Removing Douglas-fir Cones With a Lower-Crown Branch Shaker

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A new type of branch shaker was developed to remove cones up to 25 ft (7.6 m) above the ground. In 1997 and 1998, the lower-crown branch shaker removed 64.5% and 76.0% of the cones from trees that averaged 28 ft (8.5 m) and 40 ft (12.2 m), respectively. The shaker had a crank arm mechanism that moved a vertically oriented 15-ft-long, 4-in-diameter (4.6-m-long, 10-cm-diameter) energy bar in a rapid oscillating motion. The shaker was most effective in removing cones when the energy bar was inserted 3 to 5 ft (0.9 to 1.5 m) into the interior of the crown and was powered so that it completed 1.5 to 2.0 oscillations per second. Shaking a 15-ft-high (4.6-m-high) zone around each tree required an average of 5.3 min, whereas shaking from 0 to 25 ft (0 to 7.6 in) required an average of 11.1 min. Tree Planters' Notes 49(3): 51-55; 2000.

Results from harvesting cones of Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco) with bole shakers are reported by the Missoula Technology and Development Center (MTDC 1972), Copes and Randall (1983b), and Copes (1985). These reports and additional results from operational cone collections in 3 different seed orchards (unpublished reports in the senior author's files) show that cone removal averages 60% to 70% when proper shaking techniques are used. Bole shakers remove most of the cones from the upper third of the crown, have intermediate success from the middle third, but have poor removal from the lower third of the crown (Copes and Randall 1983a).

A bole shaker must be physically attached to the lower bole of each tree to transfer the shaking energy to the tree. Most of that energy moves to the upper crown due to the pyramid or cone shape of the crown and bole. The result is that insufficient motion is transferred to branches in the lower crown. Thus, most of the cones remaining after shaking are in the lower crown. This situation has limited machine harvest of Douglas-fir, though bole shakers reduce cone collection costs by 50% (Copes and Randall 1983a).

In this report, we describe our research in developing a new cone shaker that increased harvest efficiency in the lower crown. The machine used an unusual oscillating mechanism to transfer shake energy directly to the cone-bearing branches. The lower-crown branch shaker is described, shaking procedures are detailed, and results from field tests in 1997 and 1998 are presented.

Methods and Equipment

A lower-crown branch shaker was designed and built with a 15-ft-long (4.6-m-long), 4-in-diameter (10-cm-diameter), aluminum energy bar (figure 1). The energy bar was the part of the shaker that hit the branches and cones and caused them to move rapidly back and forth. The shaker's crank arm mechanism (Pitman arm) pro-

