United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Research Station**

Research Paper
PSW-RP-219

Winter Sowings Produce 1–0 Sugar Pine Planting Stock in the Sierra Nevada

James L. Jenkinson **Arthur H. McCain**

Abstract:

Jenkinson, James L.; McCain, Arthur H. 1993. **Winter sowings produce 1–0 sugar pine planting stock in the Sierra Nevada.** Res. Paper PSW–RP–219. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture; 10 p.

Seed source and sowing date effects on first-year seedling growth and Fusarium root and collar rot of sugar pine were analyzed in two consecutive nursery tests at the Pacific Southwest Research Station's Institute of Forest Genetics, near Placerville in the western Sierra Nevada. The experimental design in both tests consisted of four replications of a randomized complete block of split-split plots, with sowing date split for disease treatment and seed source. Seed sources were natural stands at low, middle, and high elevations on the western slope of the northern Sierra Nevada. Seeds were soaked 36 hours in aerated water at 25° C (77° F), chilled 90 days at 1° C (34° F), and sown in fumigated soil in February, March, April, and May. Treatment plots were drenched with fungicides just before sowing in the first test, and were inoculated with *Fusarium oxysporum* f. sp. *pini* at time of sowing in the second test. Seedling emergence averaged 96 to 99 percent, regardless of sowing date. Seedlings in February sowings reached triple the size of those in the traditional May sowings, and mortality in the check and inoculated plots averaged 3 and 6 percent in the February sowings, against 17 and 33 percent in the May sowings. The results show that seedlings in early sowings (February, March) consistently escape Fusarium disease and produce 1–0 planting stock. Those in late sowings are highly susceptible to Fusarium and the survivors must be carried through a second growing season to produce 2–0 planting stock.

Retrieval terms: genetic variation, seedling emergence, seedling growth, seedling mortality, *Pinus lambertiana*, Fusarium disease, root rot, collar rot, *Fusarium oxysporum* f. sp. *pini*

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Acknowledgments:

We thank Melford Greenup, Program Manager, Interregional Port-Orford-Cedar Program, Pacific Northwest and Southwest Regions; John Kliejunas, Pathology Group Leader, Pacific Southwest Region; Michael Rutty, Silviculturist, Stanislaus National Forest; and Patricia Trimble, Superintendent, Placerville Nursery, Eldorado National Forest, for manuscript reviews.

Publisher:

Pacific Southwest Research Station
Albany, California

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Telephone: 510-559-6300)

September 1993

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Seed source and sowing date effects on first-year seedling growth and Fusarium root and collar rot (*Fusarium oxysporum* f. sp. *pini*) of sugar pine (*Pinus lambertiana*) were investigated in consecutive nursery tests at the Pacific Southwest Research Station's Institute of Forest Genetics, near Placerville, California. Seeds of 5 to 10 trees per source were collected in wild stands at low, middle, and high elevations on the western slope of the northern Sierra Nevada. Seeds from sources at 4600 ft (1402 m) and 5600 ft (1707 m) of elevation were sown in the first test, and sources from 3400 ft (1036 m), 6250 ft (1905 m), and 6700 ft (2042 m), in the second test.

The experiment design for both tests consisted of four replications of a randomized complete block of split-split plots, with sowing date split for disease treatment and seed source. Source plots were lined across the seed beds and contained six rows of 20 spots each. Seed beds were prepared in January, in soil that had been fumigated in August to control soilborne pathogens. Seeds were soaked 36 hours in aerated tapwater at 25° C (77° F), rinsed with captan fungicide, chilled 90 days at 1° C (34° F), and sown in February, March, April, and May. Disease treatment plots in the first test were drenched with benomyl and etridiazole fungicides just before sowing. Those in the second test were inoculated with a known pathogenic culture of *Fusarium oxysporum* f. sp. *pini* at time of sowing.

Seedling emergence was not significantly affected by seed source, sowing date, or disease treatment. Emergence averaged 98 to 99 percent in the first test, and 96 to 98 percent in the second test.

