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harvesting & utilization

# ThinTool: A Spreadsheet Model to Evaluate Fuel Reduction Thinning Cost, Net Energy Output, and Nutrient Impacts

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We developed a spreadsheet-based model, named ThinTool, to evaluate the cost of mechanical fuel reduction thinning including biomass removal, to predict net energy output, and to assess nutrient impacts from thinning treatments in northern California and southern Oregon. A combination of literature reviews, field-based studies, and contractor surveys was used to develop a database and equations that are required to model these three components. The volume to be removed, tree size, slope steepness, and skidding/yarding distances were identified as key variables determining fuel reduction thinning treatment cost. The user of this model can estimate fuel reduction treatment costs for a wide range of thinning prescriptions using those key variables. Alternatively, users can enter their own assumptions to customize the tool for their own operations. The net energy output function can allow users to assess potential energy contribution for biomass recovery systems by comparing the amount of energy delivered with the total energy consumed to collect, process, and transport the biomass to an energy plant. Site nutrient removals from thinning treatments were calculated based on the biomass amounts and nutrient contents for each species and the tree components (e.g., limbs, tops, and/or bolewood) to be removed. The outputs can help users to examine the environmental effects of biomass recovery and provide nutrient retention information for sustainable woody biomass production. Additional model validation from future fuel reduction thinning projects would improve user confidence in the model. ThinTool should be a useful analysis program for forest managers and planners when they are developing fuel reduction treatments that are cost- and energy-effective as well as environmentally sound.

**Keywords:** mechanical fuel reduction thinning, forest biomass, costing model, nutrient recycling

Treatments to reduce hazardous fuel accumulations in California's forests often involve mechanical thinning because it effectively addresses high levels of fuel connectivity in high-density stands and allows the use of prescribed burning with reduced complexity. Federal land managers have identified 73 million acres of national forestlands in the western United States that are characterized as having unnatural or excessive amounts of woody vegetation, leaving these areas prone to catastrophic wildfires and susceptible to insect attack and degradation (US Department of Agriculture [USDA] Forest Service 2003). Woody biomass (defined here as small-diameter trees or forest residues that are not acceptable for solidwood products) from thinning overstocked forest stands and traditional timber harvesting operations creates an opportunity for energy generation. It was estimated that in the 15 Western States, more than 28 million acres of forestlands could benefit from mechanical fuel reduction treatments, yielding approximately 345 million oven-dry tons from accessible areas (Rummer et al. 2003).

Mechanical fuel treatments use power tools and heavy equipment to mechanically handle trees to reduce fire hazard. Operations include felling, skidding or yarding, and processing. The economics of mechanical fuel reduction thinning to reduce wildland fire hazard is often in question to forestland managers when they evaluate the practicality of thinning projects. However, there has been a lack of models to accurately predict costs of fuel reduction thinning treatments. This issue becomes further complicated when forest residues (i.e., slash and submerchantable whole trees resulting from fuel treatments) need to be removed from a site. Removal of forest residues creates opportunities to use them to produce biomass energy, but forest residue collection and transportation are often cost-prohibitive due to the low market value of woody biomass and the high harvesting and transportation cost from wildlands (Han et al. 2004). Several fuel reduction thinning studies involving various machines and systems have been conducted to address questions related to thinning prescription, biomass removal, and harvesting costs (Hartsough

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et al. 1997, Lowell et al. 2008, Pan et al. 2008, Bolding et al. 2009). Those studies found that stand condition (e.g., tree size, volume removed, and slope) and harvesting system (e.g., ground-based and cable yarding) are critical factors in evaluating the economic feasibility of fuel reduction treatments. The unit cost of harvesting smaller diameter trees is generally higher than that for larger diameter trees and the unit cost of harvesting low volumes per acre is higher than for higher per acre volumes. In addition, fuel reduction thinning with a cable system is typically more expensive than with a ground-based system.

A review of several previous case studies revealed that they do not comprehensively address the wide range of possible conditions facing forest managers including woody material characteristics, equipment used, road standards, hauling distances to markets, and silvicultural or fuel management prescriptions. A modeling technique that synthesizes past biomass studies and automatically selects useful information for site-specific application may be used to effectively address local conditions when harvesting productivity and costs are estimated (Jin 1996, Pan et al. 2008). STHarvest (Hartsough et al. 2001) was developed to estimate the cost of harvesting small-diameter trees using productivities developed from a large number of past studies. Fight et al. (2006) also developed the Fuel Reduction Cost Simulator (FRCS) to predict costs for fuel reduction treatments involving removal of trees of mixed sizes in the form of whole trees, logs, or chips from a forest. In the southwestern United States, Lowell et al. (2008) also developed the harvest cost-revenue (HCR) estimator to estimate harvest costs and raw log values of wildfire fuel reduction treatments.

Although final cost estimates using STHarvest and FRCS have been used for the purpose of overall planning of fuel reduction treatment on a large (e.g., western US) scale (Han et al. 2004, Jain et al. 2012), these models were often not applicable to estimate accurate harvesting costs for setting up a fuel reduction contract because the production equations used in those models cover a wide range of stand conditions. Many equations built in FRCS were sourced from past studies on "logging" operations, which potentially under- or overestimate a fuel reduction thinning treatment. In addition, the model developed by Lowell et al. (2008) was based on production equations generated from only one case study that was conducted in a northern Arizona ponderosa pine stand. For these reasons, existing harvesting cost models can often lead to a "ball park" estimate of fuel reduction treatments and may not be appropriate to use in the estimation of fuel treatment costs for setting up a fair contract in a stand condition and specific thinning work requirements.

