An Integrated Approach to Evaluating the Economic Costs of Wildfire Hazard Reduction through Wood Utilization Opportunities in the Southwestern United States

Eini C. Lowell, Dennis R. Becker, Robert Rummer, Debra Larson, and Linda Wadleigh

Abstract: This research provides an important step in the conceptualization and development of an integrated wildfire fuels reduction system from silvicultural prescription, through stem selection, harvesting, in-woods processing, transport, and market selection. Decisions made at each functional step are informed by knowledge about subsequent functions. Data on the resource characteristics of small-diameter ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), harvest equipment productivity, lumber recovery, and net profit (loss) by level of fuels reduction achieved were collected from four 8.1-ha (20 ac) sites in northern Arizona. These data were used to develop a Windows-based, financial and engineering software program, the harvest cost-revenue (HCR) estimator, to identify the economic costs of wildfire fuel reduction treatments that may be used to evaluate cost per acre thresholds for logging contractors, appraise contract bid rates, or assess stumpage values for ponderosa pine stands in the southwestern United States. Application of the model illustrates variability in fuels reduction costs owing to the level of fuels reduction achieved, the volume of merchantable wood removed from different forest stands, and the availability of markets for removed material. Machine productivity helps predict differences in harvest costs but is secondary to market constraints and the volume of wood harvested. FOR. SCI. 54(3):273–283.

Keywords: ponderosa pine, wildfire fuel reduction, financial analysis, harvest cost-revenue estimator

RECENT ESTIMATES SUGGEST that >27 million ha of the more than 95 million ha of forestland in the Western United States is in fire regimen condition class 2 or 3: forest lands that have departed significantly from natural wildland fire conditions and are at medium to high risk of catastrophic wildfire (Schmidt et al. 2002). About 5.4 million ha are on public and private forest lands in Arizona, Utah, Colorado, and New Mexico (US Forest Service 2003). If we assume that mechanical treatments are implemented over a 40-year period and that 5.7–11.3 m^3 of raw material are removed per ha, then between 0.75 and 1.5 million m^3 of additional raw material will enter the market per year in the Southwest alone. Westwide, treating only areas at the highest risk of wildfire (condition class 3) and assuming that treatment is appropriate on only a percentage of those forest lands because of accessibility (e.g., steep slopes, sensitive sites, regeneration difficulty), then 126 million metric oven bone dry tons of material would be available for solid wood and biomass markets across the region (Skog et al. 2006). A majority of these treatments would be located on National Forest lands with most trees harvested having dbh smaller than 25.4 cm.

The idea of offsetting the costs of hazardous fuels treatments by selling wood and biomass removed during these treatments is appealing. However, westwide, the remaining infrastructure represents remnants of an industry established to manufacture high-value lumber from larger trees with limited capacity to process small-diameter trees (Wagner et al. 1998; Larson and Mirth 2004). In 2005, the capacity of the western sawmill industry to process this small-diameter material was estimated at about 49.5 million m^3 annually (Spelter and Alderman 2005). Since 1986, processing capacity in the Southwest has declined 63% (Keegan et al. 2004), leaving the remaining infrastructure of approximately 480,000 m^3 (Spelter and Alderman 2005) to absorb the significant volume of material proposed to be removed. When combined with the generally high costs of harvesting hazardous fuels, long transportation distances between remaining processors and harvest sites, and lower values from hazardous fuels byproducts, the utilization of small-diameter trees is simply not feasible for many businesses (Monserud et al. 2004). Yet the viability of smallwood manufacturers is crucial to offsetting the high cost of thinning. A viable wood products industry aids in the ability to reduce the risk of catastrophic wildfire on public and private lands and to communities and property in the wildland-urban interface.

Offsetting Fuels Reduction Costs with Small-Wood Utilization

There are two primary processing options for recovering the costs of hazardous fuels treatments: biomass production involving high-capacity, high-capital cost processing (e.g.,

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wood chips, fiber, and pulp) and solid wood production using lower capacity, lower capital cost processing (e.g., lumber and roundwood). The biomass stream maximizes the volume of material used, but for energy, biofuels, and other applications, significant financial investment is required relative to the commonly small profit margins (Spelter et al. 1996). Compounding the problem in parts of the country is a historically inconsistent supply of timber from federal lands necessary to amortize biomass investments. As a result, much attention has been given to low-volume, low-capital investments in solid wood manufacturing, such as narrow-width lumber, posts and poles, and specialty roundwood products like decorative vigas and latillas used in traditional Southwest architecture (General Accountability Office 2006), although interest in biofuels and energy production is increasing.

The cost of investment is but one consideration. Product development is influenced by the quality and volume of material recovered for a given product type, which is a function of forest stand structure and silvicultural prescription (Monserud et al. 2004). Resource characteristics (e.g., quantity and size of knots, sweep, and rot) and manufacturing defects (e.g., warp) reduce product grade and market value, which in turn limits utilization options (Lowell and Green 2001). The challenge in the Southwest is that the suppressed growth small-diameter ponderosa pine that dominates forest lands typically possesses a high proportion of juvenile wood, making fuels reduction byproducts unsuitable for all but the least demanding structural applications (Wolfe and Moseley 2000). Making profitability of fuels reduction projects even more tenuous is the practice of diameter cap limits placed on the size of trees that can be harvested to alleviate social concerns for wildlife habitat and esthetics (Larson and Mirth 2001). Each of these decisions can limit product markets (Kluender et al. 1998, Larson and Mirth 2001). Alternatively, fuel reduction prescriptions that call for cutting a range of diameters creates greater product potential. For example, one Forest Service study (US Forest Service 2003) estimated the effects of implementing a stand density index-based thinning on Western forests. The results showed that 86% of the trees treated would be less than 20.3 cm dbh, but >70% of the total volume removed would be from trees larger than 20.3 cm dbh—merchantable material with a wider range of product potential and volume recovery.

Given the high costs of treating small trees (Lynch et al. 2000; Fight and Barbour 2005) and the significant incremental value realized by recovering a greater range of products, it is critical to extract maximum value through optimization of product identification, processing, and sorting. Project planners require tools to accomplish this to estimate the net costs of proposed actions relative to the level of wildfire risk reduction achieved. Improved estimates of harvest costs and raw material values, including more robust calculations of merchantable volumes, may expedite implementation of projects by better targeting of financial resources and prioritizing treatment locations. Because different products have different raw material requirements (e.g., log length, size, and quality), forest planners and logging contractors must be able to accurately estimate costs for varying harvest specifications knowing currently available markets and transportation distances. Accurate estimates allow them to predict financial thresholds, market products at competitive prices, and seek payments for services rendered relative to the cost of fuel reduction. They allow forest planners to prioritize location and harvest intensity relative to the cost of implementation and level of fire risk reduction desired. Ultimately, markets will determine the final product output, but the manner in which fuels reduction treatments are designed and implemented will have a bearing.