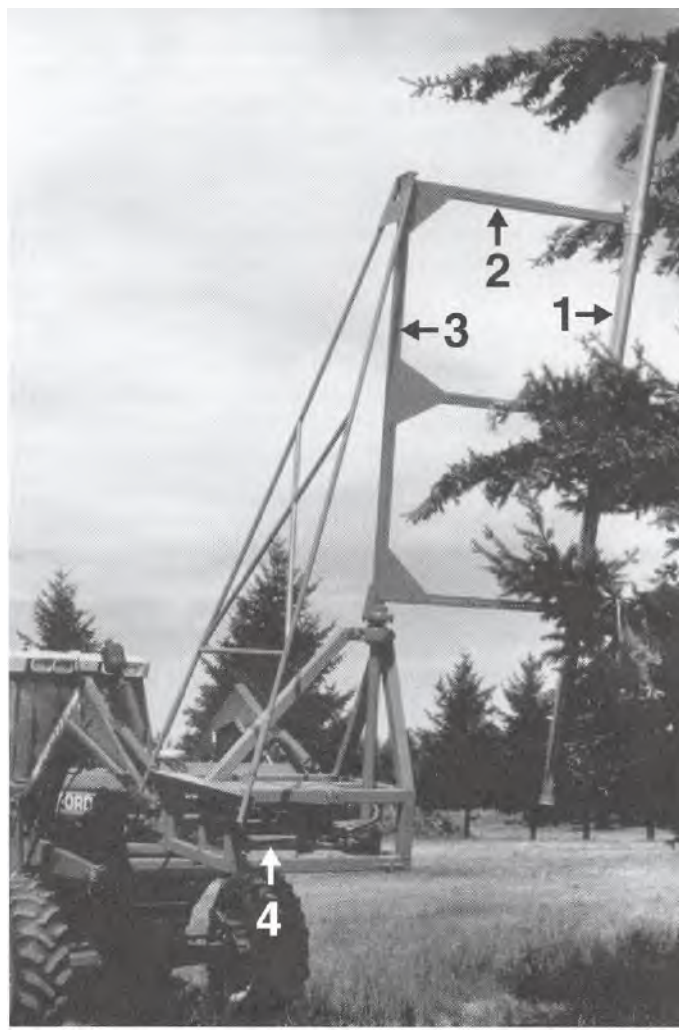

Figure *1—The* 1997 *lower-crown branch shaker is shown properly positioned within the perimeter of the crown.* 1 = *energy bar; 2 = horizontal support; 3 = vertical drive shaft; 4 = crank arm.*

duced the shaking action. Movement of the crank arm caused the vertical drive shaft to oscillate back and forth horizontally by 20 degrees, which caused a 27-in (68.6-cm) back-and-forth movement of the energy bar. A rotary hydraulic motor, connected to the tractor's auxiliary hydraulic system, powered the crank arm mechanism. An adjustable crossover relief valve was inserted in the hydraulic system to provide a safeguard in case the energy bar contacted oversized limbs or other immovable objects.

Due to the large size of the shaker, it was built on a rigid frame that mounted on the front-loader arms of a tractor (Ford model 7710; 70 HP; and 8,200 lb; 3,400 kg). A wide front end provided stability when the shaker was elevated to maximum height. The ability to raise or lower the shaker permitted the operator to position the energy bar at the proper height. Maximum reach of the energy bar was about 25 ft (7.6 m) above the ground.

The rapid back-and-forward oscillations of the energy bar created the motion needed to shake the cones from the branches. Operating the energy bar 3 to 5 ft (0.9 to 1.5 m) within the perimeter of the crown produced vigorous branch movement. The hydraulic motor caused the energy bar to oscillate horizontally (back and forth) through the crown as the tractor was driven around the outer perimeter of the crown. Cones were detached from the branches when the branches were moved rapidly back and forth following repeated impacts from the energy bar.

In 1997, the oscillation distance (stroke length) and the angle of the energy bar had to be adjusted manually by lengthening or shortening the horizontal supports holding the energy bar. Increased tilt or angle of the energy bar was obtained by adjusting the upper horizontal support so that it was longer than the lower horizontal support. In 1997, the upper and lower supports were adjusted at 52- and 38-in (132.1- and 96.5-cm) lengths, respectively. Preliminary trials showed that the energy bar did not generate sufficient impact energy when shorter bar lengths were used. The 14-in (35.6-cm) difference in length between the upper and lower supports tilted the bar about 15 degrees from the vertical. In 1998, we added a hydraulic piston that allowed the operator to change the energy bar orientation quickly and easily while shaking or moving toward a tree. The piston tilted the entire shaker in its frame and eliminated the need for unequal horizontal supports. In 1998, the energy bar was adjusted to 38 in (96.5 cm) from the vertical drive shaft. Stroke length was the same at the top and bottom of the energy bar.

During shaking, the energy bar oscillated 27 in (68.6 cm) in both forward and reverse to complete one cycle. Insufficient shaking motion was generated when the energy bar oscillated too slowly. Energy bar speeds of about 1.5 to 2 oscillations per second were effective for cone removal. Proper bar speed occurred between 1,700 and 1,900 tractor revolutions per minute. To obtain 2 oscillations per second, 8.75 gal (33.1 L) of hydraulic fluid was required per minute.

