Production, Cost, and Soil Compaction Estimates for Two Western Juniper Extraction Systems

Elizabeth M. Dodson, *College of Forestry and Conservation, The University of Montana, Missoula, MT 59812;* **Tim Deboodt,** *Oregon State University Crook County Extension, Prineville, OR 97754; and* **Glen Hudspeth,** *Crook County Soil and Water Conservation District, Prineville, OR 97754.*

ABSTRACT: *Harvesting trials were performed during the winter and spring of 2003–2004 in central Oregon to compare the costs, production rates, and soil compaction impacts of two systems for harvesting western juniper (*Juniperus occidentalis*). The two systems compared were a conventional system consisting of manual felling, delimbing, and bucking using a chainsaw and skidding logs with a rubber-tired grapple skidder and a mechanical system that used a feller-buncher, a rubber-tired grapple skidder to skid whole trees, and a stroke-boom delimber. Stump to deck harvesting costs ranged from $32.15 to $49.48/ton for the conventional system and from $60.07 to $63.11/ton for the mechanical system. A limited trial was conducted with the mechanical system that merchandized fence posts as well as sawlogs. When fence posts were produced also, stump to deck costs were reduced to $31.56/ton. Soil compaction was measured pre- and postharvest using a soil penetrometer. Paired* t*-tests showed a statistically significant difference between harvested sites and nonharvested sites at depths of 2 and 4 in. (*$P = 0.032$ *and 0.001, respectively) but no difference between harvest systems. West. J. Appl. For. 21(4):185–194.*

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Over the last 100 years, western juniper (*Juniperus occidentalis*) has greatly increased its dominance throughout eastern Oregon, northeastern California, and southwestern Idaho. There are now over 3.8 million ac with 10% or more juniper canopy cover, of which at least 1 million ac have a juniper canopy cover equal to or exceeding 20% (Azuma et al. 2005). Twenty percent or more juniper canopy cover is a key indicator of loss of vegetative diversity, groundcover, rangeland health, watershed function, and wildlife habitat (Swan 1997. Available online at www.juniper.oregonstate.edu/harvest.htm; last accessed Dec. 15, 2005). On the other hand, juniper is the least-used wood fiber resource in its range. In part, this underutilization is caused by perceptions about juniper's wood characteristics (difficulty in sawing and drying), low sawing recovery rates (less than 50%), and market potentials. Efforts to commercialize western juniper have occurred off and on for at least 50 years. In the past, juniper utilizing enterprises in central Oregon have not been able to secure an adequate and stable enough supply to serve the new market demand (Central Oregon Intergovernmental Council 2005). One of the key barriers to successful commercialization identified in many of these efforts was the cost to harvest juniper (Coulter and Coulter 2001. Available online at www.juniper.oregonstate.edu/harvest01.pdf; last accessed Dec. 15, 2005).

NOTE: Elizabeth Dodson can be reached at (406) 243-5542; Fax: (406) 243-4845; beth.dodson@cfc.umt.edu. Tim Deboodt can be reached at tim.deboodt@oregonstate.edu. Glen Hudspeth can be reached at glen.hudspeth@oregonstate.edu. Funding for this work was provided by a National Fire Plan Community Assistance and Wildland-Urban Interface Project grant. Additional contributions were made by the following: Crook County Soil and Water Conservation District; Ochoco National Forest, Look Out Mountain Ranger District; John Breese, Dixie Meadow Company; Kreige Logging; Gillen Logging; Western Juniper Work Group; OSU Extension Service, Crook County; OSU Extension Service, Warm Springs; Art Currier, District Ranger, Ochoco National Forest; Cindy Click, Assistant Forest Silviculturist, Deschutes National Forest; Crook County Court; Warm Springs GeoVisions; Santucci Ranch, Brad and Shelley Santucci; Ken Shrum, Wood Products Consultant; Line Shack Cabins, Lance Romine; Eastern Oregon Stewardship Service, Berta Youtie; Frontier Natural Resources Consulting, LLC, Kelly Crane; Oregon Forest Resources Institute, Teacher on Summer Assignment Project; Wes Pyne, Bend LaPine School District; Amy Mitchell, Redmond High School; Central Oregon Partnership/Prineville, Crook Company Community Action Team; Mike Templeton, Community Advocate; Scott Aycock, Central Oregon Intergovernmental Council.

Juniper-dominated sites often show a marked decline in overall health as measured by ground cover, forage production, loss of wildlife habitat, and overall reduction in biodiversity (Swan 1997. Available online at www.juniper.oregonstate.edu/harvest.htm; last accessed Dec. 15, 2005). As juniper density and canopy cover increase there is a loss of understory ground cover and herbaceous production, infiltration rates are reduced, surface runoff is increased, and soil erosion is increased (Bedell et al. 1993). In central Oregon, community-based organizations are now leading the way in restoring rangelands, improving watershed function, and creating family wage jobs through the harvest, product development, and marketing of western juniper.

Discussions of potential juniper harvesting systems have recommended low-cost systems assuming that a potential contractor would not be willing or able to afford more than $75,000 for a complete system, especially when dealing with a low-value product such as juniper (Swan 1997. Available online at www.juniper.oregonstate.edu/harvest.htm; last accessed Dec. 15, 2005). Based on these reports, harvest trials were designed to explore the use of used or shop-built equipment and low-skilled labor (Coulter and Coulter 2001. Available online at www.juniper.oregonstate.edu/harvest01.pdf; last accessed Dec. 15, 2005). Results of these studies indicated that specialty built harvest systems were plagued by breakdowns, the need to fabricate all replacement parts, and operator limitations that were caused by lack of training and familiarity with the equipment.

