Micronutrients: Copper

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Copper is an essential element for plants; it plays a vital role in the efficiency of photosynthesis and the conversion of photosynthates to macromolecules, particularly lignin. The copper content of most agricultural soils is high, often because copper was added with the application of pesticides. Copper deficiency in bareroot nurseries is rare for the same reason. However, some peat moss–vermiculite growing media are completely devoid of copper, although some can be supplied from copper irrigation pipes. Toxicity generally produces iron deficiency and can also be a concern, especially for sensitive species when copper-coated containers are used for chemical root pruning. Because soil tests do not measure actual availability, copper status should he monitored through foliar analysis. Growers can ensure an adequate supply of copper by maintaining a slightly acid pH and, when needed, applying a foliar spray of copper sulfate or copper chelate. Tree Planters' Notes 49(3): 44-48; 2000.

Copper (Cu) deficiency in soil-grown plants is infrequent because the content in agricultural soils is relatively high (2 to 200 ppm) and plant requirements are relatively low (4 to 20 ppm, table 1) (Tisdale and others 1975). Copper has been used in agriculture for many centuries. Copper sulfate solution was one of the first herbicides, but it was subsequently found to be most useful as a fungicide. In 1882, a severe epidemic of downy mildew disease threatened the grape crop in the Bordeaux region of France. However, crops along the roadside were disease free, and it was determined that the grapes had been sprayed with a mixture of lime and copper sulfate to deter thieves. This "Bordeaux mixture" saved the crop and became one of the most widely used fungicides in the world (Walker 1969). Because of this widespread past use of copper sulfate, agricultural soils are rarely low in Cu.

Table 1—*Concentration of copper in plant tissue in relation to other essential micronutrients*[a]

Element	Symbol	Average (ppm)	Adequate range in seedling tissue (ppm)	
			Bareroot	Container
Iron	Fe	100	50-100	40-200
Chloride	Cl	100	10-3,000	[b]
Manganese	Mn	50	100-5,000	100-250
Zinc	Zn	20	10-125	30-150
Boron	B	20	10-100	20-100
Copper	Cu	6	4-12	4-20
Molybdenum	Mo	0.1	0.05-0.25	0.25-5.00

[a] Source: Adapted from Epstein (1972).
[b] Not reported.

Use of Cu as a fertilizer is more recent. While working with the Bordeaux mixture, researchers noted a stimulating effect on plant vigor and yield that could not be explained by the fungicidal effect alone. Copper was confirmed as an essential plant nutrient in 1931. Since then, an abundance of information has verified that Cu is essential for all plants (Reuther and Labanauskas 1965).

Copper's Role in Plant Nutrition

One of the main roles of Cu in plants is as a constituent of proteins and enzymes in oxidation–reduction processes. For example, the Cu-containing protein plastocyanin accounts for about half of the Cu in chloroplasts and is necessary for electron transfer in l'hotosystem I. As part of the enzyme superoxide dismutase, Cu is involved in detoxifying oxygen radicals generated by photorespiration (Turvey and Grant 1990). Hence, Cu plays a vital role in the efficiency of photosynthesis in general.

Copper also aids in the metabolism of phenol, carbohydrate, and nitrogen, thus making it critical for lignin biosynthesis and the conversion of photosynthates to macromolecules. The most common visual symptom of Cu deficiency is permanent bending and twisting of stems and branches. These symptoms indicate reduced lignin synthesis (Turvey and Grant 1990). The relationship between Cu nutrition and lignification is curvilinear (figure 1), and the adequate range for bareroot and container seedlings is relatively narrow—between 4 and 20 ppm (table 1). In addition to the visible effect on growth form, reduced lignification of xylem vessels weakens them to the point where water movement is impaired. This, in turn, increases susceptibility to water and heat stress.

Lack of Cu can induce nitrogen deficiency in legumes and other nitrogen-fixing plants such as alder (*Alms* sp. Mill.). The process of nitrogen fixation requires a constant supply of Cu to maintain carbohydrate availability. A steady supply of carbohydrate is used by symbiotic microorganisms in the root nodules to fix atmospheric nitrogen used by the plant (Marschner 1986).

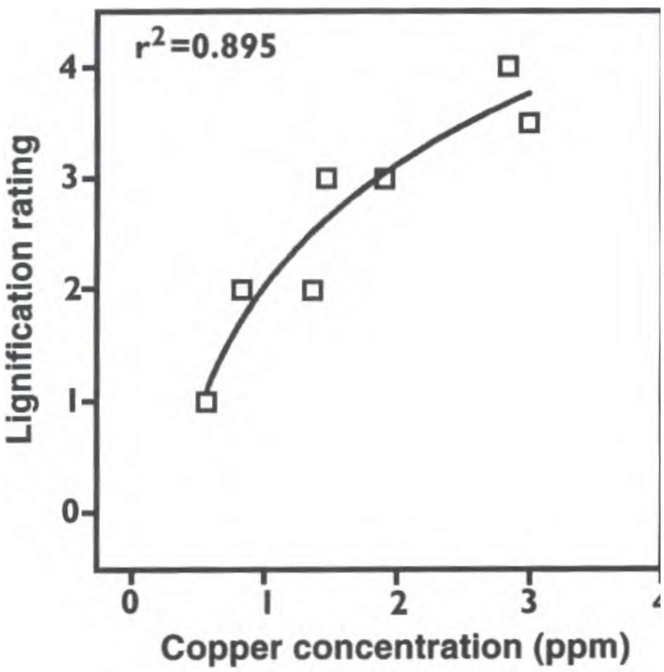

Figure 1—*Copper deficiency caused poor lignification of stem tissue of eucalyptus* (Eucalyptus maculata *Hook.) seedlings (Dell 1994).*

Availability and Uptake

Plants take up Cu as the cupric ion (Cu^{2+}), but because this ion is strongly adsorbed in most soils, it is not readily available. In bareroot nursery soils, Cu availability is affected by texture, pH, cation exchange capacity, and organic matter content. Highly leached sandy soils retain the least Cu, whereas fine-textured soils and those with high organic content retain the most. Soil pH affects Cu solubility and adsorption, and therefore its availability to plants. The Cu^{2+} ion becomes less available with increasing pH. On the other hand, low pH can depress Cu uptake by the plant due to competition with aluminum. The Cu^{2+} ion is subject to competition by other metallic ions including iron, manganese, and zinc. Heavy phosphorus fertilization has been shown to induce Cu deficiency in hybrid poplar *(Populus xeuramericana* Guinier clone DN17) (Teng and Timmer 1990). In the recommended pH range of 5.5 to 6.5, Cu availability should not be a problem for most bareroot nursery soils. In New Zealand and Australia, however, Cu deficiency has been observed in acidic nursery soils (Turvey and Grant 1990).

The situation is considerably different for container nurseries. Chemical analysis (Scarratt 1986) of a standard peat moss–vermiculite growing medium revealed that Cu was the only micronutrient to be completely absent (table 2). This has been confirmed in nursery practice; for example, Vlamis and Raabe (1985) reported Cu deficiency in manzanita *(Arctostaphylos densiflora* M.S. Baker) seedlings grown in a medium composed of tree bark and sand.

Table 2—*Chemical analysis of a commercial peat–vermiculite growing medium revealed no copper'*

Element	Concentration (ppm)
Iron	0.413
Manganese	0.046
Copper	0.000
Zinc	0.002
Boron	0.031
Molybdenum	0.010

'Source: Adapted from Scarratt (1986).

Diagnosis of Deficiencies and Toxicities

The most common visual symptom of Cu deficiency in commercial conifer plantations is a dramatic bending and twisting of stems and branches. Drooping, or "pendula" forms of Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco) in the Netherlands and radiata pine *(Pin us radiata* D. Don) in Chile, New Zealand, and Australia have been shown to be caused by a lack of Cu (Turvey and Grant 1990). Most of this published information deals with large trees, although a few instances of Cu deficiency and toxicity have been noted in nurseries.

Deficiency symptoms. Copper deficiency has been observed in forest and conservation nurseries in Canada and New Zealand. During an intensive survey of bareroot nurseries in British Columbia, Cu was one of the micronutrients found to be deficient (Maxwell 1988). At low levels of deficiency, reduced photosynthetic activity and turgor may go unnoticed but will still lower seedling quality and the ability to withstand moisture stress. Seedlings with severe Cu deficiency may exhibit chlorosis and tip dieback, looking as if they are potassium deficient. Deficiencies first appear in the youngest needles of conifer seedlings, which may be twisted, rolled inward, or curled, with needle tip burn (figure 2). There can be significant genetic variation in symptom expression, as has been demonstrated for Douglas-fir (van den Driessche 1989) and radiata pine (Pederick and others 1984). Foliar symptoms of Cu deficiency are more variable in broad-leaved species, but most leaves are smaller than normal, and some are blue-green or chlorotic (Hacskaylo and others 1969). The leaves of deficient eucalyptus *(Eucalyptus maculata* Hook.) seedlings showed necrosis and deformed margins (Dell 1994).

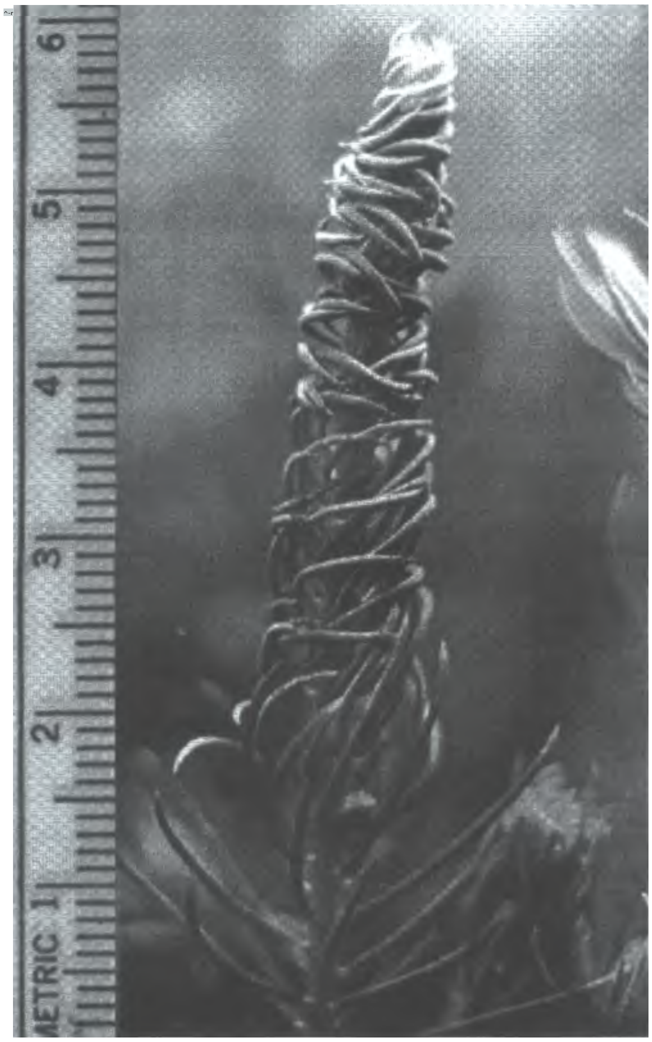

Figure 2—*Copper deficiency symptoms of white spruce* (Picea glauca *(Moench) Voss).*

Toxicity symptoms. In soil, excessive levels of Cu are rare except on sites treated with mine waste or sewage sludge and on agricultural fields subjected to repeated use of Cu-based fungicides (Turvey and Grant 1990). Toxic Cu levels generally produce iron deficiency and, in addition, shoot tips and roots may be stunted, needle and root tips may die, and roots generally turn dark brown to black (Reuther and Labanauskas 1965). In artificial growing media, Cu toxicity is more common where Cu-treated containers are used to prevent root binding and spiraling. Lodgepole pine *(P. contorta* Dougl. ex Loud.) and coastal sources of Douglas-fir are particularly sensitive in this regard (Van Steenis 1994, 1995a, 1995b). White spruce *(Picea glauca* (Moench) Voss) seedlings receiving 2 ppm Cu in a liquid fertilization experiment developed toxicity symptoms with extensive needle dieback (van den Driessche 1989).