In an attempt to identify opportunities to optimize market selection relative to harvest and transport costs and level of fuels reduction desired, we report on findings of a study to develop a decision support tool for planning hazardous fuel reduction treatments in Southwest ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) stands. From silvicultural prescription through stem selection, harvesting, in-woods processing, transport, and market selection, a decision is made at each functional step about the possible allocation and processing of woody material. In an integrated planning system, each decision is informed by knowledge about subsequent functions (Figure 1). Together, they provide forest planners and logging contractors with project-level information on the financial viability of treatments relative to the level of fire risk reduction achieved. The harvest cost-revenue (HCR) estimator, the decision support tool presented here, provides a software-assisted program to estimate harvest costs and raw log values of these treatments. We also report on results from fuels surveys, time and motion productivity studies, and product recovery assessments conducted to build the model.

Methods

A field study of alternative fuel treatment and product recovery technology was conducted to supplement the existing literature on harvest and transport productivity and cost. Data collection was focused in two areas: fuels and treatment and software model input variables. Ponderosa pine stand density and diameter were collected and pre- and posttreatment fuel surveys were performed for all research sites to determine level of fuels reduction achieved. For the model inputs, time and motion data for harvest equipment productivity were collected and lumber recovery and biomass volumes were determined.

Sites

The study was built around existing fuel reduction treatment sales. Personnel from the Coconino National Forest in northern Arizona recommended fire regime condition class 3 sites that were scheduled for fuel reduction treatments and already under contract. Two sites were chosen and from within each site, two 8-ha units were selected that represented a range of variability in slope, tree diameters, tree heights, and stand density (Figure 2). Two contractors had been awarded the contracts, with each being responsible for one of the selected sites and having different harvesting systems. Both were willing to cooperate on the project. One

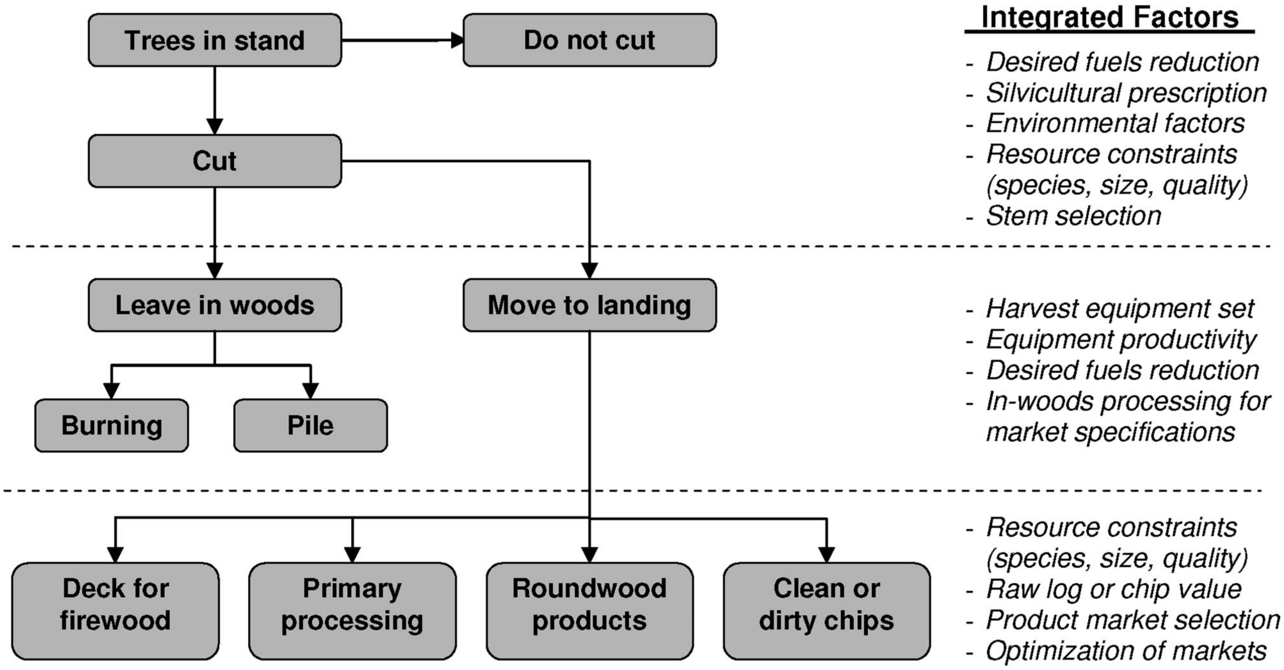
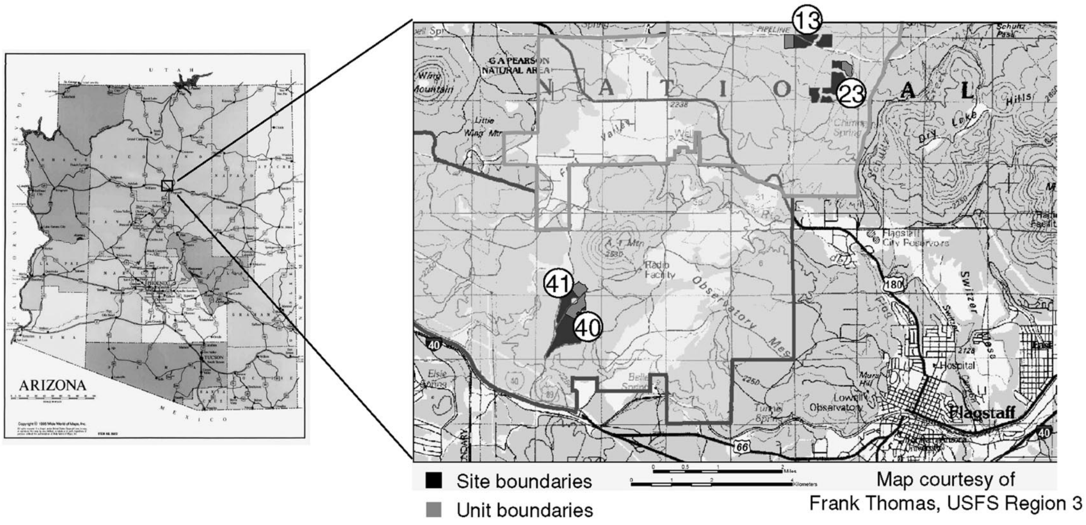


Figure 1. Integrated harvest planning system.