This study challenged this notion by comparing a conventional, low-cost system with a system composed of existing, modern commercial logging equipment. The objectives of this study were to explore the costs, productivity, and soil impacts of a mechanized harvest system against a conventional system for the purpose of commercially harvesting western juniper. Pretreatment vegetative data were collected and included tree stand characteristics (tree size and density), understory vegetation, and a measure of soil density. The study used timber-harvesting businesses that employed skilled equipment operators and timber fallers. Previous western juniper harvesting studies have either focused on the vegetative and site impacts of juniper removal (i.e., Brockway et al. [2002]) or appear only in the gray literature (i.e., Swan 1997. Available online at www.juniper.oregonstate.edu/harvest.htm; last accessed Dec. 15, 2005; and Coulter and Coulter 2001. Available online at www.juniper.oregonstate.edu/harvest01.pdf; last accessed Dec. 15, 2005).

With the use of mechanized equipment on rangeland soils, soil compaction is of great concern to landowners and public land managers. A unique component of this study was estimating soil compaction using a soil penetrometer. An additional component of this study not reported here includes short- and long-term range responses, primarily vegetative response, to juniper removal.

Methods

Study Site

Harvest trials were conducted on private lands located approximately 14 miles northeast of Prineville, Oregon. Three units were selected representing (1) a low-elevation stand of pure juniper on a southern aspect (juniper South), (2) a low-elevation stand of pure juniper on a northern aspect (juniper north), and (3) a higher-elevation, mixed stand of ponderosa pine (*Pinus ponderosa*) and juniper on a southeastern aspect (mixed). Each unit was 25 ac in size and was divided equally between the two harvesting systems. A control site that was not harvested was located adjacent to each unit. Table 1 summarizes stand characteristics for the three sites.

The study areas are located in the Crooked River Watershed of the Deschutes River basin, and are within the John Day Ecological Province (Anderson et al. 1998). This province is typified by exposed ancient sediments and tuffaceous materials representing various geologic formations. Elevations in the study area range from 3,300 to 3,700 ft. Annual precipitation is 12 in. with over 70% occurring as winter snow or spring rain. Three soil types are found in the study area (Table 2).

Harvesting Systems

Two systems were compared on the basis of production and costs. The first system, referred to as the conventional system, consisted of manual felling, delimbing, and bucking using a chainsaw, and skidding with an older-model used Caterpillar 518 rubber-tired skidder (Caterpiller Inc., Peoria, IL) with a grapple. The second system, referred to as the mechanical system, used a Timbco 445 feller-buncher (Komatsu, Shawano, WI) with a bar saw to fall and bunch stems, a Caterpillar 525 rubber-tired skidder (Caterpiller Inc., Peoria, IL) equipped with tire chains and a swing grapple to skid bunches of stems to a central landing, and a Denis 3400 (Denharco, Woodland, WA) stroke-boom delimber mounted on a Thunderbird 736DL (Madill Corp., Kalama, WA) to delimb and buck logs to length on the

Table 1. Stand characteristics.

Site	Density (TPA)			Juniper 50-year site index	Quadratic mean diameter (in.)	Average height (ft)
	Seedling/juvenile/sapling	Subadult/Mature/Decadent	Total			
Juniper south	198	144	342	21	8.2	19.2
Juniper north	161	134	296	23	8.0	21.5
Mixed	93 (J)	226 (J)	319 (J)	29	8.3 (J)	27.5 (J)
	132 (P)	22 (P)	473 (A)			

For the mixed stands, "J" refers to juniper trees per acre (TPA), "P" refers to pine trees per acre, and "A" refers to all stems combined. site index values are per Sauerwein (1982).

Table 2. Soil characteristics.

Soil type	Location	Composition	Restrictive features	Drainage	Permeability	Typical vegetation
Era ashy sandy loam–223	Juniper north and alluvial fans in juniper south	Volcanic ash over alluvium	None	Well	Moderate	Idaho fescue, bluebunch wheatgrass, mountain big sage, antelope bitterbrush, and western juniper
Slayton channery ashy sandy loam– 226	Juniper south	Volcanic ash over weathered tuff	Bedrock at a depth of 10–20 in.	Well	Moderately rapid	Bluebunch wheatgrass, basin big sage, Idaho fescue, Thurber needlegrass, antelope bitterbrush, and western juniper
Normauk-Scarpal complex	Mixed juniper-pine	Ashy sandy loam (Mormauk) and cobbly ashy sandy loam (Scarpal)	Abrupt textural change at a depth of 21 in.	Well	Slow to moderately rapid	Snowberry, currant, western juniper, and ponderosa pine

Table 3. System components and hourly costs.

	Conventional		Mechanical	
Component	Equipment	$/hr	Equipment	$/hr
Felling	Manual	$50	Feller-buncher	$110
Bunch	Skidder	$55	Feller-buncher	$110
Skid	Skidder	$55	Skidder	$70
Delimb and buck	Manual	$50/$25*	Stroke-boom delimber	$110
Deck	Skidder	$55	Stroke-boom delimber	$110

*Delimbing and bucking in the conventional system was completed by both the timber faller in the woods ($50/hr) and by a chaser on the landing ($25/hr).

landing. System components and hourly costs are summarized in Table 3.

Data Collection and Analysis

Equipment Productivity

Within each of the three units, each system harvested a contiguous 12.5 ac. The majority of harvesting took place over snow or frozen ground during the winter of 2003–2004. The decision to harvest these stands in the winter was based on (a) the greatest improvement in range health occurs after a winter cut as opposed to a spring or summer harvest (Bedell et al. 1993), (b) grant timing and the need to collect pretreatment stand and soil data, and (c) logging contractor availability. Because of steeper slopes in the mixed stand as compared with the pure juniper stands and a lack of tire chains for the Cat 518 skidder, the conventional system skidded the mixed stand in the late spring of 2004. Detailed time and motion data were taken for a sample of each process for each system working in each of the three units (Table 4). These data were used to develop predictive equations of average cycle time for felling, skidding, and processing whole trees into logs. Independent variables were selected after observing each process and breaking each down into logical components.