Critical toxicity levels vary with species and individual plant parts. Above 20 to 30 ppm is considered toxic for leaves or needles. However, a foliar analysis may not indicate an impending toxicity because roots tend to preferentially accumulate Cu when supplied in excess. Root tissue levels can be up to an order of magnitude larger than foliar levels before transport to the shoot becomes evident. In roots, high Cu levels inhibit root elongation, often resulting in the enhancement of lateral root formation just ahead of the region where Cu is toxic.

Monitoring Copper in Nurseries

Foliar symptoms are of no practical usefulness because, by the time the symptoms are evident, the seedlings are stunted and slow to respond to fertilization. Instead, Cu availability must be monitored by chemical analysis of soils, growing media, or plant tissue.

Analysis of soil or growing media. Copper concentrations in the soil solution are usually less than 1 ppm because most of the ions are chemically bound to soil organic matter (Turvey and Grant 1990). So, from a practical standpoint, chemical testing of bareroot nursery soils has very little application because no method has been developed to assay the amount of Cu that is actually available to plants (Reuther and Labanauskas 1965). Chemical analysis of artificial growing media can be done, but the high affinity with which Cu becomes adsorbed on ion-exchange sites of peat may mask its true availability.

Tissue analysis. Foliar tissue analysis is the most recommended method of determining Cu nutrition in nurseries, and young foliage has been shown to be more diagnostic than older tissue. Sampling new foliage during the growing season is recommended for radiata pine because older tissue may accumulate Cu that is unavailable to the meristems (Pederick and others 1984). Although most standards for adequate Cu are general (table 1), more precise standards have been developed for a few species. For hybrid poplar, a midseason foliar Cu concentration of 3 ppm was a good predictor *of* the proper Cu level (figure 3). This value agrees with the critical range for white spruce and Douglas-fir seedlings of 3 to 4 ppm reported by van den Driessche (1989). Similar results were reported for radiata pine, with Cu deficiency occurring when foliar tests measured less than 2 to 5 ppm (Turvey and Grant 1990). However, in eucalyptus seedlings, Cu deficiency did not occur until foliar concentration dropped below 1.5 ppm (Dell 1994).

Root tissue may be a better indicator of Cu toxicity due to preferential accumulation in roots. However, sampling difficulty and desorption problems with roots

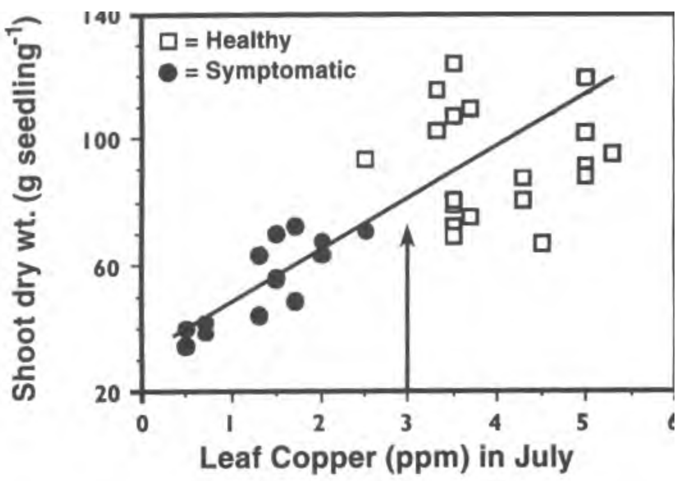

Figure 3—*Sampling hybrid poplar* (Populus X euramericana *Guinier clone DN17) leaves during the growing season was found to be more diagnostic than sampling later in the season and .3 ppm was found to be the critical copper concentration (Teng and Timmer 1990).*

make analytical testing of foliage a better option (Turvey and Grant 1990).

Management of Copper Availability

Growers can ensure an adequate supply of Cu by maintaining a slightly acid pH and, when warranted, supplying Cu as fertilizer.

pH. Copper availability, like that of iron, zinc, and manganese, is largely pH dependent. Keeping soil and growing medium pH between 5.0 and 6.5 will prevent problems. Alkaline irrigation water can cause high pH in soils or growing media but can easily be treated by injecting a small quantity of mild acid into the irrigation water. In bareroot nurseries, however, soil amendments often are needed. The pH of naturally calcareous or over-limed soils can be lowered with sulfur applications, although this can take many years.

Fertilization. A wide range of compounds can be used to supply Cu to soil or as a foliar spray (table 3). The most common fertilizers in bareroot nurseries are copper sulfate or copper oxychloride, with the choice dependent on cost and availability. An application rate of 10 kg/ha (9 lb/a) was effective in treating Cu deficiency of a variety of species (Turvey and Grant 1990). Maxwell (1988) recommended a soil treatment of 25 kg/ha (23 lb/a) of copper sulfate. Other familiar formulations used are copper ammonium sulfate and various copper chelates. Because root growth is affected by Cu, it is important that Cu be accessible at all times. Once Cu becomes deficient, plant roots cannot be expected to "grow" in search of it. For this reason, applying small granules or droplets and ensuring good mixing if the fertilizer is incorporated into the medium before planting are imperative. Soil-applied Cu normally has a long residual effect.

Sprays of copper sulfate (table 4) or copper chelate are commonly used to quickly ameliorate symptoms. With hybrid poplar, a single foliar treatment of 0.5% copper sulfate raised the Cu concentration of the foliage better than a higher soil application (Teng and Timmer 1990). Although foliar sprays are easy and effective, follow-up applications are almost always needed (Turvey and Grant 1990).

Summary

Copper deficiency is not a common problem in forest and conservation nurseries and, if diagnosed early, is easily corrected with the addition of copper sulfate or chelate. Deficiency can be due to "starvation in the midst of plenty" because Cu needs to be not only present but also available. Ensuring proper mixing of fertil-

Table 3—*Common fertilizers containing copper*

Fertilizer	Chemical notation	Copper (%)	Use in nurseries
Single nutrient fertilizers			
Copper sulfate	$CuSO_4 \cdot 5H_2O$	24	Foliar or soil applications
Copper oxychloride	$CuCl_2 \cdot 3CuO \cdot 4H_2O$	52	Foliar or soil applications
Copper ammonium phosphate	$Cu(NH_4)PO_4 \cdot H_2O$	32	Foliar or soil applications
Copper chelate	CuEDTA	14	Foliar or soil applications
Multi-nutrient fertilizers			
Soluble Trace Element Mix · STEM ®	Copper as $CuSO_4$	2.30	Foliar or soil applications
Micromax ®	Copper as $CuSO_4$	0.50	Incorporation in growing medium
Plant-Prod ®Chelated Micronutrient Mix	Copper as EDTA	0.10	Foliar or soil applications
Copper frits	CuO_2	0.03-3.80	Only soil applications
Compound 111 ®	Copper as EDTA	0.11	Incorporation in growing medium
Osmocote Plus ®	Copper as $CuSO_4$	0.05	Incorporation in growing medium

Table 4-Copper *sulfate was the only fertilizer treatment that cured symptomatic, copper deficient manzanita* (A. densiflora M.S. *Baker) seedlings grown in an organic growing mediums'*

Treatment	Nutrients supplied	Oven-dry weight of new growth [g (1b)]b	
Control	None	2.6 (0.0057)	b
Boric acid	Boron	1.9 (0.0042)	b
Copper sulfate	Copper. sulfate	24.8 (0.0547)	a
Calcium sulfate	Calcium, sulfate	2.0 (0.0044)	b
Hoagland's solution	All	2.3 (0.0051)	b

•Source: Adapted from Vlamis and Raabe (1985).
°Significant at the 5% level.

izer into soil and/or artificial growing medium, along with maintaining slightly acid pH levels and proper balance with other fertilizer elements, will help maintain availability. Maintaining an active and healthy root system is imperative.

Toxicities are rare in nature. They are usually self-inflicted through application of manures, sewage sludge, industrial waste, or the excessive application of Cu-based fungicides. Lately, Cu-treated containers for chemical root pruning are testing the fertilizer mixing and managing skills of seedling growers.

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Low-Budget Pollen Collector

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Built from off-the-shelf materials at a cost of under $200, this pollen collector downscales and modifies precipitators developed for large-scale pollen collections. Its efficiency is surprisingly high. Tree Planters' Notes 49(3):49-50; 2000.

Commercial dust precipitators have been successfully modified to collect tree pollen on a commercial scale (Copes and others 1991). Small seed orchards need to collect substantial quantities of pollen, but the price of even the smallest commercial precipitator is a major investment. The advantage of a precipitator over vacuum devices, such as canister vacuums for shop use or leaf blower vacuums, is that it has no filter. Filters plug as pollen collects, and efficiency is lost. The following is a description of a successful initial design of an inexpensive precipitator for small orchard needs.

A 32-gal (121-L) sturdy plastic garbage can was fitted with a 0.25-in (0.6-cm) smooth plywood lid (figure 1). The lid was centered by blocks mounted on the underside and had a 4-in-diameter (10-cm-diameter) hole in the center. A hand-held leaf blower, 4-in-diameter PVC pipe, and 25 ft (7.6 m) of light-weight, 4-in-diameter vacuum hose were assembled according to the sizes and specifications in figure 2. A light-weight, plastic collector head (figure 1) was mounted to a 20-ft (6-m) extension pole of the type used for window washing. The total cost for the equipment was under $200. The total weight was 20 lb (9.1 kg).

Commercial dust precipitators, from which this design was adapted, draw air in through a slanted tube at the top of a container. The air (containing dust) swirls downward, circling the container many times at high velocity, and exits the container (without the dust) through a vertical tube at its middle. The dust—or pollen in this case—moves down along the inside surface and deposits at the outer edge of the bottom of the container. The air pressure is reduced somewhat within the container and vacuum hose during this process. Be sure that thin-walled containers and hoses not designed for vacuuming are not used, as they can collapse. A benefit of the reduced air pressure is that the lid is held firmly in place without clamps or a gasket.

During operation, the collector head at the swiveled end of the 25-ft (7.6-m) vacuum hose is lifted into the tree crown and brushed against the pollen-shedding strobili. After vacuuming, the collected pollen is poured from the garbage can into a bucket covered with a framed screen to remove the minor amount of foliage and trash.

Figure *1—Inexpensive pollen collector for small orchard needs.*

Checks on the efficiency of pollen collection were made using weighed amounts of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western white pine (*Pin us tnonticola* Dougl. ex D. Don) pollen. For both species, greater than 95% of the pollen drawn into the machine was recovered.

A precipitator needs a firm base to prohibit the device from tipping over during vacuuming, as well as a very secure lid to prevent air leaks that cause pollen to be sucked out of the container. The 350 ft^3/min (9.9 m^3/min) air flow of the present blower is only half the flow per hose used by Copes and others (1991). More pollen would be collected with a sturdier machine having a greater air flow. Nevertheless, the low cost, efficiency, simplicity, ruggedness, and light weight of this preliminary device make it attractive for those on low budgets.