Map courtesy of
Frank Thomas, USFS Region 3

Figure 2. Location of study sites and harvesting units.

contractor treated his site using a cut-to-length (CTL) harvest system and the other contractor treated the remaining site with a conventional whole-tree (WT) harvest system. The 8-ha unit size ensured that harvesting occurred at an operational range of skidding distance and variations in productivity, whereas the use of two units simply provided a wider range of terrain and stand condition for each harvesting system. The statistical analysis of the harvesting productivity data was based on regression analysis of individual machine cycles without regard to unit. Treatments covered a range of options for fuel reduction outcomes, processing, transportation sorts, and product markets.

The CTL harvest units were located on the Fort Valley Experimental Forest (Units 13 and 23) in cooperation with the Rocky Mountain Research Station and the Greater Flagstaff Forests Partnership. These units were harvested late summer of 2002. The two WT harvest units were located on A-1 Mountain (Units 40 and 41) in the Coconino National Forest within existing fuels reduction projects in the Flagstaff, Arizona, wildland-urban interface. These units were harvested in the fall of 2002.

Stand Data

Stand density

Each unit was characterized by collecting a range of stand data including initial stand density, dbh distribution, stems removed, and volume per hectare by size class. Eight regularly spaced plot centers were located in each unit, which served as the center of both a 0.04-ha fixed-radius stand inventory plot as well as the center for pre- and posttreatment fuel survey plots. Stand inventory data included dbh and height of all trees larger than 2.54 cm dbh, species identification, leave or cut mark, and status indication—live or standing dead. Inventory data were analyzed to estimate volume, basal area, and stems per hectare.

Fuel Survey

Pre- and posttreatment fuel surveys, in which crown and surface fuels were measured, were conducted for each plot. The intent of this measurement was to characterize the fuel treatment outcomes for future comparison with other studies. Data collection was coordinated with the Forest Service Southwestern Region (Region 3) fuels team as part of an ongoing effort to characterize fuel loadings and fire influences across the Southwest, including effects of mechanical treatment on fuel load. Plot data were gathered before and after treatment. Overstory fuels data collected on 0.04-ha plots for trees >5 cm dbh included species, dbh, crown class dominance, total height, height to first live branch, and crown ratio. The planar intercept transect method of Brown et al. (1981) was used to measure dead and down fuel. Regeneration was measured on 0.0013-ha plots by using the 0.04-ha plot centers. Fuel loads in slash piles resulting from harvesting activities were recorded.

Fire behavior and crown fuel variables were modeled for each unit by using Fuels Management Analyst Plus Version 3.0 (FMAPlus) (Carlton 2005) for weather modeled under the 97th percentile derived for the month of June (wind speed 40 km/h; 32°C) (Fulé et al. 2001). Fire behavior parameters modeled included rate of spread (m/h), flame length (m), and type of fire (surface, passive crown fire, or active crown fire). Fuel characteristics predicted by FMAPlus were crown base height (m), crown bulk density (kg/m^3), and basal area (m^2/ha). Canopy bulk density was measured at the stand level for the mass of available canopy fuel per unit canopy volume. Canopy base height was measured as a function of the lowest point above the ground providing sufficient canopy fuel to propagate fire vertically into the canopy (Scott and Reinhardt 2001). FMAPlus was also used to model the torching index and crowning index. Both torching index (open wind speed where transition from surface to crown fire is expected) and crowning index (open wind speed at which active crowning is possible) were measured, with the assumption that the open wind speed is measured at a distance of 6.1 m from the surface (Scott and Reinhardt 2001).

Harvesting Systems

To determine harvest costs relative to wildfire risk reduction levels measured above, time and motion studies were used to assess machine productivity. The CTL harvesting system processed trees at the stump into product lengths, leaving limbs and tops in the stand. On one-half of Units 13 and 23, the residual slash was piled by a six-wheeled Timberjack 1270B CTL harvester for jackpot burning, and on the other half, slash was collected by a six-wheeled 1010B forwarder and transported to the landing. The forwarder was also equipped with tracks over the bogie tires and used to transport processed logs to the landing. The WT harvest system removed felled trees to the landing where they were processed to the merchantable top. The system consisted of three machines—a Hydro-Ax 421E drive-to-tree feller-buncher with a 46-cm shear that cuts and piles trees, a Caterpillar 528 grapple skidder that pulls whole trees to the landing, and a Denharco 4400 stroke-delimber mounted on a Caterpillar 320C to process trees into merchantable logs and sort the logs at the landing.

Machine productivity, ownership costs, and operation and maintenance cost, as functions of stand and system variables, were quantified for each piece of harvesting equipment. Machine operations were videotaped for detailed time sequencing and analysis. Skidding and forwarding elemental data were collected by using continuous stopwatch timing. Both WT feller-buncher and CTL harvester productivity were studied on a random sample of premeasured standing trees. Skidder and forwarder production were assessed using randomly selected premeasured piles of harvested trees and processed logs. The stroke delimber was timed as it processed premeasured trees from the landing piles. Stem size, slope, and extraction distance were tested as predictors of machine productivity.

Solid Wood and Biomass Recovery

A random sample of 200 small-diameter trees of 13–23 cm dbh was selected from each of the four 8-ha units and transported to Skyline Forest Resources in Escalante, Utah, for the product recovery study. Log specifications based on manufacturing capability were a maximum 25.4 cm outside bark on the large end and 12.7 cm outside bark on the small end. Log lengths were merchandized in multiples of 2.4 m with an additional 7.6 cm of trim for the CTL harvest system and 10 cm of trim for WT system. Researchers marked and measured the length of each bucked log and the small- and large-end diameter before forwarding or skidding to the landing so that they could be tracked during yarding, loading, and subsequent milling, surfacing, and grading at the sawmill.

An SLP 5000 Diesel MicroMill small-diameter portable sawmill was used to process logs into cants, which were later manufactured into posts used in fencing. The MicroMill was selected to assess product recovery using portable milling technology that could be moved from one location to another, thus having the potential to reduce costs of transporting raw logs (Becker et al. 2004). All logs from each 8-ha unit were scaled according to the National Forest Scaling Handbook (US Forest Service 1985) and the National Forest Cubic Scaling Handbook (US Forest Service 1991) for gross and net volume determination. Logs were processed into cants (10.2 × 10.2 cm and 7.6 × 7.6 cm) and jacket boards (2.5 × 10.2 cm lumber cut from the outer shell of larger logs), kiln-dried, surfaced, and graded by certified lumber graders. Volume and grade recovery data were collected for all cants, as well as for the jacket boards. The volume and grade of all products from each log were collected so that different end uses (e.g., chips, roundwood, and sawn products) could be evaluated, volume recovery determined, and the value of each log calculated.