Vegetation Measurements

Preharvest vegetation data were collected and included understory vegetative cover, density, and frequency for major plant species and plant groups (grasses, forbs, and shrubs) per Miller et al. (2000). Three permanent plots per treatment (including control) per site were established. Plot size was 196 (60 m) by 131 ft (40 m), staked with fence posts in three of the plot corners for permanent recording, and marked with flagging at each of the four corners for temporary identification. Within each plot three permanent transects were established. Three 196-ft transects were located along the 131-ft line spaced every 66 ft. Tree counts were recorded within a 6 by 196-ft (2 by 60 m) strip cruise. Trees were recorded in the following classes: seedlings (less than 1 ft in height), juveniles (1–3 ft), saplings (3–10 ft), subadults (trees with pointy leader growth), and mature or old-growth trees (trees with rounded tops). Data measured for subadult and mature juniper trees were dbh and total tree height (estimated using a 10-ft pole). Pine trees were measured for dbh and total height.

Soil Compaction

Soil compaction was measured using a soil penetrometer (Herrick and Jones 2002). Because of the rocky nature of

Table 4. Number of observations and time included in detailed time and motion study.

	Conventional		Mechanical	
Component	Total time	Number of observations	Total time	Number of observations
Felling	475 min (7.9 hr)	347	299 min (5.0 hr)	489
Skidding	549 min (9.2 hr)	102	439 min (7.3 hr)	78
Delimb and Buck	421 min (7.0 hr)	294	336 min (5.6 hr)	166

many range soils, methods for estimating changes in soil compaction, such as calculating bulk density using a sand cone, often are difficult if not impossible to implement in the field (Coulter and Coulter 2001. Available online at www.juniper.oregonstate.edu/harvest01.pdf; last accessed Dec. 15, 2005). Six samples were recorded along each of the 196-ft permanent transects at 32-ft intervals. The penetrometer hammer was dropped from the top of the guide with the number of blows recorded to drive the penetrometer to 2, 4, 6, and 8 in. Penetrometer readings were recorded as number of blows (drop of the hammer from a constant height). Soil compaction was measured in October 2003 before harvest activities and in October/November of 2004 after harvest activities. In both years, soil moisture was at the lowest point of the year, the soil was not frozen and no snow was on the ground. Soil moisture readings were not taken.

Tree Volume Estimation

Volume for individual juniper trees was estimated using Chittester and MacLean (1984):

$$CFTS = BA * \left(0.307 + 0.00086 * H - \frac{0.0037 * D * H}{H - 4.5}\right) * H * \left(\frac{H}{H - 4.5}\right)^2, \quad (1)$$

$$CV4 = \frac{CFTS + 3.48}{1.18052 + 0.32736 * e^{-0.1*D}} - 2.948, \quad (2)$$

where

CFTS = total cubic volume excluding all branches;
CV4 = cubic foot volume from a 12 in. stump to a 4-in. top;
BA = square foot basal area;
H = total tree height in feet;
D = diameter in inches at breast height outside bark.

This equation was developed using only dominant, tall (greater than 18 ft in height), good-form juniper and therefore its appropriateness for use with poor-form, subdominant trees is questionable. However the development of a new volume relationship was beyond the scope of this study.

Heights were not taken for individual stems within multistemmed trees. A height-diameter relationship developed from the inventory data was assumed to be appropriate for individual stems of multistemmed trees. For volume calculations, stems of multiple-stemmed trees where the division occurred below breast height (4.5 ft) were treated as individual trees.

Volume estimates for each harvest unit are shown in Figure 1. To convert cubic foot volume to tons, an average green (approximately 40% moisture content) density of 36 lb/ft^3 was assumed.

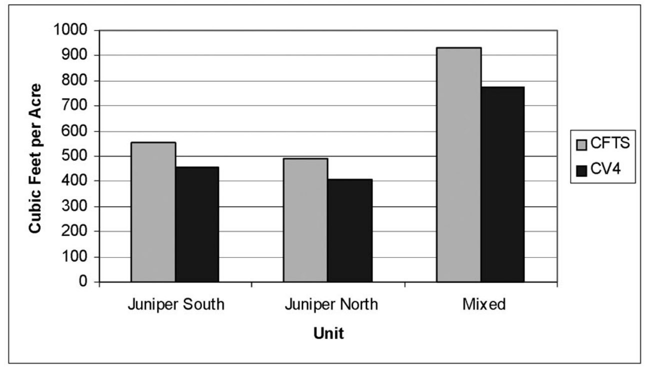

Figure 1. Western juniper cubic foot volume per acre estimates for the three units, where CFTS is the total stem volume and CV4 is the volume to a 4-in. top diameter per Equations 1 and 2.

Results

Conventional System

Felling in the conventional harvesting system was performed with a chainsaw operated by an experienced timber faller. A felling cycle consisted of prelimbing as much of the tree as possible while it was still standing (25% of the total cycle time), felling (19%), limbing (33%), bucking (2%), and moving into position for the next tree (6%). Log lengths were not measured and small end diameters were determined by an ocular estimate of 6 in. Delays averaged 15% of the total cycle time per tree and most commonly included refueling the chainsaw. A backward stepwise regression was performed using variables representing harvest unit, BA, and diameter. Time required to fell a tree increased with the diameter of the tree per Equation 3 (adjusted $R^2 = 0.70$; SE = 0.70; $n = 325$; Figure 2).

$$CF = -0.6413 + 0.2359\,D \quad (3)$$

where

CF = productive cycle time to conventionally fell and limb, in minutes.

At an average diameter of 12 in., the average time to fall a tree was equal to 2.39 minutes, including delay, or

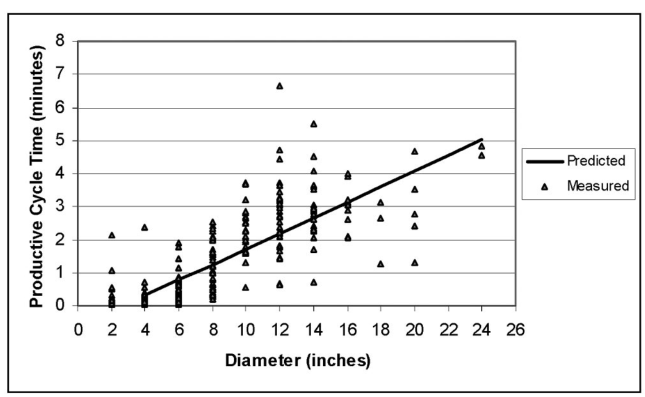

Figure 2. Predicted versus measured total productive cycle times for felling and delimbing western juniper using a chainsaw in the conventional harvest system.