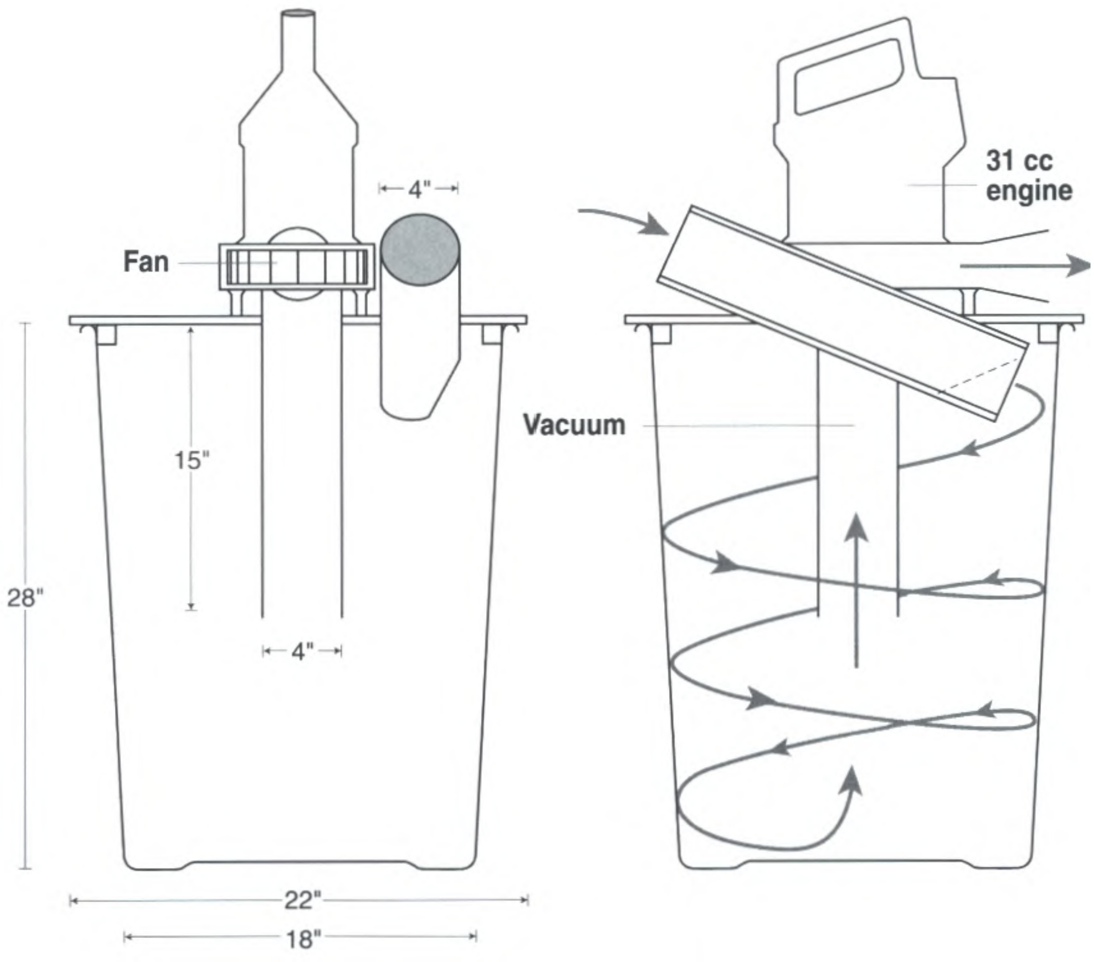

Figure *2—Specifications for assembly of the pollen collector, comprised principally of a plastic garbage can and a leaf blower, with the resulting air flow pattern.*

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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-

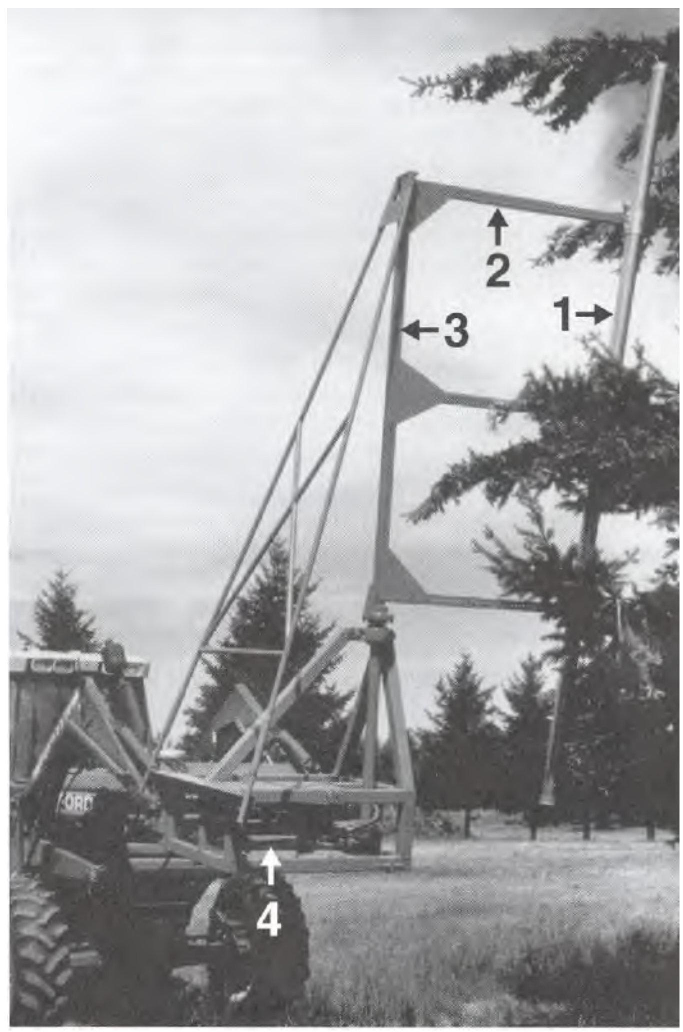

Figure 1—*The 1997 lower-crown branch shaker is shown properly positioned within the perimeter of the crown. 1 = energy bar; 2 = horizontal support; 3 = vertical drive shaft; 4 = crank arm.*

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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Production and Quality Requirements of Forest Tree Seedlings in Finland

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About 45% of the total area regenerated each year in Finland is currently planted with nursery stock. Scotch pine (Pinus sylvestris L.), *Norway spruce* (Picea abies (L.) *Karst.), and birches* (Betula *spp. L.) are the primary species. Container production comprises 86% of the total. Over half the seed for production of these species comes from seed orchards. Seedling quality standards are high, and compliance is monitored by inspectors supervised by the Finnish Ministry of Agriculture and Forestry. Health and vigor standards and height and diameter specifications for various stock size classes are provided for container-grown and bareroot seedlings, along with average selling prices.* Tree Planters' Notes 49(3): 56-60; 2000.

Seedling Production

Natural regeneration was the prevailing forest renewal method in Finland before 1960. Artificially regenerated areas increased rapidly during the 1960's (figure 1) (FFRI 1998). By 1997, 19% of the overall regeneration area was seeded, 45% was planted, and 36% was regenerated naturally by seed-tree and shelter-tree methods.

About 210 to 250 million seedlings were produced annually in the 1980's (figure 2). In the last few years, this figure has decreased to 150 million. The total number of central nurseries, excluding smaller family-owned nurseries, is 25 (table 1). The total production area of the nurseries is 456.2 ha (1127 a), of which 33.6 ha (83 a) are dedicated to production under plastic. In the early 1990's, nurseries owned by the Central and District Forestry Boards, producing more than half of the planting stock, were converted into commercial enterprises.

Nursery practices have been subject to changes during the past 30 years. The use of regular farmland and nutrients in the form of livestock manure, compost, and green manuring were replaced in the 1970's by use of light sandy soils and peat as substrates and inorganic soluble fertilizers. In addition, plastic greenhouses with automated irrigation, fertilization, and temperature-regulating devices were introduced.

About 42% of the nursery stock produced is Scotch pine *(Pinus sylvestris L.);* 45%, Norway spruce *(Picea abies (L.)* Karst.); 9%, silver birch *(Betula pendula* Roth); and 2%, downy birch *(Betula pubescens* Ehrh.). The remaining 3% is lodgepole pine *(Pinus contorta* Doug. ex Loud.), Siberian larch *(Larix sibirica* Ledeb.), and others (figure 2). Container seedling production increased in the 1980's for all the main tree species to such an extent that in 1998 container planting stock amounted to 86% of all planting stock (figure 3). However, bareroot seedlings continue to be planted, mainly in southern Finland.

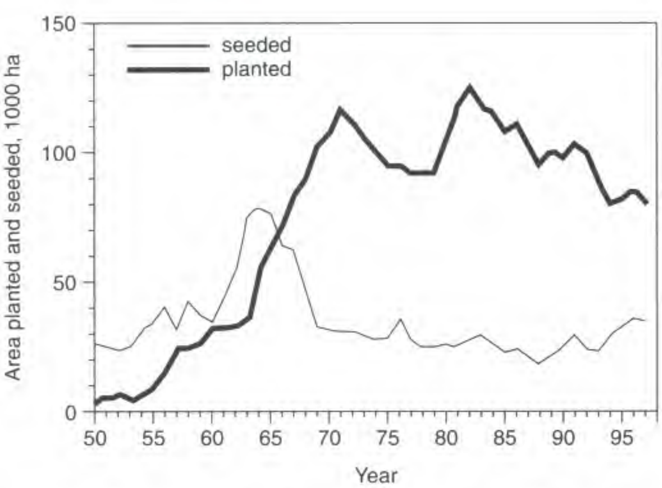

Figure 1—*Areas planted and direct seeded in Finland in the years 1950–1997.*

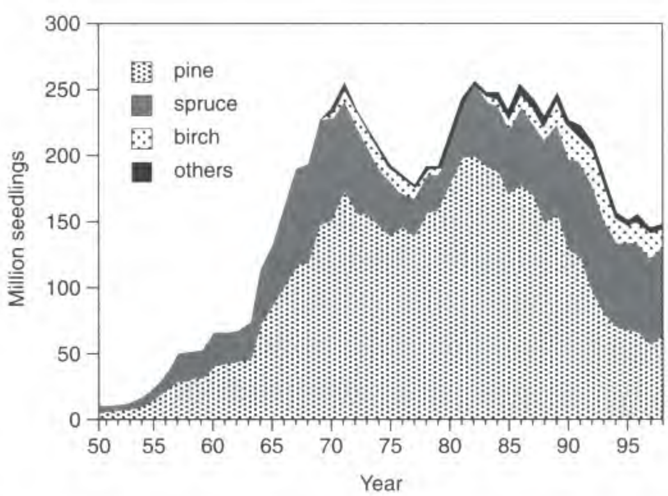

Figure 2—*Seedling material delivered for planting by tree species in the years 1950–1998. The tree species compositions presented for the years 1950–1964 are estimates.*

Table 1—*Nursery area and seedling production by main ownership categories in 1998*[a]

Nursery ownership category	No. of nurseries	Land area (ha)[b] Open land Bareroot	Open land Container	Plastic-covered	Millions of seedlings delivered
Finnish Forest & Park Service	3	7.2	9.6	6.5	32.7
Finnish Forest Research Institute	1	3.0	1.5	0.7	1.6
Commercial nursery companies (8)	20	293.3	79.4	21.7	89.9
Forest industry	1	0.0	5.8	1.3	7.1
Others (family-owned)	~70	11.3	11.5	3.4	17.6
Total	—	314.8	107.8	33.6	148.9

[a]Adapted from Finnish Ministry of Agriculture and Forestry.
[b]1 hectare = 2.47 acres.

