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The Cost of Forest Thinning Operations in the Western United States: A Systematic Literature Review and New Thinning Cost Model

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Abstract

Mechanical forest thinning treatments are implemented across the western United States (US) to improve forest health and reduce hazardous fuels. However, the main challenge in thinning operations is low financial feasibility. This study synthesized the stump-to-truck cost of forest thinning operations in the western US based on operations research articles published over the last 40 years (1980–2020). We systematically selected and reviewed 20 thinning studies to analyze key variables affecting machine productivity and harvesting costs. The average cost of forest thinning was lowest for a mechanized whole-tree thinning operation at $21.34/ton or $2,075/ha. Feller-bunchers and skidders showed the highest productivity in felling and extraction machines, respectively. We found that extraction cost accounted for the largest proportion of the stump-to-truck cost of forest thinning (33%, 43%, and 34% in whole-tree, tree-length, and cut-to-length thinning, respectively). Tree diameter and machine travel distance are common variables affecting thinning productivity and thus cost, regardless of the harvesting methods used. With thinning productivity and cost data from the selected studies, we developed a spreadsheet-based model to estimate thinning costs for various harvesting systems. This literature synthesis and new thinning cost model can help foresters develop a cost-effective plan for thinning operations.

Study Implications: Forestland managers often have a keen understanding of the cost of operations based on personal experience and rules of thumb and try to increase productivity and reduce costs whenever possible. Unfortunately, it can be difficult to integrate high-resolution operations research into their planning because these studies can be very site specific and tend to use statistical designs that are not always easy to interpret or apply in practice. This review provides a comprehensive synthesis of research on mechanical thinning operations in the western US with two main implications for managers: (1) broader knowledge of thinning operations with an understanding of key variables and their effects on productivity and cost and (2) better information, data, and tools that can be used to calculate and compare the productivity and cost of thinning for various methods and systems to quickly evaluate alternatives in planning. This literature synthesis, along with a new thinning cost model, can help managers develop more efficient treatments and ultimately reduce treatment costs.

Keywords: forest harvesting, logging machine, economic feasibility, machine productivity, machine rate

The increase in frequency and size of landscape-scale wildfires is a challenge for forest managers across the western United States (US). From 2002 to 2013, 55% of forest fires and 95% of the total area burned were concentrated in this region (Brusentsev and Vroman 2016). The number of wildfires is increasing by seven fires per year on average, and the area burned is increasing by 355 km^2 per year (Dennison et al. 2014). To reduce the risk of catastrophic fire and restore forest health, landscape-scale forest restoration projects are being implemented across the western US to reduce stand density and remove hazardous fuels (Waltz et al. 2014; Kalies and Yocom Kent 2016).

Prescribed fires can reduce fuel loads and wildfire intensity because they can effectively consume fuels at a low cost (Chalmers and Hartsough 2001). They also provide ecological benefits (Fulé et al. 2012; Brose et al. 2013). However, prescribed burning has several limitations to its application, such as widespread smoke, escaped wildfire risk, and operational constraints related to forest structure and density, weather conditions, seasonal factors, and higher risk in overstocked forests that have high crown fire potential.

Mechanical forest thinning treatments do not have the same limitations as prescribed fire and are employed to reduce stand density and achieve similar objectives. Thinning treatments positively affect wildfire behavior in western US forests by reducing fuel loads and increasing the distance between remaining trees (Fulé et al. 2012). Additionally, forest thinning treatments can have ecological benefits, including decreased tree mortality, reduced fire severity, and improved forest structure (Stephens and Moghaddas 2005). Treatments can also facilitate prescribed burning in dense stands, which is frequently conducted following mechanical treatments.

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In forest thinning operations, three harvesting methods are commonly used: whole-tree (WT), tree-length (TL), and cut-to-length (CTL) (Figure 1). The choice of harvesting method determines the equipment and systems used (Han et al. 2004), where each system typically includes a combination of felling, extraction, and processing machines to complete a stump-to-truck harvesting operation. Each harvesting method is named based on the type of woody materials moved during the extraction process. In a WT harvesting operation, no tree processing activities occur at the stump where felling occurs. Entire trees are extracted to the landing area or roadsides where they are processed. In the TL method, branches and tops are removed at the stump after felling, and the remaining length, often including multiple merchantable logs, is moved to the landing or roadside. In the CTL method, the length of the tree is further processed at the stump into individual merchantable logs, which are then moved to the landing or roadside.

Under a single harvesting method, there could be different combinations of harvesting machines that complete a stump-to-truck operation. Here, we refer to the specific configuration of machines as a system. Mechanized felling using feller-bunchers and harvesters is common on gentle ground slopes (<35%), whereas manual felling with chainsaws is typically used for felling on steep slopes (>35%). Typical machines used for extraction are skidders (WT and TL) and forwarders (CTL) on gentle slopes and yarders (typically WT or TL) on steep slopes. Processing typically takes place at the stump or landing using a manual chainsaw, harvester, or processor. In some areas, delimbers are also used in processing. The final operation in all these systems is to load logs from the landing or roadside onto a truck, typically using a grapple on an independent loader or a self-loading truck. Because various machines and configurations have different capabilities, productivities, fixed costs, and variable operating costs, the use of different systems and methods for felling, processing, and extracting trees directly affects the overall cost of thinning operations (Han et al. 2004; Vitorelo et al. 2011; Han and Han 2020).

Commercial thinning generates revenue from merchantable products at least equal to the value of the direct costs of treatment (Helms 1998). Often, the main financial challenge of thinning treatments is their high operating cost measured against the low value of the trees being removed, which can result in noncommercial thinnings with high net treatment cost (Bolding and Lanford 2001; Hjerpe et al. 2009; Nicholls et al. 2018). Trees slated for removal are typically small in diameter, resulting in low harvesting productivity (Han et al. 2004; Vitorelo et al. 2011; Han and Han 2020). Sometimes they have poor form and lower quality due to insects, disease, and other factors. Another reason for high net costs is the lack of markets for the small-diameter wood and biomass materials produced from thinning treatments. Even if removals generally meet commercial specifications, a lack of nearby markets can make utilization impossible. The value of small-diameter logs and biomass is often not high enough to offset operating costs, including harvesting and transportation (Lynch 2001; Nicholls et al. 2018). As a result, the unfavorable economic feasibility of thinning operations is one of the key barriers to large-scale forest restoration and fuel treatment efforts (Larson and Mirth 2004; Huffman et al. 2020). The lack of logging and trucking contractors adds another layer of challenges because available contractors from distant locations need to move their equipment long distances to job sites and work far from home.