In fuel reduction thinning, mechanical harvesting of forest biomass for energy also raises questions about the net energy contribution due to the use of fossil fuel. A net energy analysis is often performed to investigate the net energy ratio comparing the amount of energy delivered to society by a technology with the total energy consumed to harvest, extract, process, transport, and comminute for energy production. Adams (1983) found that net energy ratios ranged from 18.2 to 25.0 in smallwood harvesting using a cable system (stump to truck). Pan et al. (2008) estimated the net energy generated from mechanical fuel reduction thinning treatments using a ground-based system on a pure ponderosa pine stand in Arizona. They reported that the net energy ratio between energy output and input was 10.41. These past studies also found that the net energy contribution in fuel reduction thinning was significantly associated with hauling distance to the market because energy used for hauling biomass represented the largest part (36%) of the total input energy. In addition, tree size had a direct effect on net energy ratio. Harvesting larger size trees should generally improve the net energy ratio by increasing machine productivity.

An additional limitation of previous biomass harvesting studies is the lack of integration between woody biomass removal and the environmental effects of these operations. Removal of woody biomass including small whole trees, limbs, and tops can remove on-site nutrients at a greater rate than harvesting stem wood only in traditional logging. In many forest stands, nutrient depletion by whole-tree harvesting was found, but in other stands, whole-tree harvesting had little or no effect on total ecosystem nutrients (Mann et al. 1988). In addition, the impacts of stand removal on site productivity were varied with soil type, tree species, ecosystem, or climatic regime (Grigal and Vance 2000). Although several past studies stated that loss of nutrients from fuel reduction thinning could have negligible short-term impacts on site, it is still important to quantify the amount of nutrient loss from fuel reduction treatments to monitor the impact of thinning operations on long-term stand productivity. It would also help forest managers and land owners to determine tradeoffs between disparate objectives (i.e., nutrient recycling versus removal of hazardous fuels) that require integration of biomass availability, harvest cost analysis, and environmental effects simultaneously to facilitate decisionmaking.

Mechanical fuel reduction thinning including biomass removal is expensive compared with prescribed fire and may cause nutrient loss, but it creates opportunity for biomass energy. Forest managers often look for a comprehensive tool to effectively evaluate economic feasibility of fuel reduction thinning, potential for biomass energy, and impacts on nutrient recycling from fuel treatments. However, there has been no tool that effectively simultaneously addresses these topics in fuel reduction thinning projects. The objective of this research was to develop a comprehensive spreadsheet-based model that allows forest practitioners to accurately predict the cost of fuel reduction thinning treatment using ground-based and skyline thinning systems, to estimate energy contribution, and to assess the impacts on soil nutrients in fuel reduction thinning treatments in northern California and southern Oregon. We also conducted a field-based validation of the model to evaluate how accurately it estimates fuel reduction thinning costs. Our model should directly benefit land managers who prepare contractual documents of hazardous fuel reduction treatments.

## Methods

We developed a spreadsheet-based fuel reduction cost model, named ThinTool, which incorporates net energy output and nutrient impacts on fuel reduction thinning sites in northern California and southern Oregon. The model was developed using Microsoft Excel in conjunction with Visual Basic for Applications (VBA). ThinTool can be used for ground-based and skyline thinning systems over a wide range of stand and site conditions, silvicultural prescriptions, operations requirements, and road standards and distances. Three components (cost, energy output, and nutrient removal) are directly linked to each other and sensitively respond to any change in thinning prescriptions (e.g., thinning intensity and species selection) and operations requirements (e.g., skidding distance and machine size) (Figure 1).

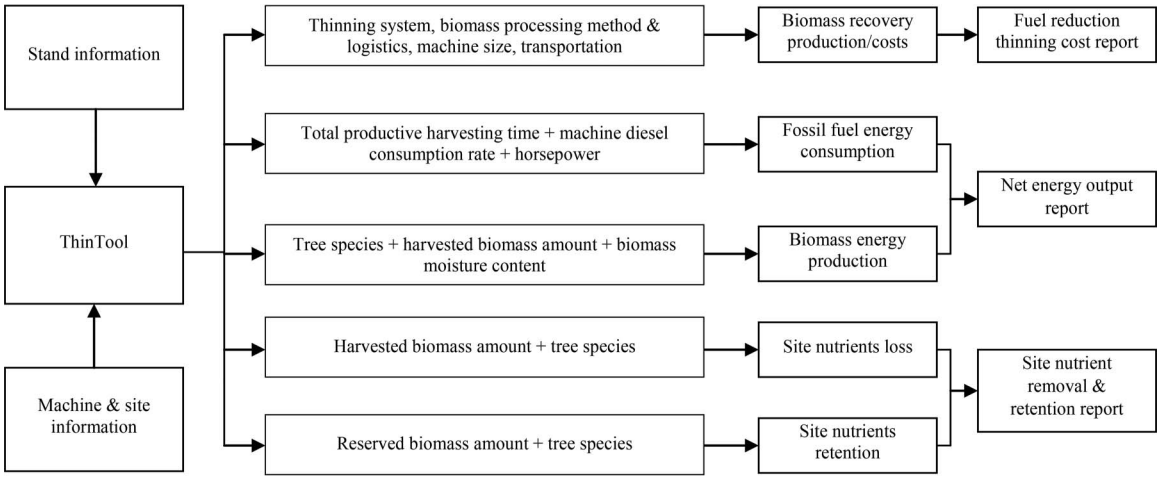


**Figure 1. Fuel reduction thinning cost, net energy contribution, and site nutrient removals calculation model diagram.**

## Development of a Spreadsheet-Based Model to Estimate a Fuel Reduction Thinning Treatment Cost

A combination of literature review, field-based studies, and a contractor survey was used to develop a database and set of equations required to run the model.

### *Estimation of Tree Volume Removed from Thinning Treatments*

ThinTool is a stand-level thinning production and cost prediction model. Production and cost estimates are based on specific thinning prescriptions and stand conditions, including total volume, merchantable trees and energy wood volume removed, stand density, dbh, tree height, biomass retention amounts on site, and total harvest area. For volume estimation in the model, individual tree height was estimated using height-diameter equations developed by Vitorelo (2011). Species-specific regional tree biomass equations (Zhou and Hemstrom 2010) developed in the Pacific Northwest were used to predict current standing tree volume and sawlog volumes (cubic foot volume) from 1-ft stump to a 4- or 6-in. top.

