Decking**
Processor Total Delay Time/Cycle	0.12	0.11
Wait on skidder	0.05 (24%)	0.04 (44%)
Wait on loader	0.01 (8%)	NA
Other	0.06 (68%)	0.07 (56%)
Skidder Total Delay Time/Cycle	0.38	0.63
Waiting on processor	0 (0%)	0 (0%)
Waiting on loader	0.00 (1%)	NA
Other	0.38 (99%)	0.63 (100%)
Loader Total Delay Time/Cycle	0.55	NA
Waiting on processor	0.01 (1%)	NA
Waiting on skidder	0.50 (91%)	NA
Other	0.04 (8%)	NA

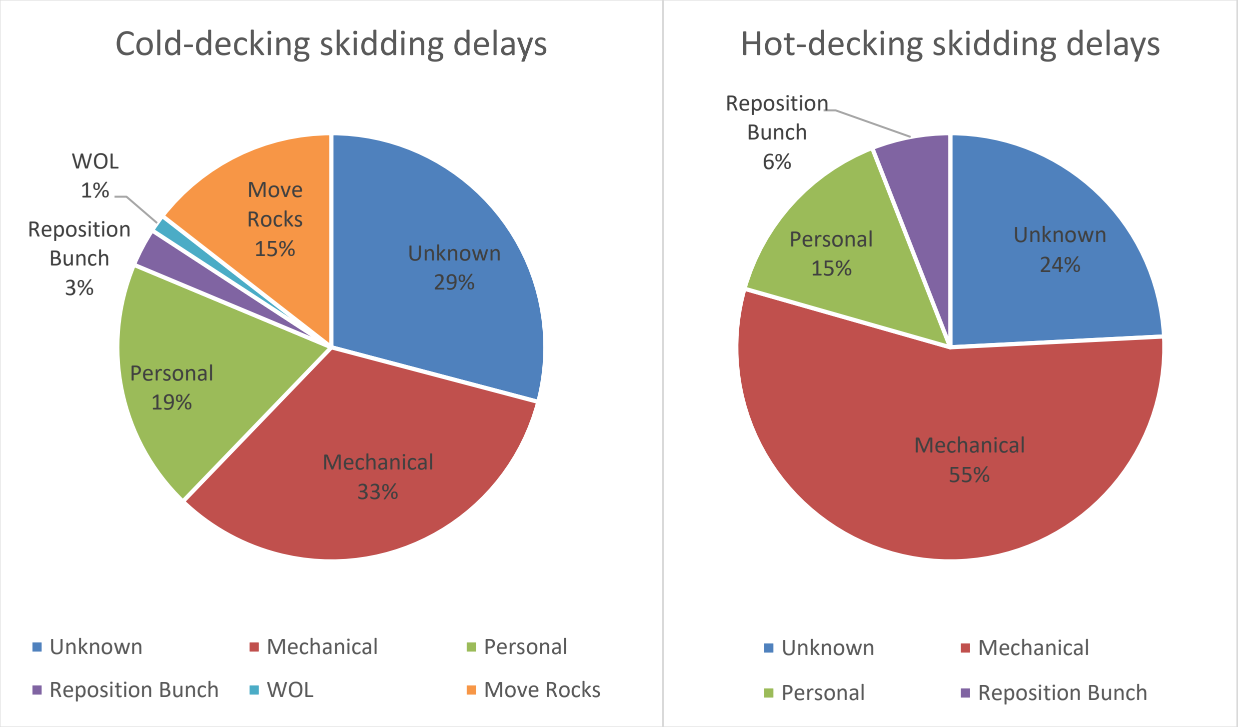


Figure 3.1. Skidding delays by system. Key: WOL = waiting on loader

However, delays where the processor was waiting on the skidder to return to the landing were considerable, accounting for 56% of observed delay during hot-decking and 24% of observed delay during cold-decking (Table 3.1). During the cold-decking system, the processor was still observed waiting on the skidder second hand because the processor had run out of logs and was waiting for the skidder to return to the loader with more trees. Delays experienced by the loader were significant and accounted for 44% of total time. This means a single loader could likely keep up with two skidders (Table 3.1).

This analysis of delays would suggest a third system configuration that may likely better balance production and minimize delays if implemented well. We suggested a system using two skidders to deliver material to a single processor at a landing when long skid distances are characteristic of a site. This would not require a loader to deck or sort. Successful implementation would depend on skidder operators to work together to balance skidding turn times so that they stagger their arrival at the landing and balance long- and short-distance turns. Landing space was not observed to be a limiting factor in this system, however, if it were and required the cold-decking system to be used, balancing the arrival of skidding turns at the landing from two skidders would also optimize the loader's utilization rate and increase productivity.

3.3.2 Is it beneficial to separate skidding of logs from biomass?

During observations in 2017, Operation 2 cut and sorted bunches of sawlog-containing trees separate from small diameter biomass stems so that biomass grinding and sawlog operations could be separated in time. The sawlog-containing stems were skid during sawlog-harvesting operations while the biomass bunches were skid to a grinder after sawlog harvest had been completed. Because bunches were separated by size class, this system used a pair of larger skidders dedicated to skidding sawlog material and a separate pair of smaller skidders delivering biomass material. These smaller skidders would work a landing only after processing and loading was complete, optimizing landing space during sawlog operations and allowing slash to air-dry prior to grinding. While this optimized landing space, it required more maneuvering on behalf of the hot saw which slowed felling operations. Separating bunches also required skidder operators to identify which bunches to skid and maneuver around the biomass bundles.

Based on our observations, separating the skidding is not an efficient operational method because of the high cost per tonne of biomass grindings and requiring multiple skidders to treat the same areas twice. Of course, there may come a time where separating bunches is necessary, such as very limited landing space in units where a large volume of non-sawlog material is removed. Under observed conditions, this practice cost \$17.31 gt^{-1} of sawlogs and biomass for skidding alone, while under modeled conditions when bunches were created with mixed size classes skidding cost only \$9.38 gt^{-1}, a \$7.93 gt^{-1}decrease in skidding cost (46%) because of the low weights associated with biomass-only bunches. The two skidding operations, sawlog and biomass, worked at the same pace when traveling and assembling bunches despite being different size machines ($p = 0.54$).

Separating the skidding of biomass from sawlog material also likely had an influence on felling times. Operation 1, which experienced similar market and stand conditions, harvested biomass material as well, but was 5% faster per stem during felling operations than Operation 2 ($p = 6.6*10^{-9}$). This difference could be due to Operation 2's cutting of biomass separately, the different prescription requiring 68% of cut trees to be biomass stems on Operation 2 versus 17% on Operation 1, or different operators. Our models suggested that stem size was not an important determinant of cycle time and therefore we attribute the difference in cutting rate to sorting while cutting.

3.3.3 Does Saturday production pay?

In 2017, Operation 2 consistently operated their skidders on Saturdays to skid biomass bunches to the landing and stockpile slash for grinding during the workweek. An active grinder to provide a sense of urgency was not present on Saturday shifts and skidding operations were not as productive as they were during the Monday-Friday workweek. While skidding an additional day of the week would add biomass reserves to landings, it may be less efficient and more costly than workweek skidding.

Unlike during the standard workweek, the distance a skidder traveled on Saturday was not well correlated to total cycle time ($r=0.81$ versus $r=2.7*10^{-3}$; Figure 3.2) and turns on average were 1.19 minutes longer despite an insignificant difference in distance traveled ($p=0.44$).

However, the number of bunches assembled per cycle was significantly larger, by an average of 0.38 bunches, approximately 25% more than during the regular work week (p=0.006). Strictly comparing the skidding of biomass bunches between Saturday and the work week, our model (Table 3.2) showed that the number of bunches was insignificant in determining cycle time. Assuming operators were paid a base wage of \$30 per hour for overtime compensation, skidding biomass bunches on Saturday cost \$38.73 gt^{-1} compared to \$30.04 gt^{-1} during the normal work week, a 29% increase in cost. These numbers are different than shown in Chapter 2 because these only account for biomass bunch skidding, not combined bunches or any sawlog material. Given that skidding on Saturday is 29% more expensive than during the normal work week, Saturday skidding may not be a wise investment.

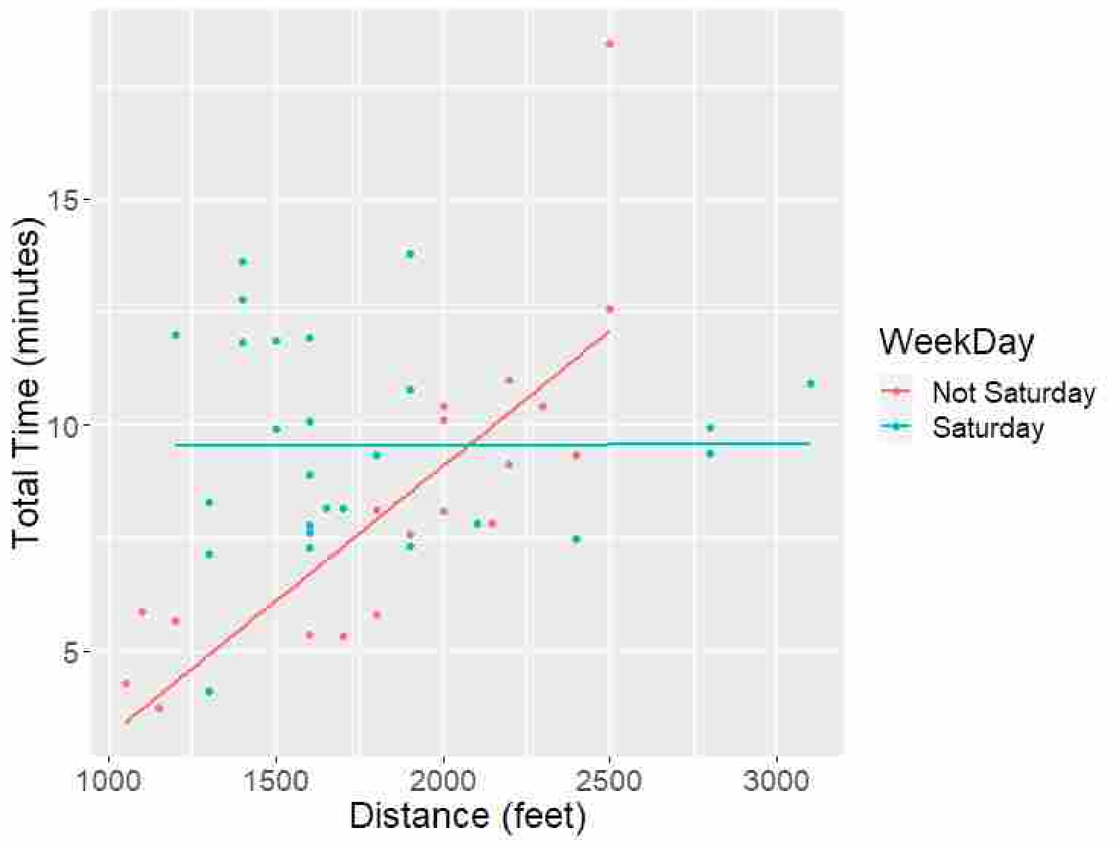


Figure 3.2. The relationship between total cycle time and total distance traveled for skidders on Saturday compared to the rest of the week.

Table 3.2 Saturday skidding model

Operation	Intercept	β_1 Distance (100s of meters)	β_3 Saturday	R^2
2	3.9619	0.07	-0.0200	0.19

3.3.4 Other Observations:

Operators we spoke with during observations tended to profess they did not have a strong understanding of other operations within the production cycle. This resulted in a tendency to attribute problems to the other operators and failure to recognize changes in a process that might help the efficiency of the operation as a whole. One strategy for increased cooperation and understanding of how one step in the operation influences other steps would be to institute some level of cross-training of operators. Cross-training would also allow for greater flexibility in staffing.

Span of control issues relating to operator efficiency might be addressed through the means of a production-related cash bonus program or some element of profit sharing via company stock, but this would be dependent on the financial capabilities of the operation.

3.4 Operation 3

Operation 3 presented unique opportunities for suggestions, as they were the only contractor in the study observed to use a harvester for felling and processing and a dangle-head processor for loading. This operation was fully aware that loading with the processor was inefficient but had no other equipment available to them during our period of observation.

3.4.1 How much is slash dispersal for later prescribed burning costing this operation and should it switch to a whole-tree system?

One of the primary reasons Operation 3 used a modified cut-to-length system was because of the perceived savings in slash dispersal by processing at the stump. However, when modeling a whole-tree system with the parameters observed on Operation 3, the stump to landing cost was \$18.81 gt^{-1} compared to the observed cost of \$24.54 gt^{-1} with the modified cut-to-length system. This modeled whole-tree system was 23% less expensive than their current modified cut-to-length system. A modeled whole-tree system using the observed parameters for Operation 3 was compared to the observed modified cut-to-length system so that the direct impacts from the anticipated size of timber frequently encountered by this operation could be assessed. In this modeled whole-tree scenario, I used the combined wheeled hot saw model from Chapter 2 assuming 5 stems cut per cycle, Operation 3's skidding model with 1.5 bunches assembled and 257 meters traveled, and the average modeled dangle-head processor cost per tonne from Operation 1, 2, and 4. The modeled conditions presented in Townsend et al. (2019) show that if all stems were greater than 8 inches, this modeled system would be on par with whole-tree systems or better, but small diameter stem removal is often characteristic of restoration treatments and is often tasked to logging contractors. While whole-tree logging may typically be more cost effective and more productive, the slash dispersal for later burning would be different between these two methods and depending on the specifications in the prescription, could result in greater cost-efficiency one way or another. If return skidding of slash provided adequate dispersal, return skidding may not cost the operation anything or very little, as observed on Operation 4 ($p=0.78$). If the slash dispersal was not adequate via return skidding, extra time and money may be required to provide an even fuel bed using a skidder or other equipment with a subsequent operation. This could render the modified cut-to-length system that was observed more cost effective. The skidder on this operation was matching its pace to the harvester because of the harvester’s lower productivity. Were a more productive machine used, like the hot saw that created optimal sized whole-tree bunches, this operation could increase its skidding efficiency. Additionally, if a market for slash exists, the use of a harvester does not allow for economic utilization of limbs and tops as compared to road-side processing.

3.4.2 How much is loading with a dangle-head processor costing this operation?

On average, loading with a processor cost 2.6 times the observed mean average cost per green tonne of knuckle-boom loaders, a raw increase of \$5.76 gt^{-1}, or \$136 per load. This operation would greatly benefit from the use of a knuckle-boom loader.

3.4.3 Would some degree of sorting in the woods benefit efficiency?

On average, 18% of time loading a truck was spent sorting sawlogs from firewood logs. There could be potential benefits to implementing some degree of sorting during either the processing or skidding operations to separate decks/piles. However, a more nimble grapple from a log loader would help reduce this sorting time.

3.5 Operation 4

Operation 4 did not show great room for operational improvement, but instead operator experience. Both the processor operator and skidder operator were relatively young, inexperienced operators. The skidder operator was observed on just his second day on the job, and the processor operator had only a year of experience total and about two weeks with the new processor Operation 4 had purchased. The only infrequent operational practice that we observed and questioned was processing at small in-woods landings. This was done to ideally reduce the time spent return skidding slash to the unit.