In 1997 and 1998, the shaker was tested on Douglas-fir trees growing in the Snow Peak and Vernonia blocks, respectively, of the State of Oregon's J. E. Schroeder Seed Orchard near St. Paul, Oregon. In 1997, only the lower 15-ft (4.6-m) zone of each tree was shaken. In 1998, all areas up to 25 ft (7.6 m) were shaken. In 1998, the lower 15-ft (4.6-m) zone was shaken first and then the shaker was raised to maximum height. The process was repeated in the 15- to 25-ft (4.6- to 7.6-m) zones of each tree.

Cones removed by the shaker were collected from plastic tarpaulins placed under each tree before shaking. Orchard workers handpicked all cones that remained attached to the branches in the shaken zone following shaking. Cones above the shaken zone were not handpicked and thus are not included in this report.

The shaken and handpicked cones from each tree were weighed (±1.0 lb, ±0.45 kg) with a spring scale. Ten- and 20-cone subsamples were weighed to ± 0.0001 lb (0.045 g) with a pan balance in 1997 and 1998, respectively. Average cone weights were calculated and used to estimate the total number of cones that were removed by shaking or handpicking. T-test and correlation analyses were made for all variables measured. Significance was set at P 0.05. No transformation of data before analysis was required.

Results and Discussion

The average percentage of cones removed by shaking (weight basis) was 64.5% in 1997 (table 1) and 76.0% in 1998 (table 2). The difference between years was significant ($P = 0.001$). The crop in 1997 could be described as a distress crop; many small cones were found on a few trees in the orchard block, but most of the trees were barren. The average weight of a cone removed by the shaker in 1997 was only 0.0293 lb (13.3 g) (table 1). The cone crop in 1998 was a normal crop in which most trees produced cones of normal size (average = 0.0453 lb, 20.5 g) (table 2). The difference among years in average cone weight was significant ($P = 0.005$).

The presence of larger and heavier cones resulted in greater cone removal. Correlations between cone size and removal percentage were significant in 1997 (P = 0.01 and 0.005 for percentages based on weight and number of cones, respectively). The same relation in 1998 approached significance (P = 0.08 and 0.06). The addition of the hydraulically controlled tilt mechanism permitted the operator to quickly and accurately position the energy bar so that it matched the vertical slope

Table *1-Tree size, cone data, and percentage of cone removal for 10 trees shaken in 1997*

Tree no.	Bole diameter (in, cm)	Height (ft, m)	Crown diameter (ft, m)	Single cone weight (lb, g) Shaker	Single cone weight (lb, g) Handpicked	Total cones in the 0- to 15-ft (4.6-m) zone (lb, kg)	Total cones in the 0- to 15-ft (4.6-m) zone (no.)	Cones removed by shaking (% by wt)	Cones removed by shaking (% by no.)	Time shaken (min)
1	12.1 (30.7)	33.5 (10.2)	34.0 (10.4)	0.0298 (13.5)	0.0245 (11.1)	85 (38.5)	3161	50.6	45.7	4.8
2	10.7 (27.2)	27.0 (8.2)	28.5 (8.7)	0.0222 (10.1)	0.0188 (8.5)	77 (35.0)	3597	77.4	74.4	5.2
3	9.0 (22.9)	30.0 (9.1)	20.5 (6.2)	0.0535 (24.3)	0.0439 (19.9)	54 (24.5)	1053	79.6	79.6	5.4
4	11.4 (29.0)	29.0 (8.8)	31.0 (9.4)	0.0263 (11.9)	0.0259 (11.7)	84 (38.0)	2831	62.2	61.9	5.1
5	12.0 (30.5)	33.5 (10.2)	31.0 (9.4)	0.0249 (11.3)	0.0241 (10.9)	80 (36.5)	3253	60.0	59.2	5.6
6	9.6 (24.4)	27.0 (8.2)	23.0 (7.0)	0.0278 (12.6)	0.0203 (9.2)	68 (31.0)	2581	85.3	80.9	5.7
7	8.3 (21.1)	27.5 (8.4)	21.0 (6.4)	0.0355 (16.1)	0.0335 (15.2)	86 (39.0)	2494	47.4	46.3	4.8
8	8.1 (20.6)	26.0 (7.9)	23.5 (7.2)	0.0250 (11.3)	0.0183 (8.3)	56 (25.5)	2678	46.4	38.9	6.5
9	6.3 (16.0)	21.0 (6.4)	20.5 (6.2)	0.0217 (9.8)	0.0156 (7.1)	76 (34.5)	3932	68.4	61.1	4.6
10	11.8 (30.0)	30.0 (9.1)	26.5 (8.1)	0.0263 (11.9)	0.0203 (9.2)	77 (35.0)	3207	67.5	61.6	5.4
Mean	10.0 (25.4)	28.4 (8.7)	25.9 (7.9)	0.0293 (13.3)	0.0245 (11.1)	74 (33.5)	2879	64.5	61.0	5.3