### *Harvesting System and Machine Cost*

Harvesting system and machine type and size are varied with thinning treatment regions and stand conditions. To estimate more representative and accurate thinning costs in ThinTool, two representative harvesting systems and one representative machine type for each operation were selected through literature reviews and personal communications with five logging contractors working in northern California and southern Oregon. ThinTool includes ground-based and cable yarding systems for fuel reduction thinning. Both harvesting systems apply a whole-tree harvesting method because it is common in fuel reduction units where managers wish to remove residues from the site to reduce fuel loading. In each harvesting system, machine cost information was collected from past studies developed in northern California and southern Oregon (Vitorelo 2011). In ThinTool, chipper or grinder can be selected to process waste material (limbs, tops, chunk, and small whole trees) into a mixture that can be used for fuel in various power generation plants or conversion technologies. The model classifies the chippers into two major categories by their horsepower (hp). Chippers with engine sizes $<$500 horsepower are defined as small chippers; otherwise, they are treated as large chippers. Grinders are classified into three different categories (i.e., small, $<$500 hp; medium, 500–900 hp; and large, $>$900 hp). Machine cost information for chippers and grinders was collected from the database study for biomass recovery costs developed by Han and Johnson (2012).

Two different biomass operation logistics (i.e., processing at landing versus centralized biomass processing) and three different prehauling options (modified dump trucks, hook-lift truck, and log truck) were included in the model. Machine cost information for prehauling was collected through literature reviews (Harrill and Han 2010, Vitorelo 2011, Han and Johnson 2012). There are two different biomass loading options applied in the model: hot operation and cold operation. Hot operation means that chippers and grinders process forest residues that are directly loaded into a chip van. In cold operation, chippers or grinders process forest residues and produce piles on the ground that are then later loaded into a chip van using a front-end loader.

Prefinance and tax machine costs were estimated using a methodology first developed by Matthews (1942) that was modified by the USDA Forest Service (2007) to incorporate the capital cost formula to more correctly account for interest when capital costs are allocated over time. Machine costs, which were calculated per scheduled machine hour and per productive machine hour, were combined with other costs to determine the profit or loss on the sawlog and biomass operations to determine the amount that could be bid or price that must be received for the logging operations contract.

### *Machine Productivity Estimation*

The most critical part of developing the cost model is determining how to accurately predict machine productivity for a given stand condition and harvesting system. There are several approaches for estimating machine productivity. Rummer (2008) described four basic approaches to assign a cost to forest operations: expert opinion method, transaction evidence method, accounting method, and engineering cost analysis. To accurately predict fuel reduction thinning costs on a wide range of local site conditions in southern Oregon and northern California, a new approach was applied in ThinTool using a combination of the results from literature reviews, time and motion studies (engineering cost analysis), and expert opinion surveys conducted in this region. We estimated machine productivity using three steps.

The first step of this approach was to identify key independent

variables affecting the machine productivity through a comprehensive literature review. Twelve different fuel reduction thinning studies that include regression equations to predict machine productivity were categorized based on different biomass recovery systems and machine types (Johnson 1988, Hartsough et al. 1997, Coulter 1999, Keatley 2000, Spinelli and Hartsough 2001, Largo and Han 2004, Halbrook and Han 2005, Han and Renzie 2005, Adebayo 2006, Lowell et al. 2008, Pan et al. 2008, Bolding et al. 2009).

The second step of this approach was to obtain representative machine productivities for mechanical fuel reduction thinning treatments on three different stand conditions using expert opinion surveys. The survey was designed to collect representative cost estimates from contractors who have performed mechanical fuel reduction thinning treatments on National Forests in northern California and southern Oregon. Initially we contacted potential respondents to survey, and then we sent out surveys through the mail or e-mail to contractors who said they were willing to participate in the survey. A total of 29 contractors participated in the survey. Of these, only five cable yarding contractors provided their cost estimates. However, cable yarding operations are not often implemented with fuel reduction thinning in this region due to high operation costs (Hochrien and Kellogg 1988). Cost figures for sawlog extraction and biomass extraction were asked to be reported separately for ground-based and cable yarding systems. Based on key independent variables identified from the literature review, three "typical" stand conditions that are often treated for fire hazard reduction in the study area were developed for this survey. Each stand consisted of mixed conifers with an average size sawlog removal of 13 in. dbh. Biomass removal for each stand consisted of trees ranging in size from 3 to 9 in. dbh totaling 7 green tons per acre (GT/ac). Average slope and skidding distance for the ground-based system were set as 15% and 400 ft, respectively. In the cable yarding system, average slope and yarding distance were 40% and 500 ft, respectively. The variable that changed for each stand scenario was sawlog removal volume, which was 4 thousand board feet (MBF), 7 MBF, and 10 MBF, to find the effect of this variable on machine productivity.

The final step was to develop factors to adjust representative machine productivity to accommodate a wide range of site variables found in the first step, such as average tree size, slope, and skidding/yarding distances. Time and motion studies on ground-based and skyline fuel reduction thinning treatments were conducted in Klamath National Forest near Yreka, California. These studies were to calculate machine productivity ($ft^3$/productive machine hour [PMH]) and evaluate interactions between equipment, personnel, and harvesting attributes on each phase of the thinning treatment. In addition, regression equations were developed to estimate the machine cycle time and to understand how independent variables might affect thinning productivity. The data set from these studies allowed us to perform various sensitivity analyses to develop adjustment factors in estimating thinning operation productivity that accurately reflect stand conditions and thinning operations requirements. For each machine operation, when 1 unit (e.g., 1 in. in dbh, 1% in slope, and 50 ft in skidding/yarding distance) is changed from the basic stand condition used in the survey, percent changes of machine productivity were calculated using a prediction equation developed in each case study. Percent changes developed from each case study were averaged and then used to adjust representative productivity by the user's entered stand conditions. We believe this approach allows an accurate estimation of thinning treatment costs on a wide range of local site conditions in southern Oregon and northern California because all key variables affecting harvesting costs were included in cost estimates, based on case studies, expert opinion surveys, and literature reviews conducted for this region.