Fusarium disease inexplicably bypassed the first test, and first-year seedling mortality in the check and fungicide plots averaged just 1 percent. *Fusarium* recolonized fumigated soil in the second test, and Fusarium disease was prevalent in the check plots as well as in the inoculated plots. With or without Fusarium inoculation, seedling mortality increased fivefold with later sowing. Mortality in the check and inoculated plots averaged 3 and 6 percent, respectively, in the February sowings, against 17 and 33 percent in the traditional May sowings.

First-year seedling height and stem diameter increased markedly with earlier sowing, and growth was greater for seed sources of lower elevation than for those of higher elevation. Seedlings in February sowings averaged up to 40 percent taller in the first test and up to 120 percent taller in the second test, compared to those in the traditional May sowings. Seedling size in both tests depended almost entirely on sowing date and onset of emergence. Sowing fully chilled seeds in February, as opposed to May, gained at least 2 critical months at the front end of the growing season, even though the soils were cold and delayed and prolonged seedling emergence. Such utilization of the natural growing season in the second test effectively tripled the average seedling stem volume of every source, regardless of the elevation of seed origin.

First-year size and survival of sugar pine from sources at low, middle, and high elevations in the Sierra Nevada demonstrated that nursery management of sugar pine is highly successful when seedling emergence and early growth occur under environmental conditions that match those in natural habitats. Seedlings in winter sowings (February, March) practically escape Fusarium infection and grow large enough the first year to produce 1–0 planting stock. Seedlings in later sowings (April, May) are highly susceptible to Fusarium disease, and survivors require a second growing season to reach acceptable sizes and produce the traditional 2–0 planting stock.

Introduction

Sugar pine's (*Pinus lambertiana* Dougl.) superior growth and diverse habitats recommend it for widespread planting in the Pacific Slope forests of western Oregon and northern California. Largest of all pines, this choice, highly millable softwood thrives on mesic to xeric sites in both coastal and inland regions (*fig. 1*). Its distinctive, open crowns of large, horizontally projecting, randomly arrayed limbs and typically massive old-growth trees make this white pine a highlight of the mixed conifer forests in the Sierra Nevada (Critchfield and Little 1966, Griffin and Critchfield 1976, Kinloch and Scheuner 1990).

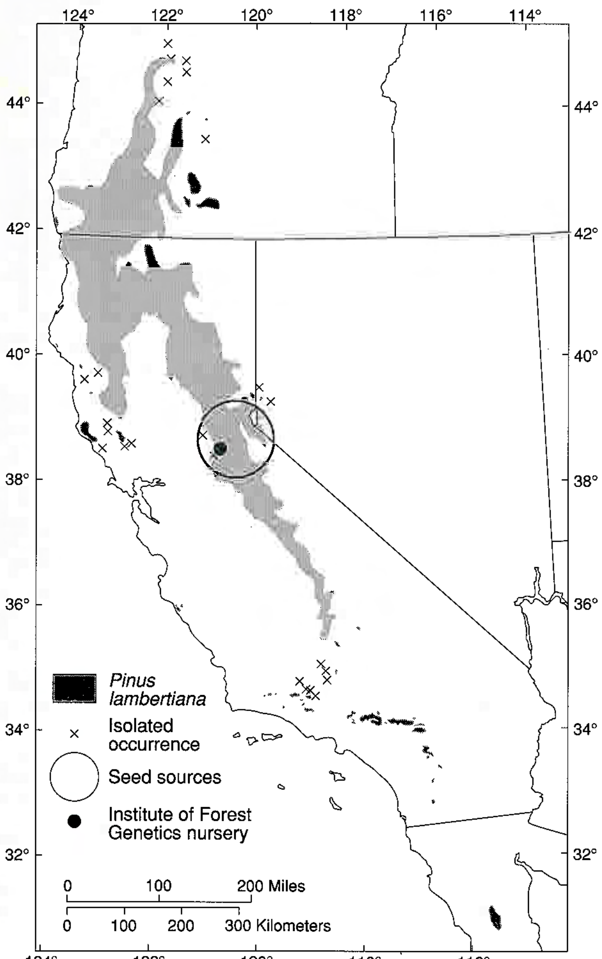


Figure 1—Sowing windows for sugar pine were determined in the Institute of Forest Genetics nursery, at 2750 ft (838 m) of elevation near Placerville. Seedling emergence, mortality, and first-year growth were evaluated for seed sources from low, middle, and high elevations in the Sierra Nevada.

