Early Precommercial Thinning of Redwood Sprout Clumps: Evaluation of Four Techniques

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ABSTRACT

Redwood (*Sequoia sempervirens* (D. Don) Endl.) responds favorably to sprout clump thinning in clearcut environments, but appropriate silvicultural techniques for this practice have not been developed. Four power tools for this unique application were evaluated: standard mid-sized chainsaw (long saw), small arborist chainsaw (short saw), power hedge trimmer, and a customized power brushcutter. Linear mixed effects model analysis was conducted to determine tool differences in clump processing speed, transit time, cycle time, and worker difficulty (peak heart rate). Machine costs and unit production costs were calculated separately for each tool, and perceived ease-of-use by workers was noted. Clump difficulty (sprout clump size) was a strong determinant of processing time and affected the performance of each tool differently. The long saw performed well across the range of clump difficulties but forced the highest heart rates in operators and was the most costly. The short saw was especially proficient on easy to moderate clumps, was among the least difficult, and was the least costly; it was the clear favorite for easy clumps. The hedge trimmer was among the fastest and least difficult, but its capability was constrained by sprout caliper. The brushcutter's lackluster performance and several inadequacies prevent its recommendation. Regardless of tool selection, the condition of the sprout clump is a factor that must be taken into consideration since it strongly affects average production rates (clumps processed per productive machine hour) and area costs. Sprout age and clump size should guide tool selection, but should also be considered by operators in selectively choosing a subset of crop stumps for sprout clump thinning.

Keywords: *intensive silviculture, coppice, stump sprout, natural regeneration, reforestation, machine cost analysis, Sequoia sempervirens, sprout clump thinning*

Introduction

The capacity of redwood (*Sequoia sempervirens* (D. Don) Endl.) to regenerate vegetatively from epicormic basal sprouts (stump sprouts) is a rare characteristic among conifer species of major commercial importance. Like redwood, oak species (*Quercus* spp.) of eastern North America sprout vigorously after cutting, and sprouts are actively managed in coppice-based silvicultural strategies (Johnson 1975, Gardiner and Helmig 1997, Cook et al. 1998). There, the practice of thinning oak sprout clumps at an early age has been deemed a valuable tool for increasing volume growth in commercial oak forests (Lamson 1988, Lowell et al. 1989, Groninger et. al. 1998), even resulting in models of growth that are specific to thinned sprout clumps (Johnson and Rogers 1984). To date, however, little attention has been given to the operational potential of sprout clump thinning on redwood timberlands.

Sprouting, as an alternative to sexual reproduction, provides redwood with high levels of productivity, a competitive advantage following disturbance, and the ability to survive a wide range of disturbances (Douhovnikoff et al. 2004). Often emerging from stumps within weeks of cutting (Olson et al. 1990), and prolifically within 2 years (Barrette 1966), redwood stump sprouts have long been depended upon to complement planted seedlings and contribute to full stocking following harvest. Historically, establishment of redwood seedlings from seedfall in clearcuts has been infrequent, whereas redwood sprouts have established successfully under a wide variety of disturbance conditions (Fritz 1951). One survey of 163 second-growth stands revealed that stump sprouts comprised the majority of stems in fully stocked stands following harvest and reforestation (Lindquist and Palley 1963).

Sprout clump thinning is a form of early competition control that is analogous to stand density management and is intended to expedite the natural thinning process that sprout clumps undergo as sprouts compete within clumps. In partial cuttings, shade from overstory trees reduces sprout density and growth (O'Hara et al. 2007), and voids gains from sprout clump thinning (Cole 1983), but in the full-light environment that is typical of intensive forestry, all studies indicate that sprouts respond favorably to early clump thinning (Barrette 1966, Boe 1974, Cole 1983). All sprout clump thinning studies were conducted on clumps emerging from old-growth stumps, and none on sprout clumps from the smaller and more vigorous

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second-growth stumps that are now populating the region's third-growth forest.

In addition to growth enhancement, early thinning of sprout clumps can be seen as a form of forest protection that helps stands avoid or resist redwood's primary damaging agencies. Because redwood often sprouts prolifically, and with sprouts originating from the root collar, side, and top of a parent stump, early thinning of sprout clumps allows for selection of future crop trees that have favorable stability properties (Keyes and Matzka 2005). Foresters have routinely observed mechanical instability in sprouts that do not develop an independent root system and are prone to eventually "peeling off" the parent stump. Thinning at a young age also avoids bear damage common in older pre-commercially thinned redwood stands. Young redwoods are routinely targeted for cambium feeding by black bears (*Ursus americanus*) (Glover 1955, Olson et al. 1990), and the occurrence of such feeding damage is often intensified by local thinning activity (Russell et al. 2001).