3.5.1 Does in-woods processing from decks (and subsequent re-skidding of logs) make up for reduced slash dispersal cost?

Our data showed that there was no statistical difference in the amount of time a skidder took to travel empty with and without the return skidding of slash ($p=0.78$). However, to skid processed logs there was an additional average assembly and decking time of 2.21 minutes per cycle with the new operator, a 33% increase in total cycle time and therefore cost. Additionally, remote processing operations disturbed more landing spaces, creating increased soil disturbance within the forest stand. For these reasons, we recommend roadside processing where stems and logs are only handled once by the skidder.

3.6 Operation 5

Operation 5 demonstrated multiple areas for improvement, largely relating to the type of equipment used. This operation used hand-felling, often without directional felling, in areas suitable for ground-based mechanical equipment which prevented stems from being bunched and efficiently transported to the landing.

3.6.1 Would a monthly payment for a hotsaw with an accumulating head be justified for the increase in production it would yield?

Largely, yes. Hand-felling was shown to be very expensive, costing 300% gt^{-1} more than a hot saw. Not only would felling productivity and cost efficiency be increased, but so would skidding, as the operator could then assemble a bunch of stems rather than stray individual stems. Of course, this increase in productivity would only be useful if markets supported the increased output.

3.6.2 Other equipment-based observations

While the potential benefit from a hot saw was the primary observation made in the field, other ideas were considered later regarding equipment used by this operation. Operation 5 could benefit from a skidder that had properly functioning gears that allowed faster travel. For a given skidding turn under modeled conditions outlined in Chapter 2, the combined skidding model had a time of 5.22 minutes, the skidder on Operation 5 modeled under these same conditions had a time of 9.06 minutes, a time 42% slower.

A dangle-head processor would also increase efficiency and productivity; however, the increased productivity would need to be accompanied with a market supporting the increased supply. The efficiency of the pull-through delimber could likely be improved by fixing the topping saw and would also represent a lower capital investment. Because cash-flow for this operation is a concern, these recommendations would be secondary to obtaining a hot saw. Overall, the hot saw would increase operational productivity the most and possibly provide the extra cash-flow necessary to invest in better equipment.

Without the purchase of new equipment, this operation could improve their efficiency with use of directional felling. Given that stems are scattered and not bunched, using a skidder with a winch may also increase productivity and efficiency by allowing the operator to spend less time assembling a bunch.

4.0 Harvesting Forest Biomass in the US Southern Rocky Mountains: Using Forest Operations Research to Improve the Productivity and Efficiency of Forest Restoration

4.1 Abstract

In the summer of 2017, five ground-based forest operations in the US southern Rocky Mountains were observed using a detailed time study and their cost and production rates quantified. A set of recommendations was constructed based on discussions with contractors to improve their operation's productivity and cost efficiency. Suggestions were made to contractors regarding operational methods, equipment selection, and harvest system conversion. In the summer of 2018, three of the five operations were revisited. All operations worked on forest restoration contracts and produced biomass energy products in some form, ranging from traditional firewood to hog fuel for thermoelectric power generation. Piece sizes in 2018 were on average 29% larger and resulted in a 26% decrease in costs. After implementing changes and accounting for piece size, most operational functions increased their productivity from 2017 to 2018 and the average stump to truck cost across all operations decreased by \$3.77 gt^{-1} (18%) under modeled conditions. Here, we identify the specific mechanisms driving changes in cost and productivity rates. Generally, restoration treatments are economically challenging and even minor operational improvements can increase their economic viability. This study demonstrates the value of working together with contractors to improve operational efficiency.

4.2 Introduction

Since the arrival of Euro-American colonizers, southwestern ponderosa pine and mixed conifer forests have grown uncharacteristically dense and overstocked relative to their historic open, park-like structure due to intensive forest grazing practices, high-grade logging, and the exclusion of fire (Covington and Moore 1994; Reynolds et al. 2013; Allen et al. 2002). Because many of these forests are now prone to uncharacteristic stand replacing crown-fires and no longer exhibit their historic structure and function, managers are attempting to restore historic forest conditions via restoration treatments. Mechanical treatments are often necessary to restore historic structure, especially before reintroducing a low-severity frequent fire regime (Allen et al. 2002; Hampton et al. 2008). Restoration treatments deviate from conventional timber harvests because their primary goal is to improve ecological function through recreation of historic stand structure and ecosystem function. In the case of southwestern mixed-conifer forests, this means the largest and most economically valuable trees are typically retained while subdominant, smaller, and less economically valuable trees are removed. In response to increased severe wildfire risk, public land managers have organized landscape-scale restoration projects like the Four Forests Restoration Initiative (4FRI) in the state of Arizona to both restore historic forest conditions and stimulate local and regional forest product economies (Lucas et al. 2017). Forest restoration treatments, many of which also serve as fuel treatments, have shown potential to reduce future wildfire suppression costs (Thompson et al. 2013).

Restoration treatments are economically challenging in southwestern forests because few markets are available for the small diameter material removed (Hayes et al. in press; Townsend et al. 2019). One way to utilize this small diameter and low value wood is by using it for biomass energy in the form of wood chips for thermoelectric power, pellets for wood stoves, and traditional fuel wood (Hayes et al. in press). These bioenergy markets and other assorted markets such as animal bedding and erosion control products now account for the highest sales by value in the region, deviating from historic products of lumber, timbers, and other sawn wood products (Hayes et al. in press). Because of biomass energy's significant impact on current forest management and its critical role in moving towards sustainable energy, it has been the focus of many forest operations studies. Biomass energy and other forest operations' costs and production rates have been explored in the northern Rocky Mountains (Anderson et al. 2012; Bell et al. 2017; Kim et al. 2017), the US southeast (Santiago et al. 2018; Hanzelka et al. 2016), the US interior northwest (Vitorelo et al. 2011; Han et al. 2004;), as well as internationally (Di Fulvio et al. 2017; Belbo and Vivestad 2018).

Forest operations researchers frequently use time studies to evaluate single or multiple operations during a given time period but rarely follow-up to quantify changes made after observations. This study is unique to forest operations research because of its recommendation and follow-up approach. Time studies that evaluate areas for future operative improvement are frequently found in the context of industrial engineering to identify bottlenecks in the manufacturing process (Al-Saleh 2011), agriculture to analyze autonomous machines with live video feeds (Panfilov and Mann 2018), and medical fields to understand how nurses spend their time and how much time is required for vaccinating young children (Hendrich et al. 2008; Washington et al. 2005).

In the summer of 2017, five forest operations in the southern Rocky Mountain region were observed and their costs and production rates quantified (Townsend et al. 2019). After discussing the 2017 results with each operation, a set of recommendations to improve productivity and cost efficiency were proposed. In this paper, we seek to answer the questions:

1. Given operational changes made after observations in 2017, how have productivity rates and costs changed in 2018?
2. What are the specific mechanisms behind the changes observed?
3. What implications do the observed changes and their associated results have for other forest biomass harvesting systems?

4.3 Materials and Methods

4.3.1 Study site and contractor selection

Five contractors were selected in January of 2017 based on their willingness to participate in the study, use of operations and equipment characteristic of the region, and a steady workflow of forest restoration-focused contracts. Our goal was to observe 10 consecutive operational days for each operation in both 2017 and 2018. In 2017 five contractors were observed, but in 2018 only three of the five operations were observed due to complications with fire season.

Field sites were selected as forest restoration-focused contracts already held by participating contractors. During 2017, four of the five contractors were operating on United States (U.S.) Forest Service projects, with the fifth contractor operating on a state-owned wildlife area. In 2018, all three observed contractors were operating on U.S. Forest Service projects (Figure 4.1). Pre-treatment stand information was collected for all sites using fixed-radius 0.04 ha plots (0.1 acre) for mature trees (diameter at breast height, DBH ≥ 13 cm), 0.004 ha (0.01 acre) fixed radius plots for saplings (DBH < 13 cm, height > 1.4 m), and 0.001 ha (0.003 acre) plots for seedlings less than 1.4 m tall. The density of small trees and regeneration was highly variable by site and therefore required varying levels of treatment by contractors (Table 4.1). Large overstory tree density also varied by site, but not near as much as small tree density. On most sites, ponderosa pine (*Pinus ponderosa*) was the dominant species, with Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), Gambel oak (*Quercus gambelii*), and quaking aspen (*Populus tremuloides*) as secondary cohabitants (Table 4.1).

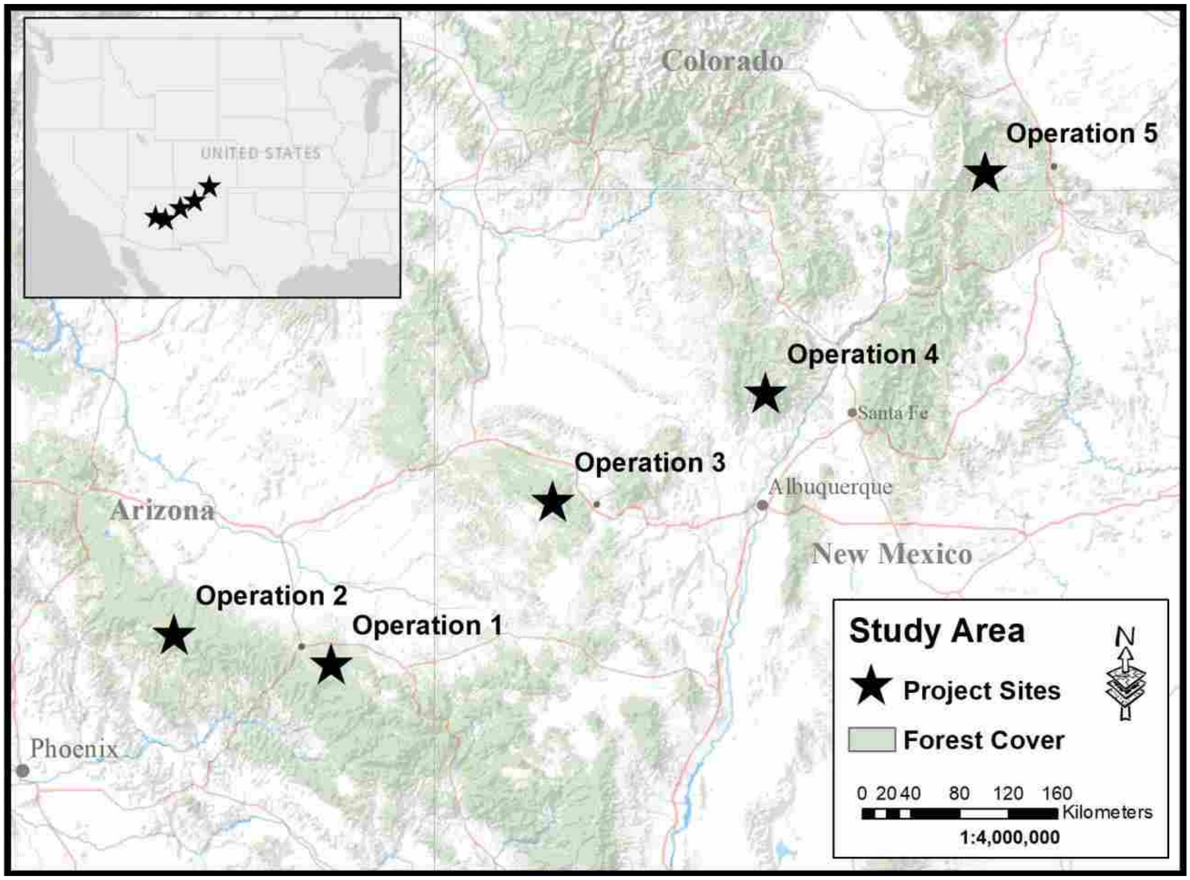


Figure 4.1 Map of study sites spanning both 2017 and 2018.

Table 4.1. Pre-treatment stand conditions by operation and year (Townsend et al. 2019). Species key: PIPO = *Pinus ponderosa*, PSME = *Pseudotsuga menziesii*, ABCO = *Abies concolor*, QUGA = *Quercus gambelii*, PIST = *Pinus strobiformus*

Operation and year	**Slope (%)**	**TPH < 10 cm**	**TPH > 10 cm**	**BA > 10 cm (m^2/ha)**	**QMD > 10 cm**	**Avg Ht (m) > 10 cm**	**Species Composition (% by basal area)**				
							PI PO	PS ME	AB CO	QU GA	PI ST
2 – 2017	7	618	404	29.9	30.7	14.3	97.3	0.2	0.1	2.4	0
2 – 2018	9	706	496	34.2	33.5	17.4	24.3	31.6	33.8	5.2	5.0
3 – 2017	7	41	315	19.0	27.7	12.4	100	0	0	0	0
3 - 2018	7	395	227	21.5	37.9	15.4	100	0	0	0	0
4 - 2017	15	2801	694	30.0	23.5	15.3	96.5	1.4	2.1	0	0
4 - 2018	16	165	478	32.0	29.5	17.1	98.9	1.1	0	0	0

4.3.2 Field data collection

To model productivity rates, detailed time study methods (Olsen and Kellogg 1983) were used to evaluate each harvesting function within an operation (Table 4.2). Because hot saws operated too quickly for accurate data collection by activity, activity sampling was used periodically, approximately every 45 minutes, to describe the proportion of time spent on individual activities within a cycle during observational periods. All tree and log diameters estimated in the field were based on diameter inside bark after visually calibrating from standing trees measured at DBH and processed logs, while distance was estimated with the aid of a laser-rangefinder. Delays were recorded but were not used to develop utilization rates because the recording of “long delays”, defined as delays longer than 30 minutes, were not consistently targeted and recorded. The only time observed delays were used to estimate full cycle times was to evaluate a cold-decking system on Operation 2 compared to its previous hot decking system.

Table 4.2. Cycle descriptions for each function and machine type (Townsend et al. 2019).

Machine type	Timed cycle elements	Independent variables
Felling		
Wheeled hot saw	Total time to build and lay down one bunch	Tally of trees cut per 10 cm size class
Tracked hot saw	Total time to build and lay down one bunch	Tally of trees cut per 10 cm size class, distance traveled (feet)
Skidding		
Rubber-tired grapple skidder	Travel empty, assemble turn, travel loaded, decking/piling	Travel empty (feet), travel between each bunch (feet), tally of bunches assembled, travel loaded (feet)
Cold decking Knuckle-boom loader	Total time decking and sorting a single skidder’s turn	Number of log swings, number of slash swings
Processing		
Dangle-head processor	Limb and buck, slash management	Large-end diameter to 5 cm size class, tally of logs produced by sort
Loading		
Knuckle-boom loader	Time per swing of logs loaded onto truck	Number of logs in each swing
Biomass grinding		
Horizontal grinder	Time per swing of biomass material into grinder	Categorization of material in each swing (slash, logs, mix of logs and slash, or fines)

4.3.3 Logging systems, recommendations, and products produced

All operations studied in 2018 utilized fully-mechanized ground-based whole-tree systems (Appendix 4.1) and all feller-bunchers observed used hot saws (also known as disk saws). While all operations were similar in this regard, there were variations within each system regarding the specific equipment used, such as tracked versus wheeled hot saws and trailer mounted loaders versus excavator-based loaders (Appendix 4.1).