Sugar pine commonly grows with ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), white fir (*Abies concolor* [Gord. & Glend.] Lindl. ex Hildebr.), incense-cedar (*Libocedrus decurrens* Torr.), and California black oak (*Quercus kelloggii* Newb.) at low and middle elevations in the western Sierra Nevada, joins Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) and California red fir (*Abies magnifica* A. Murr.) at higher elevations, and inhabits most of the groves of giant sequoia (*Sequoiadendron giganteum* [Lindl.] Buchholz) in the central and southern Sierra Nevada. Like ponderosa pine and white fir, sugar pine is strongly adapted to climatic gradients associated with elevation on the western slope (Harry and others 1983, Jenkinson 1994).

Observations in mixed plantations indicate that sugar pine lags behind ponderosa pine and Jeffrey pine in the sapling stage, but outgrows them both in the pole stage. Because of sugar pine's overall growth rate and softwood quality, foresters continue to plant it despite two major problems. Nursery management is especially difficult, and white pine blister rust (*Cronartium ribicola* Fischer) imperils regeneration (Bega 1978, Kinloch and Dulitz 1990, Patton and Cordell 1989, Quick 1954).

Disease Problems and Nursery Management

Of the two dozen or more conifers commonly raised in California forest nurseries, sugar pine is probably the most susceptible to seedling diseases. The worst of the diseases are damping-off and root and collar rots caused by *Fusarium oxysporum* f. sp. *pini* (Hartig) Sny. & Hans., *Phytophthora cinnamomi* Rand, *Macrophomina phaseolina* (Tassi) Goid, and various other species of *Fusarium, Phytophthora, Pythium,* and *Rhizoctonia* (Hamm and Hansen 1989, Johnson and others 1989, Kelley and Oak 1989, Kuhlman and others 1989, McCain and others 1989, Smith 1975, Smith and others 1989). Effective control of these soilborne pathogens is crucial and is normally achieved by fumigating the seed bed soils with a mixture of methylbromide and chloropicrin (Cordell and others 1989, Peterson and Smith 1975).

Effective control of soilborne pathogens depends on soil preparation and fumigation timing. To improve drainage and aeration, dry, fallow soil in late summer is ripped in two directions to a depth of 2 to 3 ft (0.6 to 1 m). To get it ready for fumigation, ripped soil is disked to level, irrigated by impact sprinklers, allowed to drain to field capacity, and cultivated using a power harrow. The fumigant usually consists of 67 percent methylbromide and 33 percent chloropicrin and is applied at a rate of 325 lb per acre (364 kg per hectare). The gas is injected 8 inches (20 cm) deep and sealed beneath a continuous sheet of clear polyethylene when the soil temperature is 68° F (20° C) or higher. Summer fumigation is effective, but does not preclude Fusarium disease because strong winds in autumn-winter can reinoculate the seed bed areas with *Fusarium*.

In the USDA Forest Service's Placerville Nursery, situated at 2750 ft (838 m) of elevation in the western Sierra Nevada, Fusarium disease has often destroyed sugar pine sowings. In memorable years, Fusarium killed a million or more seedlings and severely weakened survivors. Damping-off, epicotyl wilt, and wire-stem are common symptoms of the disease, and their appearance signals that Fusarium infestation is already beyond control.