Table *2-Tree size, cone data, and harvest success from 20 trees shaken in 1998*

Tree no.	Bole diameter (in, cm)	Height (ft, m)	Crown diameter (ft, m)	Single cone weight (lb, g) Shaker	Single cone weight (lb, g) Handpicked	Total cones in the 0- to 25-ft (7.6-m) zone (lb, kg)	Total cones in the 0- to 25-ft (7.6-m) zone (no.)	Cones removed by shaking (% by wt)	Cones removed by shaking (% by no.)	Time shaken (min)
1	10.6 (26.9)	32 (9.8)	23.0 (7.0)	0.0422 (19.1)	0.0445 (20.2)	95 (43.0)	2237	89.5	90.0	12.3
2	8.6 (21.8)	37 (11.3)	21.5 (6.6)	0.0274 (12.4)	0.0215 (9.8)	61 (27.5)	2412	72.4	67.2	13.2
3	12.9 (32.8)	42 (12.8)	29.0 (8.8)	0.0425 (19.3)	0.0392 (17.8)	46 (21.0)	1103	76.1	76.4	8.1
4	8.0 (20.3)	34 (10.4)	21.0 (6.4)	0.0235 (10.7)	0.0199 (9.0)	68 (31.0)	3024	75.0	71.7	15.2
5	11.8 (30.0)	40 (12.2)	26.5 (8.1)	0.0433 (19.6)	0.0364 (16.5)	68 (31.0)	1606	88.2	86.3	16.4
6	11.3 (28.7)	38 (11.6)	29.0 (8.8)	0.0367 (16.6)	0.0319 (14.5)	61 (27.5)	1761	60.7	57.2	9.2
7	13.7 (34.8)	44 (13.4)	34.5 (10.5)	0.0518 (23.5)	0.0463 (21.0)	87 (39.5)	1739	70.1	67.7	10.5
8	11.3 (28.7)	44 (13.4)	30.5 (9.3)	0.0503 (22.8)	0.0395 (17.9)	105 (47.5)	2225	76.2	71.5	7.7
9	9.7 (24.6)	44 (13.4)	22.0 (6.7)	0.0420 (19.1)	0.0353 (16.0)	37 (17.0)	949	59.5	55.2	7.2
10	10.9 (27.7)	39 (11.9)	27.5 (8.4)	0.0525 (23.8)	0.0524 (23.8)	77 (35.0)	1468	71.4	71.4	8.6
11	10.6 (26.9)	41 (12.5)	26.5 (8.1)	0.0678 (30.8)	0.0617 (28.0)	47 (21.5)	706	80.5	79.3	8.3
12	12.6 (32.0)	46 (14.0)	25.5 (7.8)	0.0636 (28.8)	0.0530 (24.0)	94 (42.5)	1528	83.0	80.2	10.0
13	12.0 (30.5)	42 (12.8)	30.5 (9.3)	0.0270 (12.2)	0.0295 (13.4)	110 (50.0)	4002	79.1	80.5	10.4
14	10.7 (27.2)	38 (11.6)	29.0 (8.8)	0.0307 (13.9)	0.0239 (10.8)	57 (26.0)	1993	73.7	68.5	11.5
15	11.8 (30.0)	41 (12.5)	32.5 (9.9)	0.0282 (12.8)	0.0264 (12.0)	171 (77.5)	6201	68.1	64.5	16.0
16	11.3 (28.7)	39 (11.9)	25.0 (7.6)	0.0542 (24.6)	0.0504 (22.9)	156 (71.0)	2923	78.8	77.6	12.2
17	12.0 (30.5)	34 (10.4)	29.5 (9.0)	0.0698 (31.7)	0.0676 (30.7)	262 (119.0)	3789	72.1	71.5	10.9
18	9.4 (23.9)	40 (12.2)	25.5 (7.8)	0.0660 (29.9)	0.0648 (29.4)	54 (24.5)	820	83.3	83.0	6.9
19	10.5 (26.7)	41 (12.5)	31.5 (9.6)	0.0673 (30.5)	0.0649 (29.4)	73 (33.0)	1088	90.4	90.1	11.7
20	10.0 (25.4)	40 (12.2)	27.0 (8.2)	0.0269 (12.2)	0.0228 (10.3)	48 (22.0)	1878	70.8	67.3	16.7
Mean	11.0 (27.9)	40 (12.2)	27.3 (8.3)	0.0453 (20.5)	0.0416 (18.9)	89 (40.5)	2173	76.0	73.9	11.1