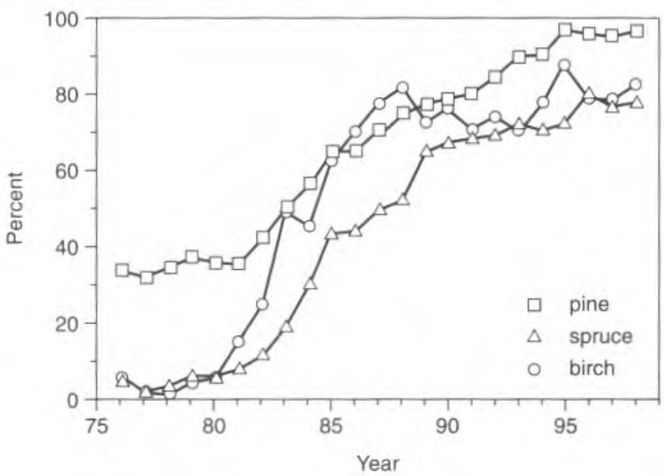

Figure 3—*Percentage of container seedlings in the years 1976–1998.*

The most common types of bareroot stock are transplants (pine, 2 + 1; spruce, 2 + 2; birch, 1 + 1), "plug + 1" seedlings, and root-pruned 2-year-old seedlings. The use of plug + 1 seedlings is currently increasing. The most common container types have been Paperpots and Ecopots (Lannen Tehtaat, Finland); in 1997 they accounted for 70% of all container stock. However, a rapid shift is taking place towards hard-plastic containers (for example, Plantek, Lannen Tehtaat, Finland; BCC, Sweden) with ribbing and air slits to facilitate air-pruning and inhibit spiraling and deformation of roots. The Vapo method, which includes root pruning as part of the cultural practice, was developed to prevent root spiraling and other forms of deformation (Parviainen and Tervo 1989) but has not become common. Most container pine and birch seedlings are planted when 1 year old, and container spruce seedlings are planted when 1 or 2 years old.

Classification and Quality Requirements of Nursery Stock

The genetic quality of seedlings is assured by sowing seed of good quality in the nursery. Seeds from seed orchards and selected seed stands used for seedling production must be approved by the Finnish Forest Research Institute. About 54% of pine seedlings, 60% of spruce seedlings, and 84% of birch seedlings are grown from seed orchard seeds (table 2). Seeds collected from known stands or regions are used mainly in northern Finland where orchard seeds are less available.

Nursery production in Finland is supervised by the Ministry of Agriculture and Forestry by virtue of the Forest Reproduction Material Trade Act of 1979 and the related decision issued in 1992. Three regional seedling inspectors appointed by the Ministry control seedling quality in nurseries by conducting surveys in the spring. They do this by checking the seedling packages readied for dispatching.

The Decision of the Ministry of Agriculture and Forestry (1533/92) requires that seedlings sold shall be healthy, vigorous, and, in other respects as well, appropriate for the purpose. Seedling lots sold may include seedlings that do not meet the requirements, but such

Table 2—*Amount of seed in kilograms*[b] *used in nurseries in 1998, by seed origin and tree species*[a]

Species	Seed orchards	Selected seed collection stands	Known stands	Known regions	Total
Pine	374	1	158	163	696
Spruce	672	46	406	6	1130
Silver birch	38	3	4	1	45
Downy birch	2	2	1	0	5
Others	144	2	85	1	232

[a]Adapted from Finnish Ministry of Agriculture and Forestry.
[b]1 kilogram = 2.2 pounds.

Table 3-*Minimum size requirements by size class for transplanted hareroot seedlings, based on median seedling height by species and lot*

Species	Size Class I	Size Class II	Size Class III	Size Class IV
Scotch pine *(Pious sylvestris)*				
Median seedling height (cm) of lot	12	13 14 15 16 17 18	19 20-21 22-23 24-25	≥ 26
Minimum seedling height (cm)	6	7 8 9 10 11 12	13 14 16 17	19
Minimum stem diameter (mm)	2.5a	3.0 3.0 3.0 3.0 3.0 3.0	3.5 3.5 3.5 3.5	4.0
Norway spruce *(Picea abies)*				
Median seedling height (cm) of lot	27	28-30 31-33	34-36 37-39 40-42	≥ 43
Minimum seedling height (cm)	18b	19 21	23 25 27	30
Minimum stem diameter (mm)	4.0b	4.5 4.5	5.0 5.0 5.0	5.5
Birch *(Behan* spp.)				
Median seedling height (cm) of lot	5_40	41-45 46-50 51-55	56-60 61-65 66-70	71-80 81-90 91-100?101
Minimum seedling height (cm)	25	25 27 30	33 37 42	46 51 56 60
Minimum stem diameter (mm)	3.0	4.0 4.0 4.0	5.0 5.0 5.0	5.5 5.5 5.5 5.5

'For seedlings in the provinces of Oulu and Lapland, the value is 2.0 mm.
°For seedlings in the provinces of Oulu and Lapland. the minimum height is 15 cm and the minimum diameter is 3.5 mm.

seedlings may make up no more than 5% of the total number. A seedling does not meet the above requirements if any of the following conditions are true:

1. The seedling is afflicted by plant diseases or pests (or damage caused by them), thereby impairing its vigor.
2. The seedling (in the case of pine, spruce, and birch) does not meet the size requirements (tables 3 and 4), or additionally for a container seedling, the growing density and container volume are such that the vitality or structure of the seedling is not suitable for planting.
3. The shoot or root system of the seedling is markedly curved, there are insufficient lateral roots, or the root system is otherwise insufficient or faulty.
4. The leading shoot of a conifer seedling is abnormal or there is more than 1 leading shoot (with the exception of spruce seedlings, which may have 2 leading shoots).
5. The seedling has serious bark injuries or the bark is torn.

If seedling lots show any of these above conditions, they must be sorted to discard the unacceptable ones or, in the case of serious diseases (Lilja and others 1997) and frost damage, the entire seedling lot may be discarded. Insects may also cause extensive damage. In the 1980's, lygus bugs *(Lygus rugulipennis* Popp.) caused growth disturbances (multiple leaders and bud disorders) (Holopainen 1986; Holopainen and Rikala 1990) in Finnish nurseries, and the affected seedlings were culled in accordance with the regulations. Subsequently, however, studies (Raitio and others 1992) showed that only the most serious of these disturbances lead to increased mortality or markedly retarded shoot growth.

Seedling size is normally determined in the autumn in conjunction with nursery stock inventory. Each seedling lot is inventoried and classified individually. A seedling lot in this context means a group of seedlings, the treatment and seedling height of which are uniform, grown in a definable area from a single seedlot or propagated vegetatively. Fractions of the seedling lot whose height clearly differs from that of the rest of the seedlings can also be defined as separate seedling lots. The median height of the seedlings in a lot is determined by a sampling protocol that provides a reliable estimate on which to base lot classifications according to size. The median height of the sample seedlings assigns the size class and the minimum acceptable height and diameter of an individual seedling in the lot (tables 3 and 4). All seedlings shorter or thinner than the lower limits of a particular class must be discarded-they may not be removed to another smaller-size seedling lot. If the median height of the lot exceeds the maximum value, the entire lot must be rejected.

The culling of seedlings that are too small with respect to the median height of the lot is based on the idea that these small seedlings are genetically inferior or damaged due to environmental factors. Be that as it may, the undersized seedlings are considered too weak to withstand the planting shock. The culling of a whole container seedling lot that is too tall with respect to the allowable median height for the particular growing density is based on the idea that the seedlings are not sturdy enough and that the root system may be compressed due to an inadequate container volume. The size requirements applied are based on seedlings measured at nurseries (for example, Huuri and others 1970; Kokkonen and Râsanen 1980) and outplanting tests (for example, Pohtila 1977; Rikala 1989).

Table 4—*Container seedlings: the maximum allowable median seedling height of a lot, determined by species and growing density, and the minimum allowable seedling height, determined by the median seedling height of a lot"*

Pine (*Pinus* spp.)

Growing density (containers/m^2)	Max. median seedling ht. (cm)	Seedling height (cm) — Median seedling height of lot: 5 8	9-10	11	12	13	14	15	16	17	18	19	20-21	22-23	24-25
		Minimum height of a seedling in the lot													
< 300	25			4	5	6	7	8	9	10	11	12	13	14	15
300-399	23			4	5	6	7	8	9	10	11	12	13	14	
400-499	21			4	5	6	7	8	9	10	11	12	13		
500-599	19			4	5	6	7	8	9	10	11	12			
600-799	17			4	5	6	7	8	9	10					
800-999	16			4	5	6	7	8	9						
1,000-1,299	15			4	5	6	7	8							
1,300-1,600	14			4	5	6	7	—	—						
1,601-2,000[b]	12	3	4	4	5										
2,001-2,500[b]	10	3	4												
2,501-3,000°	6	3													

Spruce (*Picea* spp.)

Growing density (containers/m^2)	Max. median seedling ht. (cm)	Median seedling height of lot: 5 12	13-14	15-16	17-18	19-20	21-23	24-26	27-30	31-35	36-40
		Minimum height of a seedling in the lot									
< 300	40	4	6	8	9	10	11	12	14	16	18
300-399	35	4	6	8	9	10	11	12	14	16	
400-499	30	4	6	8	9	10	11	12	14		
500-599	26	4	6	8	9	10	11	12	—		
600-799	23	4	6	8	9	10	11	—			
800-999	20	4	6	8	9	10					
1,000-1,299	17	4	6	8	9						
1,300-1,600	16	4	6	8	—						

Birch (*Betula* spp.)

Growing density (containers/m^2)	Max. median seedling ht. (cm)	Median seedling height of lot: 5 45	46-50	51-55	56-60	61-65	66-70	71-75	76-80	81-85	86-90	91-100	101-110
Minimum height of a seedling in the lot													
< 100	110	25	27	29	32	36	40	44	48	52	56	60	64
100-124	100	25	27	29	32	36	40	44	48	52	56	60	—
125-149	90	25	27	29	32	36	40	44	48	52	56		
150-174	80	25	27	29	32	36	40	44	48	52			
175-199	70	25	27	29	32	36	40	44	48				
200-224	60	25	27	29	32	36	40	44					
225-249	50	25	27	29	32	36	40						
250-275	45	25	27	29	32	36							

'When growing pine arid spruce seedlings, the minimum volume of the container is 45 cm^3 and the maximum growing density is 1600 containers/m^3. The maximum growing density for birch is 275 containers/m^2. The seedling lots are to be thinned (m^2/10.76 ft' 2.54 cm 1 in).

'Seedlings grown at densities between 1601 and 3000 seedlings/m^2 and using containers with volumes of at least 15 cm^3 may be used only in the provinces of Oulu and Lapland (northern Finland).

The quality requirements of forest reproductive material in the upcoming directive of the Council of the European Union are unlikely to be as detailed as the present Finnish national regulations. Also, on a national level in Finland, seedling specifications in contracts between growers and customers are likely to be the focus of emphasis instead of the present control by authorities.

Seedling Prices

Seedling prices are negotiated between seedling producers and customers, and they can vary from producer to producer (table 5). Seedling price depends on container size, the size class of seedling lot (only in the case of birch), and the seed class. Producers tend to enter into long-term contracts with customers.