Because of these challenges, the financial feasibility of thinning is closely tied to marginal operating costs. This study focused on near-term financial costs incurred during forest operations associated with silvicultural prescription implementation and merchantable roundwood removal, including sawlogs, pulpwood, and other roundwood. Operational costs of forest thinning treatments, which can be measured and expressed on an area, mass, or volume basis (e.g., dollars per hectare, dollars per tonne, and dollars per cubic meter), are determined by many different factors, including silvicultural prescriptions, stand conditions, and operational variables (Puttock 1995; Pan et al. 2008; Rummer 2008; Holzleitner et al. 2011). Silvicultural prescriptions (e.g., single-tree selection,

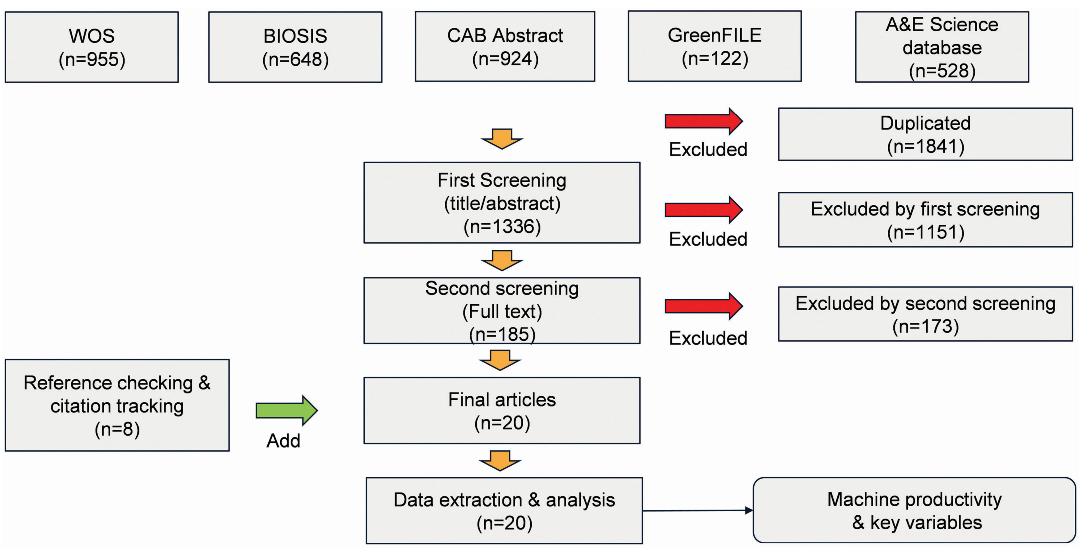

Figure 1. Three forest harvesting methods that are commonly used in forest thinning operations. Biomass: wood chips, wood slash, and residues from the harvesting process.Roundwood: sawlogs and small-diameter logs produced from thinning operations.

group selection, and variable retention) identify which trees will be retained or removed and what products will be produced if harvesting is required. Stand conditions influence the thinning intensity and tree selection criteria and often determine the amount of tree volume removed. Numerous operational variables, such as ground slope and extraction distance, affect machine productivity and logging costs. Furthermore, logging machine type, size, and technological advances directly affect machine performance (Nordfjell et al. 2010; Conrad et al. 2018; MacDonaugh et al. 2019). High variability in stump-to-truck thinning costs makes it difficult to develop accurate cost estimates and implementation plans for thinning treatments under tight budget constraints. More broadly, there is a need for statistical models that span different conditions, systems, and configurations relevant to modern fuel treatment implementation for forestland managers.

Although logging cost studies exist, there are no systematic reviews or syntheses that focus on thinning treatment costs across the western US. The lack of systematic assessment of thinning costs makes it difficult to understand how different key variables affect cost variability and prevent foresters from accurately estimating the costs of planned activities at the project scale. By analyzing previous studies of forest thinning costs, we present a framework to assess how different variables affect cost, thus enabling land managers and planners to make better-informed decisions on thinning treatment methods or harvesting systems and to better predict and reduce their costs.

Three forest-thinning cost prediction models have been developed since 2000: ST Harvest (Hartsough et al. 2001), HCR Estimator 2.0 (Becker et al. 2008), and ThinTool (Han et al. 2017). However, these three models have common limitations. For example, their use is restricted to the specific areas and species where they were developed. Also, it is necessary to update the factors applied to the models over time because using outdated information may cause errors in estimating the current cost. To address these limitations, it is necessary to develop a model that can be applied throughout western US forests based on current stand conditions and operational information and adjust to current currency value using inflation for appropriate estimates.

The goal of this study was to systematically assess operational stump-to-truck costs of forest thinning across the western US. We reviewed and synthesized case studies to address the four study objectives: (1) summarize the costs of forest thinning treatment by weight (dollars per tonne), volume (dollars per cubic meter), and area (dollars per hectare) across the western US; (2) identify key variables that predict forest-thinning treatment costs; (3) compare the cost and productivity of the machines used for forest thinning; and (4) develop a spreadsheet-based model to estimate forest-thinning treatment costs that can be used to help guide decision making.

Study Methods

Literature Search and Selection

The literature search and data collection process involved setting up literature search keywords and selection criteria (Pullin and Stewart 2006), evaluating published articles for their fit within the context of this study, collecting data from selected articles, and finally, summarizing and analyzing the data (Figure 2). Research papers published from 1980 to

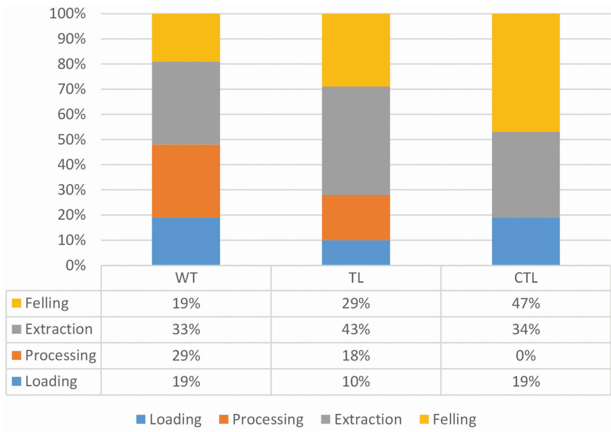

Figure 2. Systematic literature search process in this study.

2020 were searched, and our initial search on thinning productivity and cost studies suggested there was lack of research articles investigating the productivity and cost of thinning operations that took place on public forestlands. We specifically looked for research studies examining forest restoration or fuel reduction thinning treatments.

Forest machines commonly used in today's thinning operations in this region, such as harvesters and forwarders, were first introduced in the US in the 1980s (Kellogg and Bettinger 1994). In aggregating data on machines of different vintages, the basic technologies used in harvesting remained relatively consistent during the study period. For example, data quantifying forwarder productivity in 1994 was combined with data from more recent forwarder studies. Recently, tethered and winch-assisted machines for steep slope operations are becoming more common in the study region, but are still rare compared to traditional equipment, especially on thinning operations, and are not yet well represented in the operations literature on thinning (Petitmermet et al. 2019). Even so, there were improvements in technology and productivity over the study period. The relationships between technological advances in machines, their productivity, and the cost of operations are discussed in more detail in the Results and Discussion section.

Five databases were used for the literature search, including Web of Science, BIOSIS, CAB Abstract, GreenFile, and Agricultural & Environmental Science Database, which include almost all relevant English language forestry publications. The search was limited to three main categories of terms describing forest thinning, cost, and region to find research articles suitable for this study. Literature search keywords were selected for each term and applied to each database. To refer to forest thinning, "forest thinning," "thinning treatment," "thinning treatments," "fuel reduction," "fuels reduction," "reducing fuels," "forest operation," and "forest operations" were used as keywords. For the term cost, "cost," "costs," "feasibility," "merchantable," "productivity," "economics," and "economic" were used. The study region was limited to the continental western US using the following keywords: "western states of USA," "pacific states of USA," "southwestern states of USA," "north central states of USA," "western US," "southwestern US," "northwestern US," "California," "Arizona," "Montana," "Washington," "Oregon," "New Mexico," "Nevada," "Utah," "Colorado," "Wyoming," "Idaho," "Kansas," "Nebraska," "South

Dakota," "North Dakota," and "rocky mountains." Though western in geography, Alaska and Hawaii were not included in this study.