### Net Energy Output Analysis

Net energy output was estimated by comparing the amount of energy generated with the total energy consumed from stumps to energy plants to produce the biomass energy. Direct energy consumption consisted of fuel consumed for harvesting and extracting small trees, comminuting forest residues including limbs, tops, chunks, and small trees, and transporting forest residues. Indirect energy consisted of fuel consumed for moving equipment and for crew transportation. The amount of diesel used by each machine was determined from machine productive time, specific fuel consumption rate, and engine horsepower. The total direct and indirect diesel consumption amounts were converted to an equivalent heating value (British thermal units [Btu, BTU]) as the total energy input. The energy content was taken at 137,000 BTUs per gallon for diesel and 125,000 BTUs per gallon for gasoline (Adams 1983).

Recoverable energy output was based on the amount of harvested woody biomass, moisture content, and species. Energy output was defined as the total recoverable heating value from the forest residues produced and was calculated using the following formula (Ince 1979):

$$RHV = HHV \cdot (1 - MC_{wb}/100) - THL$$

where RHV is recoverable heating value (BTUs/lb of wet fuel), HHV is higher heating value or the maximum potential energy (BTUs/lb of oven-dried fuel), $MC_{wb}$ is wet-based moisture content (percentage), and THL is total heat loss (BTUs/lb of wet fuel).

Total heat loss consisted of conventional heat losses and the sum of stack gas heat losses caused by moisture, hydrogen, dry gas, and excess air. Total heat loss was estimated under the following assumptions (Ince 1979): the combustion heat recovery system was operated with 40% excess air and a stack gas temperature of 260° C, which is typical for an industrial system; and the ambient temperature of hog fuel before combustion (room temperature) was 20° C. The conventional heat losses included heat losses resulting from thermal radiation, conduction and convection of heat, incomplete combustion, and miscellaneous or unaccounted for heat losses. In this study, the constant conventional heat loss factor was assumed to be 4%.

### Assessment of Site Nutrient Removal Impacts

The site nutrient removals were calculated based on the biomass amounts and nutrient concentrations (i.e., nitrogen [N], phosphorus [P], potassium [K], calcium [Ca], and magnesium [Mg]) for each species and tree biomass component (i.e., stem, bark, limbs, and foliage) removed. Nutrient contents for each species and tree biomass component were collected from past studies conducted in northern California and southern Oregon (Pearson et al. 1987, Ranger et al. 1995). Biomass weight of tree components removed from thinning treatments was estimated using biomass predicting equations developed by Jenkins et al. (2003), who compiled their formulas from the literature for predicting the biomass weight of tree components from diameter measurements of species found in North America. However, potential amounts of biomass that could

be harvested and delivered to energy plants and manufacturing facilities are actually less than what was estimated using those tools because of harvesting and handling loss. In particular, limbs and tops are often broken and left on site during felling and skidding activities and additional biomass loss occurs at landings. Therefore, biomass recovery rate in this study was set to 80% of total estimated biomass volume in a fuel reduction thinning treatment unit (Stokes 1992), but this default value can be changed.

### Model Validation

Validation is the process of evaluating how accurately the model estimates fuel reduction thinning treatment costs and overall economics for any given harvesting system and biomass processing option. A past fuel reduction thinning study conducted in northern California and southern Oregon was used to validate the model (Vitorelo 2011). This study involved a ground-based harvesting system. Stand information in this study was input to ThinTool, and the model-estimated harvesting costs were compared with the reported harvesting costs. There was no statistical comparison between ThinTool's estimates and reported results in this article because only one past study conducted in southern Oregon and northern California was available to validate the ThinTool model.

### Statistical Analysis

Statistical analysis for data obtained from expert opinion surveys was performed using SAS 9.2 (SAS Institute, Inc. 2003). Machine productivity data were sorted by each harvesting system, and each machine and then average machine productivity was calculated. The effect on machine productivity of sawlog volume to be removed was separately tested using one-way analysis of variance for each harvesting system (i.e., ground-based and cable yarding systems) and machine operation (i.e., felling, skidding/yarding, processing, and loading). The significance levels were set to 5% ($\alpha = 0.05$).

### Sensitivity Analyses

Sensitivity analyses for the key machine combination input variables to the harvesting and hauling systems are automatically calculated. The analyses consider the total maximum contracting bid or the minimum price that must be received, the ratio of energy output to energy input, and how that ratio changes for different harvesting systems. The analyses are located on various worksheets on which variables are entered. There are a number of sensitivity analyses displayed in the *Input* worksheet. However, sensitivity analyses are also located on *Productivity-Sawlog, Productivity-Biomass, Misc. Costs*, and the *Cost & Revenue* worksheets. Some of the sensitivity analyses are fixed, based on the variable choices that are allowed (e.g., the choice of thinning systems is either "ground-based skidding" or "cable yarding"), although some of the sensitivity analyses allow users to set the midpoint for each analysis along with the increment for the variable under consideration.

## Results and Discussion

### ThinTool Model Organization and Use

ThinTool was created to estimate a site-level fuel reduction cost for varying thinning prescriptions and harvesting systems, covering a wide range of local site conditions in southern Oregon and northern California. ThinTool allows the user to specify stand conditions, thinning systems, biomass processing methods, biomass operation logistics, hauling options, and market values that allow the model to calculate the production and costs of the specified thinning treatments. Overhead, profit allowance, and market adjustment are also included in the cost estimates. The model is constructed with 10 linked worksheets. All of the worksheets include default data developed from literature reviews, field-based studies, and a contractor survey but also allow users to input their own data (i.e., loading and unloading time and hauling characteristics) and cost information.