Biomass recovery for potential wood chip and energy markets was also assessed. To obtain a volume estimate that would not go to a solid wood product market, 40 trees ranging in size from 2.5 to 10 cm dbh were randomly selected from the four harvest sites, felled, and bucked into 0.6-m sections. A 15-cm stump height was assumed for each tree. For each section, diameter of the outside bark and inside bark was measured at each end to the nearest 0.25 cm. Remaining top lengths were measured to the nearest 3 cm for obtaining total tree height, and a top diameter of 0.25 cm was assumed for calculating volume of the top piece. Volumes of individual tree sections were calculated to determine total stem cubic volume. The total volume of slash material that could be chipped was then calculated for each 8-ha site on the basis of harvesting technique and stand treatment.

Results

Stand Data

Stand Density

The fuel treatments focused on reducing smaller diameter stems to achieve a reduction in Fire Regime Condition Class. In the CTL harvest sites, more than half of the stems cut were <10 cm dbh (Table 1). Basal area was reduced 55% (to 14.0 m^2/ha) in Unit 13 and 29% (to 15.8 m^2/ha) in Unit 23. Together in the WT harvest sites, nearly 90% of trees were <25.4 cm dbh, but a majority, 77% were 12.7–22.6 cm dbh and provided different utilization options than in Units 13 and 23. Basal area was reduced 30% (to 16.5 m^2/ha) in Unit 40 and 40% (to 18.8 m^2/ha) in Unit 41.

Fuel Survey

Posttreatment canopy fuel measurements show that canopy base height increased for all stands, whereas canopy bulk density decreased, indicating that ladder and canopy fuel conditions require higher wind speeds to initiate and sustain crown fire (Table 1). Consequently, the TI and CI increased for all sites and fire behavior indicators rate of spread (ROS) and flame length decreased. Canopy fuel variables most affecting TI are canopy base height and foliar moisture content, whereas CI is related most closely to canopy bulk density (Scott and Reinhardt 2001). FMAPlus predicted posttreatment surface fire behavior for all treated plots exhibiting passive or active crown fire behavior pretreatment. The rate of speed appears to have remained near pretreatment levels in Units 40 and 41 caused by the more open nature of the stand posttreatment. Wind increased in influence on surface fire spread owing to an

Table 1. Forest stand fuel conditions and fuel reduction costs

	Harvest unit			
	13	23	40	41
Hectares	6.9	8.1	49.8	26.7
Basal area (m^2/ha)				
Pretreatment	31.4	22.2	23.6	31.4
Posttreatment	14.0	15.8	16.5	18.8
Cut trees per ha	183	43	46	42
Average canopy base height (m)[1]				
Pretreatment	3.5 (1.1)	3.0 (1.4)	5.0 (1.8)	5.4 (1.8)
Posttreatment	9.9 (2.4)	5.5 (4.1)	6.7 (1.9)	7.0 (2.3)
Average canopy bulk density (kg/m^3)[1]				
Pretreatment	0.142 (0.059)	0.067 (0.038)	0.105 (0.041)	0.090 (0.069)
Posttreatment	0.079 (0.037)	0.048 (0.017)	0.065 (0.047)	0.041 (0.028)
Torching index (6.1 m wind speed)[1]				
Pretreatment	31.12 (7.69)	19.51 (9.20)	31.28 (10.52)	33.72 (10.71)
Posttreatment	90.89 (19.39)	42.25 (28.88)	59.58 (21.15)	46.49 (12.42)
Crowing index (6.1 m wind speed)[1]				
Pretreatment	21.43 (8.62)	38.99 (15.32)	26.58 (10.13)	35.29 (17.71)
Posttreatment	33.25 (12.58)	45.34 (14.18)	46.98 (31.39)	56.96 (24.34)
Rate of spread (m/h)[1]				
Pretreatment	1019.68 (686.1)	903.39 (321.92)	861.14 (412.46)	772.61 (217.30)
Posttreatment	581.47 (2.01)	756.51 (233.39)	752.49 (442.64)	760.54 (146.88)
Flame length (m)[1]				
Pretreatment	10.8 (12.6)	3.7 (1.8)	4.8 (6.6)	2.9 (1.6)
Posttreatment	1.5 (0.1)	2.8 (1.6)	4.0 (6.9)	2.0 (0.2)
Harvest system	Cut-to-length	Cut-to-length	Whole-tree	Whole-tree
Pallet lumber market with dirty chips				
Total project costs ($/ha)	4,693	2,334	3,315	3,222
Total project revenue ($/ha)	4,686	2,779	4,702	4,522
Net profit (loss) ($/ha)	(7)	445	1,388	1,300
Pallet lumber market (no dirty chips)				
Total project costs ($/ha)	3,839	2,208	3,135	2,993
Total project revenue ($/ha)	4,663	2,759	4,679	4,493
Net profit (loss) ($/ha)	823	551	1,543	1,500

[1] SD in parentheses.

offset in reductions in surface fuel loading and fire line intensity. In all, predicted values are a measure of success of the fuels treatments.

Biomass

The biomass cubic volume equation for ponderosa pine <10 cm dbh was developed from destructively sampled trees by using a general linear models procedure (Rao 1997). The best estimators for predicting cubic foot volume for ponderosa pine trees on the Coconino National Forest (2.5–10.2 cm dbh) were dbh squared and total height, which predicted most of the variation ($R^2 = 0.96$). Figure 3 (Equations 1 and 2) shows the predicted volumes for each sample tree by using Smalian's formula (US Forest Service 1991).

Total stem volume (m^3 inside bark)

$$= 0.033 + 0.000925 + 0.00002795D^2H \qquad (1)$$

$$R^2 = 0.96, \quad \text{CV} = 13.73, \quad n = 40$$

Total stem volume (m^3 outside bark)

$$= 0.002256 + 0.0000366D^2H \qquad (2)$$

$$R^2 = 0.96, \quad \text{CV} = 11.91, \quad n = 40$$

where D is dbh (cm) and H is total height (m).

Harvesting Systems

CTL System

A total of 138 machine cycles were videotaped during the time study of the Timberjack 1270B CTL harvester. The average dbh of trees harvested was 19.7 cm. The average cycle time per tree was 43.7 seconds, which equated to 82.4 trees per productive machine hour cut, delimbed, and processed into market specified log lengths. Lengths ranged from 3 to 9 m with logs averaging 0.23 m^3 solid volume. Time per tree was a function of dbh (Figure 4, Equation 3). Gross time study for the harvester indicated an average production rate of 0.30 ha per productive hour.

$$\text{Time per tree (sec)} = 24.80 + 0.0487D^2 \qquad (3)$$

$$R^2 = 0.50, \quad \text{CV} = 33.1, \quad n = 138$$

where D is dbh (cm).