In 2017, Operation 2 used rubber-tired feller-bunchers, rubber-tired grapple skidders, and roadside processing with dangle-head processors. This operation had a hog fuel market available to them, therefore after slash piles air dried, horizontal grinders were used to comminute slash directly into chip vans. After observations were made in 2017, we recommended that Operation 2 consider felling and bunching all size classes together rather than the feller-buncher separating biomass and sawlog-containing stems. We also recommended that some element of cross-training be implemented so that operators understood their impact on the harvesting system as a whole. In 2018, Operation 2 used the same equipment but feller-bunchers did not cut by sort. Instead, Operation 2 used a knuckle-boom loader for “cold-decking” at the landing. In the cold-decking system, a loader sat at a landing sorting turns delivered by skidders to create a large deck of sawlog-containing whole trees and separate slash pile of small diameter stems. Skidders would then move slash to a pile the processor would contribute to. Ideally, the processor would be able to work through landings faster due to a lack of operational delays from interacting with skidders, and the skidders would minimize delays from interacting with the processor on short skids. However, for this system to be cost effective, the reduction in delay time, increase in productivity, or increase in overall speed among all machines needs to outweigh the additional cost of the loader. In 2018, the processor produced three sorts of logs from the whole-tree decks created by the cold-decking loader (Table 4.3).

Table 4.3. Products produced by each operation by year. Key: SED = Small end diameter (inside bark), LED = Large end diameter (inside bark)

Operation	**Year**	
	2017	**2018**
2	• "Large logs" with LED ≥ 40 cm (16 in) with preferred lengths of 4.9 m (16 ft) • "Small logs" with LED ≤ 40 cm (16 in) and SED ≥ 11 cm with preferred lengths of 4.9 m (16 ft) • Whole-tree chips	• Tree-length logs to 11 cm (4.5 in) SED • "Large logs" with LED ≥ 40 cm (16 in) with preferred lengths of 4.9 m (16 ft) • "Small logs" with LED ≤ 40 cm (16 in) with preferred lengths of 4.9 m (16 ft) • Whole-tree chips
3	• SED > 11 cm (4.5 in) and lengths > 2.4 m with 0.6-meter (2-foot) multiples	• SED > 11 cm (4.5 in) and lengths > 2.4 m with 0.6-meter (2-foot) multiples
4	• SED > 6 cm (2.5 in) starting at 2.4 m (8 ft) • SED > 11 cm (4.5 in) with preferred lengths of 7.6, 8.2, and 8.8 m (25, 27, 29 ft)	• SED > 11 cm (4.5 in) with preferred lengths of 7.6, 8.2, and 8.8 m (25, 27, 29 ft

In 2017, Operation 3 used a modified cut-to-length system. In this system, a harvester was used to fell and process stems in the woods and to evenly distribute slash for a later prescribed broadcast burn, followed by a rubber-tired grapple skidder that assembled processed logs and transported them to a landing where it also decked them. Log trucks were loaded using a dangle-head processor. After observations in 2017, we recommended that Operation 3 consider using a feller-buncher for its ability to quickly cut small diameter stems and a knuckle-boom log loader for loading. In 2018, Operation 3 converted to a whole-tree system with a rubber-tired feller-buncher, a rubber-tired grapple skidder, a dangle-head processor for roadside processing, and a knuckle-boom log loader.

In 2017, Operation 4 used a tracked, leveling feller-buncher due to steep slopes, a rubber-tired grapple skidder, and roadside processing with a dangle-head processor. Both the skidder operator and processor operator were inexperienced. In 2018, Operation 4 used the same logging system and equipment, and the operators had an additional year of experience.

4.3.4 Cost and productivity analysis

This study analyzed productivity and cost in two different scenarios: one based on observed stand and site conditions for each operation; the other a modeled productivity and cost analysis assuming a standard set of stand and site conditions based on average observed variables from all sites in 2018. The modeled analysis was used to directly compare operations between years and between operations.

To model productivity and detect change, if any, between 2017 and 2018, a single least squares regression model was fit between randomly selected, equal sample sizes of 2017 and 2018 data for each function on each operation to estimate cycle time. This model included main effects for explanatory variables (Table 4.2), and interaction terms for each main effect and year. From here, backwards step-wise regression methods were used to create a final model using a significance threshold of $p \leq 0.05$. With this modeling approach, a single model can describe the difference between years and estimate delay-free cycle times for 2017 and 2018 (Appendix 4.2). For functions not observed in 2018, such as the harvester, Townsend et al. (2019) models were used. For operational functions where regression models could not be constructed, the observed mean cycle time was used in place of a modeled delay-free cycle time. Each model, cost, and productivity estimate is given on a per machine basis rather than in aggregate, as Operation 2 had multiple machines performing the same function (Appendix 4.1). Each cycle time used an associated number of pieces, along with other variables, based on averages within each operation for observed calculations and an average number of pieces across all operations for modeled calculations. For each function in each operation, an estimated number of cycles and therefore pieces per hour was calculated for productive machine hours (PMH) using developed models. Delay-free cycle times were adjusted to total estimated cycle times using standardized utilization rates (PMH/SMH) adapted from the literature. This average delay was calculated by dividing the delay-free cycle time by the machine's utilization rate. Inclusion of delays allowed an estimate of the number of cycles per SMH to be developed. While delay data was collected in the field, these observed delays are not used in determining the average delay per cycle because of the highly-variable nature of delay, and to make operations as comparable to each other as possible. However, improving utilization rate is one way for operators to differentiate themselves and provide a competitive advantage.

Both observed and modeled costs and productivity piece weight estimates were calculated assuming a standard 23.6 tonne (U.S. 26 ton) payload per log truck. Based on this payload and piece counts per load, we estimated a weight per piece for each log sort. Productivity rates (tonnes SMH^{-1}) could then be estimated for each machine given cycles per SMH and weight per piece. Allometric equations were used to estimate weights for trees with large end diameters less than 10 cm (4 in) (Jenkins et al. 2003). Machine rates were calculated (USFS Machine rate calculator) using 2018 purchase prices for new machines in each class of equipment (Table 4.4). The following machine rate assumptions were held constant: 1500 hours worked per year; 5-year machine life; salvage value 20%; interest rate 6.5%, insurance rate 1.3%; taxes 2%; fuel use 13.35 L/kW-hr (0.0263 gal/hp-hr); repair and maintenance at 100% of depreciation; operator wage of $20 per hour; benefits 50% of wage; hand-felling wage $35 per hour; rubber tire replacement at 1500 machine hours and $20,000 per set. Machine rates, given in cost per scheduled machine hour (SMH), were then divided by productivity rates (tonnes SMH^{-1}), to estimate cost per green tonne ($\$ gt^{-1}$). Anytime "tonne" is referenced throughout this document, it is referring to green tonne except in the case of small diameter biomass stems. The weight estimates from Jenkins et al. (2003) are based on dry weights, however, we assume this dry weight is appropriate enough because these pieces were air dried in an arid climate before being ground into a product (U.S. Forest Service Forest Products Laboratory 2001).

Table 4.4. Purchase prices, utilization rates, and hourly machine rates used for evaluation (Townsend et al. 2019).

Machine	Horsepower	Purchase Price (USD)	Utilization rate (%)	Cost USD/SMH	Operations used
Felling					
Wheeled hot saws	270-285	$287,000	60[b]	$133	2, 3
Tracked hot saw	300	$525,000	60[c]	$187	4
Harvester	177	$540,000	70[a]	$183	3
Skidding					
Rubber-tired grapple skidder	203-263 300	$330,000 $370,000	65[c] 65[c]	$143 $156	3,4 2
Processing					
Dangle-head processor	139-166 190-194	$475,000 $540,000	75[a] 75[a]	$164 $183	3,4 2
Loading					
Knuckle-boom loader	164-188	$277,000	65[c]	$113	All Operations
Biomass grinding					
Horizontal Grinder (including loader)	1050	$900,000	85[a]	$473	2

Footnote:

Utilization rates were assumed to be different for each function and were sourced from literature ([a]Anderson et al. 2012; [b]Brinker et al. 2002; [c]Dodson et al. 2015).

Hot saw cycles assumed two trees at 20 cm (8.0 in) large-end diameter inside bark, plus 1.3 trees with diameters less than 10 cm (4 in) per bunch, usually requiring three to four cycles to create a full skidder bunch. An average travel distance of 6.5 m (21 ft) per cycle was used to model tracked hot saw cycle time. An average round-trip skid distance of 225 m (740 ft) with 1.6 bunches assembled containing a total of 11.7 trees per turn was assumed. All modeled processing estimates assumed a diameter of 20 cm (8.0 in) inside bark, 1.17 logs produced per stem, and a uniform piece weight of 0.34 tonnes (0.38 tons) per log. The harvester was modeled with a cut-tree large-end diameter inside bark of 14.7 cm (5.8 in) and 0.7 logs produced per tree to account for felling small diameter biomass stems, and an average travel distance of 6.5 m (21 ft). Loading was not modeled in this analysis because of insufficient sample sizes required to create a reliable model for Operations 3 and 4, therefore averages were used.

4.4 Results

4.4.1 Productivity summary statistics and model evaluation

4.4.1.1 Felling

All felling in 2018 was completed with hot saws and averaged 0.90 minutes per cycle, 0.06 minutes shorter than in 2017 (Table 4.5). On average, hot saws cut 1.7 fewer stems per cycle in 2018, partially due to the reduced amount of cutting small diameter regeneration on Operation 4 and larger stems on Operation 2 (Figure 4.2).

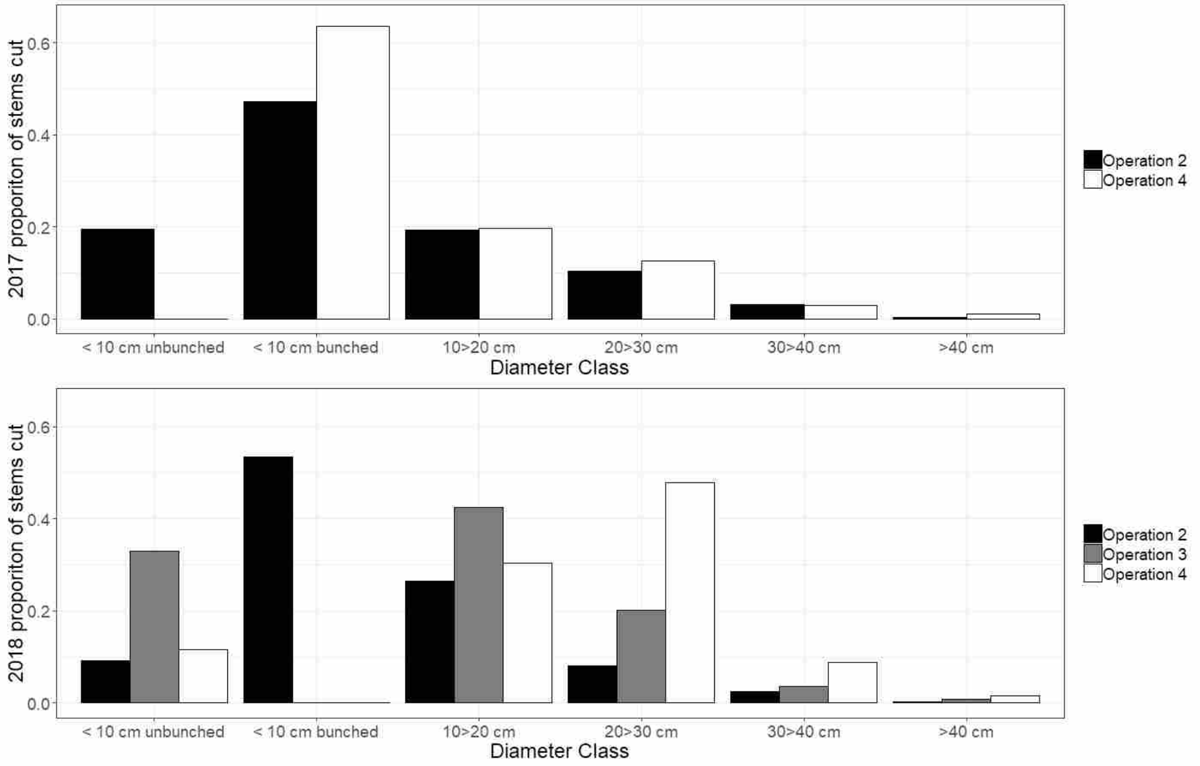


Figure 4.2. Hot saw cut tree diameter distributions for 2017 and 2018.

The average proportion of time spent in each activity of a cycle changed within operations (Figure 4.3) and was correlated to the number of large and small-diameter stems in pre-treatment stand conditions. Travel empty was negatively correlated to the number of small diameter stems (r = -0.41) while time spent felling was positively correlated (r = 0.71). The proportion of time spent traveling loaded was negatively correlated to the large tree density (r = -0.62) and time spent bunching was positively correlated (r = 0.76). These correlations were moderately strong, however, the small sample size of five pretreatment stands used in this analysis should be noted. Operation 2 spent more time traveling unloaded and cutting, and less time traveling loaded. Operation 4 spent more time traveling loaded and unloaded, and less time cutting and bunching. Overall, hot saw activities and the proportion of time spent in each activity category was largely determined by site conditions.