Table 5—*Average seedling prices for contract customers in 1998; value-added tax (VAT) of 22% and package costs not included*

Species and stock type	Age (yr)	US$/1,000[a]
Scotch pine (*Pinus sylvestris*)		
Bareroot, root-pruned	2	84
Bareroot, transplanted, Plug + 1	2–3	160
Container	1–2	79–183
Norway spruce (*Picea abies*)		
Bareroot, transplanted, Plug + 1	3–4	200
Container	1–2	120–193
Silver birch (*Betula pendula*)		
Bareroot and container	1–2	165–313

[a] 1 euro = US$1.047

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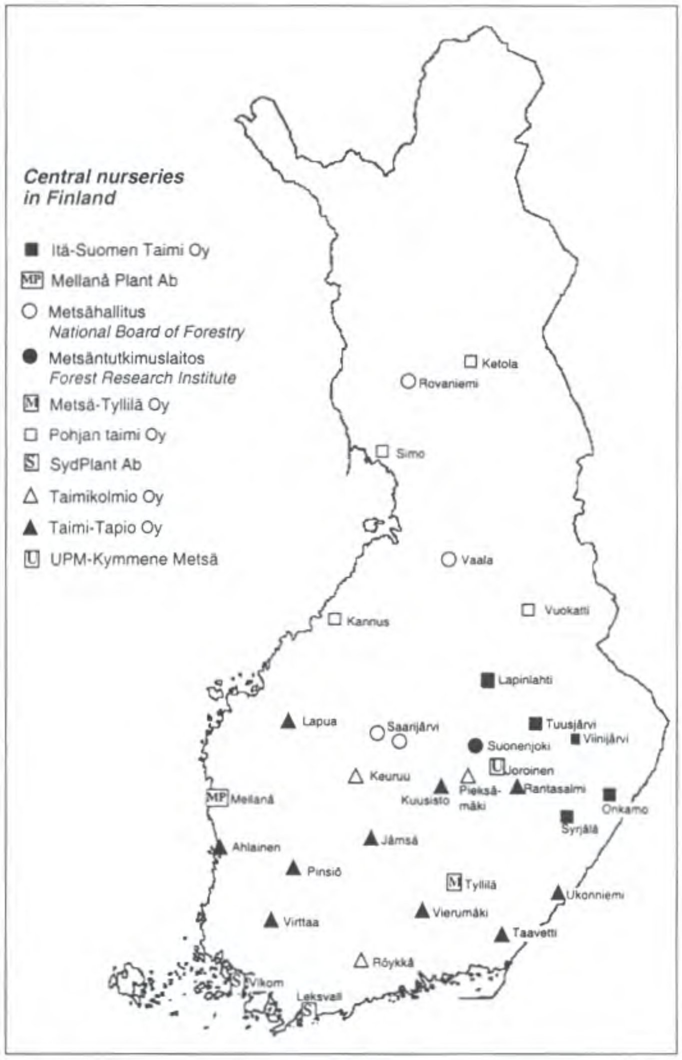

Figure 4—*A map showing the location of forest tree nurseries in Finland.*

Effect of Nitrogen Fertilization Rate in the Seedbed on Growth of Loblolly Pine in the Field

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Varying rates of nitrogen were applied to loblolly pine (Pinus taeda L.) *seedbeds at 2 nurseries in Virginia. At the New Kent Nursery, the rates were 168, 336, and 504 kg/ha (150, 300, and 450 lb/a) of elemental nitrogen. Seedlings with root collar diameters averaging either 4.7 or 5.5* mm *from each nitrogen rate were planted in the field. At the Sussex Nursery, seedlings were fertilized with either 336 or 672 kg/ha (300 or 600 lb/a) of elemental nitrogen combined with either 13 or 25* mm *(0.5 or 1.0 in) of sawdust tilled in just before seeding. Due to a higher seedbed density, only seedlings with root collar diameters averaging 4* mm *were planted in the Sussex study. For both studies, nitrogen rate did not have a statistically significant effect on survival, height growth, or diameter growth after 7 years in the field.* Tree Planters' Notes 49(3): 61-63; 2000.

In 1987, the Auburn University Southern Forest Nursery Management Cooperative established a loblolly pine *(Pin us taeda* L.) study at the New Kent Nursery to compare 3 levels of nitrogen at 2 seedbed densities. The target densities were 215 and 323 seedlings/m ^{2} (20 and 30 seedlings/ft^2), and the nitrogen rates were 168, 336, and 504 kg/ha (150, 300, and 450 lb/a) of elemental nitrogen (N). There were 4 seedbed replications of the 6 treatments using plots 15.2 m (50 ft) long. Seeds were sown using a vacuum seeder, but the seeder did not perform as expected for the higher density plots. In September, the average seedbed density for the lower density plots was 210 seedlings/m^2 (19.5 seedlings/ft2) but the higher density plots had been incorrectly sown and had only 191 seedlings/m^2 (17.8 seedlings/ft^2). Due to the small difference in stocking, the study was modified to compare 4.7- and 5.5-mm-diameter seedlings from the 3 nitrogen rates. We lifted samples from the 12 plots with the lowest stocking (191 seedlings/m ^{2}) to ensure getting enough 5.5-mm seedlings.

In 1987, we installed additional loblolly pine monitoring plots at the Sussex Nursery. We compared 2 application rates of sawdust (13 and 25 mm, 0.5 and 1.0 in) tilled into the soil just before seeding, in combination with the operational N rate or double the operational N rate (Dierauf 1991). The operational N rate at the Sussex Nursery ranged from 302 to 336 kg/ha (270 to 300 lb/a). We lifted samples from 3 of the 4 treatments, from 3 seedbed replications scattered about the nursery. In addition to the moderate operational treatment, the 2 extremes in N status were lifted:

- ► Low N — operational N plus 25 mm (1 in) of sawdust
- ► Moderate N — operational N plus 13 mm (0.5 in) of sawdust
- ► High N — double operational N plus 13 mm (0.5 in) of sawdust.

Lifting and Measuring Seedlings

New Kent study. Seedling samples were lifted on January 25, 1988. Thirty-six samples — 3 samples, evenly spaced from within each of the 12 plots — were lifted, each 15 cm (0.5 ft) long and spanning the 60-cm-wide (2-ft-wide) seedbed, for a 0.186-m^2 (2-ft^2) sample size. Seedlings were measured on January 26 and 27, 1988. Seedlings from each sample were graded into the 2 diameter classes, and the shoot length of each seedling was measured. From the 3 samples from each plot, we proportionally selected twenty 4.7-mm and twenty 5.5-mm seedlings. Each field replication contained 2 rows of 20 seedlings, with the seedlings from each of the 4 seedbed replications kept separate in each of 4 field replications.

Sussex study. Seedling samples were lifted on February 3, 1988. Eighteen samples were lifted, each 15 cm long and spanning the seedbed. Two evenly spaced samples were lifted from each of the nine 3-m-long (10-ft-long) nursery plots. Seedlings were measured on February 10. The seedlings in each sample were separated into 0.8-mm-wide diameter classes, and their shoot lengths were measured. For 8 of the 9 plots, there were more 4-mm-diameter seedlings than any other diameter class. Consequently, we selected only 4-mm seedlings for planting in the field. From each of the 2 samples from each plot, we proportionately selected 15 seedlings for planting in the field (we did not have enough 4-mm seedlings from 1 of the 9 plots to plant 20-seedling rows). Seedlings from each of the 3 seedbed replications were kept separate in each of 3 field replications.

Seedbed Results

New Kent study. Average root collar diameters, shoot lengths, and seedbed densities at lifting are presented in table 1. Seedlings were not top-pruned during the growing season. The data suggested that the highest nitrogen rate produced the shortest seedlings, but the differences were not statistically significant. Producing shorter seedlings with extra N has been observed in other studies (Dierauf 1991). Nitrogen rate had little effect on root collar diameter.

Sussex study. Average root collar diameters, shoot lengths, and seedbed densities are presented in table 2. Seedlings were operationally top-pruned 3 times during the growing season. The low-N seedlings were the smallest. It was obvious during the growing season that this treatment was not providing enough N because the seedlings were chlorotic as well as small. Average bed densities were similar for the low-N and moderate-N plots, but bed density was considerably lower for the high-N plots, which would be expected to favor diameter growth. An analysis of covariance was performed to adjust average root collar diameters for differences in bed density. The effect of N status on diameter was statistically significant ($P = 0.033$).

Field Planting

Seedlings from both studies were planted on March 1, 1988. The New Kent seedlings were planted in 4 randomized blocks, each block containing a 20-seedling row of each of the 6 treatments (2 diameter classes X 3 nitrogen rates). The Sussex seedlings were planted in 3 randomized blocks, each block containing a 15-seedling row of each of the 9 treatments (3 nitrogen levels X 3 seedbed locations). New Kent and Sussex blocks were alternated in the field, so performance of the 2 seedling sources could be compared. Spacing was 2 x 2 m (6.6 X 6.6 ft) for both studies. Seedling heights were measured after 7 years in the field. Diameters at breast height (d.b.h.) were measured to the nearest 2.5 mm (0.1 in).

Table 1—*Average loblolly pine root collar diameter, shoot length, and seed bed density at lifting (1988), by rate of nitrogen application for all seedlings at the New Kent Nursery*

Nitrogen rate[a] (kg/ha)	(lb/a)	Diameter (mm)	(in)	Shoot length (cm)	(in)	Seedbed density (no./m²)	(no./ft²)
168	150	5.1	0.2019	24.9	9.8	198	18.4
336	300	5.2	0.2066	25.6	10.1	202	18.8
504	450	5.1	0.2013	22.6	8.9	200	18.6

[a]Nitrogen rate had no significant effect on root collar diameter or shoot length.

Field Results

New Kent study. Average survival decreased only 0.4% between age 1 and 7 (combining all 24 rows). At age 7, survival of 4.7-mm seedlings (89.6%) was slightly better than 5.5-mm seedlings (87.1%) (table 3). Seedlings receiving 504 kg/ha (450 lb/a) of N had the best survival (90.6%), followed by seedlings receiving 168 kg/ha (150 lb/a) of N (88.8%). In an analysis of variance, after first transforming to arc sine percent, these differences in survival were not statistically significant ($P = 0.259$ for diameter class and $P = 0.262$ for N rate).

Average height at age 7 was slightly greater for the 336- and 504-kg/ha (300- and 450-1b/a) N rates (6.34

Table 3-*Average loblolly survival, height, and diameter at breast height (d.b.h.) at age 7 by seedling diameter class at lifting for 3 rates of nitrogen application in the New Kent study'*

Root collar diameter (mm)	(in)	Nitrogen rate (kg/ha)	(lb/a)	Survival (%)	Height (m)	(ft)	d.b.h. (cm)	(in)
4.7	0.1875	168	150	92.5	6.18	20.3	9.6	3.8
		336	300	85.0	6.34	20.8	10.2	4.0
		504	450	91.2	6.25	20.5	9.9	3.9
5.5	0.2188	168	150	85.0	6.15	20.2	9.6	3.8
		336	300	86.2	6.28	20.6	9.9	3.9
		504	450	90.0	6.43	21.1	10.2	4.0
Mean				88.3	6.27	20.6	9.9	3.9

[a]There were no significant differences between diameter classes or among rates of nitrogen application.

Table 2-*Average loblolly pine root collar diameter, shoot length, and seedbed density at lifting (1988) and survival, height, and diameter at breast height (d.b.h.) at age 7, by nitrogen status for the Sussex Nursery study*

Nitrogen status[a]	Nitrogen rate (kg/ha)	(lb/a)	Sawdust rate (mm)	(in)	Diameter (mm)	(in)	Shoot length (cm)	(in)	Seedbed density (no./m²)	(no./ft²)	Survival (%)	Height (m)	(ft)	d.b.h. (cm)	(in)
Low	336	300	25	1.0	3.5	0.1366	20.8	8.19	418	38.8	88.9	5.88	19.3	9.14	3.6
Moderate	336	300	13	0.5	3.8	0.1497	22.0	8.67	410	38.1	88.9	5.79	19.0	8.64	3.4
High	672	600	13	0.5	4.1	0.1619	22.1	8.71	351	32.6	88.9	5.85	19.2	8.89	3.5

[a]The effect of nitrogen status on root collar diameter was significant ($P = 0.033$). There were no other significant effects of nitrogen.

and 6.25 m; 20.8 and 20.5 ft, respectively) than for the 168-kg/ha (150 lb/a) N rate (6.18 m; 20.3 ft) (table 3). The 5.5-mm seedlings were slightly taller (6.29 m; 20.6 ft) than 4.7-mm seedlings (6.26 m; 20.5 ft). However, in an analysis of variance, these differences in height were not statistically significant (P = 0.328 for N rate and P = 0.782 for initial diameter). There was no difference in average d.b.h. between 4.7- and 5.5-mm seedlings, and the slight differences in average d.b.h. among N rates were not statistically significant (P = 0.346) in an analysis of variance.