Very little is known about the operational aspects of redwood sprout clump thinning despite its apparent potential value. In other regions, the novelty of the practice has invited the development of innovative silvicultural techniques. For example, in Appalachian mixed oak forests, Groninger et al. (1998) determined that selective herbicide stem spray and injection treatments were cost-effective alternatives to chainsaw thinning for 12-year-old oak sprout clumps, with comparable (positive) effects on residual sprout diameter growth. Others have focused on the sprout-generating harvest, assessing stump height, cutface angle, cutting year, and timing of cutting as means of reducing sprouts (Roth and Hepting 1943, Harrington 1984, Ducrey and Turrel 1992, Tappeiner et al. 1996). Knowledge of the costs and gains associated with alternative sprout treatments (Dwyer et al. 1993) is equally important yet is rarely addressed. In the redwood region, only Boe (1974) touched upon this subject with scant anecdotal information on the labor costs for five tools – all manual, none motorized – used to thin sprout clumps on old-growth stumps of 60 to 300 cm in diameter. That information is clearly outdated now.

Understanding the efficiency and accuracy of the tools capable of sprout clump thinning is important for guiding land managers' decisions regarding the thinning process. Since the potential economic benefits from thinning redwood sprout clumps at an early age remain unknown, any investment in the practice of sprout clump thinning will seek to minimize costs as much as possible. To address this need, this study was designed to evaluate the efficiency and thinning capabilities of four tools in a typical clearcut of 2-year-old redwood stump sprout clumps.

Methods

Study Area

The study site is located in the Freshwater Creek watershed of Humboldt County, California (N1/2 of SE1/4 of Section 27, T5N, R1E, Humboldt base and meridian). At the time of the study, the timberland lands were owned and operated by The Pacific Lumber Company; the current owner is Humboldt Redwood Company. In nearby Eureka, California, mean annual precipitation is 96.8 cm, varying in its seasonal distribution from 0.41 cm in July to 16.1 cm in December, and daily mean temperatures range from 8.8°C (December and January) to 14.8°C (August) (based on 1971 to 2000 monthly normals of Station EKA, National Climatic Data Center ID No. 042910).

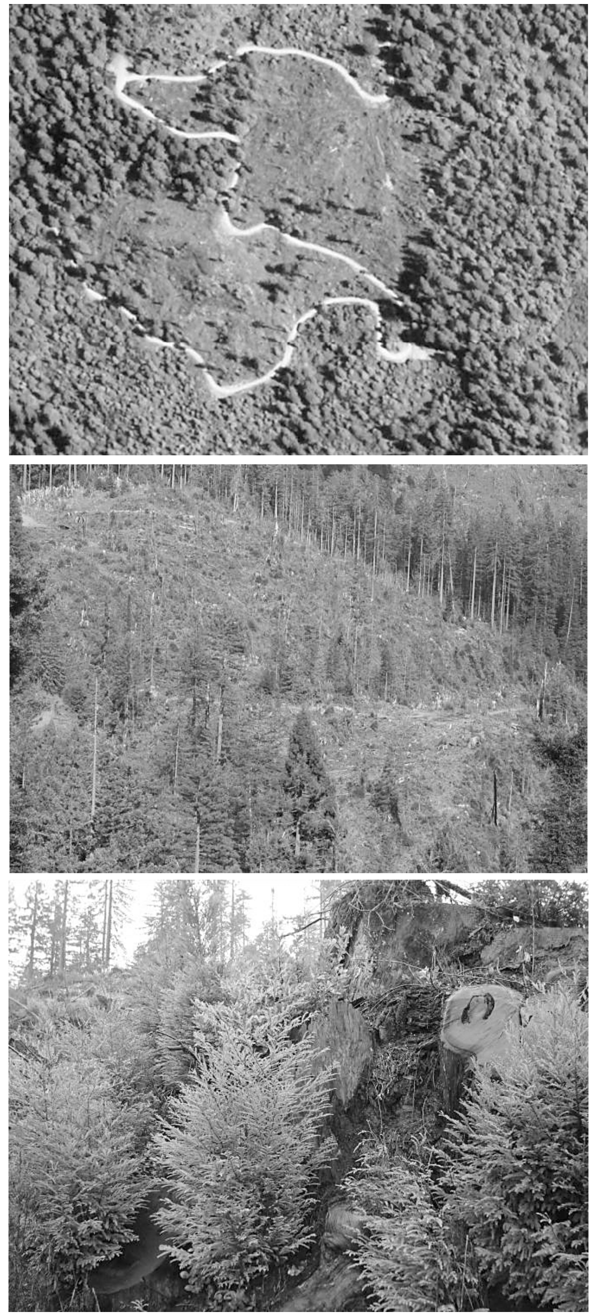

Figure 1. ~ *Aerial view of the study area immediately after clearcut harvest in 2005 (top). Cross-slope view 2 years later at the time of the present study (middle). Typical stump sprout clumps prior to thinning (bottom).*

The site had been clearcut in 2005 and broadcast-burned in 2006 (**Fig. 1**). Slash depth at the time of the study varied from several centimeters to more than 2 meters, but typically was approximately 60 cm deep. Stumps numbered approximately 247 to 296 per hectare with an average diameter of 83.1 cm (± 53.1 standard deviation [SD]) and height of 72.9 cm (± 47.0 SD). More than 95 percent of stumps exhibited sprouting around 25 percent or more of the stump circumference. The mean sprout density was 17 stems per clump but varied widely (± 19.7 SD). Basal sprouts accounted for 77.6 percent of all stump sprouts, the remainder emerging from the tops and sides of stumps. The mean sprout height was 323.6 cm (± 70.1 SD).