The first worksheet is an input page that consists of two parts: the user input for stand condition and the selection of harvesting and hauling systems for sawlogs and biomass. In the stand condition section, the user provides the total number of acres to be thinned for a forest stand, slope, moisture content for biomass, and a minimum log top diameter (4- or 6-in.) for sawlog (>9 in. trees at dbh) production. In addition, the anticipated average number of trees to be cut and present trees per acre by tree diameter at dbh are entered to generate sawlog volume in $ft^3$/ac and biomass in GT/ac. Biomass for energy production includes logging slash generated from sawlog production and energy wood (≤9 in. trees at dbh) volume.

In ThinTool's harvesting and hauling system worksheet, a user selects from a ground-based system or a cable yarding system. In a ground-based system, trees are felled and bunched using a feller-buncher. Rubber-tired skidders collect and transport whole trees to a landing area. Trees are processed mechanically with a single-grip processor and loaded onto trucks using a loader at a landing. Cable yarding systems are used where terrain is too steep (e.g., >40% ground slope) or too wet for ground-based systems. All cable-yarding studies used to develop ThinTool were for uphill yarding only, so the results are not applicable to downhill yarding operations. Trees are felled using chainsaws but not limbed. Whole trees are yarded to the landing for processing and loading onto a log truck.

After harvesting system selection, the user also defines biomass processing methods (chipping or grinding) and machine size for chipper (small or large) or grinder (small, medium, or large) for biomass harvesting. With selecting the chipping or grinding option, comminution location is selected from dropdown lists for biomass processing logistics (i.e., at harvesting sites or centralized biomass processing sites). Forest residues could be comminuted at the landing if chip vans are able to access the site. However, if field sites are difficult to access areas with lower amounts of available forest residues, distributed forest residues could be accumulated from harvest sites to centralized processing areas using modified dump trucks or hook-lift trucks. In this model, centralized biomass processing logistics assume an additional loader is needed for loading forest residues at the landing. ThinTool has two different options (i.e., hot operation or cold operation) for biomass loading.

The second, third, and fourth worksheets are the machine cost information pages for sawlog, biomass, and transportation operations, respectively. Each worksheet is linked with the input page. Based on the harvesting and hauling system selected in first worksheet, machine costs are automatically set to default values in the program, but ThinTool's interface allows users to change these default values to match their machine characteristics.

The fifth and sixth worksheets are machine productivity pages for sawlog and biomass production, respectively. With linking the input page, representative machine productivity is estimated by volume to be removed and then adjusted by key variables affecting machine productivity for each machine operation. In sawlog production, the user can enter skidding/yarding distance to adjust representative machine productivity for a skidder or yarder. In biomass production, machine productivities for chippers, grinders, bundlers, and loaders are set to default values obtained through literature

reviews (Han and Johnson 2012), but users can change default values into their own values for their machine characteristics.

The seventh worksheet is a machine productivity page for transportation. Travel times are determined by travel distance and travel speed on five different road classes (i.e., spur road, single-lane dirt road, single-lane gravel road, double-lane road, highway, and freeway). Travel speeds on each road class were obtained from literature review (Pan et al. 2008, Harrill and Han 2010, Han and Murphy 2012) and set as default values. We also provide default loading and unloading times and payloads for each truck type based on past studies (Pan et al. 2008, Harrill and Han 2010, Han and Murphy 2012). However, if users do not wish to apply default values in their analysis, they can input their own times and payloads.

The eighth worksheet includes log defect, biomass recovery rate, mobilization costs, and other costs such as road and landing construction, dust control, fire trailers, fuel truck, and crew transportation costs that affect the harvesting cost analysis. To estimate actual sawlog volume to be harvested, 10% of total sawlog volume was assumed as log defects and added into biomass volume in this model. In biomass harvesting, actual amounts of biomass that could be harvested and delivered to energy plants and manufacturing facilities are often less than what was estimated using biomass equations due to harvesting and handling loss. In this model, biomass recovery rate was set as 80% of total estimated biomass volume (Stokes 1992). In mobilization cost section, users can provide information specific to the mobilization of equipment to the project site, specially travel distance (one-way), the number of machines to be hauled, travel speed, loading and unloading time, and lowboy costs. In this model, default values for other costs are not suggested because these costs vary with stand conditions and contractor practices. Therefore, users need to input specific values for this part and enter "0" if other costs do not apply in their cost analyses.

The ninth worksheet is a total harvesting cost and revenue page. Within this page, estimated machine costs in dollars per scheduled machine hour ($/SMH) are transferred from machine cost worksheets. Estimated production rates ($ft^3$/SMH for sawlog production and GT/SMH for biomass production) are also presented to show the machine productivity when individual machines are working in the system. To facilitate different model users, ThinTool predicts production cost in terms of dollars per acre ($/ac) and dollars per thousand board feet ($/MBF) for sawlog harvesting. A production cost in term of dollars per bone dry ton ($/BDT) is also assigned to the biomass product. To estimate total fuel reduction thinning costs, users need to provide contract information and items that contribute indirectly to harvesting costs. Indirect harvesting costs in this model included administrative overhead and profit allowance. All of the indirect harvesting cost items are entered in terms of percentage of total production costs. Market values for each species and product type (sawlog or hogfuel) are entered to estimate total revenue from fuel reduction treatments. Net profit (loss) is the sum of total fuel reduction thinning cost and total revenue produced from fuel reduction treatments.