Sussex study. Average survival decreased 2% between age 1 and age 7 (combining all 27 rows). At age 7, survival was identical for all 3 nitrogen rates (table 2). The small differences among the 3 treatments in height and d.b.h. at age 7 were not statistically significant (P = 0.464 for height and P = 0.336 for d.b.h.). Although the seedbed density in the Sussex nursery was double that at New Kent, average height and d.b.h. at age 7 were only about 7% and 10% smaller, respectively, than seedlings from the New Kent Nursery.

Conclusions

There were no benefits demonstrated from applying more than 336 kg/ha (300 lb/a) of N to the sandy nursery soils at New Kent and Sussex. There were no gains in survival, height, or d.b.h., after 7 seasons in the field from applying heavier rates.

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Lateral Roots Extending From the Planting Hole: How Serious?

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Planting loblolly pine (Pinus taeda L.) *seedlings so that one or more long lateral roots extended from the planting hole and were exposed on the surface did not reduce survival or subsequent height growth.* Tree Planters' Notes 49(3): 64-65; 2000.

The undercutting blade of the lifting machine prunes taproots of loblolly pine *(Pinus taeda* L.) seedlings in most instances to 13 to 15 cm (5 to 6 in). Quite often, however, long lateral roots remain because they occupy the soil profile above the depth of the undercutting blade and because they run parallel to lateral pruning blades. Since long lateral roots are difficult to get completely into the planting hole, loblolly pine are operationally root-pruned at the end of the grading table to cut lateral roots to 13 to 15 cm (5 to 6 in). Do lateral roots left exposed on the ground surface after planting have a negative influence on future survival or growth? We are confident they should not be stripped off, but is it worthwhile to prune them off before planting?

Studies were established during the 1986-1987 and 1987-1988 planting seasons. The objective was to determine if survival and growth were reduced by planting with long lateral roots left outside the planting hole.

Methods

On March 4, 1986, we carefully hand-lifted seedlings at the New Kent Nursery in Providence Forge, VA, saving as many long roots as possible. Two days later, on March 6, we selected pairs of seedlings of similar root collar diameters and randomly selected 1 seedling of each pair to be pruned. Root systems were pruned by smoothing all lateral roots down along the taproot and cutting all roots about 13 cm (5 in) below the first lateral root. The other seedling in each pair was not root-pruned. Both types of seedlings were planted according to established standards, that is, by placing the tap root at the bottom of a hole 18 to 20 cm (7 to 8 in) deep and closing the hole properly. For the seedling that was not root-pruned, we left at least 1 lateral root extending out of the hole and lying on the surface. We planted 2 rows at a time, 1 row root-pruned and the other not, with 15 seedlings in each row. This constituted a replication, and we replicated the treatments 3 times, totaling 45 seedlings of each type.

The 1987-1988 study was similar. We hand-lifted seedlings on December 8, 1987, from the Sussex nursery. The next day, on December 9, we installed four 20-seedling rows, 2 rows root-pruned and 2 rows not, following the same procedures as before. Later in the season, on February 16, 1988, we planted 4 more rows, 2 rows of each treatment, using seedlings that had been hand-lifted a few weeks earlier from the Sussex nursery and kept in cold storage.

Obviously, the seedlings that were not root-pruned had more lateral roots than the seedlings that were pruned. This difference in root quantity between the 2 groups, however, was greater than if we had selected the 2 groups from operationally root-pruned seedlings. Operational root pruning removes all or most of the long laterals and does not leave all lateral roots long, as in the unpruned seedlings in these 2 studies. Seedling survival and height were measured annually for 3 years.

Results and Conclusion

We examined the exposed lateral roots 2 or 3 weeks after planting. They had air-pruned to the ground surface by this time. The exposed roots did not reduce survival or height growth (table 1). Three-year survival was actually slightly higher in both studies for seedlings planted with roots exposed, but the differences were not statistically significant (analysis of variance using an arc sine transformation of survival percentages: 1986-1987, $P = 0.70$; 1987-1988, $P = 0.82$). However, if exposed lateral roots air-prune so quickly that they present no problem, then additional lateral roots on unpruned seedlings may have favored survival over the pruned seedlings.

Table 1—*Average loblolly pine survival and height after 3 growing seasons in the field*

	Survival (%)			Height (cm, in)		
	1986-1987	1987-1988		1986-1987	1987-1988	
Treatment	Mar.	Dec.	Feb.	Mar.	Dec.	Feb.
Roots pruned and buried	80.0	95.0	95.0	110, 43	186, 73	182, 71
Roots unpruned, some exposed	82.3	100	97.5	107, 42	192, 75	188, 74

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This article is a revision of: Dierauf TA. 1992. Lateral roots extending from the planting hole—how serious? Charlottesville (VA): Virginia Department of Forestry. Occasional Report 104. 3 p. We thank the department for permission to publish this revised article.

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Comparison of Adjuvants Used in Fall-Release Herbicide Mixtures for Forest Site Preparation

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Tank mixes of the herbicides imazapyr and glyphosate were applied at 3 rates with 3 adjuvants (LI-700®, Nu-Film-IR®, Silwet L-77°) over California hazelnut (Corylus cornuta *Marsh. var.* californica *(A. DC.) Sharp), vine maple* (Acer circina turn *Pursh), and brackenfern* (Pteridium aquilinum (L.) *Kuhn var.* lanuginosum *(Bong.) Fern.). The herbicide 2,4-D was applied at 3 rates with 2 adjuvants (Herbimax®, Nu-Film-IR) over greenleaf manzanita* (Arctostaphylos patula *Greene). Tank mixes of imazapyr and glyphosate with LI-700 or Nu-Film-IR were sprayed at 3 rates over seedlings of Douglas fir* (Pseudotsuga menziesii *(Mirb.) Franco.). The herbicide rate strongly influenced the percentage of foliage injured and percentage of stems killed for all herbicide treatments. The adjuvants evaluated did not influence efficacy of herbicide applications on California hazelnut, vine maple, or brackenfern. Herbimax increased visual foliar damage resulting from 2,4-D application on greenleaf nianzanita. Douglas-fir foliage was damaged by the higher herbicide rates; the damage was greater from Nu-Film-IR than from LI-700.*
Tree Planters' Notes 49(3): 66-71; 2000.

In reforestation settings, herbicides are commonly used to eliminate potential competitors prior to planting conifers or to release established conifers from competition (Walstad and Kuch 1987). Spray adjuvants are often applied in conjunction with foliage-active herbicides to increase herbicide effectiveness (Prasad 1992a, 1992b). Adjuvants enhance efficacy by increasing herbicide assimilation by the target plant through various modes (Harvey 1993). Adjuvants used in our study can be grouped into 3 categories by their modes of action:

1. Surfactants—such as Silwet L-77® (Osi Specialties Inc.) and LI-700® (Loveland Ind.)—increase efficacy by reducing the surface tension of water and allowing it to spread over the leaf more readily, thus increasing the surface area exposed to herbicides. Silwet L-77 is a nonionic organosilicon surfactant that reduces the surface tension of water and relies principally on enhanced stomata! flooding to increase herbicide absorption (Stevens and others 1991). LI-700 is composed of an organic acid in combination with a soybean derivative that increases absorption through enhanced cuticular penetration and stomata! flooding (Harvey 1993).
2. Oil penetrants—including Herbimax® (Loveland Ind.)—are often used when target plants have thick waxy cuticles. The oil solubilizes cuticular waxes and increases penetration of the leaf surface, aiding in the absorption of the herbicide used.
3. Sticking agents—including Nu-Film-IR® (Miller Chemical and Fertilizer Corp.)—prevent loss of herbicide through wash off and sheeting action, thus prolonging the leaf's contact with the herbicide.

The purpose of this study was to compare the efficacy of 3 herbicide applications using several adjuvants. Because adjuvants can injure conifers (Fredrickson 1994), this study also evaluated the phytotoxic effects of the treatments on Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco.) seedlings.

Methods

Three experimental trials were performed. Trials 1 and 2 tested the effect the adjuvants had on the efficacy of site preparation weed control. Trial 3 evaluated the potential for the adjuvants tested to increase herbicide phytotoxicity to Douglas-fir when used as fall release treatments.

Trial 1—Vine maple, California hazelnut, and brackenfern response. We tested differences in efficacy as a result of spray adjuvants for 3 common Oregon Coast Range shrub species: vine maple *(Acer circinatum* Pursh), California hazelnut *(Corylus cornuta* Marsh. var. *californica* (A. DC.) Sharp), and brackenfern *(Pteridium aquilinum (L.)* Kuhn var. *lanuginosum* (Bong.) Fern.). All of these species have relatively thin leaf cuticles and are susceptible to late-summer application of imazapyr and glyphosate tank mixes.

A herbicide tank mix was applied at 3 rates using 3 spray adjuvants (table 1) on vine maple, California hazelnut, and brackenfern during September 1995. In addition, a no-herbicide-application control treatment and a treatment at the highest herbicide rate with no surfactant were also applied, for a total of 11 treatment combinations per species. The herbicide tank mix consisted of imazapyr (Arsenal⁰) and glyphosate (Accord®). From operational experience, the highest rate (0.071 kg ai/ha of imazapyr and 1.41 kg ai/ha of

Table 1-Treatments for weed control trials 7 and 2 and conifer safety trial 3

Treatment	Adjuvant Name	Adjuvant Dose (LAO'	Trial 1 Imazapyr (kg ai/ha) b	Trial 1 Glyphosate (kg ai/ha)	Trial 2 2,4-D (kg ai/ha)	Trial 3 Imazapyr (kg ai/ha)	Trial 3 Glyphosate (kg ai/ha)
Control	No adjuvant	0	0	0	_C		
High rate	No adjuvant	0	0.071	1.41	1.48		
	Herbimax®	2.365			1.48		
	LI-700®	0.147	0.071	1.41	—	0.143	2.08
	Nu-Film-IR®	1.034	0.071	1.41	1.48d	0.143	2.08
	Silwet L77®	0.237	0.071	1.41	—		
Moderate rate	No adjuvant	0			0.98		
	Herbimax	2.365			0.98		
	LI-700	0.147	0.036	0.62	—	0.071	1.41
	Nu-Film-IR	1.034	0.036	0.62	0.986	0.071	1.41
	Silwet L77	0.237	0.036	0.62	—		
Low rate	No adjuvant	0			0.48		
	Herbimax	2.365		—	0.48		
	LI-700	0.147	0.018	0.31	—	0.018	0.62
	Nu-Film-I	1.034	0.018	0.31	0.48d	0.018	0.62
	SilOwet L77	0.237	0.018	0.31	—		

N../ha x 9.3527 = gaVa
Ng/ha x 1.1208 = lb/a
Untested treatment combination.
d i's/a-Film-IR rate with 2.4-0 over greenleaf manzanita was 0.296 Uha.

glyphosate in a low-volume 95-L/ha spray) applied without surfactant was expected to achieve approximately 75% control of target species. Thus, even at the highest rate, added efficacy due to the surfactants could be recognizable and measurable. Three spray adjuvants were tested: LI-700 at 0.147 L/ha, Nu-Film-IR at 1.034 L/ha, and Silwet L-77 at 0.237 L/ha. To simulate an aerial application, all treatments were applied with a gas-powered boom backpack sprayer.

Five replications of the 11 treatments were applied randomly to 55 hazel clumps. Three replications of the 11 treatments were applied randomly to 33 vine maple clumps and 33 brackenfern areas. In late summer of 1995, before the treatments, the shrub clumps and brackenfern areas were located and flagged in a 2-year-old Douglas-fir clearcut 3.2 km west of Philomath, Oregon. The hazel and vine maple clumps covered areas ranging from 1.4 to 3.2 m^2 (16 to 34 ft^2). Brackenfern areas consisted of 2.4 X 1.5 m (8 x 5 ft) rectangular strips with brackenfern cover of 70°A, or greater. All treatments were applied on September 22, 1995, between 9:00 AM and 12:30 PM. Winds were calm, and air temperature ranged from 18 to 24 °C (64 to 75 °F) during the applications; relative humidity was 65%. The weather remained clear and warm for 2 days following the application, however, the next 3 days it rained, for a cumulative precipitation total of over 5 cm.