To select research articles meeting the study criteria (Table 1), two screening steps were applied to assess suitability for this study. The first screening was to select papers by reading the title and abstract of each paper. In this step, the relevance to three categories (forest thinning, cost, and region) was evaluated. Once the papers passed the first screening process, the full texts of the papers were reviewed to evaluate the study subject (e.g., thinning) and data presented (e.g., site description and cost). Additional papers were manually selected and added to the final list of papers that were used for this study through citation checking and reference tracking. Finally, data were extracted from the selected papers and organized for data analysis. The literature search focused on papers published in peer-reviewed journals, but conference proceeding papers that were not peer-reviewed were also used for this study. Requirements for selection were that the studies observed and empirically evaluated forest-thinning operations and included associated data such as machine productivity, thinning cost, machine cycle time regression models, and site information. Studies modeling exercises without primary field data collection were not selected.

From the literature search process, 20 articles were selected (Table 2), with 47 independent thinning case studies reported. Of the 20 articles, 12 were identified in the database search, and eight were identified through citation checking and reference tracking. The data collected from the final set of selected studies included forest stand conditions, operational variables, machine productivity, and thinning costs. Stand condition data includes overstory species, stand density, and average diameter at breast height (DBH). The operational variables included harvesting system, harvesting method, thinning intensity, ground slope, and travel distance of machines. To evaluate thinning productivity of each machine, the harvest volume and weight of wood produced were summarized based on productive machine hour (PMH). Also, the hourly costs of each harvesting machine and the operational stump-to-truck costs (felling, extraction, processing, and loading) were initially summarized for further analysis. The cost of on-road transportation was excluded from the data collection in this study because it largely depends on the distance to the mill. Distance ranges vary greatly by site and region. Therefore, the cost calculations included in this study represent stump-to-truck costs.

Standardizing Data and Performing Data Analysis

The data units reported in the selected studies were diverse, so they had to be standardized before being combined for analysis and modeling. The thinning productivity of each machine was calculated and summarized in metric green tonnes per PMH. PMH refers to machine's working hours without delay time. Scheduled machine hour (SMH) refers to machine's working hours including any form of delay time such as operational delays (e.g., system imbalance), mechanical delays (e.g., times used for machine repair and gas filling), and personal delays (e.g., personal break time). Machine utilization rate, a ratio between PMH and SMH, can fluctuate greatly, depending on harvesting machines used, harvesting variables, operational logistics, and other factors. To avoid productivity variability caused by delays in this study, PMH was used in productivity calculations, and we assumed foresters selected the most appropriate and efficient harvesting system available in each case study. Thinning productivity (tonnes per PMH) was calculated with an assumption of 50% moisture content (wet basis). In cases where the study reported moisture content, reported data were recalculated by applying a 50% moisture content. When only harvest volume was reported without wood weight, thinning productivity in terms of weight was calculated using the specific gravity of the species to standardize productivity to uniform units (Kretschmann 2010). The volume unit of MBF (1,000 board feet) was converted to CCF (100 cubic feet) based on the average DBH to convert units on a cubic-meter basis (Oester and Bowers 2003). When calculating mean values, points considered outliers were excluded if they were greater than 1.5 times the value of the difference between the third and the first quartile (Wan et al. 2014). Relatively few points were excluded on this basis, with the justification that unusual conditions in a handful of particular cases drove extreme values that were not representative of the central tendency of thinning cost and productivity under most conditions. In studies using SMH as the basic unit without reporting utilization rate, the utilization rate of each machine that was reported by Brinker et al. (2002) was used as they are based on an accumulation of long-term data on machine utilization.

Reported variables affecting thinning productivity and cost varied by study. Because different machines have different operational activities, the regression equations were classified according to machine types, and harvesting variables corresponding to each machine were organized. The values of the variables used in each study were equally weighted, and the frequency of each variable was counted to identify key variables. In this article, cycle time describes the time required to complete a harvesting activity that is repeated to complete each phase of thinning operations. Key variables collected along with each cycle time are used to explain the amount of time required to complete each cycle. Because the variables were reported independently under the machine type, independent models were developed for each machine type and then combined to summarize thinning costs for each harvesting method.

For comparative analysis, the reported thinning costs were adjusted to 2021 US dollars using the Producer Price Index (PPI). Although commonly used for inflation adjustment, the Consumer Price Index (CPI) covers many industries and does not clearly explain the variability in the cost (machine costs, wages, etc.) of logging operations as much as PPI (Rummer 2008). Although CPI reflects general cost trends, logging is included as a producer industry and monitored for producing prices over time in the PPI program. This study used PPI

Table 1. Criteria used to select references.

Category	Research paper selection criteria
Harvesting method	Mechanical thinning operations (commercial, fuel reduction, restoration)
Study period	Papers published from 1980 to 2020
Region/species	Conifer forests in the western United States
Data collection	Harvesting and stand variables, machine productivity, or thinning costs

Table 2. A summary of thinning productivity and cost papers published over the last 40 years (1980–2020) that were used for this study.

No	Author (year)	Species	Harvesting method	Forest ownership	Thinning objectives
1	Han and Han (2020)	MC	WT/CTL	Plc	FR
2	Townsend et al. (2019)	PP	WT/CTL	Plc	R
3	Petitmermet et al. (2019)	MC	CTL	Plc	FR
4	Vitorelo et al. (2011)	MC	WT	Plc	FR
5	Bolding et al. (2009)	MC	WT	Plc	FR
6	Pan et al. (2008)	PP	WT	Plc	FR
7	Halbrook and Han, (2005)	MC	WT	Plc	FR
8	Largo and Han (2004)	MC	WT	Prv	FR
9	Spinelli and Hartsough (2001)	MC	WT	Prv	Unreported
10	Drews et al. (2001)	MC	CTL	Plc	FR
11	Brown and Kellogg (1996)	MC	CTL	Plc	FR
12	Kellogg et al. (1996)	MC	TL	Prv	C
13	Hartsough and McNeel (1994)	MC/ PP	WT/CTL	Plc	FR
14	McNeel and Rutherford (1994)	MC	CTL	Prv	C
15	Kellogg and Bettinger (1994)	MC	CTL	Unreported	C
16	Hochrein and Kellogg (1988)	MC	Unreported	Plc	Unreported
17	Tesch and Lysne (1986)	MC	WT	Unreported	C
18	Kellogg et al. (1986)	MC	TL	Plc	R
19	Kellogg and Olsen (1984)	MC	TL	Plc	R
20	Host and Lowery (1983)	PP	WT/TL	Prv	C

MC, mixed conifer species growing in the western U.S. including ponderosa pine; PP, ponderosa pine only; Plc, public land; Prv: private land; FR, fuel reduction; R, restoration; C, commercial thinning; WT, whole-tree; CTL, cut-to-length.

values in the logging industry to calculate the average conversion factor for five-year increments to avoid a discrepancy between thinning operation year and publication year in case the operation year is not reported (U.S. Bureau of Labor Statistics 2021). Adjusting to 2021 US dollars using PPI accounts for inflation allows the costs reported in studies from previous years to be compared and aggregated but does not account for cost changes due to other factors, such as technological innovation.

Production costs of machines used for forest thinning were collected from each study, and data were organized by stand conditions and operational variables. Data from studies that reported costs for all four stages of thinning (felling, extraction, processing, and loading) were collected separately and used to show the range of forest thinning costs over the study period. The production cost of each machine was summarized in dollars per tonne and dollars per cubic meter, and if possible, dollars per hectare was also calculated.