\$1.99/tree. Swan (Swan 1997. Available online at www.juniper.oregonstate.edu/harvest.htm; last accessed Dec. 15, 2005) reported an average of 4.6 minutes or \$2.30/tree to prelimb and fell using semiskilled fallers (\$30/hour) with an average 12.6-in. dbh.

A skidding cycle consisted of the skidder traveling unloaded from the landing to the first stem to be skidded (on average 21% of the total cycle time), bunching of individual stems into a turn (37%), skidding the turn to the landing (17%), and pushing logs into a deck (23%). The average skidding distance was 350 ft with a turn of three trees. Only stems of sawlog quality were skidded to the landing. All others were left in the unit and later piled. One operator worked in all three units with a second operator occasionally operating the skidder in juniper south. When the contractor was able to skid the mixed unit in the spring he first spent 8 hours prebunching merchantable stems before skidding. A backward stepwise regression was performed using variables representing harvest unit, skidding distance, number of stems per turn, and operator. Cycle times increased with the number of trees per turn, with the square of distance, and in the mixed unit per Equation 4 (adjusted $R^2 = 0.94$; SE = 1.75; $n = 102$; Figure 3).

$$\mathrm{CS} = 0.7138 + 2.5455(\mathrm{mixed})(Ns) + 1.1338\,Ns + 0.0101\,\mathrm{DistSq} \quad (4)$$

where

CS = productive cycle time for conventional skidding, in minutes;
Ns = number of stems per turn;
mixed = 1 if in the mixed stand, 0 otherwise;
DistSq = skidding distance squared divided by 1,000, in ft.

The average delay per turn was 0.16 minutes. This gives an average total turn time of 5.51 minutes (\$1.68/stem) for the pure stands and 13.15 minutes (\$4.02/stem) for the mixed stand, including prebunching, assuming an average skidding distance of 350 ft and a turn of three trees.

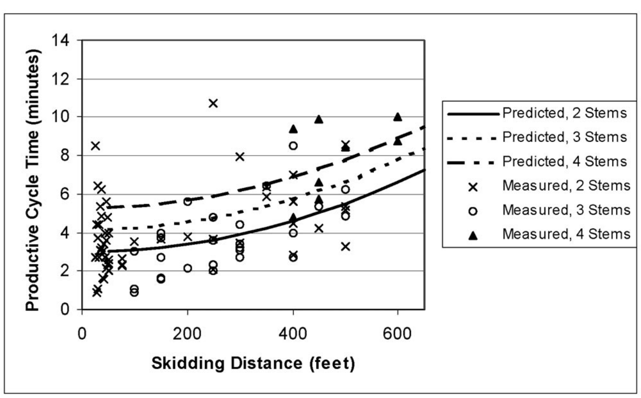

Figure 3. Predicted versus measured total productive cycle times for skidding western juniper with the conventional harvest system in the juniper north and juniper south units.

The faller did not remove all limbs from the stems; therefore, a chaser used a chainsaw at the landing to remove the remaining limbs. Forty percent of the chaser's time was spent delimbing with the remainder waiting for the skidder to return to the landing with the next turn for a total of 1.60 minutes/stem (\$0.67/stem).

Table 5 presents a comparison of per piece costs per component and total costs per piece, per cubic foot, and per ton for each harvest unit.

Mechanical System

A winter snowfall occurred immediately before harvesting in the mixed stand. With a large amount of snow stored in the tree canopies, anytime the operator bumped a tree a large cloud of snow would obscure his vision. Therefore, the operator would use a cut tree to knock the snow off of standing trees, adding to the cycle time. This snow was a confounding variable not directly included in the models. Separate models for mechanical felling were developed for the mixed stand and for the two pure juniper stands.

The felling cycle using a feller-buncher consisted of positioning the machine (23% of the total cycle time on average in the pure juniper stands, 37% in the mixed stand), grabbing the tree with the felling head and felling (40% in the pure stands, 20% in the mixed stand), and bunching the tree with other stems (30% in the pure stands, 29% in the mixed stand). Backward stepwise regressions were performed using variables describing the harvest unit and stem diameter. Felling time in the pure stands increased with an increase in diameter and in juniper north per Equation 5 (adjusted $R^2 = 0.31$; SE = 0.21; $n = 205$; Figure 4).

$$\mathrm{MFP} = 0.1523 + 0.0854\ \mathrm{north} + 0.0284\ \mathrm{D} \quad (5)$$

where

MFP = productive cycle time for mechanical felling in the pure stands, in minutes;
north = 1 if in juniper north, 0 otherwise.

Felling time in the mixed stand increased with an increase in BA per Equation 6 (adjusted $R^2 = 0.14$; SE = 0.37; $n = 204$; Figure 5).

$$\mathrm{MFM} = 0.4530 + 0.4271\ \mathrm{BA} \quad (6)$$

where

MFM = productive cycle time for mechanical felling in the mixed stand, in minutes

Delays averaged 7% of the total cycle time in the pure stands and 14% in the mixed stand. For a 12-in. diameter stem, this gives an average of 0.61 minutes (\$1.12) per stem in juniper north, 0.52 minutes (\$0.96) per stem in juniper south, and 0.66 minutes (\$1.21) per stem in the mixed stand.

A skidding cycle within the mechanical system consisted of the skidder traveling unloaded from the landing to the prebunched turn to be skidded (25% of the total cycle time), assembling a turn (11%), and skidding the turn to the

Table 5. Cost results for the three harvest units using the conventional harvest system.