In addition to redwood and tanoak (*Lithocarpus densiflorus*) stump sprouts, vegetation included planted redwood seedlings and evergreen huckleberry (*Vaccinium ovatum*), but stump sprout clumps were free from external competition. A few overstory trees had been retained in the clearcut but none of these were in the vicinity of this study's experimental units (stumps).

Treatments and Data Collection

The attributes of four sprout thinning tools were quantified based on timing and operator heart rate. All of the tools were tested by two technicians on 2-year-old sprouts on a single uniform site. Tools included

- a small engine arborist's chainsaw with a 35.5 cm bar (Echo CS-341; 33.4cc engine; "short saw"),
- a typical mid-sized chainsaw with a 71 cm bar (Husqvarna 359; 59.0cc engine; "long saw"),
- a power hedge trimmer (Stihl HS-80; 25.4cc engine; "hedge trimmer"), and
- a power string trimmer modified for this purpose into a brushcutter with a shortened shaft and a rotary toothed cutting blade (Husqvarna 324LDx; 25.0cc engine; "brushcutter") (**Fig. 2**).

Each operator used each tool in a monitored trial of approximately 2 hours. A total of 157 sprout clumps were processed.

A timekeeper assigned to each operator recorded shift times with a stopwatch and distinguished each cycle element (clump-to-clump transit, clump processing) in addition to any mechanical or personal breaks. Each equipment trial began with an unmonitored clump thinning to warm up the operator. The first cycle was initiated when the operator began his traverse from the warm-up clump to the next nearby clump. Operators were required to carry all tools, fuel, and bar oil during operation. They worked simultaneously in different areas to reduce any potential influence of worker competition on performance and speed. The operators worked with each tool at a typical working pace and did not interact with timekeepers except to read and announce peak heart rate during operation. Timekeepers also determined the distance and average percent slope of each clump-to-clump traverse with the use of an Impulse 200 LR laser rangefinder and a Suunto clinometer.

Each clump's processing time was calculated as the total time necessary to thin the sprout clump down to the two largest and vigorous-appearing basal sprouts. Any effort necessary to clear stumps of thinning debris was included in processing time. Treatment success was determined by timekeepers observing the condition of the two residual sprouts following treatment. If both sprouts remained intact and undamaged after processing, the processing at that clump was considered "successful." Each tool was graded on overall success rate, with a grade of Excellent for an overall success rate of 95 percent, Acceptable at 90 percent, and Unacceptable below 90 percent.

Figure 2. ~ *Sprout clump thinning with the long saw (top), hedge trimmer (middle), and brushcutter (bottom).*

In addition to processing time, timekeepers recorded transit time as the duration of the clump-to-clump traverse (inclusive of any pre-processing brushing around clumps). Each clump's cycle time was calculated as the sum of its processing time and antecedent transit time. Based on cycle time, production rate was calculated as the number of clumps processed per productive machine hour (PMH). Timekeepers noted any personal breaks taken by operators, as well as delays due to maintenance, refueling, and mechanical adjustments.

To further explain variability in responses and help isolate tool type as an explanatory factor, clump difficulty was visually rated by labeling them "Easy," "Moderate," or "Hard" based on the stump size and density of sprouts that comprised a clump. "Easy" clumps included stumps ≤ 61 cm in diameter with less than 100 percent sprout cover by stump circumference; "Moderate" clumps included stumps ≤ 61 cm in diameter with 100 percent sprout cover; and "Hard" clumps consisted of any stump with a diameter greater than 61 cm.

As an estimate of worker difficulty, peak heart rate during clump processing was measured using a chest-mounted pulse monitor with digital wristwatch-style recorder. Heart rate has been used as a proxy for worker difficulty in a wide range of studies measuring physical stress and intensity during athletic training (Jeukendrup and Van Diemen 1998). In a workplace example comparable to the present study, Sicking (1995) used heart rate to test firefighter response to various tool types. Different vibration frequencies also play a role in heart rate, a consideration given the variety of vibration levels of the tools used in this study (Jiao et al. 2004).

Following the standard method described by Miyata (1980), machine rate calculations were conducted to determine each tool's hourly cost in dollars ($USD) per PMH and per scheduled machine hour (SMH). The relatively short duration of the study precludes any determination of a tool-specific utilization rate, so a constant utilization rate of 80 percent was used for all four tools. Production rates calculated from this study's cycle times enabled calculation of per-tool unit production costs in dollars per treated clump. All machine cost input assumptions and value assignments are provided in **Table 1**.

Statistical Analysis

There were four responses of primary interest. Transit time was analyzed as a response to determine whether tool weight/balance affected a worker's clump-to-clump traverse. Processing time described the efficiency of tools in thinning clumps. Cycle time, calculated as the sum of each clump's processing time and its antecedent transit time, determined the overall per-clump processing time per tool, and allowed calculation of production rates. Peak heart rate (measured immediately following clump processing) was analyzed as a metric indicating a tool's ease-of-use.