New Forest Thinning Cost Estimation Model: ThinCost_1.0

Using the data collected in the systematic literature review, a new model (referred to as ThinCost_1.0) was created for application throughout the western US The model estimates the general productivity and cost of machines in forest-thinning operations and provides a framework and benchmarks to calculate these metrics based on stand conditions. ThinCost_1.0 estimates production costs for roundwood removal in a thinning operation and does not include biomass harvesting (i.e., chipping or grinding and loading biomass). The ThinCost_1.0 model consists of five spreadsheets of input, machine productivity, machine rates, thinning cost, and tree volume. For cost estimation, this model calculates production rate (tonnes per cycle), cycle time, and machine rate (dollars per PMH) based on user input, with default values drawn from analysis included in this review. The input step allows a user to enter thinning prescription data. Allometric equations were used for five species (*Pinus ponderosa*, *Pseudotsuga menziesii*, *Calocedrus decurrens*, *Abies concolor*, and *Pinus lambertiana*). Prescription data on tree removal is used for the tree volume calculation, and the average DBH of trees is used to estimate the average log volume per tree, which is for estimating production rates per cycle of each machine. Thinning productivity of each machine is calculated based on the calculated log weights per cycle. The cycle time was calculated with 42 independent regression equations collected from the literature review and averaged. With the produced weight per cycle (tonnes per cycle) and cycle time (minutes), the machine productivity (tonnes per PMH) was calculated. The machine rate in 2021 US dollars (dollars per PMH) is calculated using the standard machine rate calculation method with the machine type data collected from selected studies (Brinker et al. 2002). The current purchasing price of each harvesting machine was obtained from a dealer. The production cost of each phase was calculated with the machine productivity (tonnes per PMH) and machine rate (dollars per PMH) for the stump-to-truck cost calculation. Finally, the model estimates final thinning costs for three harvesting methods (WT, TL, and CTL).

Based on this model, machine productivity and production cost were simulated under different harvesting conditions. Commonly used machines were selected according to the harvesting method (Figure 1), and the results were compared by changing the key variables. The average DBH was changed to analyze the felling machines, and the extraction machines were analyzed by changing the moving distance. For the simulation, the commonly used input value was set to a slope of 15°, species of Ponderosa pine, and thinning intensity of 1,236 trees/ha to be removed. When comparing extraction machines, the average DBH was set to 15 cm, with a lateral distance of 30 m for cable yarders.

Results and Discussion

Key Harvesting Variables Reported in Regression Models Estimating Thinning Productivity

In operations research, independent variables are used in regression models to predict machine cycle time and productivity based on material characteristics (e.g., diameter, mass, piece count), site conditions (e.g., slope, ground operability), machine movement (e.g., distance, swing arc) and other measurable variables (e.g., operator experience). Not all regression models used the same variables, but we sought to identify and use the most important key variables across these diverse case studies. For felling machines (Table 3), there were five chainsaw cycle time regression models, eight feller-buncher models, and six harvester models represented in the literature we reviewed. The moving distance and DBH were identified as key variables, but DBH was not a key variable for the feller-buncher because feller-bunchers were often used to cut small-diameter trees (4–35 cm). Also, the number of trees felled increased with decreasing tree diameter. In the case studies, the feller-buncher felled five trees per cycle on average, whereas the harvester and chainsaw cut one tree per cycle. Because harvesters conduct additional processing activity at the stump, the number of cuts per log was the key variable in harvester models. Many variables that were significant predictors of thinning productivity in specific models—such as species, slope, height, and worker experience—were dropped from the aggregate model because they were used only in one or a small number of studies.

For the cycle time regression models for extraction machines, there were nine skidder models, and five and six models for forwarder and cable yarder, respectively (Table 4). Each machine moves logs in different ways, but the activity of moving wood to a landing is the same. Since the travel time is the longest part of a cycle compared to other machines (Drews et al. 2001; Spinelli and Hartsough 2001; Pan et al. 2008; Han and Han 2020), the travel distance is the most important variable explaining extraction productivity, so the travel distance was used as a predictor in every extraction model. The number of trees or logs per cycle is also an important variable, but it was selected as a key variable only for the skidder. In the reviewed studies, the forwarder and cable yarder harvested relatively large trees in log form compared to skidders, so the count measurement is often replaced by the volume or weight of the timber in each cycle for these machines.

For the processor and loader, seven and eight models were analyzed, respectively. The number of cuts per tree and the number of trees were the key variables (Table 5), with all seven processor models using the number of cuts per tree and six of the eight loader models using the number of trees. The DBH was selected as an additional key variable for the processor.

The key variables that affect thinning productivity and cost for each machine varied greatly from study to study. Cycle time estimation models ranged from simple to multiple regression models including up to six variables. In previous studies, the reported variables were selected based on statistical tests and estimates of prediction error (e.g., F-test, adjusted R-squared value, or Akaike Information Criterion) or to meet different research objectives to facilitate cost estimation from generalizable variables that can be easily measured in the field. For example, Petitmermet et al. (2019) compared regression models, using different variables, with statistical tests and explained that the results could be different depending on the data they collected and used. Therefore, many variables not identified as key variables in this study significantly affect thinning productivity in the original models used in the studies. Their exclusion here should not be interpreted as a judgment on their statistical significance. Additionally, the variables that affect harvested wood volume or weight per cycle were not applied. DBH, height, and species might affect the amount of wood handled per cycle, but it is difficult to

Table 3. Variables used in the delay-free cycle time regression models for felling machine productivity. Bold indicates variables determined to be key variables.

Chainsaw	$n = 5$	Feller buncher	$n = 8$	Harvester	$n = 6$
DBH	4	**Travel distance**	7	**DBH**	5
Distance to tree	3	**The number of trees per cycle**	7	**Travel distance**	5
Slope	2	DBH	3	**The number of cuts/logs per cycle**	4
Number of bucking	2	Slope	1	The number of trees per cycle	1
Wedge	2	Forest type	1	Weight	1
Tree volume	2	Non-Merchantable pieces	1	Height	1
Species	1	Merchantable Pieces	1	Slope	1
Cutter experience	1	Plots	1	Forest type	1
Site	1	Draws	1		
Wide treatment	1				
Strip treatment	1				

n is the number of papers that included each variable in cycle time regression models. Travel distance includes distance variables such as the move distance to tree or intermediate travel distance. The number of logs per cycle includes the number of cuts per cycle.

Table 4. Variables used in the delay-free cycle time regression models for extraction machine productivity. Bold indicates variables determined to be key variables.

Skidder	*n* = 9	Forwarder	*n* = 5	Cable Yarder	*n* = 6
Travel distance	9	**Travel distance**	5	**Lateral distance**	6
# of trees per cycle	6	Slope	3	**Yarding distance**	6
Slope	3	Product type	3	The number of logs per cycle	2
# of bunches per cycle	2	Log weight/volume	3	Volume per cycle	2
Machine type	2	# of logs per cycle	2	preset	2
type of material	1			The number of choker setter	1
Weight	1			Slope	1
				Yarding direction	1
				The number of chokers	1
				Crew size	1
				Damage	1
				Log angle	1
				Grapple	1

n is the number of papers that used the variable when developing regression models. Log weight includes log volume. Travel distance includes distance variables such as the move to bunch or intermediate travel distance.

Table 5. Variables used in the delay-free cycle time regression models to estimate productivity for processors and loaders. Bold indicates variables determined to be key variables.

Processor	*n* = 7	Loader	*n* = 8
The number of cuts per tree	7	**The number of logs per cycle**	6
DBH	4	Log volume	2
Material	2	Branding	1
Forest type	2	The number of swings per truck	1
species	1	Log sort	1
Pieces per grapple	1	DBH	1
		Weight	1
		# of bunches per cycle	1
		Travel distance	1

n is the number of papers that used the variable. The number of cuts per tree includes the number of logs per tree.

estimate the volume or weight based on the data as they were provided in these studies. These variables should be explored in future research.