A total of 23 forwarder cycles were recorded with separate cycle times for travel empty, loading, travel loaded, and unload elements. When the forwarder transported log-length material, load size averaged 18.3 m^3, and slash loads were estimated to be 1.87 m^3 based on the cubic volume of the load bunks and a solid volume factor of 0.1. Total travel distance was the most significant factor affecting travel time (Equation 4) with a linear relationship as

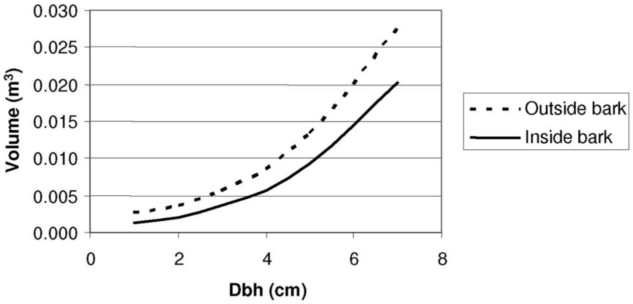


Figure 3. Cubic volume of 2.5–18 cm dbh ponderosa pine trees.

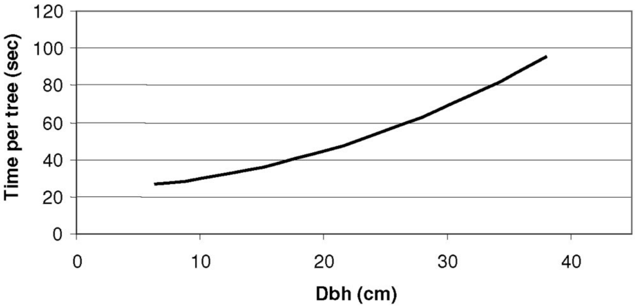


Figure 4. Cut-to-length harvester productivity in a fuel reduction thinning.

$$\text{Travel time (min)} = 1.466 + 0.0200\text{TDist} \qquad (4)$$

$$R^2 = 0.74, \quad \text{CV} = 32.60, \quad n = 23$$

where TDist is the sum of travel empty and loaded distance in m.

For sawlog forwarding cycles, the intermediate travel time (Figure 5) was best predicted by the load size expressed as the interaction of volume and number of pieces:

Intermediate Travel Time (min)

$$= 1.128 + 0.0072\text{Vol} - 0.2773\text{Pcs} \qquad (5)$$

$$R^2 = 0.27, \quad \text{CV} = 57.57, \quad n = 23$$

where Vol is total load volume in m^3 and Pcs is total piece count of the load.

For biomass forwarder cycles, the intermediate time was not significantly affected by the independent variables measured. Thus, the average intermediate travel time for biomass loads is the best estimator (4.9 min, SD 2.16). Loading time for sawlog loads was directly related to the number of swings to fill the bunks with the relationship:

$$\text{Load Time (min)} = 47.157 - 678.0/\text{Swings} \qquad (6)$$

$$R^2 = 0.40, \quad \text{CV} = 19.75, \quad n = 23$$

Loading time for biomass loads was not significantly related

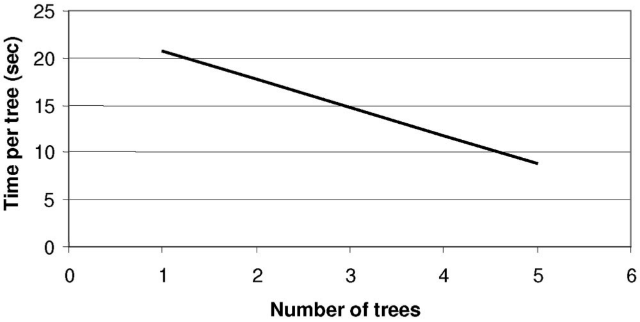


Figure 5. Feller-buncher productivity in a fuel reduction thinning.

to the independent variables; thus the best estimator was the mean loading time (15.6 min, SD 4.98). Adding the elemental times for forwarder activity allows estimation of total cycle time for either biomass or sawlog recovery.

WT System

Feller-buncher productivity was recorded for 409 machine cycles (935 trees) for the Hydro-Ax 421E rubber-tired feller-buncher (18-in. shear felling head). Individual tree data were recorded for 157 of the 409 cycles (Thompson 2003). Cycle elements included move-to-tree, fell, move-to-dump, and pile. On average, the machine cut 2.29 trees (average dbh of 21.8 cm) per cycle. The average total cycle time per tree was 16.43 seconds or 220 trees per productive machine hour. The efficiency of the feller-buncher was affected by the operator's ability to cut multiple small trees in each accumulation cycle. Figure 5 (Equation 7) illustrates how the time per individual tree decreased as the operator was able to more completely fill the head. Thus, the productivity regression Equation included both the number of trees per cycle and the basal area per cycle to best predict time per tree.

$$\text{Time per tree (sec)} = 28.02 - 2.988\text{NT} - 50.8410\text{BAA} \tag{7}$$

$$R^2 = 0.34, \quad \text{CV} = 35.24, \quad n = 409$$

where NT is the number of trees per cycle and BAA is the total basal area of trees in the cycle (m^2).

Grapple skidder productivity was measured over 100 cycles (525 trees). Machine elements included travel empty, loading, travel loaded, and decking. Skidding distance ranged from 20 to 180 m (average 90 m). There were 5.25 trees per cycle on average, resulting in productive time per tree of 36.5 seconds. By use of regression analysis to model time per tree, the log of the number of trees per cycle and the distance were the best predictors. This finding is illustrated in Figure 6.

$$\text{Time per tree (sec)} = 95.36 + 0.138\text{DIST} - 105.4976 * \log(\text{PCS}) \tag{8}$$

$$R^2 = 0.69, \quad \text{CV} = 36.17, \quad n = 100$$

where DIST is one-way skid distance (m) and PCS is number of stems in the cycle.

The Denharco 4400 stroke delimber mounted on a Caterpillar 320C excavator base was studied while processing 218 trees. The average dbh was 26.7 cm with a maximum of 49.8 cm. The number of pieces processed from each tree ranged from 1 to 4 with an average of 1.43. The average total time per cycle was 40.83 seconds, which yielded a productivity of 88 trees/h. Machine elements included reach, process, stack, clear, and move. The results of the regression analysis to model time per tree indicated that the number of pieces per tree and dbh^2 accounted for most of the variability in the data (Figure 7).

$$\text{Time per tree (sec)} = -0.27 + 20.1944(\text{LOGS}) + 0.0172D^2 \tag{9}$$

$$R^2 = 0.68, \quad \text{CV} = 30.00, \quad n = 218$$

where LOGS is the number of pieces cut from stem and D is dbh (cm).