Linear mixed effects model analysis (McLean et al. 1991) was conducted as a hypothesis-testing instrument, with F-tests (α = 0.05) utilized to determine the significance of differences among the four response (dependent) variables. Three factor (categorical) variables (tool type, clump difficulty, operator) and two covariate (continuous) variables (traverse distance, traverse slope) were included in models as fixed effects. In order to determine whether there was any difference between tools for different types of clumps, the (tool type) × (clump difficulty) interaction term was also included. The statistical software package NCSS (Hintze 2007) was used to conduct all of the mixed model analyses. The Newton-Raphson method was used to solve restricted maximum likelihood equations. Results are reported as means followed by standard errors in parentheses.

Table 1. ~ *Assumptions and value assignments used in machine rate calculations.*

Assumption	Long saw	Short saw	Hedge trimmer	Brush cutter
Purchasing price ($)	640	310	469	380
Salvage value ($)	0	0	0	0
Economic life (yr)	1	1	1	1
Scheduled machine hours (SMH)	2,000	2,000	2,000	2,000
Utilization (%)	80	80	80	80
Productive machine hours (PMH)	1,600	1,600	1,600	1,600
Interest, insurance, and taxes (%)	15	15	15	15
Maintenance and repair (%)	100	100	100	100
Fuel use rate (*l*/PMH)	3.79	0.50	1.89	0.47
Fuel cost ($/l)	1.00	1.00	1.00	1.00
Lubricant consumption rate (*l*/PMH)	2.84	0.06	0.04	1.18
Lubricant cost ($/*l*)	1.84	1.84	1.84	1.84
Wages ($/SMH)	15	15	15	15
Benefits (%)	40	40	40	40

Table 2. ~ *Summary attributes of work and working conditions, provided separately for each tool. Values for distance are medians of observed values; values for slope are means of observed values; and values for transit time are fitted least-squares means, adjusted for covariates (traverse slope and traverse distance). Standard errors are in parentheses. Only distance was a significant determinant of transit time (p < 0.0001).*

Assumption	Long saw	Short saw	Hedge trimmer	Brush cutter
Traverse distance (cm)	46.5 (4.8)	45.7 (6.4)	40.0 (8.9)	51.3 (10.7)
Traverse slope (%)	–4.0 (3.6)	–17.7 (3.2)	–10.9 (3.8)	–6.6 (3.7)
Clumps processed	52	42	32	31
Transit time (s)	79.9 (9.3)	65.4 (10.0)	56.6 (11.5)	92.0 (11.8)

Results

Attributes of the working conditions and work performed, including aspects of the clump-to-clump traverse, are summarized separately for each tool in **Table 2**. Transit time between clumps averaged 74 (± 5.3) s but varied with a distribution that was non-normal (**Fig. 3**). Slope did not affect transit time ($p >$ 0.3392), but distance did ($p < 0.0001$), and the distribution of traverse distances resembled transit time (**Fig. 3**). There were substantial differences in the mean transit time between tools (fastest for hedge trimmer at 56 [± 11.5] s; slowest for brush-

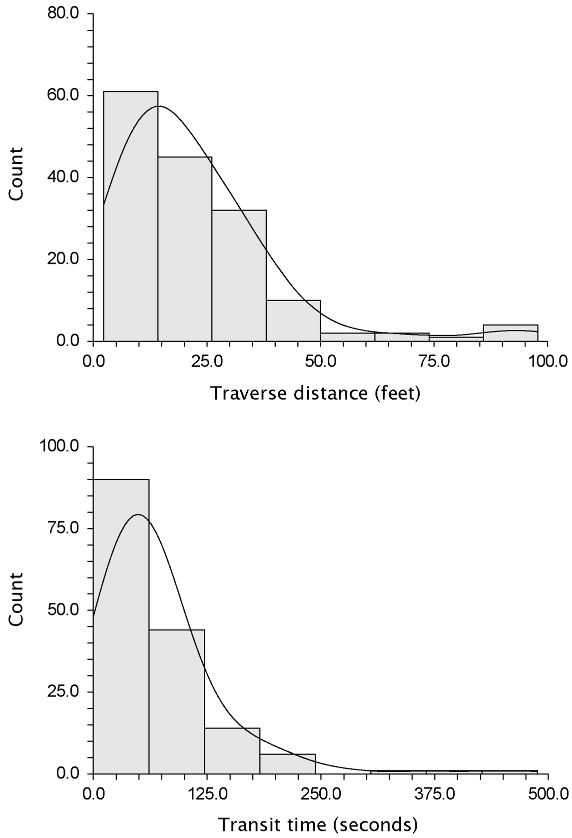

Figure 3. ~ *(Top) Frequency distribution of stump-to-stump traverse distances and (bottom) transit times. Traverse distance was the only significant factor determining transit times (p < 0.0001); neither tool type (p < 0.1376) nor slope (p > 0.3392) affected transit time.*

cutter at 92 [± 11.8] s), but these were not proven statistically significant even after accounting for operator, distance traveled, and the slope of terrain traveled ($p > 0.1376$). The two operators moved at a similar pace and were distinguished by an average difference of just over 9 s per transit, an amount that was not statistically significant ($p > 0.4106$). Tool hauling time appeared to depend in part upon the quantity of slash and brush the operators needed to traverse through, but this study did not account for those factors.