Trial 2-Manzanita response. We tested differences in efficacy as a result of spray adjuvants on greenleaf manzanita *(Arctostaphylos Willa* Greene), a thick-cuticled species that is susceptible to late-summer application of 2,4-D. Three rates of the herbicide 2,4-D were applied factorially, with the addition of either no adjuvant, Herbimax (2.365 L/ha), or Nu-Film-IR (0.296 L/ha). A low-volume (95-L/ha) spray was applied at random over 45 greenleaf manzanita clumps, for a total of 9 treatment combinations replicated 5 times (table 1). The high-rate treatment was 1.48 kg ai/ha of 2,4-D. From experience, we expected about 75% control of the manzanita clumps with this rate. In the time between establishment of trial 1 (September 1995) and trial 2 (August 1996), the manufacturer lowered the recommended dosage of Nu-Film-IR from 1.034 L/ha to 0.296 L/ha for low-volume spray applications. Treatments in trial 2 reflect this change.

The greenleaf manzanita clumps were flagged in late summer of 1996 on a 4-year-old Douglas-fir clearcut west of Yoncalla, Oregon. Applications were made on August 12, 1996, between 9:00 AM and 11:30 AM. Winds were calm, temperatures remained below 24 °C (75 °F) and relative humidity was approximately 62%. The weather remained clear and dry for over a week after the application.

Trial 3—Douglas-fir **response.** Two adjuvants were tested for phytotoxic effects on crop Douglas-fir using release herbicide applications. LI-700 and Nu-Film-IR were applied over first-year Douglas-fir seedlings at 2 sites, in combination with each of 3 rates of an imazapyr-glyphosate tank mix, resulting in 6 treatment combinations (table 1). Each treatment was replicated 4 times. These sites were located in the Oregon Coast Range, the first near the town of Eddyville and the second near the town of Falls City. Both had been logged 2 years previously and planted 1 year before treatment. The highest herbicide rate tested was set unusually high to ensure that there would be easily observable damage as a result of the treatment.

The experiment was blocked by the 2 sites (Falls City and Eddyville). Each site consisted of 24 treatment plots in which 4 replications of the 6 herbicide treatments were randomly applied. Each plot consisted of a row of 1-year-old planted Douglas-fir, each row containing 15 seedlings. The treatment applications were applied using a gas-powered boom backpack sprayer on October 16, 1995.

Measurements

Trials 1 and 2. Control efficacy for trial 1 was assessed on May 31, 1996, and on May 15, 1997, for trial 2 (8 and 9 months after the treatment, respectively). Visual estimates of the percentage of clump stems killed and the percentage of foliage showing signs of herbicide injury were made for each California hazelnut, vine maple, and manzanita clump. Because brackenfern has a different growth habit, only a cover value could be estimated visually for this species, and so cover is used as the principal response variable in all analyses for brackenfern control.

Trial 3. Seedling vigor was assessed before treatment, and any seedling that did not appear vigorous at that time was excluded from the reevaluation the following fall. The treated Douglas-fir seedlings were visually assessed for damage on September 25, 1996, 11 months after treatment. The assessment consisted of assigning each seedling a 5-point damage index rating:

1 = No visible herbicide damage to seedling
2 = Slight bottle brushing or needle loss
3 = Moderate bottle brushing or stem dieback
4 = Severe bottle brushing and stem dieback
5 = Seedling mortality

Analysis

Treatment differences for all 3 trials were assessed with ANOVA and means comparisons made using the Waller-Duncan method. In trials 1 and 2, means comparisons for percentage of stems killed, percentage of foliage injured, and brackenfern cover were made. The data were arcsin(sqrtlp])-transformed prior to the analysis to achieve normality and to allow for analysis of percentage or proportionate data; reported results are back-transformed values.

In trial 3, means for each treatment unit (consisting of a row of 15 trees) were generated and subjected to ANOVA blocked by study site. In addition, mean percentages of seedlings exhibiting herbicide damage (a damage index ranking of 2, 3, or 4), and of seedlings killed by the treatments were also evaluated. Residuals were examined for unequal variance and normality, and no transformations were needed.

Results

Herbicide damage increased with herbicide concentration for all the weed species and for conifer seedlings. None of the 3 adjuvants tested resulted in increased efficacy when applied to vine maple, California hazelnut, or brackenfern at the highest herbicide rates (table 2). At the lower rates, control efficacy differed little among adjuvants. In contrast, addition of either Herbimax or Nu-Film-IR to 2,4-D applied to greenleaf manzanita enhanced efficacy at the highest herbicide rate tested, though less so at the lower rates (table 3). Conifer damage varied with adjuvant at the highest herbicide rates, with Nu-Film-IR consistently resulting in greater damage than Li-700 (table 4). At lower herbicide rates, conifer damage did not vary by adjuvant used.

Trial 1. All high-rate treatments resulted in obvious visual signs of herbicide damage on vine maple and California hazelnut clumps, ranging from off-colored foliage to severe leaf deformities and death of stems. No similar deformities were apparent on brackenfern fronds; the only indication of herbicide activity was a reduction in the cover of fronds produced the following spring.

At the high rate, spray adjuvant did not influence the percentage of California hazelnut stems killed or foliage injured, nor did it influence the total cover of brackenfern (table 2). However, the percentage of vine maple stems killed at the high rate with Nu-Film-IR was significantly less than the other treatments.

At the medium rate, no differences in percentage of foliage injured were observed for vine maple or California hazelnut (table 2). However, differences were observed in the percentage of vine maple stems killed; the Nu-Film-IR treatment resulted in a greater percentage of stem kill than LI-700. Similarly, at the medium rate, the Nu-Film-IR treatment reduced brackenfern cover by significantly more than the LI-700 treatment. Silwet L-77 treatments were similar to other adjuvants.

Table 2—*Efficacy of imazapyr–glyphosate tank mixes in combination with spray adjuvants on vine maple* (Acer circinatum *Pursh, California hazelnut* (Corylus cornuta *Marsh. var.* californica *(A. DC.) Sharp), and brackenfern* (Pteridium aquilinum *(L.) Kuhn var.* lanuginosum *(Bong.) Fern.) (trial 1)*[a]

	Vine maple		California hazelnut		Brackenfern
Treatment	Stems killed (%)	Foliage injured (%)	Stems killed (%)	Foliage injured (%)	Cover (%) spring after treatment
Control	0 a	0 a	0 a	0 a	53.0 a
High rate					
No adjuvant	89.0 e	100 e	98.0 e	100 e	6.3 d
LI-700®	94.3 e	100 e	98.8 e	100 e	6.8 d
Nu-Film-IR®	56.4 d	96.8 cde	98.9 e	100 e	6.3 e
Silwet L77®	86.2 e	98.9 de	95.6 de	99.8 de	5.0 d
Medium rate					
LI-700	0.5 ab	72.7 c	77.7 c	79.4 c	36.6 ab
Nu-Film-IR	18.9 c	80.2 cd	73.5 c	90.6 c	15.0 c
Silwet L77	6.7 bc	90.1 cde	83.3 cd	92.3 cd	25.5 bc
Low rate					
LI-700	3.2 ab	31.3 b	6.6 b	9.3 b	25.0 bc
Nu-Film-IR	0.0 a	9.5 ab	13.1 b	18.1 b	42.9 ab
Silwet L77	0.0 a	13.3 ab	18.1 b	18.9 b	29.7 b

[a]Values within a column with the same letter are not significantly ($P \leq 0.05$) different using the Waller-Duncan means comparison test.

Table 3—*Efficacy of 2,4-D treatments in combination with spray adjuvants on greenleaf manzanita* (Arctostaphylos patula *Greene) (trial 2)*[a]

	Stems killed (%)	Foliage injured (%)
High rate		
No adjuvant	25.9 bc	69.3 b
Herbimax®	96.8 a	99.1 a
Nu-Film-IR®	61.4 b	78.4 ab
Medium rate		
No adjuvant	19.6 c	42.5 bc
Herbimax	25.6 bc	76.0 ab
Nu-Film-IR	25.5 bc	37.5 bc
Low rate		
No adjuvant	2.1 c	8.2 c
Herbimax	4.7 c	23.1 c
Nu-Film-IR	3.3 c	10.1 c

[a]Values within a column with the same letter are not significantly ($P \leq 0.05$) different using the Waller-Duncan means comparison test.

Table 4—*Effect of imazapyr–glyphosate treatments in combination with spray adjuvants on seedlings of Douglas-fir* (Pseudotsuga menziesii *(Mirb.) Franco.) (trial 3)*[a]

	MDIR[b]	Seedlings killed (%)	Seedlings damaged (%)
High rate			
LI-700®	1.7 b	8.6 b	31.3 b
Nu-Film-IR®	3.0 a	24.4 a	61.8 a
Medium rate			
LI-700	1.4 bc	7.0 bc	14.1 cd
Nu-Film-IR	1.6 b	7.6 bc	23.6 bc
Low rate			
LI-700	1.0 d	0.0 d	2.3 d
Nu-Film-IR	1.2 cd	2.4 cd	8.7 d

[a]Values within a column with the same letter are not significantly ($P \leq 0.05$) different using the Waller-Duncan means comparison test.
[b]MDIR = mean damage index rating.

Finally, at the low rate, there were no differences in treatment effects in any of the parameters measured.

Trial 2. Control of manzanita using 2,4-D with and without adjuvants was highly variable. Because of this, differences in means that might seem quite large and that may be biologically significant are not necessarily statistically distinct, except with a few exceptions (table 3).

At the highest 2,4-D rate, the percentage of greenleaf manzanita stems killed was greater with Herbimax than with Nu-Film-IR (table 3). Addition of Nu-Film-IR did not increase the percentage of stems killed or foliage injured. In addition, at the highest rate, Herbimax caused greater injury than treatment with no adjuvant added, but results did not differ from those for the Nu-Film-IR treatment. No differences in injury were observed between the Nu-Film-IR treatment and the no-adjuvant treatment. Finally, at the medium and low rates, no significant difference in percentage of stems killed or injured was observed for either of the adjuvants used.

Trial 3. As expected, when the herbicide rate was increased, the conifer damage index rating increased for both adjuvants tested. At the highest rate tested, damage was greater with Nu-Film-IR than with LI-700. Likewise percentage of seedlings damaged or killed was also greater for the Nu-Film-IR treatment than the LI-700 treatment (table 4). At the highest herbicide rate, 61.8% of the seedlings were damaged by the Nu-Film-IR tank mix, in contrast to 31.3% with the LI-700 mix. Similarly, at the highest herbicide rate tested, 24.4% of the seedlings treated were killed when Nu-Film-IR was used, in contrast to 8.6% with LI-700. At the 2 lower herbicide rates, there were no significant differences in seedling damage or mortality between the 2 adjuvants.

Discussion

Efficacy. Findings suggest that under ideal conditions, the use of an adjuvant is unnecessary when applying an imazapyr—glyphosate site preparation spray over leafy deciduous plants with relatively thin cuticles, such as vine maple, California hazelnut, and brackenfern. These species are typically susceptible to both herbicides used (William and others 1996). Under ideal conditions (moderate temperature, moderate humidity, and no rain for 48 hours), adjuvants apparently provided no additional herbicide absorption.