Lumber Recovery

Raw material requirements for most solidwood products are based on log size not tree diameter. The volume of products manufactured from small-diameter ponderosa pine was directly related to the size of logs produced from harvested trees. Volume (and value) recovery is also influenced by defects such as sweep, rot, or checking. There was little measurable defect (e.g., sweep or rot) in the sample logs, with sweep being the primary deduction (Table 2). Mill productivity influences market potential to the extent that per unit costs of production are greater for small logs, and log volume recovery, although dependent on log diameter, is also affected by the type and dimension of products manufactured. At the time of this research, the market available to the MicroMill owner was 2.4-m long cants (7.6 × 7.6 cm and 10.2 × 10.2 cm) with no wane for use in fencing. The MicroMill also produced 2.54-cm jacket boards (sawn from the outer portion of the log). Table 2 shows the cubic percent recovery for the sample. There is an optimum log size for producing the different size cants. Both the 8 and 10 cm small-end diameter (SED) logs produced one 7.6 × 7.6 cm cant. Therefore, the smaller log size had higher volume recovery because the MicroMill could process the log more efficiently. At 13 cm SED log size, both cant sizes (7.6 × 7.6 cm and 10.2 × 10.2 cm)

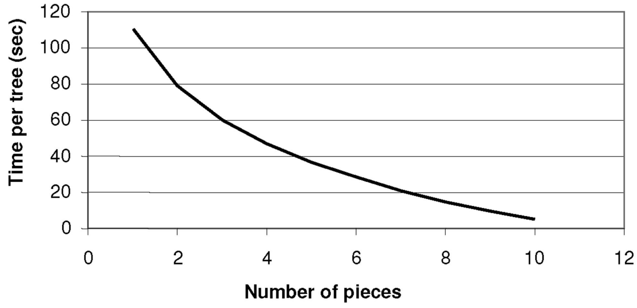


Figure 6. Grapple skidder productivity as a function of load size (100 m skidding distance).

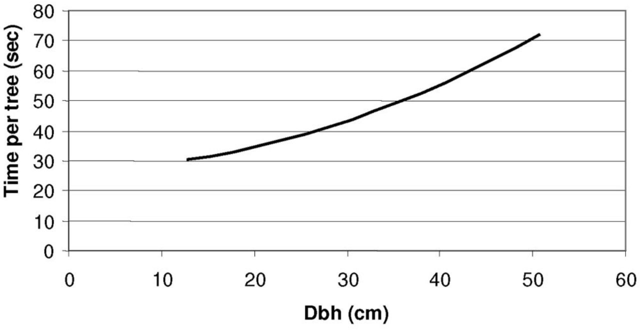


Figure 7. Stroke-boom delimber productivity processing ponderosa pine (1.4 pieces from each stem).

Table 2. **Cubic gross and net volumes, lumber volume, and percentage lumber recovery by log size (small-end diameter, inside bark) for ponderosa pine**

Log size	No. of logs	Log scale Gross	Log scale Net	Surfaced dry lumber volume	Lumber recovery Green	Lumber recovery Surfaced dry
		(m^3)	(m^3)	(m^3)	(%)	(%)
8 cm	17	0.3	0.3	0.16	77.1	54.0
10 cm	306	7.6	7.5	3.45	67.6	47.5
13 cm	589	20.8	20.4	9.67	67.5	47.7
15 cm	374	18.7	18.4	7.76	63.7	44.4
18 cm	57	3.6	3.5	1.42	58.8	40.0
Total	1,343	51.0	50.1	22.45	62.9	44.0

were produced from a log depending on log taper. Mill personnel determined cant size on the basis of log form, quality, and more refined measurement. The logs that were 15 cm SED primarily produced a single 10.2 × 10.2 cm cant. Also, only one cant of this size was produced from the 18-cm log, again lowering the volume yield. Jacket boards (2.54 cm thick) were only cut from logs that were 15 cm SED or larger.

Grade recovery refers to the quality of products that can be manufactured from a given log. For lumber markets, grade recovery affects the total value of a log. Independent of total volume recovered per tree, grade recovery was also related to the size of trees harvested. Percent grade recovery (Table 3) displays log size and corresponding grades for products manufactured by the MicroMill.

Harvest Cost-Revenue Estimator Software Program

Using these data, the HCR estimator financial analysis software program was created to assess site-level project costs for varying harvest prescriptions and contract specifications. Equipment productivity was determined using the regression equations reported above and, where applicable, previously published empirical studies were used (Becker et al. in press). Tree profile equations used to calculate merchantable tree volumes were developed for southwestern ponderosa pine using data collected in this study and in a previous study by Lowell and Green (2001). These data were incorporated in the development of the HCR estimator program, which provides public domain software to users for calculating financial costs and raw material product values from fuels reduction treatments. Because growing conditions differ by region of the country, application of the model is only valid in the Southwest on slopes of less than 30% for which machine productivity data were collected.

The model has three parts with user-defined inputs: log and biomass calculators that determine the size and per ha volume of logs generated, biomass recovered from trees too small for log markets, and biomass recovered from residual harvest slash and allocation of these to user-defined product markets; a cost estimator that determines harvesting costs from production rate relationships for commercial harvesting equipment; and a revenue predictor to estimate net financial return ($/ha) of the biomass and logs removed from forest treatments and sold to wood processors. The program output allows users to conduct simple sensitivity analyses by changing model parameters related to fuel reduction prescriptions, harvesting equipment, labor costs, transportation and mobilization distances and costs, and market specifications.

By using the HCR estimator, cut-tree data were extrapolated to the harvest sites in the study to predict total net profit (loss) on a per ha basis. Comparable assumptions were made for each site pertaining to wages, overhead costs, fuel costs, mobilization of equipment, moisture content of logs, and market specifications. A CTL harvest system with harvester, forwarder, and whole-tree chipper was modeled for Units 13 and 23. A WT harvest system with feller-buncher, grapple skidder, stroke-delimber, loader, and whole-tree chipper was modeled for Units 40 and 41. Comparable assumptions were made regarding equipment size, utilization rate, and operability for each system. The volume of logs harvested varied by site, reflecting actual conditions. Solid wood and biomass markets were modeled to reflect existing market opportunities in the Southwest for small-diameter ponderosa pine. A solid wood market for pallet lumber was assumed for logs having a minimum length of

Table 3. **Percentage grade recovery by log size (small-end diameter, inside bark) and product**

Log size	Product size and grade: 2.5 cm × 10 cm No. 1 and 2 common	2.5 cm × 10 cm No. 3, 4, and 5 common	7.6 cm × 7.6 cm Standard	7.6 cm × 7.6 cm Economy	10.2 cm × 10.2 cm Standard	10.2 cm × 10.2 cm Economy
	(%)	(%)	(%)	(%)	(%)	(%)
8 cm	0.0	0.0	5.9	94.1	0.0	0.0
10 cm	0.0	0.0	20.7	46.6	5.3	27.4
13 cm	0.0	0.3	8.7	7.9	34.3	48.9
15 cm	0.3	11.7	0.1	0.5	51.6	35.7
18 cm	2.7	24.0	0.0	0.0	25.8	47.7

1.8 m and 15.2 cm SED. Distance to the mill was assumed to be 56 km with a delivered log price of $18.14/green tonne and a delivered biomass chip price for energy production of $10.88/bone-dry tonne.