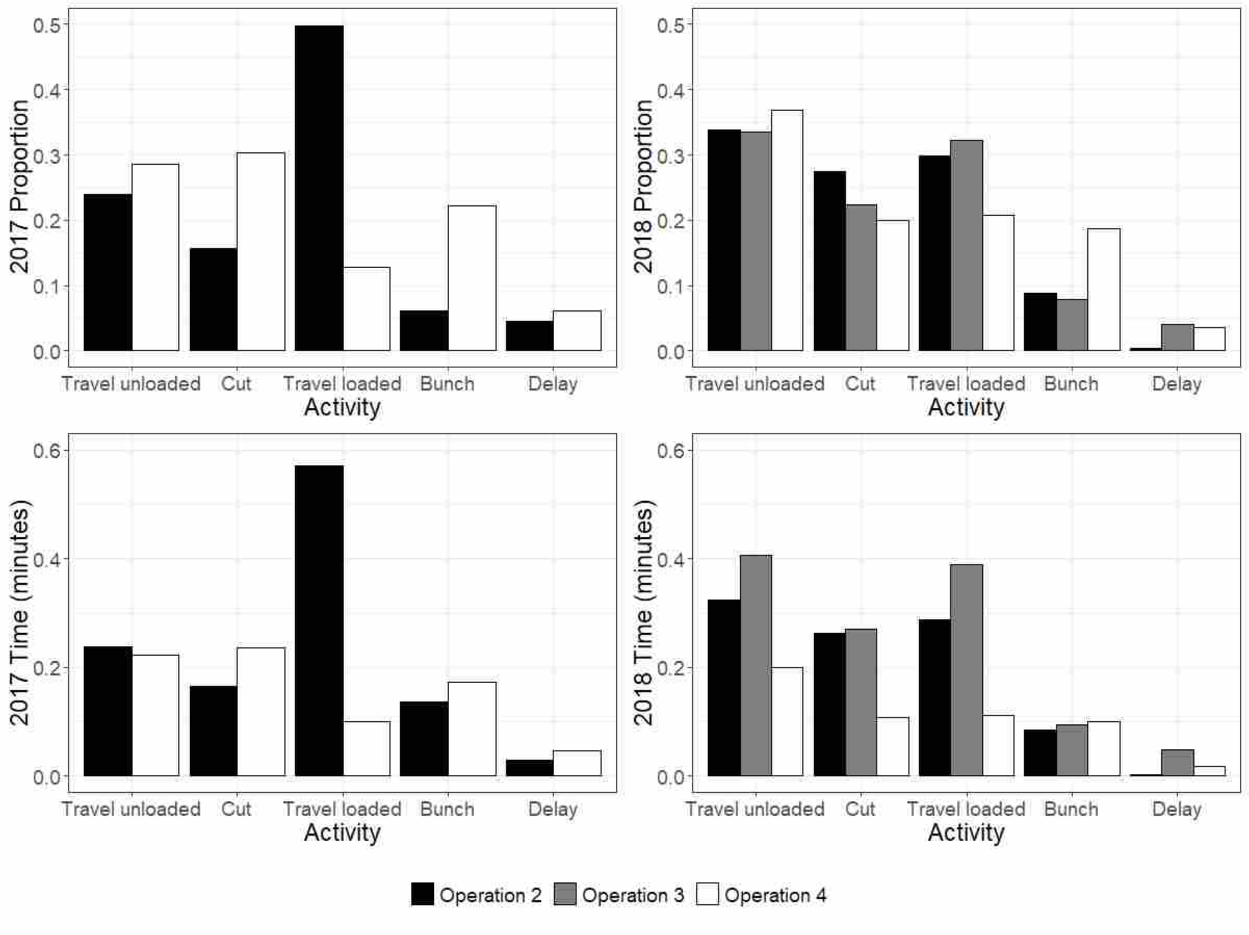


Figure 4.3. Activity sampling results by operation by year in time per cycle and proportion of total time of each activity per cycle.

In 2018 Operation 2 spent 63% of time cutting stems less than 10 cm in diameter, resulting in a lower observed productivity rate (23.3 tonnes SMH^{-1}) compared to Operation 4 (62.5 tonnes SMH^{-1}) despite a similar number of stems cut per minute. Operation 3, which recently acquired a hot saw for felling, also spent a considerable amount of time, approximately 33%, cutting stems less than 10 cm in diameter but did not bunch these stems for transport back to the landing (Table 4.5). Instead, these stems were left in the woods for later broadcast burning. The average observed productivity rate for all hot saws in 2018 was 36.0 tonnes SMH^{-1}, with operations varying from 62% to 173% of the mean. Once conditions were standardized, the 2018 modeled hot saw productivity averaged 35.1 tonnes SMH^{-1}, with operations ranging from 77% to 122% of the mean. Using the models generated in 2017 with the 2018 input data, productivity rates averaged 30.0 tonnes SMH^{-1} with operations ranging from 64% (the harvester) to 127% of the mean.

Table 4.5. Felling summary statistics with observed and modeled productivity. The differences between years on Operation 3 demonstrates the change between a harvester and wheeled hot saw.

Factor	**Units**	**Mean Values, by operation**					
	Operation	**2**		**3**		**4**	
	Year	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
Observed delay-free cycle time	Minutes	1.14	0.96	0.55	1.21	0.78	0.54
Diameter	Centimeters	10	11	18	21	11	28
Distance	Meters	NA	NA	2.4	NA	4.3	6.5
≤ 10 cm	Stems/bunch	3.54	2.42	0.43	1.45	3.02	0.21
> 10 cm	Stems/bunch	1.76	1.44	0.67	2.88	1.73	1.60
Total stems	Stems/cycle	5.30	3.86	1.10	4.33	4.75	1.81
Observed Delay	Minutes/cycle	0.20	0.20	0.23	0.06	0.14	0.10
Productivity observed	Tonnes/SMH	17.2	23.3	13.9	22.3	49.8	62.5
Productivity modeled	Tonnes/SHM	32.9	35.6	19.2	27.1	38.1	42.7

When comparing felling models from 2018 to 2017, Operation 2 showed a 19% modeled decrease in time per stem cut regardless of size class ($p=1.79*10^{-5}$). Operation 3 converted from a harvester to a wheeled hot saw for felling and experienced a felling productivity increase of 41%. Operation 4 showed no statistically significant difference in felling time per stem cut (p=0.69), although there was a 34% increase in travel speed ($p=2.01*10^{-5}$). Overall, models suggested that felling operations in 2018 were more productive than in the previous year. Model comparison shows that Operation 2 was on average 2.7 tonnes SMH^{-}1 more productive, an increase of 8%, due to increased cutting speed. Operation 4 was on average 4.6 tonnes per hour more productive, an increase of 12%, due to faster traveling.

4.4.1.2 Skidding

Skidding operations varied greatly between 2017 and 2018, especially in observed conditions (Table 4.6). In 2018, average observed cycle times across all operations were 2.0 minutes shorter than in 2017 due to an average 86-meter decrease in skidding distances. The number of bunches assembled per cycle averaged 1.6 in 2018, a decrease of 0.4 bunches from 2017. Under observed conditions, skidders averaged 37.8 tonnes SMH^{-1}, ranging from 78% to 127% of the mean. When conditions were standardized, the average productivity rate was 36.6 tonnes SMH^{-1}, ranging from 85% to 110% of the mean. As the average volume per stem increased during 2018, bunch compositions for Operations 2 and 4 showed a slight decrease in the number of pieces per bunch, 1.1 and 0.3 respectively. Operation 3 increased its average bunch size from 8.7 to 14.1 stems, an increase of 5.4 stems per bunch despite the increase in stem size because of the change from a harvester to a feller-buncher where most bunching was now completed by the hot saw rather than the skidder.

Table 4.6. Summary statistics and production rates for skidding.

Factor	**Units**	**Mean Values, by operation**					
	Operation	**2**		**3**		**4**	
	Year	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
Observed delay-free cycle time	Minutes	7.60	5.55	6.63	3.93	6.08	3.47
Number of bunches		1.7	2.1	3.0	1.5	1.4	1.2
Number of pieces		17.1	16.0	8.7	14.1	5.5	5.2
Total distance	meters	455	310	257	138	206	213
Observed delay	Minutes/ cycle	0.55	1.43	0.89	0.44	1.16	1.44
Productivity observed	Tonnes/ SMH	9.0	47.8	12.6	36.2	30.8	29.3
Productivity modeled	Tonnes/ SMH	31.9	40.4	34.5	31.0	31.0	38.5

Skidding model comparisons suggest some operations increased efficiency, while others declined. On Operation 2, skidders spent 0.55 minutes less per bunch assembled in 2018 versus 2017 ($p=7.52*10^{-7}$) while travel rate remained unchanged ($p=0.25$). Operation 3 experienced a decrease in skidding productivity with a new operator spending 0.40 minutes longer in 2018 to gather a turn of bunched whole trees as compared to the experienced operator in 2017 assembling scattered processed logs ($p=2.94*10^{-6}$). However, these new bunches contained twice the payload and number of pieces compared to the previous year. The rate at which the skidder traveled did not change ($p=0.75$). Operation 4 also experienced a large difference in time spent assembling bunches in 2018, with a 0.62-minute decrease per bunch assembled ($p=2.0*10^{-3}$). Like the other operations, the rate at which the skidder traveled did not change ($p=0.34$).

4.4.1.3 Processing

Processing metrics and productivity rates varied between operations, and within the same operations between years (Table 4.7). On average, in 2018 Operation 2 increased its cycle time by 0.15 minutes per stem, a 32% increase, and produced 0.9 fewer logs per tree. Operation 3 now processed whole-trees at a landing rather than in-woods with a harvester. Operation 4 reduced its cycle time by 0.31 minutes and produced 0.39 fewer logs per stem. Under observed conditions, dangle-head processors averaged 28.1 tonnes SMH^{-1} with operations varying from 80% to 115% of the mean. Once variables had been standardized, the average modeled productivity rate was 31.8 tonnes SMH^{-}1 with operations varying from 74% to 143% of the mean.

Table 4.7. Processing summary statistics.

Factor	**Units**	**Mean Values, by operation**					
	Operation	**2**		**3**		**4**	
	Year	**2017**	**2018**	**2017**^{a}	**2018**	**2017**	**2018**
Observed delay-free cycle time	Minutes	0.58	0.73	0.55	0.36	1.08	0.77
Large-end diameter	cm	22	20	18	18.9	21	22
Large logs produced	Logs/cycle	0.18	0.34	0.77	.29	0.94	1.07
Small logs produced	Logs/cycle	2.21	1.06	NA	0.73	0.52	NA
Delay	Minutes/cycle	0.15	0.10	0.23	0.15	0.50	0.39
Productivity observed	Tonnes/SMH	22.5	25.5	13.9	32.3	25.3	29.5
Productivity modeled	Tonnes/SMH	35.9	26.6	19.2	45.3	19.7	23.4

Footnote: ^{a}Harvester time includes felling and processing.

During the observational period in 2018, Operation 2 changed sorts half-way through data collection to match those produced in 2017. In 2018, Operation 4's contract no longer required utilization down to a 6-cm (2.5 in) top size, allowing the production of a single preferred-length log. Operation 3's switch to a dangle-head processor from a harvester showed an observed productivity increase of 332%, and modeled increase of 136% (Table 4.7). For Operation 4, processing a log of the same diameter required 0.12 minutes less, a 23% decrease in time providing a 19% increase in productivity.

4.4.1.5 Loading

Loading comparisons from 2017 to 2018 were made with observed mean rather than modeled values because of small sample sizes on Operations 3 and 4, five and seven cycles, respectively (Table 4.8). On average, Operation 2 decreased their loading time by 4.04 minutes per truck, a 19% reduction and required 8 fewer swings and 71 fewer logs per cycle compared to 2017. Operation 3, which had switched from loading with a dangle-head processor to a knuckle-boom loader, had an average reduction in loading time of 21.51 minutes per truck, a 41% decrease, and 13 fewer swings per cycle. Operation 4 only used a self-loading log truck in 2018 and had an average time 11.38 minutes shorter per cycle with 5 fewer swings than observed from the same self-loader in 2017.

Table 4.8. Loading summary statistics.

Factor	**Units**	**Mean Values, by operation**					
	Operation	**2**		**3**		**4**	
	Year	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
Observed delay-free cycle time	Minutes	20.70	16.66	52.64	31.13	31.46	20.08
Number of grapple swings		25	17	51	38	31	26
Total pieces	Logs/load	144	73	96	116	48	50
Delay	Minutes	4.10	1.23	10.54	7.40	5.03	4.75
Productivity observed	Tonnes/ SMH	44.4	52.2	17.5	29.1	29.2	45.8

4.4.1.6 Grinding

As in the previous year, meaningful models could not be constructed with the data collected and the best description of the operation was with observed averages. In 2018, grinding cycles for Operation 2 were on average 4.56 minutes shorter than in 2017, a 21% decrease, and consisted of 12 more grapple swings than Operation 2's primary grinding operation, Site 2, in 2017 (Table 4.9). This led to an additional 13.7 tonnes produced SMH^{-1}. Although Site 1 in 2017 shows more grapple swings were used than in 2018, these averages are not significantly different ($p = 0.39$), however, these are different from Site 2 in 2017 which used fewer grapple swings per load ($p = 1.5*10^{-7}$).

Table 4.9. Summary statistics for the grinder on Operation 2.

Factor	**Units**	**Mean Values, by operation**		
		2017 (Site 1)	**2017 (Site 2)**	**2018**
Observed delay-free cycle time	Minutes/truck	20.21	22.44	16.86
Total grapple	Swings/truck	53.8	36.8	49.0
Delay/truck	Minutes	4.94	8.11	5.41
Productivity observed	Tonnes/SMH	54.0	48.6	64.7

4.4.1.7 Cold-decking analysis

The full separation of machines intended by the cold-decking system rarely happened in 2018, as the processor often worked on the same landing as the cold-decking loader, but towards the opposite end of the whole-tree deck (Figure 4.4). While both machines worked side-by-side at the landing, the intended result of minimizing machine interaction between the skidder and processor was successful. On average, the delay-free cycle time for the cold-decking loader was 3.76 minutes with 8 swings in addition to 1.23 minutes of delay per cycle. Of those 8 swings, 5.4 were for logs to the whole-tree deck and 2.6 were for slash. Most, 91%, of this delay time was waiting for a skidder to deliver a turn of whole trees. The loader was observed to sort 88.4 tonnes SMH^{-1}.

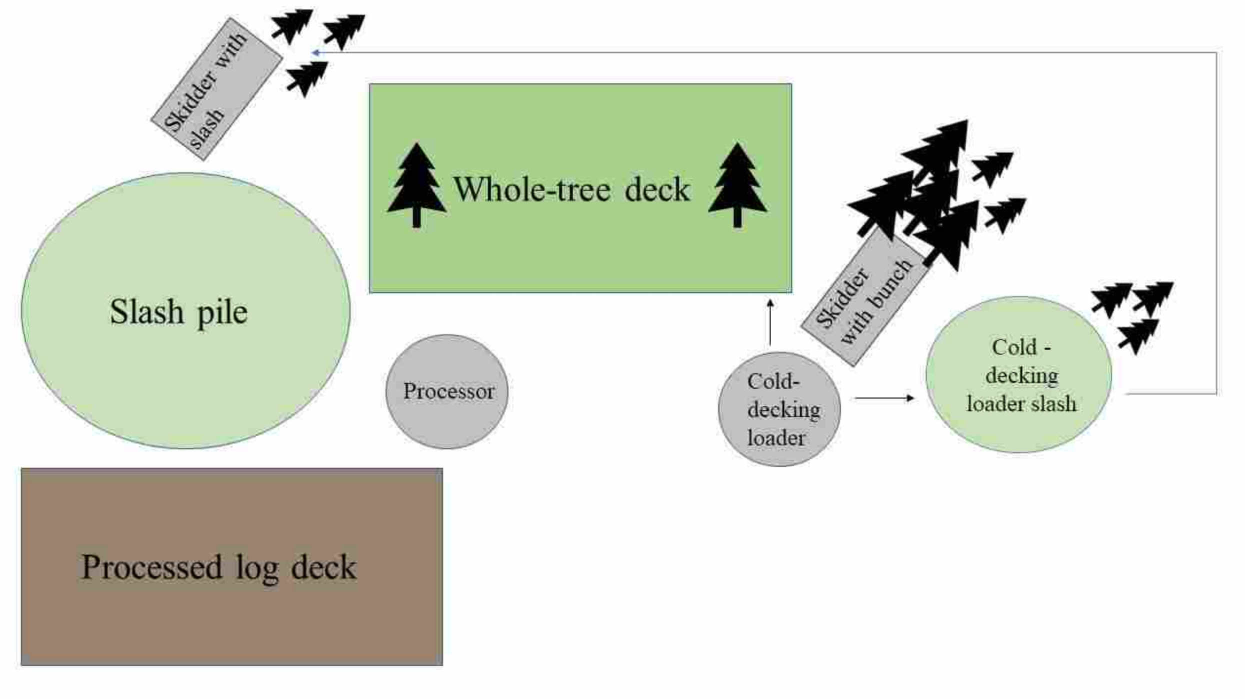


Figure 4.4. Diagram of observed cold-decking landing configuration where processor and loader work on the same landing.