	Felling	Limbing/bucking	Bunching	Skidding	Decking	Nonproductive	Total
Juniper north							
Feller	$0.38	$1.19	—	—	—	$0.42	$1.99
Skidder	—	—	$0.62	$0.64	$0.38	$0.04	$1.68
Chaser	—	$0.27	—	—	—	$0.40	$0.67
Total $/piece	$0.38	$1.46	$0.62	$0.64	$0.38	$0.86	$4.34
Total $/ft^3	$0.05	$0.19	$0.08	$0.09	$0.05	$0.11	$0.58
Total $/ton	$2.80	$10.83	$4.60	$4.73	$2.80	$6.38	$32.15
Juniper south							
Feller	$0.38	$1.19	—	—	—	$0.42	$1.99
Skidder	—	—	$0.62	$0.64	$0.38	$0.04	$1.68
Chaser	—	$0.27	—	—	—	$0.40	$0.67
Total $/piece	$0.38	$1.46	$0.62	$0.64	$0.38	$0.86	$4.34
Total $/ft^3	$0.05	$0.19	$0.08	$0.09	$0.05	$0.11	$0.58
Total $/ton	$2.80	$10.83	$4.60	$4.73	$2.80	$6.38	$32.15
Mixed							
Feller	$0.38	$1.19	—	—	—	$0.42	$1.99
Skidder	—	—	$1.49	$1.53	$0.90	$0.10	$4.02
Chaser	—	$0.27	—	—	—	$0.40	$0.67
Total $/piece	$0.38	$1.46	$1.49	$1.53	$0.90	$0.92	$6.68
Total $/ft^3	$0.05	$0.19	$0.20	$0.20	$0.12	$0.12	$0.89
Total $/ton	$2.80	$10.83	$11.02	$11.32	$6.70	$6.82	$49.48

The first four rows for each unit are in terms of dollars per piece. Cost estimates assume a 12-in. average diameter and a 350-ft skidding distance.

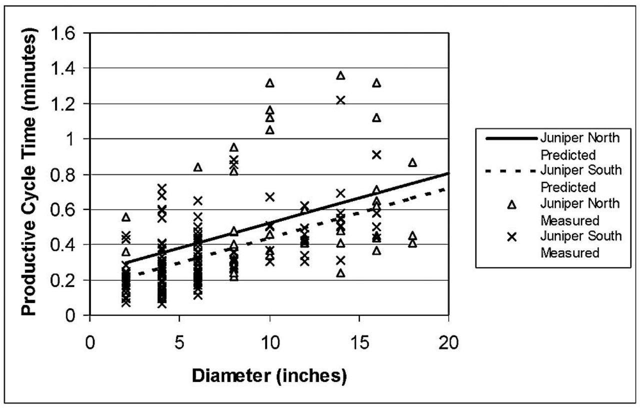

Figure 4. Predicted versus measured total productive cycle times for felling western juniper in juniper north and juniper south with the mechanical harvest system.

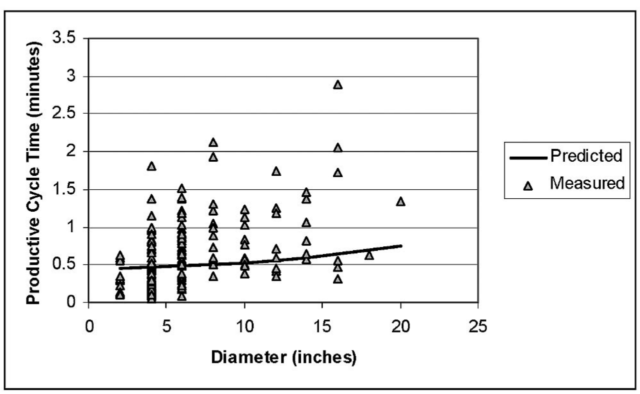

Figure 5. Predicted versus measured total productive cycle times for felling western juniper in the mixed stand with the mechanical harvest system.

landing (34%). A backward stepwise regression was performed using variables representing unit, skidding distance, and the number of stems per turn. Productive cycle times

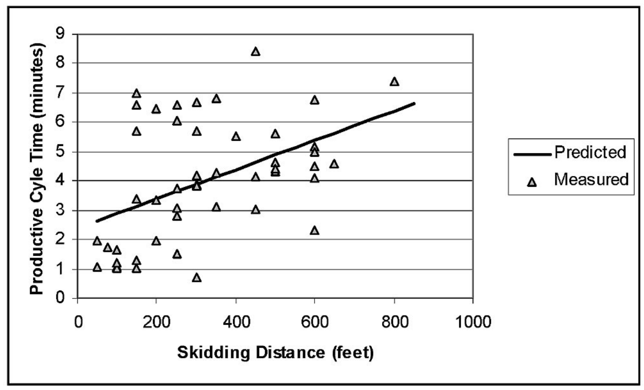

Figure 6. Predicted versus measured total productive cycle times for skidding western juniper with the mechanical harvest system.

showed a positive relationship with distance per Equation 7 (adjusted $R^2 = 0.19$; SE = 1.83; $n = 48$; Figure 6).

$$MS = 2.3862 + 0.0050 \text{ Dist} \quad (7)$$

where

MS = productive cycle time for mechanical skidding, in minutes;
Dist = skidding distance in ft.

Delays accounted for 30% (1.20 minutes) of the average cycle time. Ninety-five percent of these delays were either the skidder waiting at the landing for the delimber to finish processing trees from the previous turn (64% of total delays) or involved compacting the slash pile created by the delimber at the landing (31% of total delays). Including delays, the average total turn time was 5.21 minutes. The average skidding distance was 325 ft. The average turn consisted of nine stems, of which 2.5 stems yielded sawlogs. Unlike the conventional system where only merchantable logs were skidded to a central landing, the mechanical system skidded all stems as whole trees. With an average of nine stems per turn, this yields a skidding cost of \$1.06/stem. If only those stems that contained sawlogs are considered in cost calculations, it cost an average of \$3.82/sawlog to skid stems to a central landing.