The results in Table 1 show that harvest costs were greatest in Unit 13 in which a majority of trees harvested were smaller than 15.2 cm dbh. Where a biomass market exists for those smaller trees, additional costs were incurred for harvesting, handling, and chipping. However, the additional revenue generated was insufficient to offset those additional costs and when compared with having no biomass market present, total net profit increased by about $830/ha. Compared with Unit 23 in which the same CTL harvest system was used, total costs are nearly half of those in Unit 13. In Unit 23, fewer trees overall were harvested and of those about half were larger than 15.2 cm dbh, which resulted in a net profit of $445/ha with a biomass market present. Again, because of the marginal revenue gained from the sale of wood chips and the increased costs of harvesting and handling, total net profit increased to $551/ha when there was no biomass market present despite an overall decrease in the amount of wood used. Similar results are seen for Units 40 and 41 in which the WT harvest system was used, although net profits are significantly greater than that in other units. This was due to two factors. First, there were fewer trees smaller than 15.2 cm dbh in either Unit 40 or 41, which resulted in overall reduced harvest costs. Second, whereas fewer small trees were harvested, a greater proportion of trees produced viable logs sold for pallet lumber.

Across the four sites, volume and size of trees harvested had a significant impact on the profitability of a particular fuels reduction project. Less obvious was the effect of market specifications. Keeping the delivered log price of $18.14/green tonne constant, the minimum market-allowed SED for pallet lumber was reduced from 15.2 to 12.7 cm. In Unit 13, net profit increased from a loss of $7/ha to a gain of $1,639/ha with a biomass market present and to nearly $2,300/ha with no biomass market. Similar results were found for the other units, although not of the same magnitude because of fewer trees in the 12.7–15.2 cm dbh size class. Total net profit increased in the remaining sites by a factor of 1.5–1.9. Although total project costs increased, primarily as a result of increased transportation costs from hauling more logs, the total revenue generated from the increased use of small-diameter trees for higher value markets substantially increased profitability.

Discussion

A complex set of interacting variables influenced the economics of hazardous fuel reduction treatments modeled here. Findings from this study illustrate the value of a fully integrated planning system in which the financial costs of thinning small-diameter ponderosa pine can be compared with the benefits of wildfire risk reduction. In an integrated planning system, knowledge of stand density and species composition affects the silvicultural prescription and desired level of hazardous fuels reduction. Because these decisions dictate the size, volume, and quality of logs generated, as shown in Tables 2 and 3, logging contractors necessarily must anticipate associated costs and market opportunities. In this study, we found that as the intensity of fuels reduction increased for trees smaller than 15.2 cm dbh, net profit decreased, particularly when there was no viable market available to offset associated harvesting costs. Hazardous fuels reduction on these sites would not have been economically viable if not for a solid wood market in the region. Biomass markets, although assumed to increase financial return due to increased volume of wood used, substantially increased harvest and handling costs to the point of diminishing net profits. Depending on the volume of biomass harvested relative to its market value and distance to processing facilities, the viability of biomass markets to use substantial portions of waste material from fuels reduction projects appears limited. Perhaps as demand for wood chips increases for power generation and biofuels production, the delivered price for biomass may offset a greater proportion of those added costs.

Financial return was also found to be affected by the distribution of trees larger than 15.2 cm dbh. Labor costs, type and size of equipment used, use rate of equipment, and site slope and operability must be matched to the distribution and volume of material harvested, which can change dramatically from one fuels reduction project to another. Not only must contractors anticipate site-specific factors but they must also anticipate project-to-project differences. When one is considering regional and annual fluctuations in market return and availability, including changes in log specifications based on consumer demand, the need for an integrated approach from silvicultural prescription through product manufacture is essential. The HCR estimator was developed to provide site-level analysis of the costs of proposed actions relative to the level of wildfire risk reduction achieved. With this analysis, forest planners are able to prioritize treatment locations on the basis of per hectare costs relative to areas of greatest wildfire risk reduction need. Our analysis illustrates the complexity of predicting the economics of fuels reduction across large landscapes, given the variability of site-level conditions.

A related finding was the effect of market specifications on financial return. A change in SED of just 2.5 cm dbh increased the volume of wood available for pallet lumber manufacturing, which significantly increased profitability for the sites presented in Table 1. Similarly, as shown in Table 2, the volume of lumber recovered from a given log is dependent on the log specifications for that market. In the case of the MicroMill market for fence posts, as logs increased in size the percentage of total log volume recovered actually decreased. Had there been an alternative market capable of using a greater proportion of logs transported to the mill, the value of those logs might have increased, or had a secondary market been available, it might have made it worthwhile to alter the sawpattern more frequently and produce additional products for higher log volume and value recovery.

This research demonstrates the calculation of merchantable volumes and log potential as a function of tree profile data and log market specifications. Follow-on predictions of treatment activities are linked directly to log potential, better reflecting true stand-level conditions, total volume used, and subsequent revenue potential. The HCR estimator provides a log and biomass calculator to estimate the total volume of wood available relative to the actual volume that is merchantable for a given market. Overestimation of financial return on the basis of unrealistic utilization rates could severely affect contractor operations. Further, by assuming a greater utilization rate than practical, forest planners may underestimate the volume of material left on site that could increase risks in fire-prone areas. Unrealistic targets could be set on the number of hectares that can be treated annually if the assumed revenue generated from the sale of logs is less than initially anticipated. Results of this study demonstrate that not only may costs vary substantially from site to site but also the ability to offset those costs may not correlate with the amount of wood available for utilization if viable wood product markets are not present. The HCR estimator provides assistance to forest planners and logging contractors in calculating financial thresholds based on the actual volume that can be used with the ability to compare market options in terms of associated harvesting and handling costs.

Conclusion

The approach taken here requires consideration of the end product market opportunities and how stand-level and harvesting factors leading up to production will affect profitability. An integrated fuels reduction approach such as that described here allows for informed decisions to be made at each step. Silvicultural prescription affects the volume of material available for different markets. Stem selection affects machine productivity. Machine productivity and operations are a function of the type, size, and age of equipment used. How trees are processed in the woods affects handling and transportation costs, which is a function of the markets selected. Incomplete knowledge of how these factors affect the financial viability of wood products businesses—the viability of which is necessary for reducing the risk of catastrophic wildfire on public and private lands—threatens development of sustainable fuels reduction programs. An integrated systems approach allows for an informed assessment of options in planning fuel reduction prescriptions, which may expedite implementation of fuel treatment projects across the more than 27 million ha of forestland in the western United States at high risk of wildfire.