Although thick-cuticled species such as greenleaf manzanita are resistant to late-summer foliar imazapyr and glyphosate treatments (Cole and others 1986; William and others 1996), applications of 2,4-D often result in good control of these species. An oil adjuvant is often added to the mix to increase efficacy. As expected, the oil adjuvant Herbimax probably aided in 2,4-D absorption, resulting in greater control efficacy. The non-oil-based adjuvant Nu-Film-IR did not significantly increase 2,4-D effect, suggesting that on thick-cuticled species it is less effective than Herbimax.

The effectiveness of spray adjuvants varies depending on the species sprayed and the herbicide used (Prasad 1989; Swietlik 1989; Burrill and others 1990; Stevens and others 1991; Fredrickson and Newton 1998). Studies have shown that surfactants such as Silwet L-77 and LI-700 increase herbicide effectiveness (Swietlik 1989; Burrill and others 1990; Stevens and others 1991). This increase may not always be evident at operational rates but may be more obvious at reduced rates (Sweitlik 1989). Because we did not test adjuvants with imazapyr—glyphosate mixes at lower rates against a no-surfactant control, we cannot draw conclusions about added efficacy due to surfactant addition at lower herbicide rates. Nevertheless, at lower herbicide rates, use of all 3 of the adjuvants resulted in similar levels of control across the 3 species tested. This suggests that any benefit that might have occurred did not differ among the 3 adjuvants tested.

Surfactants generally increase the rainfastness of herbicide applications by increasing absorption rate (Stevens and others 1991; Foy 1993; Roggenbuck and others 1993). Having a surfactant in the tank mix may increase efficacy, especially when rain occurs soon after application. The efficacy afforded by the adjuvants we tested could be quite different under moist weather conditions.

Conifer safety. When used in release treatments, both Nu-Film-1R and LI-700 resulted in high levels of conifer damage at the high and medium rates. This suggests that these adjuvants should not be added to imazapyr—glyphosate tank mixes for fall-release treatments. Using adjuvants for release operations is favored by foresters because adjuvants typically aid in the absorption of herbicides (Stevens and others 1991; Roggenbuck and others 1993). Rain is common and unpredictable during the fall when release treatments are applied. Consequently, inclusion of an adjuvant in the mix may make the difference between successful weed control and failure. Thus, foresters often gamble that the benefit in increased weed control derived from adding an adjuvant will make up for any losses resulting from conifer damage. Our results suggest this is a poor gamble.

More work is needed concerning the effect of herbicide applications and conifer growth. Whereas glyphosate can generally be applied in the fall without damaging conifers (Radosevich *and others* 1980), imazapyr can result in intermediate damage (William and others 1996). This difference may be due to both soil and foliage activity of imazapyr. We could not determine whether the observed damage was a result of foliage or soil absorption. In addition, we could not determine if damage was caused by glyphosate, imazapyr, or a combination of both. It is possible that even a no-adjuvant treatment would also have resulted in a moderate amount of conifer damage.

Conclusions

1. The use of the adjuvants under good environmental conditions did not increase efficacy of imazapyr—glyphosate tank mixes for the thin-cuticled deciduous species tested.
2. Addition of an oil adjuvant significantly increased 2,4-D effectiveness for a thick-cuticled species, out-

performing the other adjuvant (a sticking agent).

3. Imazapyr-glyphosate tank mixes used as release sprays should not be mixed with either LI-700 or Nu-Film-IR adjuvants because of the potential for severe damage to Douglas-fir seedlings.

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Effects of Cold Stratification, Warm-Cold Stratification, and Acid Scarification on Seed Germination of 3 Crataegus Species.

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Successful germination of seeds of downy hawthorn (Crataegus mollis *Scheele) and Arnold hawthorn 'Homestead'* (C. x anomala *Sarg.) required at least 60 days of warm stratification at 18 to 22 °C* (64 *to 72 °F) followed by 120 days or more cold stratification at 2 to 4 °C (36 to 40 °F). Acid scarification of these two species was not beneficial to germination. Fireberry hawthorn* (C. chrysocarpa *Ashe) required at least 90 to 120 days warm stratification followed by 120 days or more of cold stratification to initiate significant germination. Cold periods of 180 or 240 days following warm stratification resulted in excessively elongated radicles in stratification. Acid scarification may be of benefit in the germination of fireberry hawthorn.* Tree Planters' Notes 49(3): 72-74; 2000.

Figure *1—Winter plant form of Arnold hawthorn 'Homestead'* (Crataegus Xanomala *Sarg.) showing uniformity of crown size and shape (© photograph by Greg Morgenson).*

The genus *Crataegus* occurs across North America, with many species, varieties, and forms having been identified and named. Many of these identities are no longer valid. Despite the taxonomic confusion, the hawthorns as a group are increasingly being used in reclamation, wildlife, and environmental plantings. Planting programs for reestablishing naturally occurring flora use native hawthorns to provide cover and food for wildlife. In addition, a number of ornamental selections have been introduced that exhibit superior form (figure 1), flowering, foliage quality, disease resistance, and showy fruit production (cover photograph). Most of these selections are budded on seedling rootstocks.

Propagation of hawthorn by cuttings is difficult at best, and propagation from seed can be disappointing if the proper sequence of treatments is not known and followed. Consistent year-to-year availability of seedlings is dependent upon proven workable seed treatments.

Procedures for germinating *Crataegus* seeds have been published (Dirr and Heuser 1987, Young and Young 1992), but these have not been found to work at the Lincoln Oakes nursery in Bismarck, ND. Hawthorn seed has embryo dormancy, and many species have a hard, thick endocarp that may inhibit germination (Vanstone and others 1982). A series of temperature stratifications and acid scarification treatments were evaluated for breaking seed dormancy in 3 hardy *Crataegus* species: downy hawthorn *(C. mollis* Scheele), Arnold hawthorn 'Homestead' *(C. xanomala* Sarg.) (USDA 1994), and fireberry hawthorn *(C. chrysocarpa* Ashe). *Crataegus anomala* is widely known in the nursery trade as Arnold hawthorn so this is the common name used here for ease of name recognition to the practitioner. The 3rd species has carried the identifications C. *chrysocarpa,* C. *succulenta, C. rotundifolia,* and C. *inacrantlia; C. chrysocarpa* is used in this paper according to Stephens (1973).

Methods

Downy hawthorn and Arnold hawthorn (USDA 1994) ripen their fruits in late August through early September in Bismarck, ND. Both species bear nonpersistent fruits that abscise and fall to the ground when ripe. Fireberry hawthorn fruits ripen in September and are somewhat persistent into winter. Fruits of the 3 *Crataegus* species were collected when fully ripe (figure 2). Pulp was removed by wet maceration. The very hard stony endocarp made cutting tests impractical for determining the full seed percentage. Instead, all depulped seeds were floated in water several times to remove empty seeds. Seeds were air-dried and stored at 4 °C (40 °F) until treated to break dormancy.

Seeds of each species were counted into sublots of 100 for each treatment, and each treatment was replicat-

Figure 2—*Fruit collection from Arnold hawthorn 'Homestead'* (Crataegus xanomala *Sarg.) on fabric mats (©) photograph by Greg Morgenson).*

ed 4 times for 400 seeds per species-treatment combination. Seeds were stratified in damp peat moss in polyethylene bags for the warm and cold stratification periods (table 1). Length of stratification ranged from 0 to 360 days in varying combinations of warm and cold periods. One treatment consisted of 2 cycles of warm-cold to determine whether a significant percentage of seeds that remained ungerminated after the 1st cycle would germinate after a 2nd treatment.

Concentrated sulfuric acid was used for the 2-hour acid soak. Immediately after the acid soak, seeds were thoroughly rinsed with water and treated with baking soda to neutralize the acid.

Seedlots were subjected to 2 to 4 °C (36 to 40 °F) for the cold treatment and 18 to 22 °C (64 to 72 °F) for the warm treatment. At the end of each stratification period, seeds were germinated at room temperature, which ranged from 20 to 25 °C (68 to 77 °F). Four germination counts were made at 7-day intervals.

Results

Seed of the 3 species had little or no response to the 2 cold treatments of 180 and 360 days, but did respond well to warm-cold treatments (table 1). Warm stratification for 60 to 120 days followed by cold stratification for 120 days produced the highest germination with minimal radicle emergence and elongation during stratification for downy hawthorn and Arnold hawthorn. However, the longer cold periods of 180 and 240 days resulted in excessive root elongation, which would make mechanical seeding difficult or impossible. Two cycles of 90 days of warm and 120 days of cold were comparable to a single cycle; only a few additional germinants were produced during the 2nd cycle with these 2 species.

Fireberry hawthorn did not respond to the cold treatments and responded only marginally to the addition of 60 days of warm preceding the cold stratification. Warm stratification of 90 to 120 days was required to initiate germination. The best treatment for this species was 2 cycles of warm-cold. After the 1st cycle, 71 germinants were obtained, and after the 2nd cycle, 78 additional germinants resulted. The longer cold periods of 180 and 240 days caused unacceptable radicle elongation in the stratification bags.

The 2-hour acid soak followed by 180 days of cold produced minimal or no germination for all 3 species. The prior acid treatment did not enhance the 60 days of warm and 180 days of cold on Arnold hawthorn and resulted in the total decay of downy hawthorn seeds in stratification. Acid treatment of fireberry hawthorn prior to warm-cold stratification did increase germination compared to warm-cold stratification without the acid treatment.

The greatest germination occurred in the first *7* days of each treatment. Only minimal germination occurred in the 2nd through the 4th weeks.

Discussion

Successful germination of downy hawthorn and Arnold hawthorn was achieved by the combination of at least 60 days warm stratification followed by 120 days or more of cold stratification. Midsummer (July) nursery planting in mulched moist beds has provided excellent germination results the following spring in North Dakota.

Seed germination of our local source of fireberry hawthorn requires at least 120 days warm stratification preceding the cold stratification. Further trials with longer warm stratification periods could be attempted to determine whether those treatments would overcome the apparent deeper dormancy in many of the seeds and provide more uniform germination. Acid scarification may be used to reduce the warm stratification period required for this species.

Results of these treatments are based on the germination of all seeds planted. Ideally, the seeds of *Crataegus* should be x-rayed to determine total filled seed percentages. A correction for the number of empty seeds would then give a more accurate measure of the success in overcoming the dormancy. These results do provide treatment information for nurseries handling bulk seedlots of these species.

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Table 1—*Three species of* Crataegus *(hawthorn): seed treatments and associated germination*[a]

Treatment		Arnold 'Homestead'		Downy		Fireberry	
Days at 18-22 °C	Days at 2-4 °C	No. of seedlings	% of 400 seeds	No. of seedlings	% of 400 seeds	No. of seedlings	% of 400 seeds
0	0	0	0	0	0	0	0
0	180	0	0	1	0	0	0
0	360	0	0	3	0	1	0
60	120	147	37[b]	202	51[b]	19	5[b]
60	180	140	35[c]	183	46[c]	18	5[b]
60	240	158	40[c]	185	46[b]	12	3[c]
120	120	170	43[b]	192	48[b]	71	18[b]
120	180	146	37[c]	200	50[c]	108	27[c]
120	240	179	45[c]	182	46[c]	106	27[c]
90	120 (2 cycles)[d]	149+7[d]	39[b]	168+2[d]	43[c]	71+78[d]	37[c]
0	acid+180[e]	9	2	7	2	0	0
60	acid+180[e]	104	26[c]	sr[f]	sr	84	21

[a]Arnold 'Homestead' (*C.* × *anomala* Sarg.), downy (*C. mollis* Scheele), fireberry (*C. chrysocarpa* Ashe)
[b]Germination began in stratification with little or no radicle elongation.
[c]Germination began in stratification with excessively elongated radicles.
[d]Cycle repeated after 1 germination period; 2 sets of data represent 1st and 2nd germination results, respectively.
[e]Given a 2-hour acid soak before stratification.
[f]sr = seeds rotted in stratification

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