The stroke-boom delimber remained stationary at a central landing and processed trees into logs as the skidder brought turns into the landing. As turns were brought into the landing, the delimber would sort sawlogs from nonsawlogs, delimb and buck sawlogs to length, and deck logs. Delays generally resulted from the delimber waiting for the skidder to deliver another turn of logs. Because of a poor correlation between juniper diameter and form, no meaningful relationship between tree size and delimbing time was found ($P = 0.27$). A statistically significant difference was found between the time required to sort ($P = 0.41$) and to delimb and buck ($P = <0.001$) in the mixed and juniper north units as compared with juniper south. No statistical difference between the mixed and juniper north units was found ($P = 0.213$ comparing productive cycle times). Table 6 presents average cycle component times. On average, it took 1.73 minutes per stem in the mixed and juniper north units (\$3.17/sawlog) and 2.04 minutes per stem in juniper south (\$3.74/sawlog).

Table 7 presents a comparison of per piece costs per component and total costs per piece, per cubic foot, and per ton for each harvest unit.

A limited trial of 65 stems was conducted in the mixed stand to examine the changes in productivity and costs if fence posts were manufactured also. It was found that, on average, manufacturing a fence post from a tree that also contained a sawlog increased the total time to manufacture a single stem from 1.33 minutes (\$2.44) per stem including delays for a sawlog alone to 1.56 minutes (\$2.86) per stem for a sawlog and a fence post. Bucking fence posts from stems that also included a sawlog increased the number of merchantable logs (both sawlogs and fence posts) per stem to 1.7. This resulted in a per piece cost of \$1.52. To manufacture fence posts from a stem that does not also contain a sawlog, the total time to delimb and buck the stem averaged 1.14 minutes (\$2.10) and resulted in 1.3 merchantable logs per stem. This merchandizing scheme resulted in a cost per log of \$1.83. The impact of these three merchandizing scenarios on the costs per piece, per cubic foot, and per ton for the mixed unit is presented in Table 8.

Soil Compaction

Soil penetrometer readings were taken pre- and postharvest at the same points along established transects. A paired t-test with an alpha (α) of 0.05 was use to compare blow counts between pre- and postharvest measurements (Table 9). Data pairs where one or both measurements hit rock were discarded for the analysis. A significant difference between pre- and postharvest blow counts was found in the control units at depths of 4 to 8 in., in the conventional harvest units at depths of 4 and 8 in., and at a depth of 2 in. in the mechanical harvest units (Figure 7). No significant difference in the test statistic (postharvest blow count minus the preharvest blow count) for the two harvest types was found at any depth ($P = 0.461$, 0.418, 0.624, and 0.525 for depths of 2, 4, 6, and 8 in., respectively). A significant difference between the test statistic in the control units and the harvested units was found at depths of 2 and 4 in. ($P = 0.032$ and 0.001, respectively), but not at the deeper depths ($P = 0.212$ and 0.665 for 6- and 8-in. depths, respectively).

Discussion

Tree form appeared to have a large impact on the time required to fell trees and to delimb trees both manually and mechanically. Trees in the juniper south unit had larger and more numerous limbs, were multistemmed more often, and had smaller height-to-diameter ratios (more taper) than trees in the other units. Trees in the mixed unit were generally the best form trees of the three units, had smaller and fewer limbs, were more often single-stemmed, and had larger height to diameter ratios (less taper). No tree form classification exists for juniper and was not used in this study. The development of a classification system for juniper tree form that includes both quantitative and qualitative descriptions of each class would be useful for future studies.

For most of this study, only stems large enough to be categorized as sawlogs (straight, at least 8 ft long, and 6 in. in diameter at the small end) were considered to be merchantable. This left a large number of juniper stems that were unused. With the mechanical system, all stems were cut and skidded to a central landing. Those stems that were not of sawlog quality were then placed in a large slash pile. This had two consequences. First, a large amount of slash

Table 6. Mechanical delimbing results using a stroke-boom delimber to delimb and buck western juniper.

Component	Mixed and juniper north		Juniper south		P Value
	Time (min)	Percent of total cycle time	Time (min)	Percent of total cycle time	
Sort	0.45	26%	0.64	31%	0.041*
Delimb and buck	0.65	37%	0.94	46%	<0.001*
Deck	0.21	12%	0.17	8%	0.644
Productive cycle	1.28	74%	1.74	85%	<0.001*
Delay	0.45	26%	0.30	15%	0.443
Total cycle	1.73	100%	2.04	100%	0.206
Cost per sawlog	\$3.17		\$3.74		
Diameter	11.4 in.		11.3 in.		0.947
n	173		152		

*Statistically significant difference between the mixed and juniper north units and the juniper south unit.

Table 7. Cost results for the three harvest units using the mechanical harvest system.

	Felling	Limbing/bucking	Bunching	Skidding	Decking	Nonproductive	Total
Juniper north							
Feller-buncher	$0.45	—	$0.34	—	—	$0.34	$1.12
Skidder	—	—	$0.42	$2.25	—	$1.15	$3.82
Delimber	—	$1.17	—	—	$1.19	$0.81	$3.17
Total $/piece	$0.45	$1.17	$0.76	$2.25	$1.19	$2.29	$8.11
Total $/ft^3	$0.06	$0.16	$0.10	$0.30	$0.16	$0.31	$1.08
Total $/ton	$3.32	$8.69	$5.60	$16.69	$8.81	$16.97	$60.07
Juniper south							
Feller-Buncher	$0.38	—	$0.29	—	—	$0.29	$0.96
Skidder	—	—	$0.42	$2.25	—	$1.15	$3.82
Delimber	—	$1.72	—	—	$1.46	$0.56	$3.74
Total $/piece	$0.38	$1.72	$0.71	$2.25	$1.46	$2.00	$8.52
Total $/ft^3	$0.05	$0.23	$0.09	$0.30	$0.19	$0.27	$1.14
Total $/ton	$2.84	$12.74	$5.25	$16.69	$10.80	$14.78	$63.11
Mixed							
Feller-buncher	$0.24	—	$0.35	—	—	$0.62	$1.21
Skidder	—	—	$0.42	$2.25	—	$1.15	$3.82
Delimber	—	$1.17	—	—	$1.19	$0.81	$3.17
Total $/piece	$0.24	$1.17	$0.77	$2.25	$1.19	$2.57	$8.20
Total $/ft^3	$0.03	$0.16	$0.10	$0.30	$0.16	$0.34	$1.09
Total $/ton	$1.79	$8.69	$5.71	$16.69	$8.81	$19.05	$60.74

The first four rows for each unit are in terms of $/piece. Cost estimates assume a 12-in. average diameter and a 350-ft skidding distance.