Productivity and Cost for Machines Used in Thinning Operations

Because feller-bunchers can cut several trees in one cycle in a relatively short time, the productivity was significantly higher (33.31 tonnes/PMH), on average, than the other felling machines. Also, the feller-buncher has $4.58/tonne of felling cost, which resulted in the most efficient machine among the felling machines (Table 6). Conversely, the chainsaw was less productive, but the production cost ($/tonne) was lower than the harvester. The chainsaw has a longer cycle time than other machines, so productivity was relatively low (10.65 tonnes/PMH on average) at $6.49/tonne. The most expensive felling machine was the harvester at $14.21/ tonne with 14.57 tonnes/PMH. When calculating the machine cost according to the volume (dollars per cubic meter), the harvester showed the highest cost among the felling machines at $10.92/m^3, followed by the chainsaw and the feller-buncher at $5.47/m^3 and $3.30/m^3, respectively (Table 7). In WT systems, feller-bunchers and chainsaws do not process the trees they fell, so a fair cost comparison to harvesters would include processing in addition to felling. Also, the average DBH felled by each machine was different. The feller-buncher was used to cut relatively smaller trees (average [avg.] 16 cm in DBH), and the DBH of the removed trees tended to be larger for harvesters (avg.) and chainsaws (avg. 32 cm). These result suggests that feller-bunchers would be the ideal machine for fuel reduction or forest restoration thinning on appropriate slopes because the small-diameter tree is the main harvest target, and the productivity of the machine tends to increase as the DBH increases (Kellogg and Bettinger 1994; Nakagawa et al. 2007). Also, due to lower production costs, feller-bunchers may be preferred over harvesters for financial reasons. However, a harvester would be preferred if a thinning prescription requires leaving limbs and branches on site for reasons such as nutrient recycling or lack of local markets for biomass. Therefore, the criteria for machine selection in thinning operations is based not only on financial outcomes but also on harvesting objectives.

Among the extraction machines, the cable yarder showed the lowest productivity at 14.52 tonnes/PMH with the highest extraction cost at $30.41/tonne. A cable yarding system requires workers (typically 3–5) on the ground, so the hourly cost of operation is higher than the other extraction machines. The low productivity of cable yarders can be explained by the timber volume produced in one cycle, which is relatively smaller than the other extraction machines, and the extra time required to change skyline corridors. However, cable systems can be applied to forests on steep slopes (>35%), so they are often used in areas where skidders or forwarders may be impractical to use or prohibited by policy or best management practices. Recent applications of tethered and winch-assisted machines on steep slopes are changing this

Table 6. Productivity and cost of each machine for forest thinning operations, converted into 2021 costs (dollars per tonne).

Machine	Production rate (tonnes/PMH)				Thinning cost ($/tonne)			
	Mean	n	Median	n	Mean	n	Median	n
Chainsaw	10.65	14	10.04	14	6.49	13	6.76	14
Feller-Buncher	33.31	16	28.98	16	4.58	15	4.52	16
Harvester	14.57	16	11.57	16	14.21	15	13.85	13
Skidder	21.29	26	19.38	27	6.56	24	5.90	25
Cable Yarder	14.52	22	16.09	22	30.41	22	28.99	22
Forwarder	14.80	9	13.68	10	10.54	8	9.53	9
Processor (WT)	24.18	10	25.74	10	6.80	10	6.98	10
Processor (TL)	22.40	2	22.40	2	6.84	2	6.84	2
Loader (CTL)	25.25	8	21.41	8	5.33	8	5.91	8
Loader (TL)	41.75	2	41.75	2	3.77	2	3.77	2
Loader (WT)	44.04	16	43.89	16	3.40	14	3.25	15

Thinning productivity and cost on whole-tree (WT) harvesting equipment (i.e., chainsaw, feller-buncher, and skidder) includes handling both sawlog trees and biomass trees, while other machines handle sawlog trees or roundwood only. Productivity and costs in this table were a summary of the data reported in the past studies. CTL, cut-to-length; PMH, production machine hour; TL, tree-length.

Table 7. Thinning costs of machines (dollars per cubic meter) in the stump-to-truck process (i.e., felling, extraction, processing, and loading) for forest thinning operations converted into standard units.

Machine	Thinning cost ($/m^3)			
	Mean	n	Median	n
Chainsaw	5.47	13	4.69	13
Feller-buncher	3.30	12	3.44	13
Harvester	10.92	14	10.27	16
Skidder	4.67	19	4.43	19
Cable yarder	23.94	15	17.17	15
Forwarder	8.07	8	7.69	8
Processor (WT)	5.16	6	5.24	6
Loader (CTL)	3.49	7	3.79	7
Loader (WT)	2.43	10	2.17	11

CTL, cut-to-length; WT, whole-tree.

calculation for operators. For example, Petitmermet et al. (2019) compared tethered and untethered machine productivity, but adequate data were unavailable to include tethered machine systems in this study. Skidders and forwarders were highly productive and showed lower costs than cable yarders. The skidder showed the highest efficiency among the extraction machines at 21.29 tonnes/PMH and the lowest cost at $6.56/tonne. Among the extraction machines, the cable yarder showed approximately five times higher extraction cost ($23.94/m^3) than the skidder ($4.67/m^3) and three times higher than the forwarder ($8.07/m^3). Although cable yarders are similar to the forwarder in average productivity, their production costs are approximately three times as much. The reason is that the machine rate (dollars per hour) of cable yarders is much higher than forwarders due to machine price and labor costs associated with a higher number of workers.

Processors and loaders were sorted by harvesting methods. The processor showed high productivity at 24.18 and 22.40 tonnes/PMH, on average, in WT and TL harvesting methods, respectively. The average cost was $6.80/tonne and $6.84/tonne, respectively. However, considering there are only two cases of TL harvesting, it is not appropriate to compare this result on a statistical basis. Similar to the processor, the productivity and costs of the loader showed high productivity and low cost. The loader had the lowest productivity, with an average of 25.25 tonnes/PMH in CTL, 41.75 tonnes/PMH, and 44.04 tonnes/PMH in TL and WT, respectively, which is consistent with past studies (Brown and Kellogg 1996; Hartsough 2003; Townsend et al. 2019).

Stump-to-Truck Thinning Costs

Based on the production cost of each machine in Table 6, the stump-to-truck cost of the most commonly used harvesting systems was calculated (Table 8). The cheapest scenario for forest thinning is the feller-buncher-skidder-processor-loader, with an average cost of $21.34/tonne and a median value of $20.65/tonne. The harvesting system with the highest cost was the chainsaw-yarder-processor-loader ($47.10/tonne). The cost of the harvesting system involving a cable yarder exceeded $40 per tonne. The stump-to-truck cost of CTL was higher than WT except for the cable yarding system because the operating cost of the harvester was more expensive than the sum of the feller-buncher and processor, and the forwarder also had a higher production cost ($10.54/tonne) than the skidder ($6.54/tonne). This result shows a simple cost difference in harvesting systems, and it does not propose the machine selection for operators; these results are simply the sum of the costs of each machine, and the operator's machine selection has already been applied in each result. Site conditions and treatment objectives may favor selection of a higher-cost system.

In the 20 cases reported, all phases (felling, extraction, processing, and loading) were considered and the cost ratio of each phase in stump-to-truck cost was compared. There were only two cases of TL (Townsend et al. 2019, Han and Han 2020), as compared to ten and eight cases for WT and CTL harvesting, respectively (Figure 3). As a result, extraction cost occupied the highest ratio in WT and TL at 33% and 43%, respectively. This result has been shown in other studies that present each phase of a stump-to-truck operation (Hartsough 2003; McIver et al. 2003; Han et al.

Table 8. Stump-to-truck costs depending on harvesting methods and systems based on information in Tables 6 and 7, excluding biomass handling activities (i.e., chipping, grinding, and loading).