The tenth worksheet is the summary output that is organized into the total harvesting cost and net profit (loss) summary, net energy output summary, and site nutrient removal summary. The total harvesting cost and net profit (loss) summary shows total volume removed, total production costs, total revenues, and total profits (losses) by product types (sawlogs and biomass). The net energy output summary includes the amounts of energy generated from thinning treatments and consumed for thinning operations as well as the net energy ratio estimated by comparing energy input with energy output. The site nutrient removal summary shows the amounts of nutrients removed with the chosen thinning treatments.

**Table 1. Representative machine productivity of sawlog removal for each operation in ground-based system (average skidding distance: 400 ft).**

| Machine | Productivity of sawlog removal at 4 MBF/ac | 7 MBF/ac | 10 MBF/ac | *df* | *P* value[a] |
|---|---|---|---|---|---|
| | . . . . . .($ft^3$/PMH) . . . . . | | | | |
| Feller-buncher | 1,323 (135) | 1,556 (149) | 1,696 (154) | 38 | 0.0154 |
| Skidder | 906 (101) | 1,087 (120) | 1,181 (151) | 35 | 0.7845 |
| Processor | 1,288 (142) | 1,306 (146) | 1,352 (146) | 37 | 0.5425 |
| Loader | 1,292 (114) | 1,292 (121) | 1,337 (124) | 36 | 0.5764 |

Values are means (SE).
[a] *P* value is significant at 0.05.

## Machine Productivity Estimation

Twelve different fuel reduction thinning studies were comprehensively reviewed to identify key independent variables affecting the machine productivity. In ground-based systems, tree size (dbh) and slope were considered as key independent variables for a feller-buncher; whereas key variables for a skidder were skidding distance and slope. Only tree size was identified as a key variable affecting processor productivity. In cable yarding systems, only tree size was identified as a key variable for hand-felling and processing, whereas the key variable for yarder was the yarding distance. In addition, the amount of volume to be removed was identified as the most significant factor affecting machine productivity in both harvesting systems, although this variable was not included in prediction equations (Johnson 1988, Hartsough et al. 1997, 2002, Lowell et al. 2008, Bolding et al. 2009).

A logging contractor survey was conducted to obtain representative machine productivities for mechanical fuel reduction thinning treatments on three different stand conditions (4, 7, and 10 MBF sawlog removals per acre). From the contractor survey, representative machine productivities for sawlog removal in fuel reduction thinning operations for both ground-based and cable yarding systems are presented in Tables 1 and 2.

In both systems, representative machine productivity for sawlog removal increases as volume per acre of removal increased. For ground-based systems, the only operation that significantly differs between treatments is felling ($P = 0.0154$). Therefore, felling costs in fuel reduction thinning treatments can be significantly reduced with increasing sawlog volume to be removed. Keegan et al. (2002) also found that travel time between trees marked for removal is

**Table 2. Representative machine productivity of sawlog removal for each operation in cable yarding system (average yarding distance: 500 ft).**

| Machine | Productivity of sawlog removal at 4 MBF/ac | 7 MBF/ac | 10 MBF/ac | *df* | *P* value[a] |
|---|---|---|---|---|---|
| | . . . . . .($ft^3$/PMH) . . . . . | | | | |
| Hand-faller | 419 (43) | 433 (51) | 440 (53) | 14 | 0.7842 |
| Yarder | 514 (39) | 685 (52) | 810 (59) | 14 | 0.3648 |
| Processor | 801 (37) | 834 (38) | 870 (37) | 14 | 0.0278 |
| Loader | 775 (73) | 804 (81) | 835 (82) | 14 | 0.1664 |

Values are means (SE).
[a] *P* value is significant at 0.05.

**Table 3. Representative machine productivity of biomass removal for each operation in ground-based system (average skidding distance: 400 ft).**

| Machine | Productivity of sawlog removal at 4 MBF/ac | 7 MBF/ac | 10 MBF/ac | *df* | *P* value[a] |
|---|---|---|---|---|---|
| | . . . . . (GT/PMH) . . . . . | | | | |
| Feller-buncher | 36 (3.54) | 37 (4.01) | 39 (4.21) | 29 | 0.9454 |
| Skidder | 29 (3.05) | 31 (3.58) | 31 (4.15) | 31 | 0.3445 |

Values are means (SE).
[a] *P* value is significant at 0.05.

reduced with increasing sawlog volume removal and results in increased feller-buncher productivity.

In cable yarding systems, only processor productivity was significantly affected by sawlog volume removal ($P = 0.0278$). Processor productivity in the cable yarding system was lower than that in ground-based system due to increases in delay time. In a cable yarding system, the processor must follow the yarder. If the yarder needs to be frequently moved to different corridors because of smaller removal volumes, then the processor experiences delay time while the yarder moves to the next row. If the removal volume is low, then the processor will be delayed longer.

Representative machine productivity for ground-based biomass removals is presented in Table 3. In both feller-buncher and skidder operations, machine productivity tended to increase with increasing sawlog removal volume, but there are no significant changes in machine productivity between stands with increasing intensity of thinning ($P = 0.9454$ for feller-buncher; $P = 0.3445$ for skidder).