Using observed delays, had Operation 2 used the hot-decking system observed in 2017 skidding productivity was modeled at 58.0 tonnes SMH^{-1}. With observed cold-decking delays, it was 49.4 tonnes SMH^{-1}. Overall, skidding productivity was modeled to be 15% more productive with the hot-decking system. Using observed delays for the hot-decking system, processing was modeled to produce 28.2 tonnes SMH^{-1}. With the cold-decking system and its observed delays, processing was modeled to produce 31.2 tonnes SMH^{-1}. Processing with the hot-decking was modeled 11% less productive. While the cold-decking system aimed to reduce both processing and skidding delays, only the processor showed a reduction in delay time.

4.4.2 Stump to truck costs

In 2018 felling costs averaged \$4.92 gt^{-1} under observed conditions and varied from 63% to 118% of the mean. Under modeled conditions in 2018, felling costs averaged \$4.34 gt^{-1} and varied from 77% to 122% of the mean. When comparing the felling models across all operations using a hot saw in both 2017 and 2018, the modeled cost in 2018 was \$0.42 gt^{-1} less expensive (Table 4.10). All operations that used hot saws in 2017 were more cost effective in 2018 (Table 4.10). The variation of costs around the means presented here do not directly mirror the differences in productivity, as operations used different sized machines that assumed different operating costs.

Table 4.10. Observed and modeled total stump-to-truck costs per tonne by operation in USD. Values may not perfectly sum because of rounding.

	Operation					
	2		**3**		**4**	
Year	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
Function	**Observed Costs (\$ gt^{-1})**					
Felling	\$7.74	\$5.83	\$13.17	\$5.85	\$3.76	\$3.08
Skidding	\$11.64	\$3.26	\$11.37	\$3.95	\$4.65	\$4.89
Processing	\$7.38	\$7.19	NA	\$5.07	\$5.89	\$5.56
Cold Decking Loader	NA	\$1.28	NA	NA	NA	NA
Loading	\$2.54	\$2.05	\$9.38	\$3.55	\$3.59	\$2.29
Grinding	\$9.24	\$6.63	N/A	N/A	N/A	N/A
Round wood cost	\$34.97	\$19.61	\$33.93	\$18.43	\$17.89	\$15.82
	Modeled Costs (\$ gt^{-1})					
Felling	\$4.05	\$3.74	\$12.39	\$4.91	\$4.90	\$4.38
Skidding	\$4.89	\$3.86	\$4.15	\$4.61	\$4.62	\$3.71
Processing	\$5.09	\$6.87	NA	\$3.62	\$8.32	\$7.01
Cold Decking Loader	NA	\$2.03	NA	NA	NA	NA
Loading	\$2.54	\$2.05	\$9.38	\$3.55	\$3.59	\$2.29
Grinding	\$9.24	\$6.63	N/A	N/A	N/A	N/A
Round wood cost	\$16.57	\$18.54	\$25.92	\$16.69	\$21.43	\$17.40

Observed skidding costs in 2018 averaged \$4.03 gt^{-1} and varied from 81% to 121% of the mean (Table 4.10). While Operation 2 had often skid biomass and sawlog bunches separately in 2017, they occasionally cut and skid mixed size-class bunches. Only costs from these mixed-bunch skidding turns are what we present for the observed value of skidding in 2017. This allows for more accurate comparison between years, hence the discrepancy from Townsend et al. (2019). Under modeled conditions for all operations, costs averaged \$4.06 gt^{-1} and varied from 91% to 114% of the mean (Table 4.10). Across all operations, when comparing models from 2017 to 2018, skidding operations on average cost \$0.49 gt^{-1} less (Table 4.10).

Processing costs in 2018 averaged \$5.94 gt^{-1} under observed conditions and varied from 85% to 121% of the mean (Table 4.10). Under modeled conditions, processing costs averaged \$5.83 gt^{-1} and varied from 62% to 120% of the mean (Table 4.10). Operations that used dangle-head processors in both 2017 and 2018 on average increased their cost by \$0.24 gt^{-1}.

In observed conditions, loading in 2018 averaged \$2.63 gt^{-1} and varied from 78% to 135% of the mean. On average, loading practices were \$2.54 gt^{-1} less expensive in 2018, largely due to Operation 3 using a knuckle-boom loader rather than a processor for loading.

On Operation 2, grinding costs in 2018 were observed to be \$2.61 gt^{-1} less than in 2017 (Table 4.10).

The observed stump to truck costs for round wood, meaning material leaving the landing in the form of a log, in 2018 exhibited a narrower range of costs per tonne than what was found in 2017 (Table 4.10). On average, the observed cost per tonne in 2018 was \$17.95 gt^{-}1 and varied from 88% to 109% of the mean (Table 4.10). Under modeled conditions, the average cost was \$17.54 gt^{-1}and varied from 95% to 106% of the mean (Table 4.10). For the modeled costs in 2017 using the previous year's equipment and productivity models, the average stump to truck cost was \$21.31 gt^{-1}. Compared to 2017, operations in 2018 were on average 38% more cost-efficient under observed conditions and 18% under modeled conditions. Regarding the modified cut-to-length system used by Operation 3 in 2017, this system would have been \$3.40 gt^{-1} (26%) more expensive than the whole-tree system they used in 2018.

In 2018, grinding biomass cost an increase of 38% over round wood alone (Table 4.10). Grinding biomass provides an additional expense to operations, but if markets are available it also provides another product and source of revenue. Therefore, grinding biomass should not be viewed as strictly an additional operational cost.

Using total cycle times based on observed delays from the hot-decking system Operation 2 used in 2017 compared to the cold-decking system used in 2018, cold-decking was \$1.86 gt^{-1} more expensive than hot-decking. To compensate for the additional loader at the landing, cold-decking would have needed to be \$2.03 gt^{-1} more efficient in processing, skidding, or a combination of both, but instead was \$1.86 gt^{-1} more costly. Even in the impossible scenario where all delays were reduced to zero in the cold-decking system, including mechanical and personal delays, it would not pay for itself based on our observations. The system would still be \$0.51 gt^{-1} more expensive. Examining data by the elements within processing and skidding cycles, the room for improvement in waiting delays was small, with a total cost of \$0.59 gt^{-1} in processing from waiting on the skidder (Figure 4.5). No skidding delays from waiting on the processor were observed in 2017 (Figure 4.5).

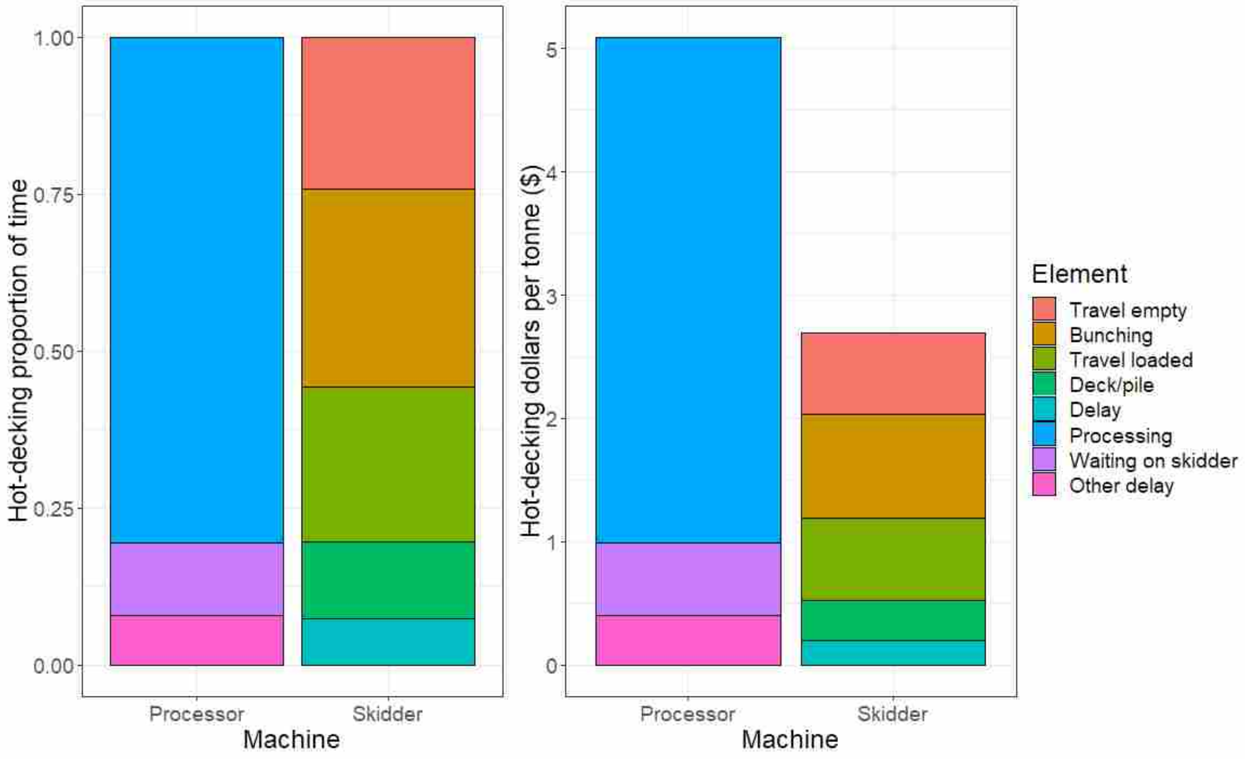


Figure 4.5. Cycle elements broken down for the skidder and processor in both proportion of time spent and dollars per tonne for the hot-decking system observed in 2017.

4.5 Discussion

4.5.1 Operational Improvements and Challenges

Across all operations, observed and modeled productivity levels increased from 2017 because of an increase in tree size (Table 4.1). These larger trees resulted in 29% heavier pieces than the average in 2017 and reduced the overall cost per tonne for every operation. When the average piece weight used in 2017 for modeled calculations in Townsend et al. (2019) was used in the calculations for the 2018 models, the average change in cost across all operations was \$6.13 gt^{-1} more expensive in 2018. This increase in piece weight is not to be associated with the 18% greater efficiency shown by contractors in 2018. The calculations for the comparison between years were made with the piece weights from 2018. Therefore, operations in 2018 were

26% more efficient due to piece weight, and an additional 18% more efficient due to operational changes.

Along with different piece weights and sizes, another change observed was that in contract specifications. On Operation 4, where the required utilization on the small-end diameter of logs changed from 6 cm to 11 cm, the processor increased in productivity and efficiency by 16%. This is likely because the processor did not process a short log as it had in 2017, which there was no market for, but was still required by the contract. However, these small pieces were still included in the 2017 load weights and piece counts.

While the increase in piece weight is not something contractors will have control over, the ability to negotiate with land managers regarding their contracts can help keep harvesting costs down. And certainly, the increase in operational efficiency and lower costs associated with harvesting larger pieces could be an important consideration for land managers to consider when developing management projects. For example, when fewer funds are available to pay contractors for restoration work, adding harvest units with larger cut trees can help offset some of the costs that would need to be paid.

Felling efficiency with hot saws increased on the two operations where hot saws were used the previous year but for different reasons (Table 4.10). On Operation 2 in 2017, operators cut and bunched material less than 10 cm in diameter separately from material over 10 cm. In 2018 Operation 2 ceased this practice and experienced an increase in cutting rate. Skidding productivity increased by 21% on Operation 2, most likely because these biomass stems were not bunched separately from sawlog containing stems. Skidding on this operation now only needed to skid one sort of bunches and did not require extra time finding one of the proper sort.

Operation 3 switched from a modified cut-to-length system in 2017 to a whole-tree system in 2018, which was more productive and less costly. The modeled stump to landing cost for Operation 3 in 2018 using a whole-tree system was \$3.40 gt^{-1} less expensive than the modified cut-to-length system. This finding suggests that whole-tree systems are generally more efficient than a modified cut-to-length system when harvesting forest biomass in the southern Rocky Mountains that requires cutting regeneration.

On Operation 4, the increase in felling efficiency is attributed to a change in contract specifications that no longer required the logging contractor to treat stems less than 10 cm in diameter. The operator could exclusively focus on cutting large trees. From a management perspective, these small diameter trees may still need to be cut in a separate treatment, but not remoing the requirement that the logging contractor to do so resulted in an 11% reduction (\$0.52 gt^{-1}) in felling costs for merchantable cut trees. This 11% reduction could potentially offset the cost of a separate treatment of small diameter stems, such as the use of a hand crew. Alternatively, this reduction in cost may not be enough to pay for another means of treatment and further mechanical activity could potentially cause an increase in damage to soils, surface flora, or residual trees.

Increased loading efficiency was most dramatic on Operation 3. In 2017, Operation 3 used a dangle-head processor for loading but in 2018 obtained and used a knuckle-boom loader. The dramatic decrease in time of 21.51 minutes (41%) per cycle, with a less costly machine to operate provided a reduction in cost of \$5.83 gt^{-1} (164%). While this operation still had the highest observed loading cost, it was only \$1.50 gt^{-1} more than the most efficient loading operation, and cost 135% of the mean.

Biomass grinding on Operation 2 in 2018 supported our finding that smaller, more consistently fed swings of biomass material increase grinding productivity and cost efficiency while decreasing delays (Townsend et al. 2019). In 2018, grinding on Operation 2 that used smaller, more frequent swings had a 33% reduction in delay compared to 2017 along with the 25% increase in productivity. This finding is valuable, as a large overview study by Bergström and Di Fulvio (2018) did not identify it as an important factor in comminuting forest biomass. Such information may be particularly important for individual operations because this is a practice that operators can control. Bergström and Di Fulvio (2018) identified other variables, such as comminuting method (chipping was more efficient than grinding), the size of chipper or grinder, and the material being comminuted as the most important factors relating to comminuting fuels, which our study did not test for.

The use of a cold-decking system on Operation 2 effectively reduced the amount of interaction between the processor and the skidders as indicated by a 33% reduction in processing delays (Table 4.7). However, the 160% increase in observed skidding delay was due to operational delays waiting for the cold-decking loader to finish sorting the previous bunch of stems delivered by the second skidder (Table 4.6). Based on our observations, the cold-decking system's reduction in processing delays did not justify the additional skidding delay or cost of the loader sorting at the landing. This system does not appear to be an efficient means of reducing system-wide delay or a cost-efficient way to harvest biomass, and contractors should refrain from using it. When modeling the hot decking system used in 2018 based on the previous year's observed delays, the hot-decking system cost \$9.17 gt^{-1}, whereas the cold decking system using this year's observed delays was modeled to cost \$11.03 gt^{-1}.