Harvesting phase	Harvesting method				
	Whole-tree			Tree-length	Cut-to-length
Felling Extraction Processing Loading	Chainsaw Skidder Processor Loader	Chainsaw Yarder Processor Loader	Feller-Buncher Skidder Processor Loader	Chainsaw Yarder Loader	Harvester Forwarder Loader
$/tonne (mean)	23.25	47.10	21.34	40.30	30.08
$/tonne (median)	22.89	45.98	20.65	39.52	29.29
$/m^3 (mean)	17.73	37.00	15.56	N/A	22.48
$/m^3 (median)	16.53	29.27	15.28	N/A	21.75

$/tonne represents the sum of the thinning costs of each harvesting system.

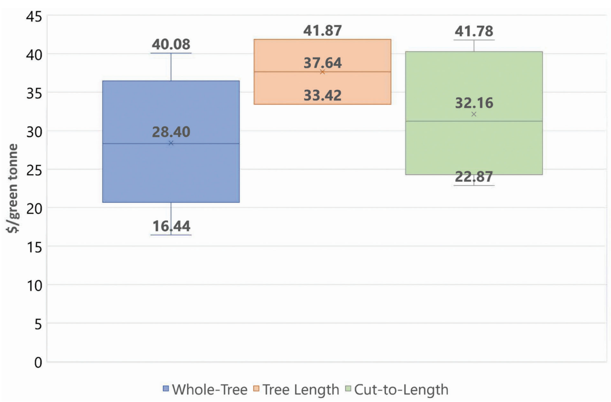

Figure 3. The ratio of each phase (felling, extraction, processing and loading) of thinning operation to total stump-to-truck harvesting cost. CTL (*n*=8), TL (*n*=2), WT (*n*=10), Felling in CTL includes felling and processing. Processing activity in the CTL harvesting system is included in the felling activities.

2004). For CTL harvesting, the extraction cost was 37% of the stump-to-truck cost, and combined felling and processing is the highest cost component at 47%. The reason for this high cost is that harvesters were used in CTL, and processing and felling was conducted at the stump in one cycle. Comparing the combined ratio of felling and processing, all three methods had similar values. Loading accounted for the lowest percentage of the total cost for all three harvesting methods.

Comparing the stump-to-truck costs for the 20 case studies, the WT harvesting method had lower costs than CTL or TL, ranging from $16.44 to $40.08 per tonne (Figure 4). TL harvesting cases ranged from $33.42 to $41.87 per tonne, and CTL thinning cases ranged from $22.87 to $41.78 per tonne. The stump-to-truck cost of CTL was slightly higher than that of WT, which was highlighted in some studies (Hartsough 2003; Townsend et al. 2019). Those studies explain that the feller-bunchers are mainly used in WT thinning operations, whereas the harvester is commonly used in CTL operations. Also, high-cost cable yarding was sometimes used when large trees were removed in CTL operations. TL thinning costs were often used for cable yarding as a strategy to minimize costs by leaving limbs and tops on site (Townsend et al. 2019; Han and Han 2020). Distributing and leaving the limbs and tops throughout the treatment unit is less costly. However, this is not always possible because contracts sometimes specify removing limbs and tops from the unit to reduce wildfire risk. Often, this residual biomass is collected and burned for disposal to meet this objective.

When comparing thinning cost per area, WT shows a slightly lower pattern in harvest cost (Figure 5). The cost of WT was in the range of $785/ha to $2,890/ha (Figure 5). In the cases of CTL, the cost ranged from $1,197/ha to $4,291/ha. Considering the harvested volume, WT methods harvested a relatively large volume compared to CTL methods, but the stump-to-truck cost was lower in the WT method on average. This result suggests machines in the WT method performed more efficiently or productively in the stump-to-truck harvesting process.

Development of a Spreadsheet-Based Thinning Cost Model

The ThinCost_1.0 model focused on estimating stump-to-truck thinning costs in the western US and was designed to estimate thinning productivities of logging machines based on regression equations reported in past studies. The STHarvest (Hartsough et al. 2001) model uses several productivity equations developed under clear-cut operations and in different regions of the US. Harvest Cost-Revenue (HCR) thinning cost model was developed in the southwest US based on a limited number of case studies and may not be applicable in other places where forest conditions and operations differ from the Southwest (Becker et al. 2008). Because the model is based on empirical studies of diverse cases in many locations across the western US, ThinCost_1.0 is applicable across the entire region in various stand conditions.

In the ThinCost simulations for felling machines (Figure 6), the chainsaw in the TL harvesting system had lower productivity than the harvester under 20 cm DBH conditions, and this trend is reversed after 20 cm DBH. The feller-buncher has much higher productivity than the other two machines. The cost (dollars per tonne) difference between chainsaw and feller-buncher was <1$/tonne except in 15 cm DBH conditions, whereas the chainsaw is more expensive than the feller-buncher for trees less than 30 cm DBH. However, the feller-buncher is more expensive than the chainsaw in >30 cm DBH conditions.

In extraction machines, the skidder showed high productivity at low extraction distances and the forwarder was more productive at distances >240 m (Figure 7). The skidder is more cost-efficient than the forwarder in <270 m of extraction distance, and the opposite is true at >270 meters

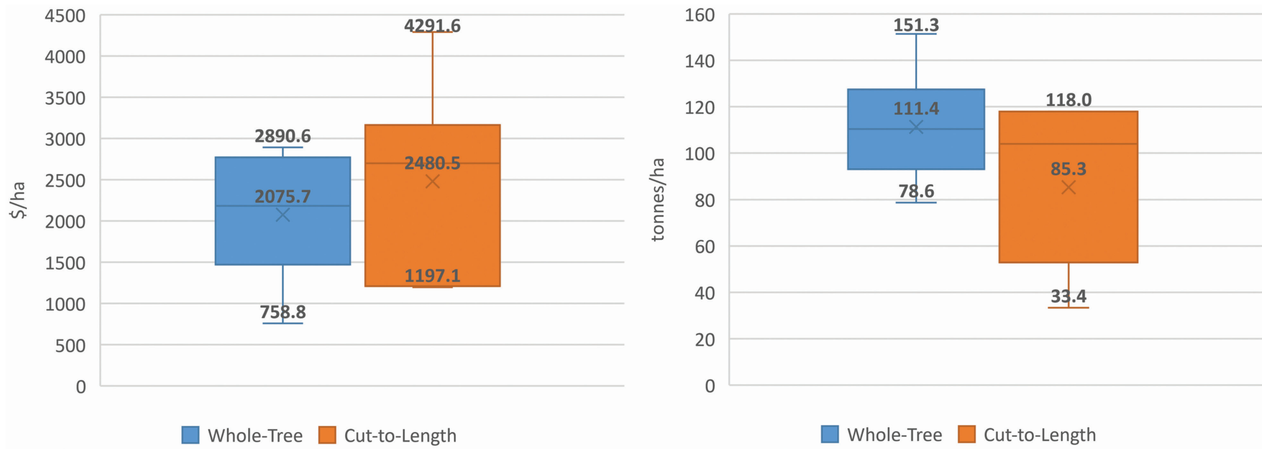

Figure 4. Average costs ($/ton; roundwood only) of thinning operations that were reported in the selected studies.