Literature Cited

Becker, D.R., E.E. Hjerpe, and E.C. Lowell. 2004. *Economic assessment of using a mobile MicroMill for processing small-diameter ponderosa pine.* US For. Serv. Gen. Tech. Rep. PNW-GTR-623. 40 p.

Becker, D.R., D. Larson, E.C. Lowell, and R. Rummer. 2008. *User's guide for HCR Estimator 2.0: Software to calculate cost and revenue thresholds for harvesting small diameter ponderosa pine.* US For. Ser. Gen. Tech. Rep. PNW-GTR-748.

Brown, J.K., R.D. Oberheu, and C.M. Johnston. 1981. *Handbook for inventorying surface fuels and biomass in the interior west.* US For. Serv. Gen. Tech. Rep. INT-129. 48 p.

Carlton, D. 2005. Fuels Management Analyst Plus software, version 3.0.2. Fire Program Solutions, LLC, Estacada, OR.

Fight, R.D., and R.J. Barbour. 2005. *Financial analysis of fuel treatments.* US For. Serv. Gen. Tech. Rep. PNW-GTR-662. 20 p.

Fulé, P.Z., C. McHugh, T.A. Heinlein, and W.W. Covington. 2001. Potential fire behavior is reduced following forest restoration treatments. P. 28–35 in *Proc. of conf. on Ponderosa pine ecosystems restoration and conservation: Steps toward stewardship*, Vance, R.K., C.F. Edminster, W.W. Covington, and J.A. Blake (compilers). US For. Serv. Proceedings RMRS-P-22.

General Accountability Office. 2006. *Natural resources: Woody biomass users' experiences offer insights for governmental efforts aimed at promoting its use.* GAO Report to the Committee on Resources, House of Representatives. GAO-06-336.

Keegan, C.E., T.A. Morgan, K.M Gebert, J.P. Brandt, K.A. Blatner, and T.P. Spoelma. 2004. *Timber-processing processing capacity and capabilities in the western U.S.* Available online at www.wflccenter.org/ts_dynamic/edu_outreach/18_file.pdf; last accessed Dec. 29, 2006.

Kluender, R., D. Lortz, W. McCoy, B. Stokes, and J. Klepac. 1998. Removal intensity and tree size effects on harvesting costs and profitability. *For. Prod. J.* 48(1):54–59.

Larson, D., and R. Mirth. 2001. Projected economic impacts of a 16-inch tree cutting cap on ponderosa pine forests within the greater Flagstaff urban-wildlands. P. 154–160 in *Proc. of conf. on Ponderosa pine ecosystems restoration and conservation: Steps towards stewardship*, Vance, R.K., C.F. Edminster, W.W. Covington, and J.A. Blake (compilers). US For. Serv. Proceedings RMRS-22.

Larson, D., and R. Mirth. 2004. A case study on the economics of thinning in the wildland urban interface. *West. J. Appl. For.* 19(1):60–65.

Lowell, E.C., and D.W. Green. 2001. Lumber recovery from small-diameter ponderosa pine from Flagstaff, Arizona. P. 161–165 in *Proc. of conf. on Ponderosa pine ecosystems restoration and conservation: Steps toward stewardship*, Vance, R.K., C.F. Edminster, W.W. Covington, and J.A. Blake (compilers). US For. Serv. Proceedings RMRS-P-22.

Lynch, D.L., W.H. Romme., and M.L. Floyd. 2000. Forest restoration in southwestern ponderosa pine. *J. For.* 98(8):17–24.

Monserud, R.A., E.C. Lowell, D.R. Becker, S. Hummel, E.M. Donoghue, R.J. Barbour, K.A. Kilborn, D.L. Nicholls, J. Roos, and R.A. Cantrell. 2004. *Contemporary wood utilization research needs in the western United States.* US For. Serv. Gen. Tech. Rep. PNW GTR-616. 49 p.

Rao, P.V. 1997. *Statistical research methods in life sciences.* Duxbury Press, Pacific Grove, CA. 912 p.

Schmidt, K.M., J.P. Menakis, C.C. Hardy, W.J. Hann, and D.L. Bunnell. 2002. *Development of course-scale spatial data for wildland fire and fuel management.* US For. Serv. Gen. Tech. Rep. RMRS-GTR-87. 41 p. + CD.

Scott, J.H., and E.D. Reinhardt. 2001. *Assessing crown fire potential by linking models of surface and crown fire behavior.* US For. Serv. Res. Paper RMRS-29. 59 p.

Skog, K.E., R.J. Barbour, K.L. Abt, E.M. Bilek, F. Burch, R.D. Fight, R.J. Hugget, P.D. Miles, E.D. Reinhardt, and W.D. Shepperd. 2006. *Evaluation of silvicultural treatments* *and biomass use for reducing fire hazard in western states.* US For. Serv. Res. Paper FPL-RP-634. 29 p.

SPELTER, H., AND M. ALDERMAN. 2005. *Profile 2005: Softwood sawmills in the United States and Canada.* US For. Serv. Res. Paper FPL-RP-630. 85 p.

SPELTER, H., R. WANG, AND P. INCE. 1996. *Economic feasibility of products from inland west small-diameter timber.* US For. Serv. Gen. Tech. Rep. FPL-GTR-92. 17 p.

THOMPSON, J.D. 2003. Productivity of a tree length harvesting system thinning ponderosa pine in northern Arizona. In *Proc. of conf. on Council of Forest Engineering forest operations among competing users* [CD-ROM]. 5 p. COFE, Corvallis, OR.

US FOREST SERVICE. 1985. *National forest log scaling handbook.* FSH 2409.11 Amendment 6. Washington, DC.

US FOREST SERVICE. 1991. *National forest cubic scaling handbook.* US For. Ser. FSH 2409.11a. Amendment 2409.11a-91-1.

US FOREST SERVICE. 2003. *A strategic assessment of forest biomass and fuel reduction treatments in western states.* Available online at www.fs.fed.us/research/pdf/Western_final.pdf; last accessed Dec. 29, 2006. 18 p.

WAGNER, F.G., C.E. KEEGAN., R.D. FIGHT, AND S. WILLITS. 1998. Potential for small-diameter sawtimber utilization by the current sawmill industry in western North America. *For. Prod. J.* 48(9):30–34.

WOLFE, R., AND C. MOSELEY. 2000. Small-diameter log evaluation for value-added structural applications. *For. Prod. J.* 50(10):48–58.