Table 8. Cost results for the mixed unit using the mechanical harvest system and three merchandizing scenarios.

	Felling	Limbing/bucking	Bunching	Skidding	Decking	Nonproductive	Total
Mixed-sawlogs only							
Feller-buncher	$0.24	—	$0.35	—	—	$0.62	$1.21
Skidder	—	—	$0.42	$2.25	—	$1.15	$3.82
Delimber	—	$1.17	—	—	$1.19	$0.81	$3.17
Total $/piece	$0.24	$1.17	$0.77	$2.25	$1.19	$2.57	$8.20
Total $/ft^3	$0.03	$0.16	$0.10	$0.30	$0.16	$0.34	$1.09
Total $/ton	$1.79	$8.69	$5.71	$16.69	$8.81	$19.05	$60.74
Mixed-fence posts out of stems with sawlogs							
Feller-buncher	$0.24	—	$0.35	—	—	$0.62	$1.21
Skidder	—	—	$0.25	$1.33	—	$0.68	$2.25
Delimber	—	$0.56	—	—	$0.57	$0.39	$1.52
Total $/piece	$0.24	$0.56	$0.60	$1.33	$0.57	$1.68	$4.98
Total $/ft^3	$0.03	$0.07	$0.08	$0.18	$0.08	$0.22	$0.66
Total $/ton	$1.79	$4.17	$4.43	$9.83	$4.22	$12.44	$36.89
Mixed-fence posts and sawlogs							
Feller-buncher	$1.24	—	$0.35	—	—	$0.62	$1.21
Skidder	—	—	$0.13	$0.72	—	$0.37	$1.22
Delimber	—	$0.68	—	—	$0.69	$0.47	$1.83
Total $/piece	$0.24	$0.68	$0.49	$0.72	$0.69	$1.45	$4.26
Total $/ft^3	$0.03	$0.09	$0.06	$0.10	$0.09	$0.19	$0.57
Total $/ton	$1.79	$5.02	$3.59	$5.33	$5.08	$00.74	$31.56

The first four rows of each merchandizing scenario are in terms of $/piece. Cost estimates assume a 12-in. average diameter and a 350-ft skidding distance.

and other nonmerchantable material was piled at the landing, providing a large obstacle to operate around; and second, costs were spread out over a smaller pool of merchantable products, increasing the per unit production price (Table 8 and Figure 8).

There was a large difference in production rates between the two harvest systems included in this study. It took the conventional system 1–2 weeks to harvest each unit whereas the mechanical system took 2 days to cut and 1 day to skid and delimb the same volume of juniper in each unit. For some managers, the time required to harvest an area may be as, if not more, important than the per unit price of harvesting.

No breakdowns or delays longer than 30 minutes were recorded for either harvesting system, and they were not known to occur at any time during the study. Equipment breakdowns have the potential to greatly increase production costs, especially with the older equipment used in the conventional system. This needs to be recognized and taken into account when extrapolating these results to other juniper harvesting situations.

Soil moisture readings were not taken for either sampling period. Although soil penetrometer readings were taken at the same time in the fall for both pre- and postharvest time periods, the study site experienced approximately 2 in. of fall rains before postharvest data collection. The data, nonetheless, suggest that both harvesting systems did cause an increase in soil compaction in the top 4 in. of the soil profile but that there was no difference between the two systems in terms of soil impacts. Although some soil compaction from harvesting is likely, managers felt that this compaction was within acceptable limits and was an

Table 9. Soil penetrometer paired *t*-test results

Depth	Mean blow count difference (post-pre)	*n*	SD	*P*	95% Confidence interval Lower	Upper
Control						
2 in.	−0.3	151	2.17	0.086	−0.65	0.004
4 in.	−1.66	131	6.57	0.005*	−2.79	−0.52
6 in.	−4.22	99	9.69	<0.001*	−6.16	−2.29
8 in.	−7.77	81	12.89	<0.001*	−10.62	−4.91
Conventional harvest						
2 in.	0.44	170	1.57	<0.001*	0.2	0.68
4 in.	0.34	153	4.87	0.390	−0.44	1.12
6 in.	−0.73	134	8.44	0.318	−2.17	0.71
8 in.	−2.56	117	12.34	0.027*	−4.82	−0.3
Mechanical harvest						
2 in.	0.38	143	1.32	0.001*	0.16	0.6
4 in.	0.14	139	3.9	0.664	−0.51	0.8
6 in.	−1.23	132	7.94	0.078	−2.59	0.14
8 in.	−1.81	124	11.1	0.072	−3.78	0.17

*Statistical significance.

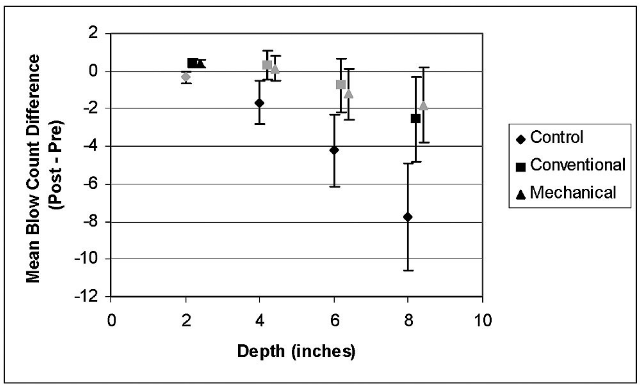

Figure 7. Soil penetrometer paired *t*-test results for the three harvest systems, where black symbols indicate statistically significant differences between pre- and postharvest blow counts and gray symbols indicate no significant change.