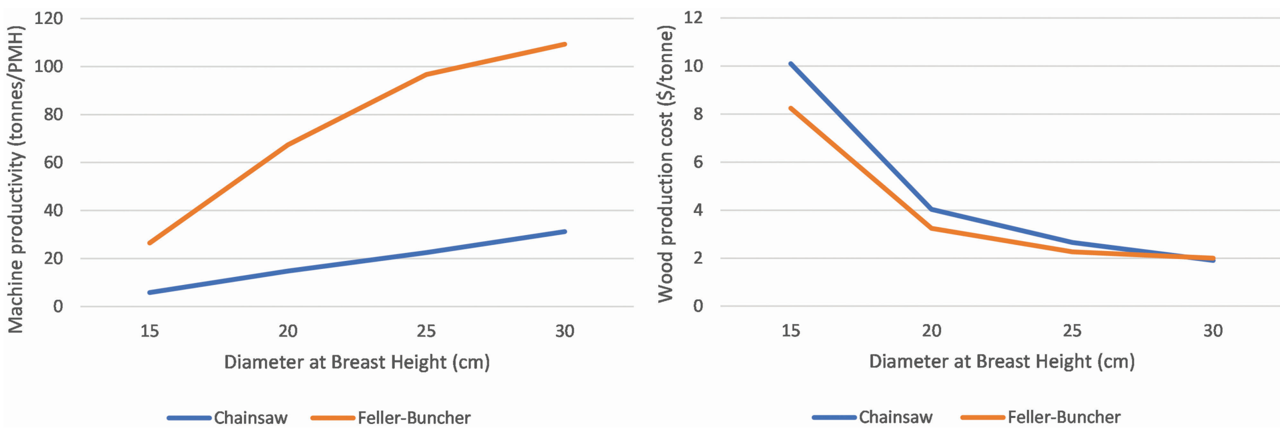

Figure 5. Average costs ($/ha) of thinning operations and harvested volume (tons/ha) from the reviewed papers. Harvested volumes include both roundwood and biomass in whole-tree and roundwood only in cut-to-length thinning operations.

of extraction distance. The cable yarder was more expensive than the other two machines. The processor showed 40 tonnes/PMH of productivity at 15 cm DBH, and the higher the DBH, the higher the productivity (Figure 8). The production costs, on the other hand, started at $5/tonne and went down as DBH went up. The productivity and production cost of the loader is most efficient in 25 cm DBH conditions.

This model allows for comparing machine productivity and costs in different stand conditions, and the user can effectively perform a sensitivity analysis to evaluate thinning cost and financial feasibility for a wide range of operational scenarios. The model can be used to develop practical operational plans and minimize overall thinning costs. Because the model was developed using many thinning productivity equations developed in field-based empirical studies, it provides cost estimates of thinning treatments reflecting average operational work conditions and stand variables.

Limitations of the Study and Areas for Future Research

In this study, we were limited to a fairly narrow slice of forest operations research because of the subject and our requirements for study design, location, and data reporting. As a result, this study does not cover many existing machines that could potentially be used in thinning operations. For example, among feller-bunchers, there are different sizes (large versus small horsepower), wheel types (rubber-tired versus tracked), and felling mechanisms (disc saw versus shear) that are not differentiated here. Each type of machine could perform at a different production rate or hourly cost on thinning operations, so future studies may quantify and summarize thinning productivity and cost data for a wide range of machines at higher resolution.

As previously mentioned, although no major paradigm shifts have occurred in this region regarding logging systems, there were some important advances in technology over the study period (1980 to 2020) that are not explicitly evaluated or quantified. In general, technological advances in logging machines have increased machine productivity over time (Nordfjell et al. 2010; Conrad et al. 2018; MacDonaugh et al. 2019). For example, skidder payloads have increased significantly since the 1980s. More recently, technologies for self-leveling cabs and tethered systems have improved productivity for felling and forwarding on steep slopes. As power transmission, hydraulic pressure, and boom lifting torque have improved, logging capacity and machine speed have increased (Nordfjell et al. 2010). As a

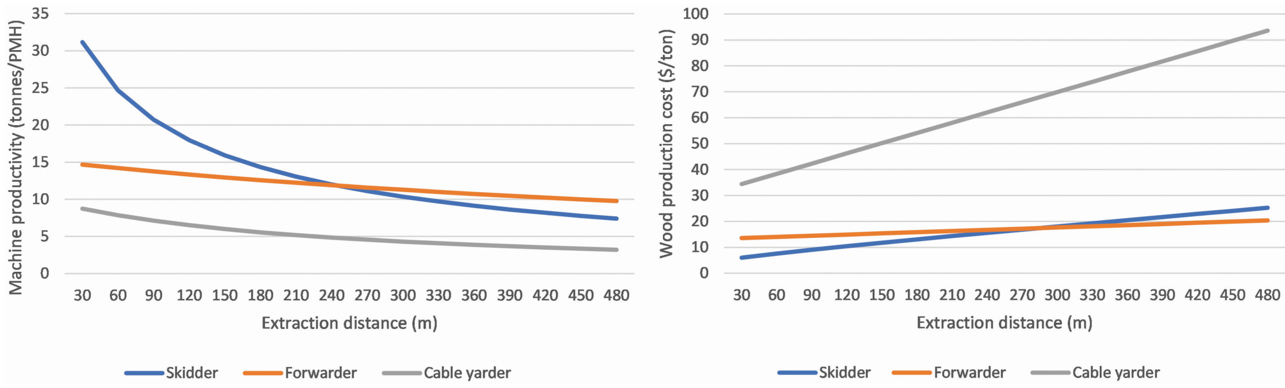

Figure 6. Productivity and cost of felling machine over different size of trees from ThinCost_1.0 model for harvesting round-wood only.

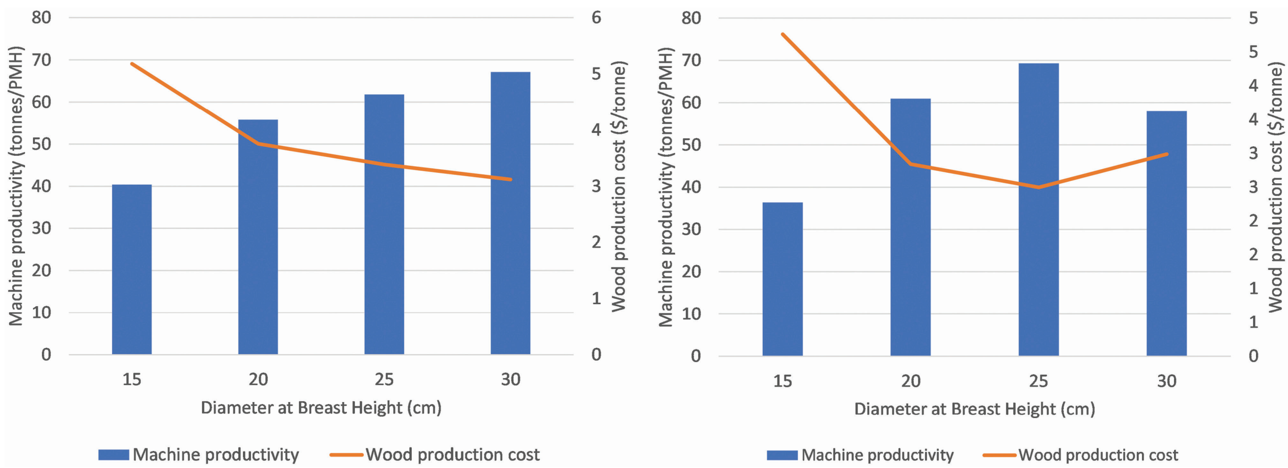

Figure 7. Productivity and production cost of three different extraction machines depending on average skidding distance from the ThinCost_1.0 for round-wood only.

result, the productivity of machines has increased in both CTL (Nordfjell et al. 2010) and WT (Conrad et al. 2018) harvesting operations.