of each crown. More accurate positioning of the energy bar permitted the bar to move faster, which increased the movement of the cone-bearing branches.

The trees shaken in 1998 were taller than the 1997 trees (40 versus 28.4 ft, 12.2 versus 8.7 m) [$P = 0.0001$), but they did not have significantly different bole or crown diameters (tables 1 and 2). Crown diameters ranged from 21 to 34.5 ft (6.4 to 10.5 m), so the distance the tractor traveled while shaking a tree ranged from 132 to 216 ft (40 to 66 m) per height zone. That distance doubled when 2 heights were shaken because the tractor had to travel around the perimeter twice.

Considerable among-tree variation in crown structure existed because no crown pruning or topping was done before shaking. Some trees had long, open internodes that allowed light to penetrate to the bole, and others had dense crowns with little light in the inner crown. The crown surface of some trees was quite irregular due to the random occurrence of atypically long branches. Trees with long, open internodes often produced many cones in the interior of the tree that could not be reached by the energy bar. It was also difficult for the operator to maintain proper energy bar position in the crowns of trees with irregular crown surfaces. Thus, most cones that required handpicking were missed or were not properly moved by the energy bar.

Large branches slowed the energy bar when it was inserted too far into the crown. Heavy branch resistance opened the crossover relief valve, which then slowed or stopped the action of the energy bar. Most effective shaking occurred when the energy bar moved through the outer 3 to 5 ft (0.9 to 1.5 m) of the crown and when the energy bar hit the branches perpendicular to their long axes. Oblique hits transferred less energy to the branches and resulted in less-vigorous branch movement. Few cones remained on vigorously shaken branches. Also, unnecessary bark abrasion occurred when the energy bar was allowed to continue oscillating while the tractor was stationary. Shaking from a fixed position caused repeated impact on the same area of a branch.

Removal percentages, based on number of cones, were about 2% to 3% less than percentages based on weight of cones harvested (tables 1 and 2). This difference was not significant. The correlation coefficient between measurements was $r = 0.985$. Average weight of a handpicked cone was 19% and 9% less in 1997 and 1998, respectively, than the weight of a cone removed by shaking. One likely cause of this difference was that handpicked cones were not weighed until the day after the trees were shaken. Cones removed by shaking were weighed immediately following shaking. Another possible cause of the size difference was that most of the handpicked cones came from the interior of the crown where the cones may have been smaller and thus less readily removed by the shaker.

The shaker created good branch movement when the energy bar completed 1.5 to 2.0 oscillations per second. Removal efficiency decreased at slower oscillations. The impact of the energy bar on its forward motion moved all engaged branches rapidly forward and quickly released the branches when the crank arm mechanism reversed the direction of the energy bar. Each branch was hit repeatedly as the crank arm oscillated the energy bar. The number of impacts per branch was determined by branch length, tractor ground speed, and the number of oscillations per second completed by the energy bar.