Processing time averaged 207 (± 9.3) s per clump (**Table 3**). Despite differences in the mean per-clump processing rates between tools (long saw fastest at 179 s; brushcutter slowest at 219 s), a high degree of clump-to-clump variability, even after accounting for operator and clump difficulty, resulted in no statistically significant difference between them ($p > 0.3226$). Clump difficulty proved to be a strong determinant of processing time ($p < 0.0001$; **Fig. 4**). "Moderate" clumps averaged 186 (± 14.3) s per clump; "Easy" clumps required just 100 (± 16) s; "Hard" clumps required 335 (± 17.3) s. For the two operators involved in the study, processing speeds were comparable: their mean difference was just 2.5 s, a difference that was negligible and not statistically significant ($p > 0.8964$).

Table 3. ~ *Least-squares mean performance responses per tool and clump difficulty level, adjusted for covariates (traverse slope and traverse distance). Cycle time is the composite of processing time and transit time (i.e., per-stump productive time). Clump difficulty is a categorical descriptor of a clump's stump size and sprout density (refer to text for details). For each response, letters across rows signify statistically significant differences between tools overall and within each difficulty level (α = 0.05).*

Response	Clump difficulty	Long saw	Short saw	Hedge trimmer	Brush-cutter	Overall
Processing time (s per stump)	Easy	98.8a	89.6a	86.9a	123.4a	99.7
	Moderate	138.5a	159.2a	258.9a	187.5a	186.0
	Hard	300.6a	393.9a	310.8a	336.3a	335.4
	Overall	179.2a	214.2a	218.8a	215.9a	207.0
Cycle time (s per stump)	Easy	190.6a	134.8a	156.7a	227.1a	177.3
	Moderate	216.7a	208.9a	308.2b	238.6ab	243.1
	Hard	370.0a	495.5b	361.5a	458.0ab	421.2
	Overall	259.1a	279.7a	275.5a	307.9a	280.5
Production rate (stumps per hr)	Easy	18.9a	26.7a	23.0a	15.9a	20.3
	Moderate	16.6a	17.2a	11.7b	15.1ab	14.8
	Hard	9.7a	7.3b	10.0a	7.9ab	8.5
	Overall	13.9a	12.9a	13.1a	11.7a	12.8
Peak heart rate (beats per min)	Easy	151.3a	125.8b	141.2c	145.4ac	140.9
	Moderate	152.8a	145.6ab	137.5b	144.7ab	145.1
	Hard	159.4a	148.0b	143.3bc	149.5abc	150.0
	Overall	154.5a	139.8b	140.7b	146.5b	145.4

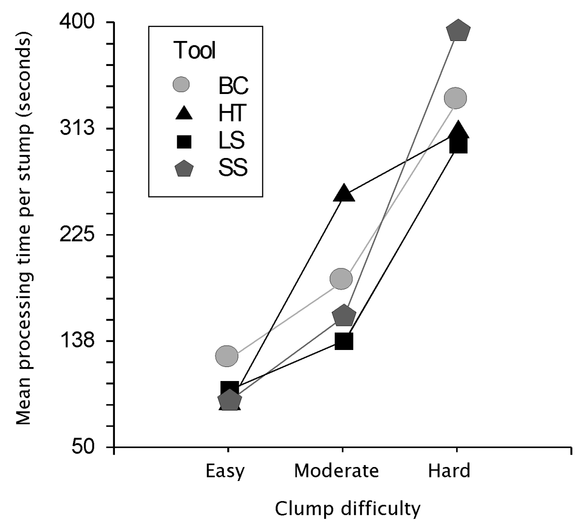

Figure 4. ~ *Mean clump processing times by tool type and clump difficulty. Clump difficulty was a strong determinant of processing time (p < 0.0001), but observed differences in tool type were non-significant (at α = 0.05) overall and within each level of clump difficulty. Legend: BC = brushcutter; HT = hedge trimmer; LS = long saw; and SS = short saw.*

Operator success rates were generally high, with just three cases of failure for the brushcutter and two for the hedge trimmer. But, the high proportion that they represented resulted in a grade of Unacceptable for the brushcutter (87% success rate) and Acceptable for the hedge trimmer (94% success rate). Both chainsaws thinned all of the clumps successfully and were graded Excellent on performance. The small number of failures prevents statistical analysis, but failure seemed associated with clump difficulty, as all but one of the failures occurred on clumps rated as Hard.

As a composite response characterizing per-clump production rates, cycle time was calculated as the sum of transit time and processing time for each clump. The average cycle time was 281 s (**Table 3**), for a production rate of 12.8 clumps per PMH. Distance and clump difficulty were significant factors in this composite productivity response ($p < 0.0011$ and $p < 0.0001$, respectively), as well as the tool × difficulty interaction term ($p < 0.0169$). The latter indicated differences in cycle time among tools depending upon clump difficulty.