4.5.2 Additional Observations and Considerations

The skidding efficiency increase on Operation 2 may be due to a change in operator since operations were scaled down and only the two most skilled operators were retained. Since bunches in 2018 were no longer separated by size class, and therefore did not need to be skid separately, fewer operators were needed on site. The same volume needed to be removed from this operation, however, this could be done by skidding the unit once. Operation 3 experienced a decrease in efficiency, also likely the result of operator. The previous operator was very skilled and the replacement operator did not match the incumbent's skill. Additionally, the operation was no longer skidding processed logs and was instead skidding bunches of greater weight and size which should have increased productivity but did not under modeled conditions because the newer operator in 2018 took 0.40 minutes longer on average to assemble a single bunch ($p = 5.30*10^{-5}$). Operation 4 experienced an increase in skidding efficiency likely due to operator increased proficiency. In 2017 the operator had one week of experience. In 2018, the same operator had a full year of experience and had improved significantly, requiring 0.69 fewer minutes to assemble a single bunch ($p = 2.0*10^{-3}$).

Processing varied in whether efficiency increased or decreased between years. On Operation 2, the processing was much costlier in 2018 than in the previous year. Part of this variability could be due to a change in environmental conditions, specifically, the machine was affected by hot, dry, dusty conditions. The high ambient air temperature and perpetual dust in the air consistently affected air filters and the machine's ability to stay cool. Therefore, the operator processed logs slower to prevent over-heating. If the machine had been operating at its full potential our observed and modeled delay-free cycle times would likely have been shorter and the efficiency and productivity would have not departed so far from the previous year's rates. For

Operation 4, the operator's skill with the machine likely increased in 2018 because the machine had been purchased two weeks before our observations in 2017 and the operator had only one year of prior experience operating a processor.

4.5.3 Significance to forest biomass research

The results in this paper highlight the amount of variability a given operation may experience year to year. Not only does this paper highlight variability, it demonstrates that operations are actively improving as required by market forces in such marginal wood. Research from the southern Rocky Mountain region modeling the effect of the size of cut trees shows that harvesting smaller-diameter wood as part of fuels and restoration treatments with full cutting restrictions at 40 cm (16 in) compared to 56 cm (22 in) resulted in increased harvest costs from 5% to 17% (Larson and Mirth 2001). This same study (Larson and Mirth 2001) showed that this reduction in cut tree size resulted in a decrease of contractor revenue from 22% to a net cost of 76%. Our research similarly demonstrates the importance of tree size, as operations became 26% more efficient as a result of larger trees.

Forest operations research often compares different types of harvesting methods. Anderson et al. (2012) compared two biomass harvesting systems on sites that were not accessible to chip vans and found that forwarding slash to a concentration site was 4% more efficient than grinding into high sided dump trucks that stored chips at a concentration site. This would be particularly relevant information for Operation 4, since this operation frequently harvested in areas inaccessible to chip vans. Using information about the most economically efficient biomass harvest system may provide opportunities to contribute to more biomass markets and produce another product, potentially offering another source of revenue. While our study did not examine different biomass grinding systems, it did find that how equipment is used is an important factor in biomass grinding efficiency.

Adebayo et al. (2007) compared a true cut-to-length operation to a whole-tree operation and found that the whole-tree harvest system was 21% less expensive. Our results also suggested that the whole-tree systems studied in the southern Rocky Mountains were more economically efficient than the modified cut-to-length system observed. However, the relative difference between these systems was dependent on the cut tree diameter distribution (Townsend et al. 2019). Whole-tree systems were also more productive than the one modified cut-to-length system observed; if contractors are paid by units of area treated, a more productive system may also be more financially attractive to the contractor.

Other studies have aimed to quantify the costs of incorporating small diameter biomass stem harvest into commercial harvests and fuel treatments. A study in northern California demonstrated that using a feller-buncher to cut small diameter stems as part of a restoration treatment was particularly expensive, resulting in 71% of the total felling costs when 80% of the cut trees did not contain a sawlog (Vitorelo et al. 2011). Vitorelo et al. (2011) related well to our results in that cutting a large proportion of biomass stems is costly, however, our study found that this relationship was directly proportional. The size of stems cut did not have meaningful predictive power and biomass stems required equal time to cut compared to sawlog-containing trees, implying that cutting small stems is costly and time could be otherwise spent harvesting more profitable sawlog material. Another study examining a fuels treatment in southwestern Oregon found that harvesting small diameter biomass stems separately during a fuels treatment as part of the commercial harvest cost 176% more than if the biomass material had been left untreated (Bolding et al. 2009). Specific functions in their study that examined the separation of biomass and sawlog material showed that skidding, when separating merchantable bunches and biomass bunches, cost 218% of what only harvesting sawlogs would. Our study supports this body of literature showing that skidding small diameter stems separately as Operation 2 did in 2017 cost 149% of what skidding integrated bunches did. When harvesting biomass, operations should integrate small diameter biomass stems into bunches of sawlog-containing trees.

Recent research has tried to quantify trends in operator skill, an apparent factor in much of the comparison within operations in our research, especially skidding. Wenhold et al. (2019) examined the use of simulated harvesters over a 12-month period and found operators showed productivity increases of up to 200% and began plateauing at 12 months. Our work coarsely shows similar learning and experience progress of operators in a skidder and processor in Operation 4, though not to as great of an extent, with only a 20% and 16% improvement in cost and productivity respectively for each machine. This discrepancy in part could be that our study observed operations in the woods rather than on a simulator. While we did not directly test for operator effects, this evidence supports that the absence of highly experienced and skilled operators like those on Operation 2's processor and Operation 3's skidder could explain some of the variability seen in 2018, as experienced operators are important for keeping steady wood flow (Kirk et al. 1997).

4.6 Conclusion

In summary, forest operations in the southern Rocky Mountains are a dynamic process that are changing over time as forest restoration activities increase. Researchers have the potential to improve operations regionally by identifying best practices, the mechanisms that increase productivity and cost efficiency, and sharing that information with other contractors in the region. While certain variables could not be controlled or fixed in this study such as operator or environmental conditions, we were able to identify practices and make suggestions regarding proper equipment use, operational methods, or harvest systems. Biomass harvest systems need to be as efficient as possible for future harvests to continue; examining year to year variability and identifying the mechanisms behind changes can play an important role in creating a sustainable future for biomass energy.

4.7 References

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4.8 Appendices

Appendix 4.1. Harvesting system descriptions.

Operation	Felling	Skidding	Processing	Loading	Grinding	Trucking
2 (2017)	Rubber-tired hot saws (John Deere 843 L (2) and CAT 573 C)	Rubber-tired grapple skidders (John Deere 948 L (2), John Deere 648 H (2), CAT 555D)	Dangle-head processors (John Deere 2454 D with Waratah 623 C, CAT 324 D with Waratah 623 C)	knuckle-boom loader (John Deere 2156 G)	Horizontal grinder, loader (Terex-Ecotec 680 (2), CAT 250 D)	Log trucks with fixed-length trailers, 12.2-meter (40-foot) Chip vans for biomass
2 (2018)	Rubber-tired hot saws (John Deere 843L (2) and CAT 573 C)	Rubber-tired grapple skidders (John Deere 948L (2)	Dangle-head processors (John Deere 2454D with Waratah 623C, CAT 324D with Waratah 623C)	knuckle-boom loader (John Deere 2156G/ 2656G (cold decking))	Horizontal grinder, loader (Terex-Ecotec 680 (2), CAT 250D)	Log trucks with fixed-length trailers, 12.2-meter (40-foot) Chip vans for biomass
3 (2017)	Harvester (John Deere 240D with Logmax 7000 XT)	Rubber-tired grapple skidder (John Deere 748 H)	N/A	Dangle-head processor (John Deere 2054 with Waratah HTH 628)	N/A	Stinger-steered and flatbed log trucks
3 (2018)	Rubber-tired hot saws (John Deere 643K)	Rubber-tired grapple skidder (John Deere 748H)	Dangle-head processor (John Deere 2054 with Waratah HTH 628)	Trailer-mounted knuckle-boom loader (John Deere 437D)	N/A	Stinger-steered and flatbed log trucks
4 (2017 and 2018)	Tracked Hot saw (TimberPro TL735B)	Rubber-tired grapple skidder (Prentice 490)	Dangle-head processor (Doosan DX225LL with Waratah 622B)	Self-loading log truck (1), Truck-mounted loader (Prentice 280)	N/A	Self-loading log truck

Appendix 4.2. Models used for 2018 analysis and comparison.

Felling

Operation	**Intercept**	**β_1 Number of stems cut**	**β_2 Distance (meters)**	**β_3 Stems:2018**	**β_4 Distance:2018 (cm)**	**R^2**
2	0.5170	0.1079	NA	-0.0200	NA	0.41
3	0.5775	0.1463	NA	NA	NA	0.43
4	0.2863	0.0684	0.0370	NA	-0.0124	0.59

Skidding

Operation	**Intercept**	**β_1 Distance (100's of meters)**	**β_2 Number of bunches**	**β_3 Bunches: 2018**	**R^2**
2	0.5951	0.8875	1.3834	-0.5493	0.58
3	0.5963	1.4095	0.5334	0.3156	0.79
4	0.1518	1.2370	1.3693	-0.6193	0.72

Processing

Operation	**Intercept**	**β_1 Total logs (cm)**	**β_2 Diameter (cm)**	**β_3 (Total Logs:2018)**	**R^2**
2	-0.1710	0.0638	0.0297	0.1484	0.42
3	-0.0752	0.1187	0.0166	NA	0.45
4	-0.0981	0.5401	0.0187	-0.1216	0.39

5.0 Discussion

This discussion chapter addresses the observations made throughout the course of this research that could not be directly quantified or did not fit well into a peer-reviewed journal article. This chapter also frames the major concepts presented in this thesis in the context of biomass harvesting research and forest restoration in the SRM. Lastly, this chapter closes with future research opportunities that would contribute to the study of forest operations and management in the SRM and addresses unanswered questions from this project.

5.1 General Observations

One key finding was how operational costs were largely influenced by small diameter stems. Estimating how much an operation would cost using a hot saw to cut varying densities of small-diameter trees (< 4 in diameter inside bark) compared to other saw-log containing trees could be a useful forest management tool for deciding how to treat a site. Below is a series of tables and figures examining the combination of bunch compositions with varying levels of small-diameter trees versus sawlog-containing trees between a wheeled hot saw and tracked hot saw using models constructed from 2017 data. Combinations were made ranging from zero to five sawlog-containing trees and one to ten small diameter trees. As the number of sawlog-containing trees in a cycle increases, the importance of the number of small stems cut in a cycle decreases (Table 5.1; Figure 5.1 and 5.2). Bunch compositions will vary for multiple reasons such as terrain, visibility, tree density, and tree size and weight. Those variables will likely render some of these hypothetical bunch compositions infeasible. Nonetheless, these are instructive in understanding the cost trends behind harvesting varying proportions of small trees.

Table 5.1. Felling costs given bunch compositions ranging from one to five sawlog-containing stems and one to ten small stems. Assumptions are an average piece weight of 0.24 tonnes per stem for sawlog-containing stems and 0.01 tonnes per small stem.

	Cost ($/Tonne)									
Sawlog Stems	**Number of small stems**									
Wheeled hot saw	1	2	3	4	5	6	7	8	9	10
0	$207.59	$126.04	$98.85	$85.26	$77.10	$71.67	$67.78	$64.87	$62.60	$60.79
1	$8.62	$9.80	$10.91	$11.95	$12.93	$13.85	$14.72	$15.54	$16.32	$17.05
2	$5.16	$5.83	$6.48	$7.11	$7.71	$8.30	$8.87	$9.42	$9.96	$10.48
3	$3.15	$3.39	$3.62	$3.85	$4.07	$4.29	$4.50	$4.71	$4.91	$5.11
4	$2.58	$2.76	$2.95	$3.12	$3.30	$3.47	$3.64	$3.81	$3.97	$4.13
5	$2.23	$2.38	$2.53	$2.68	$2.82	$2.97	$3.11	$3.25	$3.38	$3.52
Tracked hot saw										
0	$279.76	$156.61	$115.56	$95.03	$82.71	$74.50	$68.64	$64.24	$60.82	$58.08
1	$10.71	$11.46	$12.16	$12.82	$13.44	$14.03	$14.58	$15.10	$15.59	$16.06
2	$6.03	$6.50	$6.95	$7.39	$7.81	$8.22	$8.62	$9.00	$9.38	$9.74
3	$4.43	$4.77	$5.09	$5.41	$5.72	$6.03	$6.33	$6.62	$6.91	$7.19
4	$3.63	$3.89	$4.14	$4.39	$4.64	$4.88	$5.12	$5.35	$5.58	$5.81
5	$3.14	$3.35	$3.56	$3.77	$3.97	$4.17	$4.37	$4.56	$4.76	$4.94

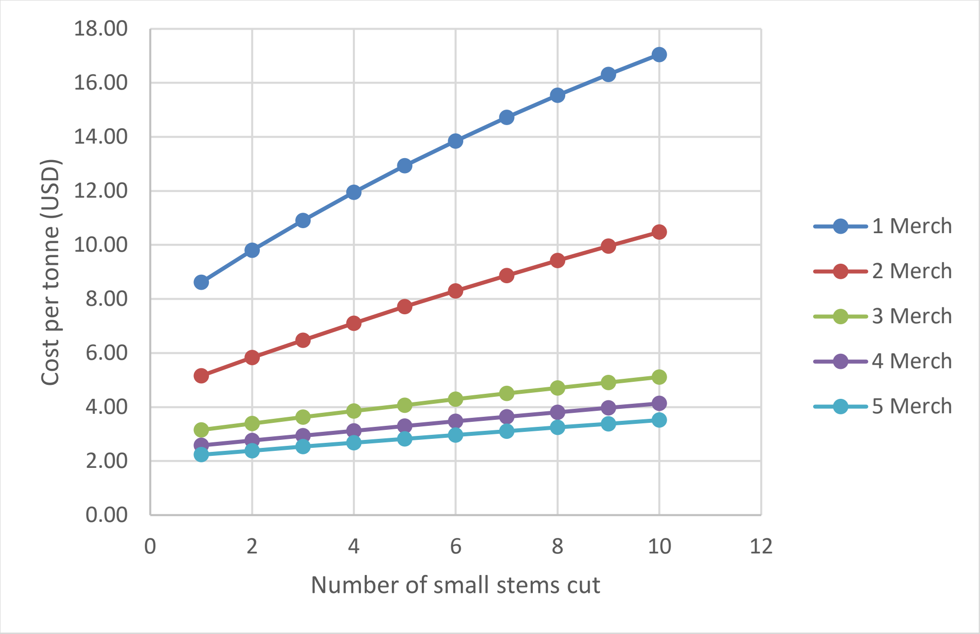

Figure 5.1. Relationship between one to five merchantable stems cut and small diameter stems cut with cost per tonne for wheeled hot saws.