The full potential of the shaker was not realized because the turning radius of the tractor was not small enough to keep the energy bar correctly positioned at all times. As the tractor moved, the energy bar was gradually carried out of the crown rather than remaining 3 to 5 ft (0.9 to 1.5 m) from the perimeter. To overcome this problem, the driver stopped the tractor when the energy bar exited the crown and drove in reverse along the original path, while continuing the shaking, until the energy bar emerged from the crown again. The machine was driven around the tree to the next unshaken area and the same forward-backward maneuver was repeated. This process was repeated 4 or 5 times until the entire circumference was shaken. Shaking while the tractor backed along its original path was very effective in removing cones.

Moving the tractor caused each succeeding stroke to hit several inches from the previous point of impact. Most large, main-whorl branches received 7 or more impacts by the energy bar each time the shaker moved across the branches during the forward or backward movement of the tractor. Failure of the operator to maintain proper orientation of the energy bar dampened the shaking action.

The tractor had to move slowly so that each branch received sufficient impacts from the energy bar to cause the cones to separate from the branches. A tractor speed of about 30 ft/min (9 m/min) was used in both years. Shaking the lower 15-ft (4.6 m) zone around each tree required an average of 5.3 min in 1997 (table 1), and shaking the lower 25 ft (7.6 m) of a tree in 1998 required 11.1 min (table 2).

Conclusions

In 1998, 76% of all cones found within 25 ft (7.6 m) of the ground were removed with the lower-crown branch shaker. The crank arm mechanism created a shaking motion that was very effective in removing cones without causing extensive physical damage to the trees. Only minor twig breakage and bark abrasion occurred. Neither jeopardized the future health or cone-producing capability of the trees.

Effective machine harvest of cones from trees taller than 25 ft (7.6 m) is possible if harvesting is done with both a bole shaker and the lower-crown branch shaker. Bole shakers can rapidly and economically remove most cones in the upper half of the crown, while the lower-crown shaker is very effective up to a height of 25 ft. (7.6 m). We propose a harvest sequence in which trees are first shaken with a bole shaker and then with the lower-crown branch shaker. The combined harvest on trees up to 40 ft (12.2 m) tall should average about 90%; 65% to 70% of all cones with the bole-shaker, plus 76% of the 25% to 30% remaining on the lower 25 ft (7.6 m) with the branch shaker. This assumes that 5% of all cones will remain on the trees above the upper reach of the lower-crown branch shaker.

Several modifications of the 1997 shaker were made before the 1998 field test. A shock-absorbing device was installed around the drive shaft. This did not increase harvest efficiency, but it did increase the durability of the machine by greatly reducing stress on the drive shaft that occurred when the Pitman arm quickly reversed the direction of travel of the energy bar. The addition of a hydraulically-controlled tilt mechanism increased harvest efficiency by enabling the operator to quickly and easily adjust the tilt of the energy bar to match crown shape. This adjustment could be made while a tree was being shaken.

For optimum performance, the shaker should be mounted on a tractor or machine that can turn in a circle less than or equal to the circumference of the trees. Also, the tractor should have a transmission that allows speeds as slow as 0.5 ft/sec (15 cm/sec). Slow movement of the shaker is required for good cone removal. The auxiliary hydraulic system of the tractor must be capable of pumping at least 8.75 gal/min (33 L/min) at 1,700 to 1,900 rev/min. The tractor should be heavy and stable so that the shaker can be safely operated when the front-loader is raised to maximum height.

Further increases in cone harvest efficiency will probably depend on changing crown structure and density such that most cones are produced on branch tips in the outer crown. Cones in that area can be actively shaken by the energy bar. Leader and branch pruning treatments could be used to regulate crown density. Branch pruning also should be used to increase within-tree uniformity for crown taper. More uniformity in crown shape will enable the tractor driver to keep the energy bar properly positioned for optimum shaking.

The lower-crown branch shaker may work effectively on other conifer species. Species with large, pendant cones are good candidates for harvesting with this machine.

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Technical drawings and specifications of the shaker tested in 1998 can be obtained from the USDA Forest Service, Missoula Technology and Development Center, Building 1, Fort Missoula, Missoula, MT 59801.

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