Multiple comparison tests revealed the effect of clump difficulty level on each tool's performance, and differences among tools for each level of difficulty (**Table 3**). In comparing levels of difficulty on tool performances, it was found that hard clumps significantly slowed the brushcutter ($p < 0.0003$), long saw ($p < 0.0013$), and short saw ($p < 0.0001$) (**Fig. 5**). For the hedge trimmer the hike in cycle time occurred even with the shift from easy to moderate clump difficulty level ($p < 0.0046$). For easy clumps, which averaged 177.3 s each, there were no differences between tools ($p > 0.1009$). For moderate clumps, the hedge trimmer (308.2 s) was more than 1.5 min slower than both the short saw (208.9 s; $p < 0.0436$) and the long saw (216.7 s; $p < 0.0306$). But the promising efficiency of the short saw faltered with hard clumps. For hard clumps, the short saw had the slowest mean time (495.5 s), significantly slower than the hedge trimmer (361.5 s; $p < 0.0181$) and long saw (370.0 s; $p < 0.0178$). Overall, the brushcutter had the greatest mean cycle time (307 s) but high variance (greatest of all tools; 23.1 s S.E.). This high variance obscured any differences from the other tools at any clump difficulty, but its mean cycle time was slowest or second-slowest at each clump difficulty level, further eroding its appeal for this practice.

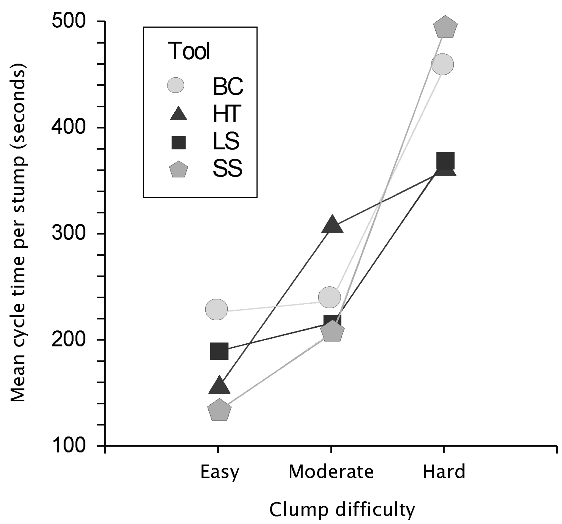

Figure 5. ~ *Mean clump cycle times (sum of processing time and transit time) by tool type and clump difficulty. Overall differences in tool type were non-significant at $\alpha = 0.05$. The interaction of clump difficulty and tool type, however, was significant ($p < 0.0169$), and differences were identified for specific tool contrasts within each clump difficulty level. By its strong influence on processing time, clump difficulty remained a strong determinant of cycle time overall ($p < 0.0001$). Hard clumps significantly slowed the brushcutter, long saw, and short saw; for the hedge trimmer this slowdown occurred even at the moderate clump difficulty level. Legend: BC = brushcutter; HT = hedge trimmer; LS = long saw; and SS = short saw.*

Peak heart rate averaged 145.4 beats per min (bpm) but varied widely depending upon clump difficulty level and tool type (**Fig. 6**), even after adjusting for operator ($p < 0.0002$) and the slope of the antecedent traverse ($p < 0.0205$). Distance of the traverse was not a significant factor ($p > 0.1525$). For all levels of clump difficulty, the highest levels of stress were induced by the long saw, which averaged 154.5 bpm (**Table 3**). This result corroborated the impressions of the operators, both of whom reported fatigue at the end of the long saw trial. The short saw produced the lowest average heart rate overall (139.8 bpm), and the lowest found in this study: 125.8 bpm for easy clumps. The hedge trimmer produced the lowest heart rates for moderate clumps (137.5 bpm) and hard clumps (143.3 bpm), though not statistically different from the short saw for the former, and the short saw and brushcutter for the latter.

Machine cost analysis (**Table 4**) revealed that the lowest treatment costs were associated with the short saw and hedge trimmer. Unit production costs for those tools ($1.70/clump and $1.77/clump, respectively) were notably less (on average, $0.31 less per treated clump) than the brushcutter ($2.01/clump) and long saw ($2.08/clump). Comparing the two ex-

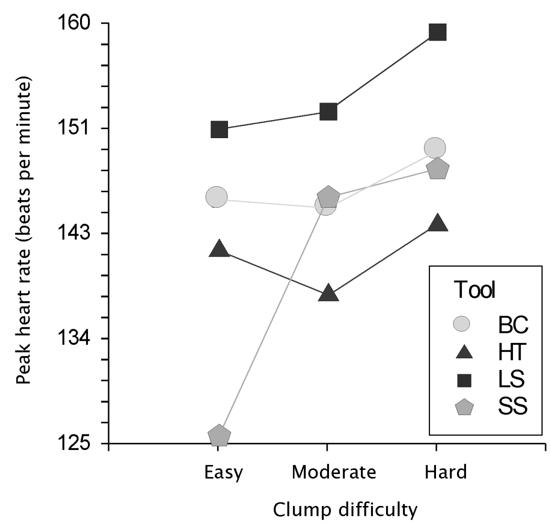

Figure 6. ~ *Mean peak heart rate experienced by operators by tool type and clump difficulty. Overall heart rate when using the long saw was significantly greater than when using all of the other tools at $\alpha = 0.05$. Legend: BC = brushcutter; HT = hedge trimmer; LS = long saw; and SS = short saw.*