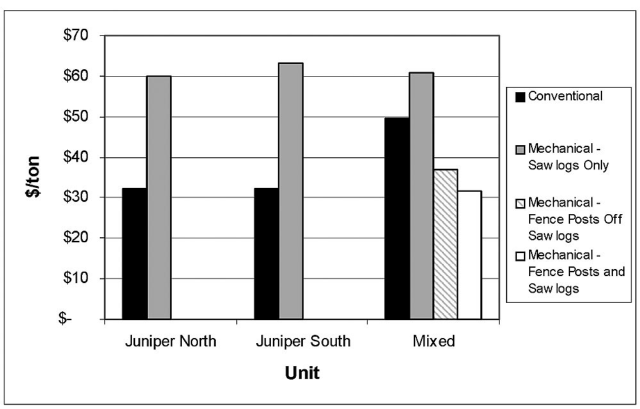

Figure 8. Comparison of total per ton cost to harvest western juniper using two harvesting systems in three units.

appropriate trade-off compared with the benefits of juniper removal.

In the mixed stand, the skidder operator for the conventional system attempted to save time (and therefore reduce costs) by prebunching the unit using the grapple skidder. This prebunching increased the total cost of bunching in the mixed unit nearly 140% over the other two units where stems were not bunched before assembling a turn during the skidding cycle (Table 5).

The feller buncher spent a disproportionate amount of time cutting and bunching nonmerchantable stems as compared with the manual felling. For example, the faller using a chainsaw spent 23% of his time limbing and felling stems less than 10 in. in diameter while this same material occupied 66% of the feller buncher's time. It would be worthwhile for future studies to look at alternative ways to fall small-diameter material. One option may be to have the feller buncher fall the larger, merchantable trees followed by a faller with a chainsaw to cut the remaining small-diameter trees. Another option would be to use a feller buncher with a hot saw (rotary disc cutting head) as opposed to the bar saw used in this study. With a hot saw the operator would not need to grab each stem to fell it and it could be faster than the bar saw in small-diameter material only if these trees do not need to be bunched and skidded to a central landing.

Many of the delays that were observed in this study resulted from unbalanced harvest systems (Tables 5 and 7). Future studies may benefit from exploring alternative system designs to better use each component of the harvesting system. For example, in the mechanical system the skidder waited for the stroke-boom delimber to finish processing the previous turn of stems before delivering the next turn to the landing. Decoupling these two components could potentially increase the overall efficiency of the harvesting system.

Conclusion

Two harvesting systems were applied to three stands of western juniper in central Oregon. The first of these two systems was a conventional harvesting system composed of manual felling and delimbing with a chainsaw and skidding with a rubber-tired grapple skidder. The other harvesting system studied was a mechanical system composed of felling and bunching with a feller-buncher, skidding whole stems with a rubber-tired grapple skidder, and limbing and bucking at a central landing with a stroke-boom delimber.

Stump to deck cost estimates ranged from \$32.15 to \$49.48/ton (\$0.58 to \$0.89/ft^3) for the conventional system and from \$60.07 to \$63.11/ton (\$0.08 to \$0.14/ft^3) for the mechanical system.

A limited trial of three merchandizing scenarios was performed with the mechanical harvest system in the mixed stand. The three scenarios were to produce sawlogs only (minimum of 8 ft in length with a small end diameter of at least six in.), to produce fence posts (minimum of 6 ft in length with a small-end diameter of at least 4 in.) out of the tops of stems that also contained a sawlog, and to produce both fence posts and sawlogs out of all stems of sufficient size. Producing sawlogs only resulted in a stump to deck cost of \$60.74/ton, also producing fence posts out of stems that also contained sawlogs resulted in a cost of \$36.89/ton, and producing both fence posts and sawlogs cost \$31.56/ton.

A soil penetrometer was used to measure soil compaction the fall before harvest and the fall after harvest. A statistically significant difference was found between the blow counts required to reach depths of 2 and 4 in. in the harvested units and the control units. There was no difference between the two harvesting systems. Although this data suggest harvesting did cause some soil compaction in the top 4 in. of the soil profile, managers did not feel this level of compaction was outside acceptable limits.

Literature Cited

Anderson, E.W., M.M. Borman, and W.C. Krueger. 1998. The ecological provinces of Oregon: A treatise on the basic ecological geography of the state. SR 990, Oregon Agricultural Experiment Station. 138 p.

Azuma, D.L., B.A. Hiserote, and P.A. Dunham. 2005. The western juniper resource of eastern Oregon. USDA For. Serv. Resourc. Bull. PNW-RB-249, Pacific Northwest Research Station, Portland, OR. 18 p.

Bedell, T.E., L.E. Eddlemann, T. Deboodt, and C. Jacks. 1993. Western juniper—Its impact and management in Oregon rangelands. EC 1417, Oregon State University Extension Service, Corvallis, OR.

Brockway, D.G., R.G. Gatewood, and R.B. Paris. 2002. Restoring grassland savannas from degraded pinyon-juniper woodlands: Effects of mechanical overstory reduction and slash treatment alternatives. J. Environ. Manage. 64:179–197.

Central Oregon Intergovernmental Council. 2005. The western juniper commercialization feasibility study for the Prineville area. Report to Oregon Watershed Improvement Board. 8 p.

Chittester, J.M., and C.D. MacLean. 1984. Cubic-foot tree volume equations and tables for western juniper. USDA For. Serv. Res. Note PNW-420. 8 p.

Herrick, J., and T.L. Jones. 2002. A dynamic cone penetrometer for measuring soil penetration resistance. Soil Sci. Soc. Am. J. 66:1320–1324.

Miller, R.F., T.J. Svejcar, and J.A. Rose. 2000. Impacts of western juniper on plant community composition and structure. J. Range Manage. 53:574–585.

Sauerwein, W.J. 1982. Western juniper site index curves. USDA Soil Conservation Service, Woodland Tech. Note 14, West Technical Service Center, Portland, OR. 4 p.