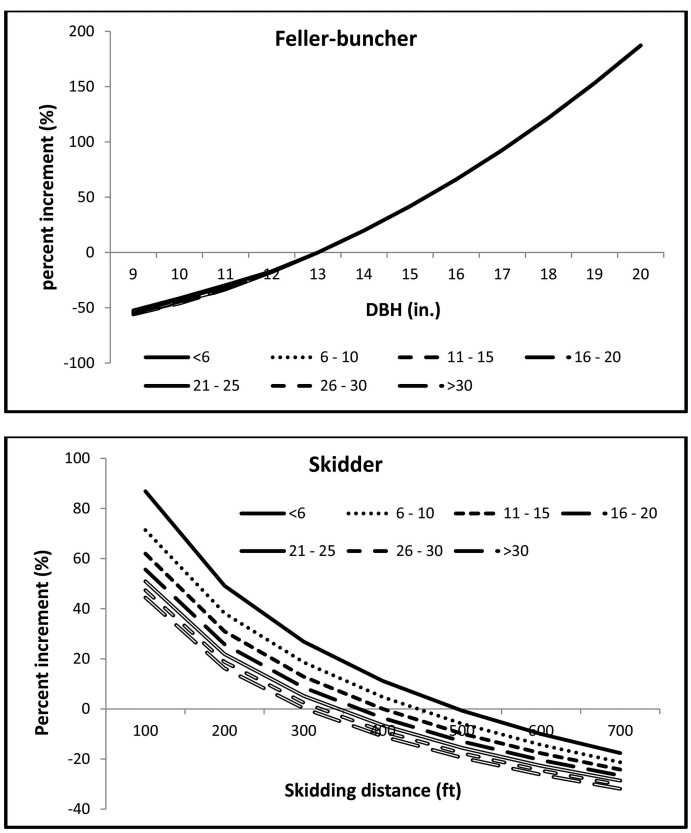


**Figure 2. Adjustment factors for a feller-buncher and a skidder developed to adjust representative machine productivity in sawlog production for different dbh, skidding distances (ft), and slopes (%).**

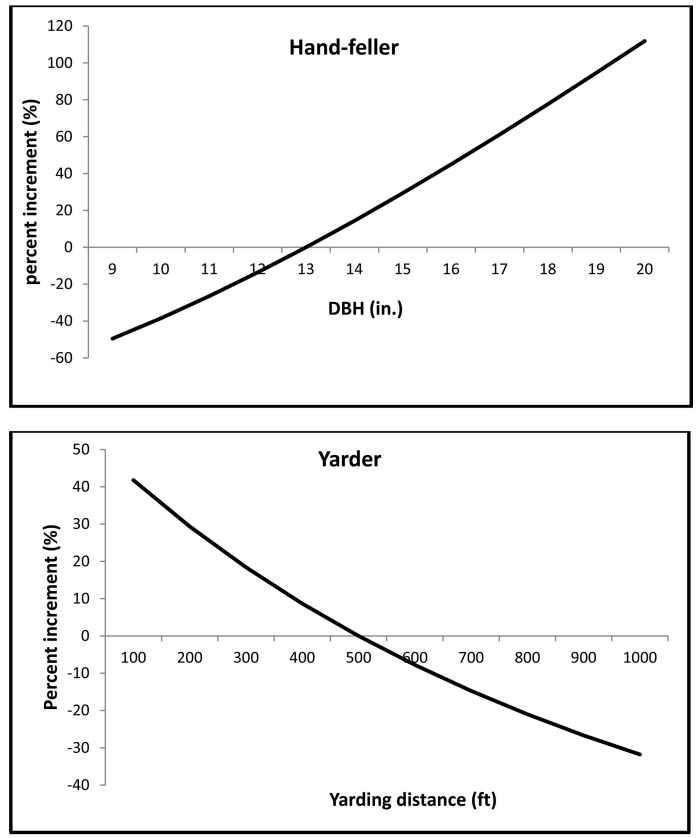


**Figure 3. Adjustment factors for hand-feller and yarder developed to adjust representative machine productivity in sawlog production.**

Similar results were found by Hartsough et al. (1997). Feller-buncher productivity is higher than skidder productivity. Average machine productivity for feller-bunchers ranges from 36 to 39 GT/PMH.

To accommodate a wide range of site variables identified from literature reviews, such as average tree size, slope, and skidding/yarding distances, we developed factors to adjust representative machine productivity determined from logging contractor surveys. Adjustment factors developed from case studies are presented in Figures 2 and 3. In the ground-based harvesting system, bigger trees have higher percent increments in adjustment factor values. This means feller-buncher productivity increases with increasing tree size for sawlog production. However, the adjustment factor value does not change with changing slope steepness, although slope was found from literature reviews to be one of the key variables affecting machine productivity. Slope steepness is inversely proportional to skidder productivity. That is, skidder productivity (i.e., the skidder adjustment factor) increases with decreasing slope steepness. In addition, the adjustment factor for skidder productivity is reduced with increasing skidding distances (Figure 2). With cable yarding systems, the effects of slope, distance, and tree size on productivity are similar to ground-based harvesting systems. Adjustment increments for hand-felling productivity increase with increasing dbh.

## Model Validation

Model validation for ThinTool was conducted to evaluate how accurately it estimates hazardous fuel reduction thinning treatment

**Table 4. Sawlog harvesting cost (stump-to-truck) comparison between actual and simulated study in ground-based harvesting system.**

| Machine | Actual study | Simulated study |
|---|---|---|
| | ($/ft$^3$) | |
| Feller-buncher | 0.09 | 0.12 |
| Skidder | 0.17 | 0.15 |
| Processor | 0.11 | 0.13 |
| Loader | 0.05 | 0.11 |
| Total | 0.42 | 0.51 |

**Table 5. Biomass harvesting cost (stump-to-truck) comparison between actual and simulated study in ground-based harvesting system.**

| Machine | Actual study | Simulated study |
|---|---|---|
| | ($/BDT) | |
| Feller-buncher | 20.72 | 15.13 |
| Skidder | 15.37 | 14.17 |
| Loader | 3.35 | 3.86 |
| Grinder | 12.97 | 11.49 |
| Total | 52.41 | 44.65 |

costs for any given harvesting system. In model validation, simulated harvesting costs estimated by ThinTool were compared to actual harvesting costs developed from a time-motion study that was conducted at the USDA Forest Service Klamath National Forest in Yreka, California. The model validation procedures show that sawlog harvesting costs simulated by ThinTool were 21% higher than harvesting costs estimated by the actual time-motion study (Table 4). In biomass production, actual biomass harvesting costs were higher by 15% than ThinTool's simulated biomass harvesting cost (Table 5). Although the current cost model produced overestimated harvesting costs for sawlog production and underestimated harvesting costs for biomass production, it was difficult to evaluate ThinTool's current accuracy because only one case study was available to be used in model validation. Therefore, further validation work will be needed to improve model accuracy using future fuel reduction thinning projects in the region.