Table 4. ~ *Machine costs as calculated according to the method described by Miyata (1980) and based on assumptions provided in Table 1.*

Cost		Long saw	Short saw	Hedge trimmer	Brush-cutter
Hourly machine cost ($/SMH)	Fixed	0.37	0.18	0.27	0.22
	Variable	7.52	0.65	1.81	2.31
	Labor	21.00	21.00	21.00	21.00
	Total	28.89	21.83	23.08	23.53
Hourly machine cost ($/PMH)	Fixed	0.46	0.22	0.34	0.27
	Variable	9.40	0.82	2.26	2.88
	Labor	26.25	26.25	26.25	26.25
	Total	36.11	27.29	28.84	29.41
Unit processing cost ($/stump)		2.08	1.70	1.77	2.01

treme cost values, use of the long saw versus the short saw results in a 23 percent increase in costs. Assuming a stump density similar to this study's project area (247 to 296 per ha), operators can anticipate that the corresponding per ha treatment cost would be as little as approximately $169 to $203 for the short saw and as great as $208 to $250 for the long saw.

Discussion

For all of the tools, the majority of total trial time was taken up by clump processing followed by transit time. Thinning sprouts was the primary activity assigned to the operators and the tools were primarily dedicated to this focus during each trial. Hence the primary focus in assessing tool properties is appropriately aimed at the processing effort.

Operators were the most familiar with the long saw and comfortable with its use. The long saw could easily cut through all of the stem diameters and had a long reach, reducing the amount of operator movement during thinning. It proved a strong performer on difficult clumps in particular due to its ease in reaching distant sprouts and in thinning quantities of sprouts quickly. The long saw, however, caused the highest peak heart rates during thinning. The long saw was the heaviest tool used during this study, requiring more strength to lift and maneuver around clumps, which could slow cycle times and increase personal time over longer timeframes. Both operators reported fatigue after the 2-hr-long saw trials were over. Although not statistically significant due to high variance, the mean transit time was high and exceeded only by the brushcutter.

The short saw was the lightest tool to carry, and the design was balanced to be operated at eye level, a cutting position used frequently by the operators. Though the shorter bar on the arborist chainsaw was an initial safety concern with regard to potential kickback, operators in this study found the small saw comfortable and convenient. It provided operators with greater cutting precision due to its shorter bar length, and operators found they could easily select and thin around desired residual sprouts. This ease of use was reflected in the lowest heart rates of all four tools (although oddly, the greatest range in heart rates came with the short saw). Although its gas tank was smaller than the long saw, its substantially lower fuel use rate (the lowest of all four tools) indicates that refueling frequency over longer timeframes is expected to be low. The saw's size was a drawback only on larger, more difficult clumps, which slowed its speed considerably relative to the other tools.

During processing with the hedge trimmer, the operators could assume comfortable standing and sitting positions that were not possible with the other tools. The hedge trimmer offered operators the greatest protection from injury with its integrated guard that covers nearly three-quarters of the cutting teeth. Hence, operators could sit on stumps being processed and allow the hedge trimmer to cut through sprouts using the weight of the tool. But the hedge trimmer worked best on small clumps with sparse sprout coverage and was overwhelmed by clumps with large and numerous sprouts. Operators reported dissatisfaction with the extra effort necessary to make the tool cut through larger sprouts. If a sprout caliper was too large, the hedge trimmer could not cut through it and it had to be left on the stump, constraining the operator's ability to select desirable residual sprouts. Operators felt that the hedge trimmer could prove an efficient tool if restricted to younger, smaller 1-year-old sprouts. In transit, the hedge trimmer was the safest tool to walk with and demanded less care by operators during its conveyance.

The brushcutter was the least familiar tool used during the study: both blade type and angle were unfamiliar to operators. It was the only tool with a four-stroke engine, making it more fuel efficient, noticeably quieter during processing, and less cumbersome during transit (fewer maintenance items). It also produced less noxious fumes during operation, a valuable attribute because tools in the study were frequently operated at eye level and exhaust may be a problem for health over long periods of use. Blade jamming, however, was a problem with the brushcutter as it was occasionally with the hedge trimmer. Small sprouts and slash occasionally jammed the teeth, requiring the operator to stop and remove the debris. The highest frequency of residual sprout damage occurred with the brushcutter, primarily because the blade was difficult to angle for certain cuts and the blade had no brake to stop the saw between cuts. The brushcutter had less power than the other tools and sometimes required revving before cutting larger sprouts.

The exposed blade of the brushcutter had no brake, and during processing operators had to wait for it to slow before safely moving around the clump perimeter to treat other sprouts. The operators felt it to be imbalanced and potentially dangerous, as it tended to kick if the blade caught on a sprout. Care was required by the operators during transit with the brushcutter due to its imbalance and exposed blade; the lack of a brake on the blade resulted in operators waiting until the blade slowed before walking safely to the next clump.