However, there is some evidence that, despite increases in productivity, the inflation-adjusted cost of harvesting has not decreased significantly since the early 1990s due to high prices of machines and the relative escalation of other operational costs. In Sweden, this appears to apply to both thinning and final felling in even-aged stands between 1985 and 2010 (Nordfjell et al. 2010). Along with technological advances in logging machines, the hourly cost of machines, including machine purchase price, repair and maintenance, and fuel also increased, offsetting the improvement in harvesting productivity and keeping costs flat in many situations. Furthermore, for new technologies to drive down unit costs with higher productivity, they must be adopted. In the US, logging companies are typically small contracting businesses with capital investments of less than a million dollars (Allen et al. 2008, Vaughan et al. 2021). In this context, the high cost of new machines using the latest technologies can be a barrier to innovation in timber harvesting (Conrad et al. 2018), and many contractors still use older models and machine styles in the western US.

As technology and productivity are related to this study, we believe that the aggregate data and associated models, which are adjusted for inflation to 2021 USD using the PPI, can be used effectively to estimate productivity and costs on thinning operations with the understanding that they do not account explicitly for any technological advances in this sector, except as captured by the studies included in the review, which represent the best available science in empirical forest operations research on thinning. The information provided can be used as a planning tool to compare the relative performance of different methods and systems under different thinning conditions. As new technologies evolve, they should be studied and incorporated into this work. As this article goes to press, the US and much of the world has experienced a period of sustained high inflation and supply chain disruptions, including in the forest sector, that should be accounted for in future estimation of real thinning costs.

The ThinCost_1.0 model was developed from published research to estimate the stump-to-truck thinning cost for roundwood produced using three harvesting methods (WT, TL, and CTL). Although it was developed using empirical data and regression models from field research, it has not undergone an independent field validation process to evaluate its outputs for accuracy. However, moving forward, new studies that conduct data collection using operations research methods similar to the studies used to develop the tool can easily be used for validation and then be integrated into the

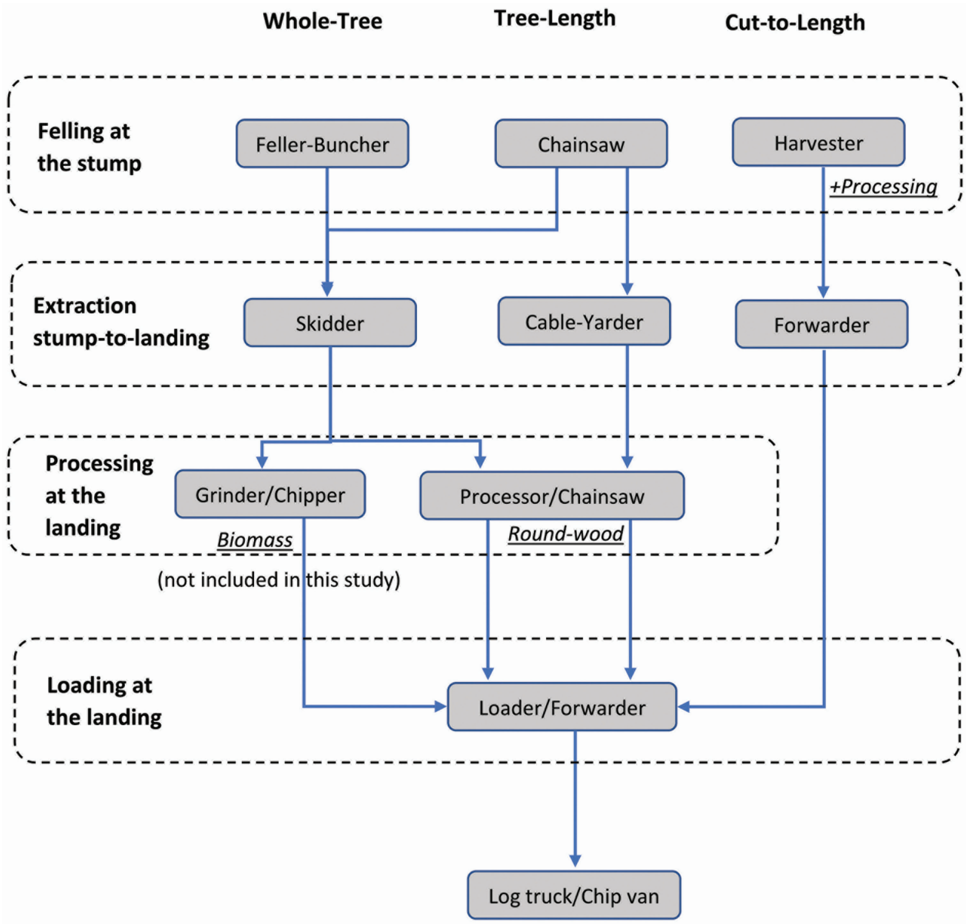

Figure 8. Productivity and production cost of processor (left) and loader (right) depending on DBH from the ThinCost_1.0 for round-wood only.

database of models driving the outputs. The transparent and open-source nature of the spreadsheet-based approach facilitates user validation and modification.

The current model also needs to be expanded to include on-road transportation and thinning treatments that harvest biomass (e.g., limbs, cull, and treetops) using different machine options. The ThinCost model will be further developed to include options for users to tailor operational conditions and machine rates to reflect their work conditions and financial realities closely.

More broadly, this work supports more innovative data collection for operations research and engineering in forestry, especially thinning treatments for hazardous fuel reduction. Traditional operations research using time study techniques provides high-quality, high-resolution data, but is highly time-consuming, labor-intensive, and expensive. As a result, it is quite limited in quantity and has been heavily focused on commercial timber production. As federal land management agencies increase the scale and pace of forest thinning on public land, they should consider integrating operational data collection. Direct support for real-time data collection and analysis using the next generation of sensors, software, and in-woods communications systems is imperative in this industry and can be included in contracting. Better data collection and operations research would bring immediate benefits to operations planning and management. This approach would also help improve cost models like this one and bring agencies into the big data and machine-learning era of precision forestry and Industry 4.0, ultimately improving cost estimation and the efficiency of planning and implementation, which would allow more treatment at a lower cost.

Conclusion

This study summarized the productivity, variability, and costs of forest thinning studies conducted in the western US. We found that forest thinning costs ranged from $16.44 to $41.87/tonne and $758/ha to $4,291/ha. The prethinning forest conditions (e.g., stand density), volume removed (tonnes per hectare), harvesting methods, and system used all directly affect the final cost of forest thinning operations.

The system configuration with the most efficient results for the WT harvesting method included the feller-buncher, skidder, processor, and loader. The feller-buncher was the most efficient machine in the felling phase, outperforming the chainsaw and harvester. Among the extraction machines, the cable yarder had three to five times higher production costs than the other machines and had the lowest productivity but can operate on steep slopes. The skidder appeared to be the most efficient machine for extraction. Processors and loaders were found to have high productivity and low cost, especially in the CTL and WT harvesting methods.

To illustrate how to use the detailed information synthesized in this literature review, we developed a thinning cost estimation model called ThinCost_1.0. It can automatically calculate the cycle time, productivity, and cost of each machine in a system based on user input, with default values and appropriate regression models pulled directly from the reviewed studies. The model needs to be further developed for functionality and field tested to validate the accuracy of its outputs, but it is the most up-to-date model available and is already being used to guide harvest system selection. The goal is to reduce thinning costs by providing useful productivity and cost information and by facilitating efficient forest operations for land managers, fuels planners, woodland owners, contractors, and others conducting critical thinning operations in the forests of the western US.

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Conflict of Interest

The authors declare no conflict of interest.

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