### Net Energy Output

A model simulation for net energy output was conducted with the case study used in model validation. The area of the case study site was 25 ac. It contained Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), white fir (*Abies concolor* [Gord. & Glend.] Lindl.), ponderosa pine (*Pinus ponderosa* Dougl.), sugar pine (*Pinus lambertiana* Dougl.), and incense cedar (*Calocedrus decurrens* [Torr.] Florin). Biomass volume removed was 46.4 GT/ac at 55% moisture content. The harvesting method used was whole-tree harvesting. The one-way hauling distance to a plant was 45 miles. Indirect fuel consumption resulting from activities such as moving equipment and crew transportation was not incorporated in this simulation.

**Table 7. Site nutrient removal estimated by ThinTool.**

| Nutrient | Amount (lb/ac) |
|---|---|
| N | 129.9 |
| P | 17.4 |
| K | 91.1 |
| Ca | 207.9 |
| Mg | 34.2 |

Total direct diesel consumption was 2,638.6 gallons for the harvesting and transport system, equivalent to 367,294,686 BTUs (Table 6). Truck hauling was the largest direct energy input component (73.9%) because it had the longest operation time with a relatively high-horsepower engine. The grinder consumed 18.8% of the total direct input energy, reflecting the machine's large engine size (>900 hp) and had the highest diesel consumption rate (gal/hr) (Table 6). In this simulation, the total recoverable energy output was 6,251,031,817 BTUs. Subtracting the energy input, the net energy output was determined to be 5,883,737,131 BTUs. The net energy ratio between the recoverable energy output and the fossil energy input was 17:1.

### Site Nutrient Removal

Site nutrient removal was simulated using the case study for model validation and net energy output simulation. The nutrient amounts estimated by ThinTool to be removed from sites by fuel thinning treatments are presented in Table 7. The greatest nutrient removal was found to be Ca. A similar result was found by Mann et al. (1988). They examined 11 forest stands located throughout the United States looking at site nutrient removals by whole-tree harvesting and sawlog harvest. N, P, K, and Ca were reported. They reported that removals by whole-tree harvesting were 98 to 650 lb/ac N, 9 to 86 lb/ac P, 31 to 291 lb/ac K, and 99 to 972 lb/ac Ca. In-tree components (i.e., stem and bark, branches, and foliage), nutrient concentrations of foliage were usually higher than those of stem and branches. However, N, P, and K at the site were removed with similar ratios in each tree component because dry mass of stem and branches was larger than foliage. Removal of stem and branches contributed to 80% of total Ca removal.

## Conclusion

ThinTool is an analytical model designed and developed for use by forest managers, planners, and project contractors to evaluate the cost of mechanical fuel reduction thinning including biomass removal, predict net energy output, and assess nutrient impacts from thinning treatments in northern California and southern Oregon. Harvesting cost, net energy output, and site nutrient removal are directly linked together and sensitively responded to any changes in thinning prescriptions (e.g., thinning intensity and species selection) and operations requirements (e.g., biomass recovery methods,

**Table 6. Direct diesel consumption in ground-based system estimated by ThinTool.**

| Parameter | Feller-buncher | Skidder | Loader | Grinder | Chip van | Total |
|---|---|---|---|---|---|---|
| Direct diesel input (gallons) | 76.2 | 65.7 | 50.4 | 495.4 | 1,950.9 | 2,638.6 |
| Heating value[a] (million BTUs) | 10.6 | 9.1 | 7.0 | 69.0 | 271.6 | 367.3 |
| Average fuel consumption (gal/hr) | 6.8 | 5.0 | 3.0 | 30.0 | 9.9 | 54.8 |
| Percent total | 2.9 | 2.5 | 1.9 | 18.8 | 73.9 | 100.0 |

[a] Based on 139,200 BTUs per gallon of diesel.

machine size, and skidding/yarding distance). The model is constructed with 12 linked worksheets. All of the worksheets include default data developed from literature review, field-based studies, and a contractor survey but also allow users to input their own data (i.e., loading and unloading time and hauling characteristics) and cost information.

ThinTool can be used to estimate a unit-specific operational cost for ground-based and skyline thinning systems over a wide range of stand and site conditions, silvicultural prescriptions, operational requirements, and road standards and distances. The cost model technique applied in this study synthesized past thinning and biomass removal studies limited to southern Oregon and northern California to effectively address local conditions when estimating harvesting productivity and costs. In addition, an expert opinion method (i.e., survey) was combined with the empirical study information to reflect regional work and wood product market conditions in southern Oregon and northern California.

ThinTool also evaluates nutrient impact and net energy output caused from thinning and biomass removal in fuel reduction thinning. Forest management activities often have impacts on site nutrient budgets in both the short and long term. Therefore, assessing potential impacts of forest residue removal is important for balancing residue removal with retention to ensure site productivity. ThinTool can allow users to effectively estimate site nutrient removal in different harvesting systems, stand conditions, and thinning prescriptions. The outputs help forest managers to examine environmental effects of biomass recovery and provide nutrient retention information for sustainable production of woody biomass. Net energy output is estimated by comparing the amount of energy delivered with the total energy consumed to collect, process, and transport the biomass to an energy plant in fuel reduction thinning operations. This function allows users to assess potential energy production and identify energy-effective biomass recovery systems.

ThinTool can be further revised to improve the prediction accuracy of the model by incorporating additional results available from future fuel reduction thinning projects. The model should be a useful tool for forest managers and planners to conduct fuel reduction treatments in a cost-effective, energy-effective, and environmentally sound manner.

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