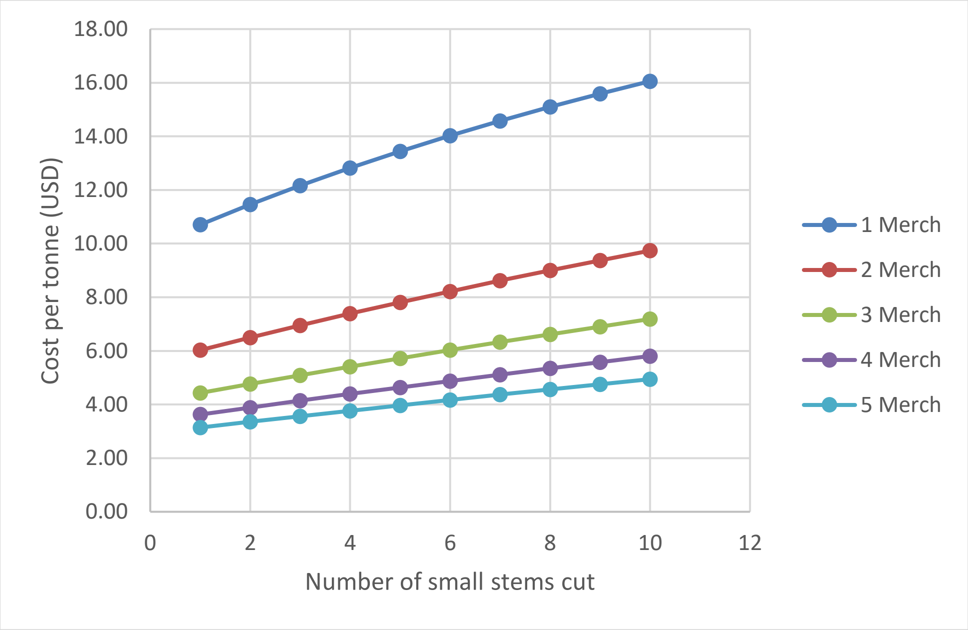

Figure 5.2. Relationship between one to five merchantable stems cut and small diameter stems cut with cost per tonne for tracked hot saws.

The difference between costs for the tracked hot saw and the wheeled hot saw are due to differences in operating costs and how the machine works to cut trees. The tracked hot saw can swing and move its boom to cut trees when sitting in the same spot, while the wheeled hot saw is required to drive to each tree with the whole machine. When bunch compositions are examined with no sawlog containing trees, the price per ton is extremely high relative to when sawlog harvest is integrated (Figure 5.3; Figure 5.4). These figures demonstrate the high price of using a costly machine to treat exclusively small diameter stems.

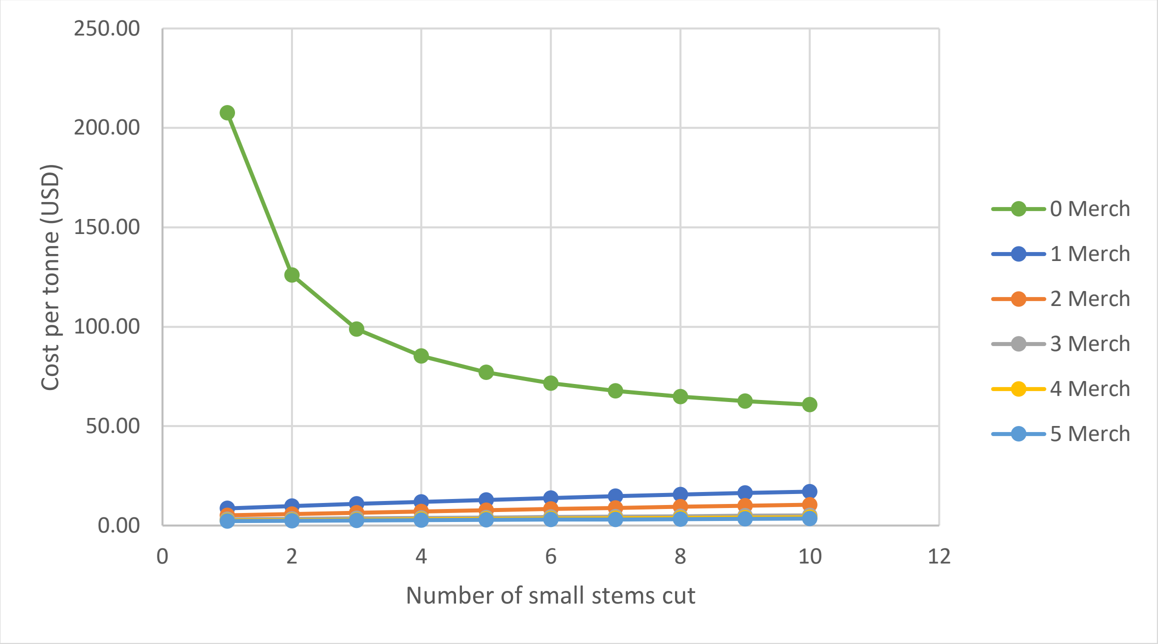

Figure 5.3. Relationship between zero to five merchantable stems cut and small diameter stems cut with cost per tonne for wheeled hot saws.

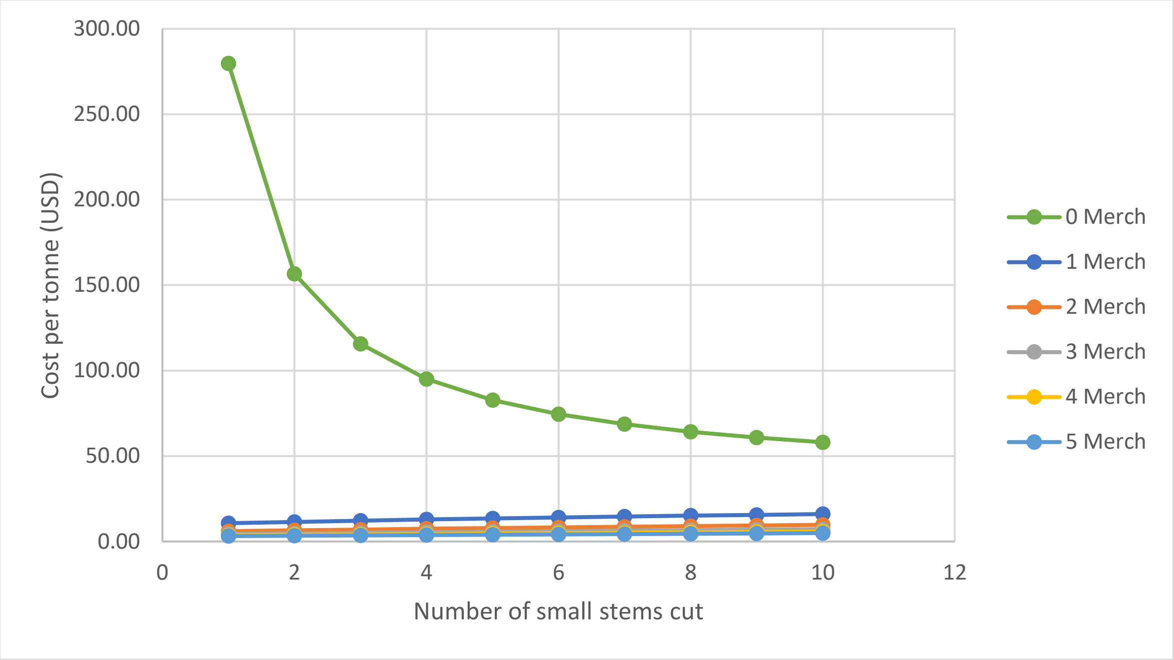

Figure 5.4. Relationship between one to five merchantable stems cut and small diameter stems cut with cost per tonne for tracked hot saws.

Operator experience frequently stood out as a variable influencing efficiency, though not one we specifically tested for. Other research has specifically examined the effects of operator and operator learning. One study based out of South Africa found that on average, operators need a 12-month period to become fully proficient when operating a harvester, however, this was a study based entirely on simulation (Wenhold et al. 2019). Other work examining operator influence found that skilled operators were important in maintaining a steady wood flow (Kirk et al. 1997).

Along with operator experience, cross-training across different operational roles could have a positive effect on operational efficiency. Operations where felling was completed by an operator who had prior skidding experience were the most efficient, as seen on Operations 1 and 4, and Operation 3 in 2018. These hot saw operators with previous skidding experience typically created optimal bunch sizes so that skidders rarely needed to assemble multiple bunches was one of the best practices observed. Operations that practiced this method also were the most efficient, suggesting that time is not lost when cutting and creating larger bunches.

Skidding pattern was another important factor determining total cycle time with observed delays. Operation 1 did an excellent job of balancing short and long skids and moved through the unit strategically to minimize delays from waiting on the processor and the processor waiting on the skidder (Figure 5.5). Other less efficient patterns were observed on Operation 2 where the nearest bunches were assembled regardless of which skid trail they were on (Figure 5.6 A) and on Operation 5, where the operator harvested from one given trail and simply moved outwards until all bunches on that trail had been brought to the landing (Figure 5.6 B)

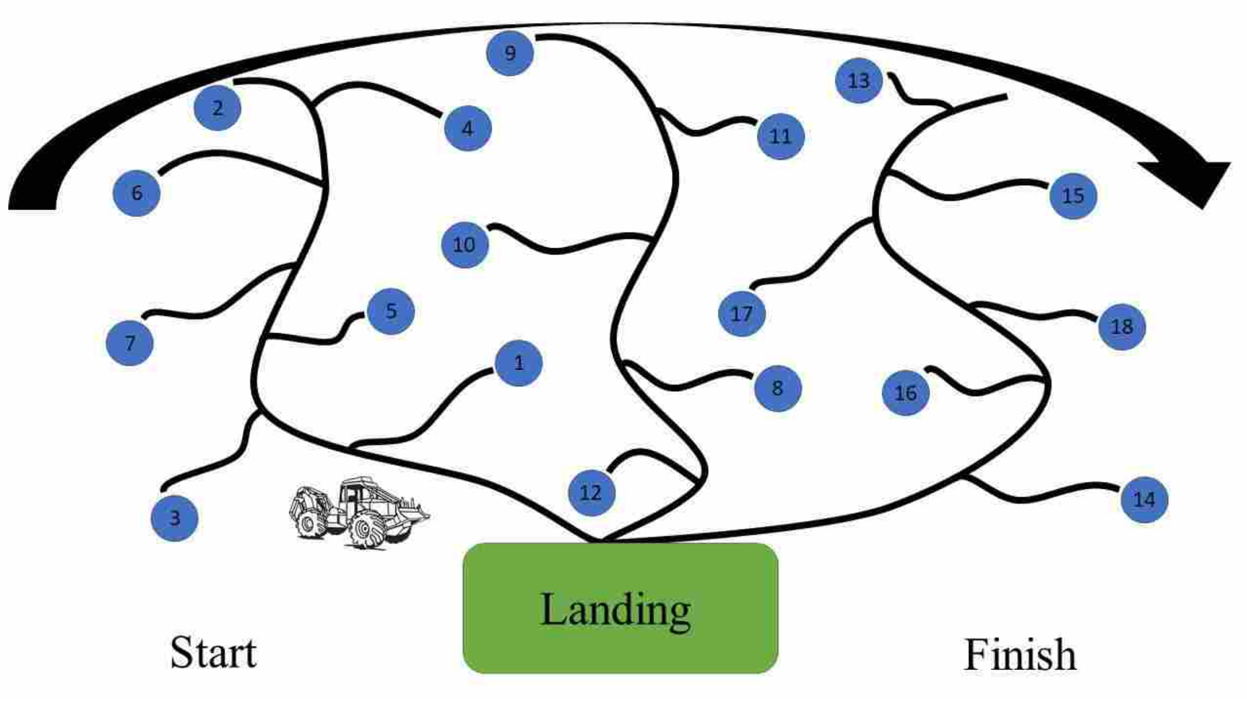

Figure 5.5. Efficient skidding pattern used by Operation 1. Blue dots with embedded numbers indicate a bunch and the order that bunches may be skid.

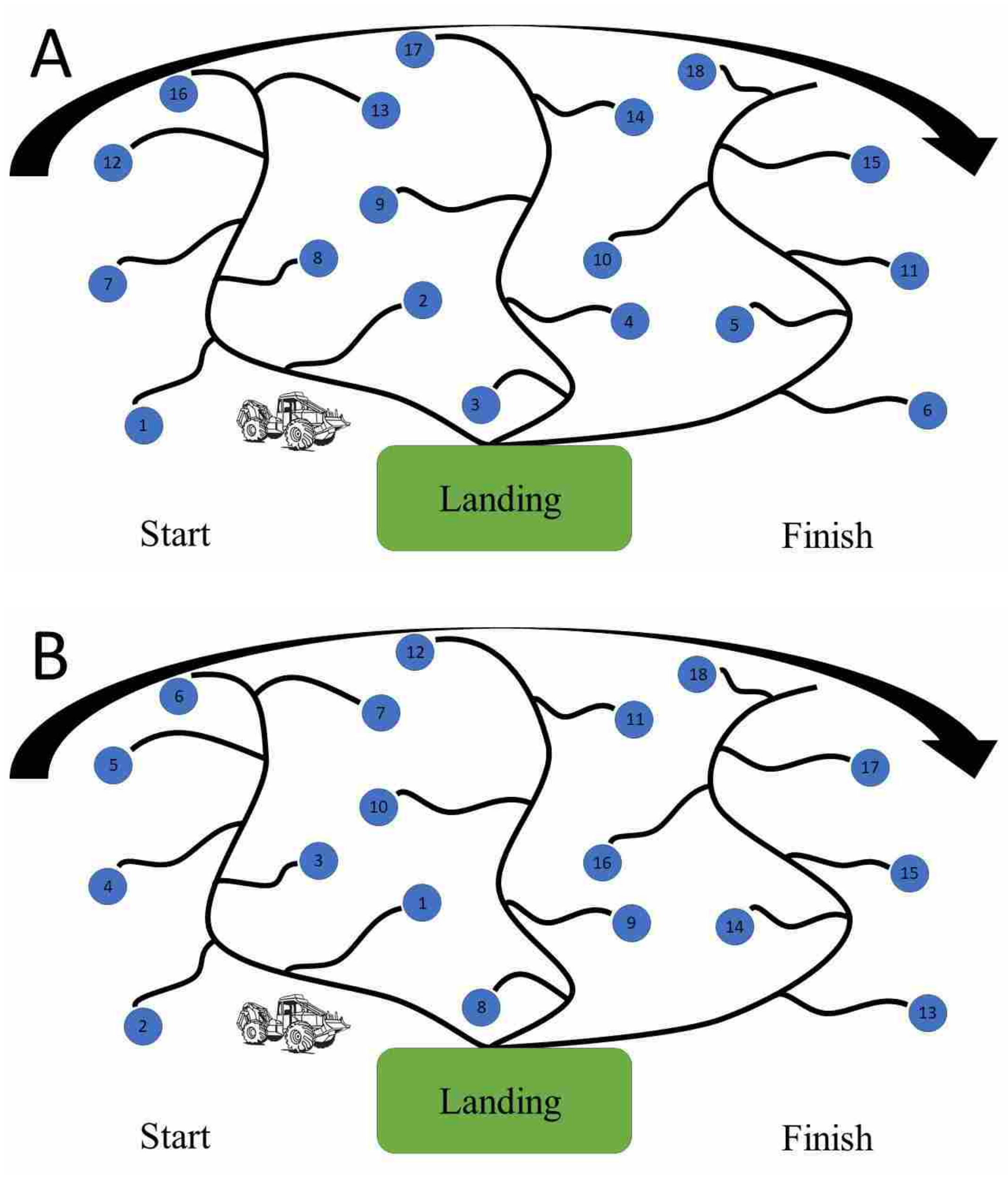

Figure 5.6. Inefficient skidding patterns where (A) the skidder assembles all the nearest bunches first indiscriminate of which trail a bunch comes from, leaving the furthest bunches for last, and (B) where the skidder assembles the nearest bunches on a single trail, saving the farthest bunches of a single trail for last.