The strong relationship of perceived sprout clump difficulty to processing time warrants consideration in tool selection and in clump selection during operations. Processing time, cycle time, and worker heart rates for all of the tools were strongly influenced by clump difficulty (used here as an integrative indicator of stump size and sprout density). More difficult clumps delayed the operator's selection of desired residual sprouts, were more cumbersome to walk around during processing, and required a longer period of active cutting. Operators often took breaks after treating particularly difficult clumps.

This factor is worth considering in the context of operational efficiency, especially given the relatively low overall production rate of 12.8 clumps per PMH. Stand-level treatment costs could be cut by the treatment by the operators of a subset of clumps representing crop trees. Given a choice among clumps to select for thinning, and assuming equivalent capacities for treatment growth response, operators could favor the selection of easy clumps, and thus enjoy measurably substantial gains in efficiency at the stand level. For example, in the time required to thin 10 hard clumps, an operator could complete over 17 moderate clumps or nearly 24 easy clumps (those numbers are inclusive of average transit times).

Favoring moderate and easy clumps for selection would also enable the use of the arborist saw, which had several advantages (including rapid processing and transit times), but which was slowed considerably by difficult clumps. But, opportunities for clump selection will be constrained by their density and spatial distribution. It could also prove true that hard sprout clumps are the manifestation of a more powerful root system that would favor growth response to thinning. If that is the case, losses in growth by selecting easy clumps would run counter to any gains in thinning efficiency. These findings also suggest that thinning younger sprouts would offer advantages in efficiency (the difficulty of all clumps should be lesser) that would further favor the arborist saw, as well as the hedge trimmer, which had several favorable properties and which was a strong performer on easy clumps.

It is an interesting finding of this study that the two tools demonstrating the greatest overall appeal for this practice (short saw and hedge trimmer) were also the lowest in cost. The short saw in particular, with highest production rates for easy and moderate clumps, lowest overall impact on worker heart rates, and lowest production costs, offers the greatest promise among these four tools for effective and efficient sprout clump thinning on an operational basis.

Although not a subject of this study, observations with regard to mechanical servicing needs were noted by the operators and timekeepers. Operators noted that the Echo CS-341 arborist saw requires a non-normal wrench size to adjust the bar. The hedge trimmer frequently had trouble starting. The brushcutter appeared to require the least mechanical service time: its blade teeth were designed to be sharpened by a common long file, it has better gas efficiency than the other tools, and it has no chain or other components requiring adjustment during operation. Had this study not illustrated serious deficiencies in the brushcutter's potential that eliminates its further consideration for this type of work, detailed study of mechanical service time in a study of longer duration would probably have been warranted.

The focus of this study was on the operation of sprout thinning, and observed differences in tool performance and efficiency were operationally significant. These differences, however, must also be considered in light of sprout clump thinning's effect on stand growth and yields for an adequate assessment of the practice's potential profitability. In oak stands of Missouri, a present net worth assessment by Dwyer et al. (1993) determined that sprout clump thinning, even when the practice was constrained to as few as 247 crop trees per hectare, is not an economical management practice for their local market conditions. In redwoods, mitigating future problems associated with dense third-growth sprout clump crops may be more important than any growth enhancements (Keyes and Matzka 2005).

From previous studies conducted in second-growth, the magnitude of the sprout clump thinning effect on residual stem diameter growth (28.6%) and height growth (35.3%) in clearcuts appears substantial (Cole 1983). If maintained to maturity, this realized gain could substantially reduce rotation length and reimburse sprout clump thinning costs. A parallel long-term study of third-growth redwood sprout growth in a clearcut located nearby the present study site has been established with treatments of no-thinning, thinning to 1 residual sprout, and thinning to 2 residual sprouts. That study is expected to consider the issue of profitability. Given the rapid rate of redwood growth, any realized gains associated with sprout clump thinning should soon be apparent.

Conclusions

This study provided useful insights into the practical operation of sprout clump thinning. Clump difficulty (stump size and sprout density) was a strong determinant of processing time, and affected the performance of each tool differently. The long saw is a common tool used by thinning crews, and it performed well across the range of clump difficulties, with high processing speeds and success rates. But, it forced the highest heart rates in operators at all three levels of clump difficulty, and its unit production cost was the highest. Fatigue over a longer period of time could further erode the production rates of the long saw. The arborist saw and hedge trimmer offered several advantages that support their recommendation. Operators felt both to be mechanically stable and safe, and both enabled stable and comfortable working positions during processing. The hedge trimmer was among the fastest and yielded low heart rates in operators, but its capability was constrained by sprout caliper. It has promise if sprouts are to be thinned at a younger age, and its efficacy on 1-year-old sprouts is worth investigating. The arborist saw was especially proficient on easy to moderate clumps, was accurate, was among the least difficult for workers, and had the lowest production cost; it was the clear favorite for easy clumps. The brushcutter was not outstanding in any regard, had the lowest success rate, and poses potential hazards to operators. Given its many drawbacks and the worthiness of alternative tools, the brushcutter is not recommended. Regardless of tool selection, stump sprout condition is a factor that must be considered, since average production rates (clumps processed per PMH) ranged widely for clumps rated as easy (20.3), moderate (14.8), and hard (8.6). Sprout age and clump size should guide tool selection, but should also be considered by operators in selectively choosing a subset of crop stumps for sprout clump thinning.

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