Experienced processor operators like those seen on Operation 1 also utilized landing space the most efficiently and reduced their time spent swinging. Inexperienced operators like those on Operation 4 in 2017 spent much of their time swinging the machine and did not organize log decks in a way to minimize swing distance. Minimizing swing time was also evident as a practice on Operation 2's grinding side in 2018. When possible, the operator kept the slash pile right in front of the belt feeding the grinder so that very little time was spent swinging and more time was spent feeding.

Forest operations were ultimately constrained by available markets and their distance in the SRM. As many studies have shown, hauling often costs 30% to 60% of the total harvest cost, and can reach levels even higher (Grebner et al. 2005; Hanzelka et al. 2016). Certainly, thermoelectric power generation offers a potential market for wood chips and hog fuel, but only if infrastructure is made available or improved and landscape-scale forest restoration continues. The only operations observed in this study with access to a thermoelectric bioenergy facility were Operations 1 and 2. Operations 3 and 4 were equally capable of grinding or chipping slash in woods into biomass feedstock but lacked the market to do so. However, these operations did supply pellet manufacturers that were able to utilize small-diameter logs which contributed to other biomass energy markets. If biomass energy facilities were installed within hauling distance for these operations, particularly in New Mexico, operations would have an outlet for such a material and could contribute to the reduction of fossil fuel use and move towards the nation's goals of increasing the contribution of renewable energy.

One site harvested by Operation 3 provided an excellent example for why a fundamental understanding of forest operations is critical for land managers. On this site, trees were marked to cut, often on trees about 1 meter tall (Figure 5.7). Marking was also done with blue paint on the green needles of regenerating ponderosa pine, providing minimal color contrast and difficulty for the operator attempting to find the marked stems from the cab of the hot saw (Figure 5.8). Additionally, individual stems were marked that grew out of a cluster of trees, not providing the operator with any room or ability to fell the marked tree without cutting or damaging the residual stems (Figure 5.9). Not only is the marking of timber inefficient in this scenario, experienced operators could likely achieve the same silvicultural objectives without the additional cost of marking to begin with. Dickinson and Cadry (2017) found that no quantitative or qualitative differences were observed in harvested spatially heterogeneous treatments between individual tree marking and using the methods of designation by description (D x D) and designation by prescription (D x P). Generally, the US Forest Service is moving towards the use of D x D and D x P cut-tree tree selection methods for these reasons. All of these points highlight the need for forest managers to understand how their prescriptions are carried out and what the capabilities of operators and modern logging equipment are.

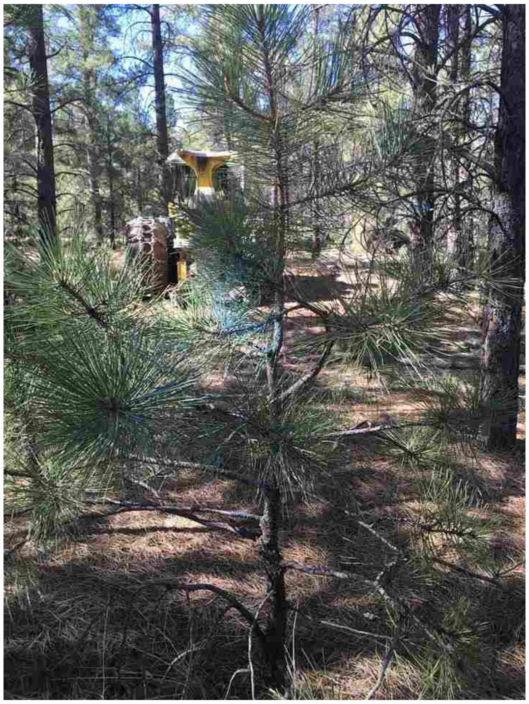

Figure 5.7. Small tree marked to cut.

Figure 5.8. Views from inside the cab of the hot saw searching for marked stems.

Figure 5.9. Stems marked to cut that will likely cause damage to residual trees.

5.2 Context in relation to biomass harvesting research

This study helps bridge the geographic gap across the western US in biomass harvesting research. Many other studies have examined the costs and productivity rates of biomass harvest in western states such as northern California and Oregon (Vitorelo et al. 2011; Harrill and Han 2012; Bolding et al. 2009), northern Idaho (Anderson et al. 2012), as well as the southeastern US (Mitchell and Gallagher 2007; Hanzelka et al. 2016; Santiago et al. 2018). Our cost results were similar with some of these studies; for example, Bolding et al. (2009) found that felling cost \$5.80 gt^{-1} when integrating biomass stems into sawlog harvest after adjusting for inflation. Our median observed cost in 2018 was \$5.83 gt^{-1} in Oregon for integrated felling. Other results, however, show contrast; Vitorelo et al. (2011) found that 71% of felling time was spent on non-sawlog containing trees when 80% of trees did not contain a sawlog. Our study, however, found the relationship between proportion of time spent and proportion of stems cut in each size class to be direct, and that tree size had little influence over time spent felling an individual tree. This is possibly due to the lack of large diameter stems exceeding 40 cm (16 in). Other results that show contrast were found in the US southeast by Mitchell and Gallagher (2007). In their study, the cost of chipping was \$12.01 gt^{-1} after adjusting for inflation, while on Operation 2 in 2018 grinding cost \$6.63 gt^{-1}. However, the chipper used in Mitchell and Gallagher (2007) had approximately half the horsepower (500 hp) to that observed on Operation 2. The time spent loading a truck with biomass in Mitchell and Gallagher 2007 took 31% longer than what was found in the SRM, however, the loader observed by Mitchell and Gallagher (2007) was smaller than the one observed on multiple sites.

This study can help other researchers attribute costs to ecological effects that result from specific restoration treatments, such as cut-to-length versus whole-tree operations. Costs calculated from this research can help inform the relative costs and values of forest restoration from aspects of carbon sequestration from maintaining a forested state. Maintaining the landscape in a forested state that provides ecosystem services will be paramount as climate continues to change because high-severity wildfire in untreated stands are struggling to regenerate (Davis et al. 2019) and human-made changes are prohibiting the landscape to store less carbon (Erb et al. 2018).

Restoration treatments in the stands studied in this thesis effectively reduced basal area stocking and decreased the likelihood of high-severity crown fire (Worley-Hood et al. 2019), meeting the requirements of not only restoration treatments (Covington and Moore 1994; Larson and Churchill 2012), but fuels treatments as well (Agee and Skinner 2005). Operational costs for this region can now be applied to the benefits from fire modeling. These costs can be used to assess the potential financial savings of fire suppression in these harvested sites, which have been found to save up to 17% of fire suppression costs, however, this relationship is complex (Thompson et al. 2017; Thompson et al. 2013). The value gained by fire suppression cost reduction may be able to offset, or fully compensate for the cost of the treatment.

The research in this thesis has also contributed to the body of literature evaluating the most efficient harvest systems. Adebayo et al. (2007) identified whole-tree systems as 21% less expensive than CTL systems for harvesting timber, and our study found that when biomass stems were harvested, the modified whole-tree system was 26% less expensive than CTL systems. However, if biomass stems were not harvested, CTL systems became more economically feasible and were equally efficient as whole-tree systems (Chapter 2, Table 2.13). These findings are supported by Hartsough et al. (1997) who found whole-tree systems were approximately 17% less costly than CTL systems when working in natural stands.

5.3 Unanswered questions and future research opportunities

One shortcoming of this study was the inability to observe Operations 1 and 5 during the second year. The loss of Operation 1 is less critical since the operation was the most efficient observed in 2017 and offered little room for improvement. However, Operation 5 presented more room for improvement, particularly, its transition to a hot saw from hand felling. This would have provided an excellent comparison to what an operation could save by converting to a fully mechanized operation. The observed grapple skidder exhibited long cycle times in part due to assembling individual stems that could have been bunched by a hot saw and in part to its mechanical problems. Another reason skidding cycles on Operation 5 took so long was that stems were not consistently directionally felled. If this operation had used directional felling, it is estimated that subsequent skidding may have cost up to 38% less (Holmes et al. 2002). Given that cash flow was an issue for this operation, “free” improvements could be made to the current system such as directional felling to make the process more efficient. Another potential improvement to the current system would be a full separation of tasks between workers, with workers specializing in specific tasks rather than frequently switching between tasks. On this operation, all three workers would fall trees for a variable period of time, and then two would resume their respective tasks of skidding and processing. Often this third worker would continue felling, but other times would use the tracked grapple skidder on site to push non-directionally felled trees into as tight of a bunch as possible. Keeping workers on dedicated tasks providing consistent wood flow may help the current state of the operation without changing machinery. While workers performing various tasks may serve as some element of cross-training and is valuable for flexibility in scheduling, identifying a balanced system that keeps a steady supply of wood leaving the landing might improve operational productivity, which was identified as a concern by the contractor.

One avenue of research of concern to operations researchers, ecologists, and fire managers is the slash distribution of a CTL system versus a whole-tree system with the return skidding of slash. Logging systems must remove enough slash to reduce heavy fuel loads after harvest, but not so much so that a site cannot effectively carry a broadcast burn following the harvest. Understanding how each method influences future stand objectives or the effects of broadcast burning in the SRM could render the use of a CTL system more effective than whole-tree systems at achieving ecological goals on specific sites. While our research showed no difference in total time between turns that return skid slash and those that did not (p=0.78), our observations were limited (n=9). Skidding with and without slash on the return skid could be tested more thoroughly in a controlled setting to determine the exact relationship between the two practices. However, other researchers on the BRDI project are examining this question in relation to market availability and how the available markets are affecting fuel loading. Other research on CTL systems could also examine the use of a forwarder versus a skidder. While a forwarder is the intended machine for a CTL system, a comparison of different equipment performing the same task could provide insights to whether a modified CTL system saves money by using a skidder, a cheaper machine, compared to a forwarder. I found limited research addressing this question and information about slash distribution would offer valuable information to managers. Hartsough et al. (1997) found that the hybrid CTL system observed on Operation 3 was approximately 31% less costly in plantations than both whole-tree and CTL while it was 11% more costly than whole-tree systems and 13% less costly than CTL systems in natural stands.

Operations that frequently treat small-diameter biomass stems could benefit from a financial analysis of different biomass stem treatment methods. As part of restoration, small stems need to be cut, but figuring out the most cost-effective way for landowners to do so is important. Some research has addressed this question, showing that mechanical treatments, when combined or not combined with prescribed fire, are substantially more expensive than strictly using prescribed fire by an average of $1685 per hectare (Hartsough et al. 2008). However, this same study found these treatments are less costly than fire alone when revenue from the products produced are accounted for, averaging a profit of $920 per hectare. Hartsough et al (2008) also found that mechanical treatments were more effective at reducing total basal area than prescribed fire; mechanical thinning only and mechanical thinning plus prescribed fire reduced basal area respectively by 66% and 133% more than fire alone. Our study found that harvesting small diameter trees in large proportions as observed across several sites is expensive, often accounting for over 50% of felling costs and was directly related to the proportion of small trees requiring cut compared to large trees (Chapter 3, Table 2). Operation 4 showed that felling overstory trees became an additional 11% less expensive when small diameter stems were not required to be cut because the operator could strictly focus on large trees. If other treatment opportunities such as mastication and hand crews are shown to be less expensive, managers could treat more acres by saving money during overstory harvest. Of course, this would not allow for any biomass utilization from small diameter trees, so analysis on how much biomass in tonnes per hectare is "lost" compared to only using tops and limbs from processed overstory trees is also needed.

Biomass utilization presents many areas of further research. Research could to be done to quantify the amount of slash available for grinding or chipping under various processing specifications. If markets exist for small end diameters such as 6 cm compared to 10 cm, the volume of biomass available for in-woods grinding operations may be less economically feasible. Also, research could be done examining the most efficient slash forwarding operations identified by Anderson et al. (2012). Research on forwarding operations specific to the SRM could inform biomass utilization decisions in places that may not have the forest infrastructure to support chip vans. Operation 4 frequently worked on roads that were under historic protection from any modification and did not lend themselves to the turning radius needed for a chip van. In this case, forwarding biomass in the form of chips or slash may be the only way biomass grinding and greater utilization is possible in some areas.

Lastly, a novel area for research is quantifying the potential costs of skyline and winch-assist operations in the SRM. Because of the higher operating costs these systems require they have not been historically used in the SRM, but many areas are too steep for ground-based operations to work on with the current equipment available. While these systems will certainly be more expensive than the ground-based systems observed in our study, steep and dense forested slopes can put communities at risk of severe wildfire. The assumptions of high costs are valid, as one study from northern Idaho showed that skyline operations were typically 300% more expensive than ground-based operations (Han et al. 2004). Historically, these steeper slopes burned under the same low-severity, frequent fire regime actively being restored across the gentle terrain of many southern forests but are excluded from treatment because of their high assumed costs. Slope also likely affected Operation 4, but because the operation consistently operated on steeper slopes and had equipment to match these anticipated slopes, we could not quantify its effect in a meaningful way. On average, this operation worked on slopes 8% steeper than the rest of the operations observed (Chapter 4, Table 4.1).

6.0 Conclusion

In this thesis, I have quantified benchmark cost and production rates for biomass harvesting forest operations in the SRM and demonstrated how operations improved their efficiency and productivity with operational changes. During the first year of observations, we modeled the average stump to landing cost of \$26.19 gt^{-1}. Suggestions were made to each operator based on conversations in the field and analysis of during the first year of study. After operational modifications had been implemented, these operations were on average 18% more efficient than in the previous year. This 18% increase in operational efficiency is in addition to the 26% increase in efficiency based on a 29% increase in average piece size. Overall, observed operations were more efficient in 2018 because of both operational improvements and increased piece size and showed an average decrease in cost of \$10.98 gt^{-1}.

In this study, whole-tree harvest systems were found to be both the most productive and efficient, however, the CTL system could be just as efficient, if not more efficient, than whole-tree systems if only merchantable sized stems (DIB at LED $\geq$ 20 cm) were cut. The cold-decking system observed on Operation 2 was also found to be inefficient, suggesting that whole-tree systems that used a hot-decking approach are favorable compared to cold-decking. Lastly, hand felling should be replaced by mechanized felling where terrain is appropriate. Hand felling resulted in felling costs almost three times that of mechanized felling, however, this cost could likely be reduced by using directional felling.

While certain questions have been answered in this thesis, others remain, and new questions exist. Other researchers can now apply this cost and productivity information to their study of best management practices, silviculture, and economics to assess the benefits of biomass energy and forest restoration.

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