Winter Sowings Investigated

Most forest nurseries on the Pacific Slope were traditionally sown in May, after the spring rains had passed. In California, where summers are normally hot and dry, sugar pine germinants are commonly shaded to reduce mortality. Cultural regimes that use late sowing and summer shading produce small or stunted first-year seedlings. Such regimes take two growing seasons to produce planting stock of acceptable size and balance. Seedlings need to be deep-irrigated twice weekly the second season and undercut in spring to reduce top growth, stimulate root growth, and control top-root ratio of 2–0 planting stock.

Sowing seeds in late spring departs substantially from the ecological conditions that accompany germination in the wild and sacrifices a critical part of sugar pine's innate growing season. Warm soil conditions prevail in May and promote rapid germination and seedling emergence. Warm conditions also promote pathogen activity and seedling infection, however, and seemingly inhibit formation and development of mycorrhizae (Jenkinson and Nelson 1986, and references cited therein).

In an April sowing of sugar pine in the Pacific Southwest Research Station's Institute of Forest Genetics nursery, which has the same soil and climate as the nearby Placerville Nursery, shade was safely omitted and first-year seedling size was markedly improved. The results of this first early sowing suggested that winter sowings might yield first-year seedlings that were large enough to outplant, that is, produce 1–0 planting stock.

This paper makes available nursery research reported at a species introduction conference in Spain (Jenkinson and others 1982), concerning successful tests of the hypothesis that sowing in winter to early spring

- Improves first-year size and survival of sugar pine seedlings by capturing the onset and critical early weeks of the nursery growing season
- Controls Fusarium disease by avoiding ecological conditions that promote seedling infection

Testing consistently demonstrated that February and March sowings produce large and healthy 1–0 sugar pines for seed sources typical of low, middle, and high elevations in the Sierra Nevada.

Table 1—***Sugar pine seed sources assessed for seedling emergence, mortality, and first-year growth in tests of winter and spring sowings in the Institute of Forest Genetics nursery***[1]

Nursery test, Seed source, trees, and Locality			Stands in the Sierra Nevada: Watershed	Elevation		Lat	Long
				ft	*m*	*°N*	*°W*
I Fungicide drench							
CC	5	Capp's Crossing	Cosumnes	4600	1402	38.67	120.40
UT	6	Uncle Tom's Cabin	American	5600	1707	38.95	120.45
II Fusarium inoculation							
SP	5	Sly Park	Cosumnes	3400	1036	38.72	120.57
MC	10	Mule Canyon	American	6250	1905	38.72	120.18
BH	10	Bunker Hill	Rubicon	6700	2042	39.05	120.38

[1] Seeds chilled 90 days at 1° C (34° F) were sown in February, March, April, and May. Seedlings were measured in November.

Methods and Materials

Experiments to assess effects of seed source, sowing date, and Fusarium disease on emergence, mortality, and first-year growth of sugar pine were run in the Institute of Forest Genetics nursery, near Placerville, California (*fig. 1*).

Nursery Site and Seed Sources

The nursery is situated at 2750 ft (838 m) of elevation on Fruit Ridge, below snow line in the American River watershed of the western Sierra Nevada (latitude 38.75° N, longitude 120.73° W). The nursery soil is Aiken clay loam (Rogers 1974). Aiken series soils are formed on volcanic rocks, mainly basalts and andesites, and support mixed conifer forests in the mountainous regions of northern California (Laacke 1979).

Seed sources were chosen to sample sugar pine in mixed conifer forests at elevations ranging from 3300 ft (1000 m) to 6900 ft (2100 m) on the west slope of the northern Sierra Nevada (*fig. 1*). Sources from middle elevations were sown in the first test, and sources from low and high elevations were sown in the second test (*table 1*).

Mature cones were collected from 5 to 10 separate trees of average or better form in natural stands situated in the Cosumnes, American, and Rubicon River watersheds. Stands were located in seed zone 526, except Bunker Hill in zone 525, just over the line from zone 526 (Buck and others 1970). Seeds of individual trees were extracted from sun-dried cones, air-dried, dewinged, cleaned to mostly filled seed, combined by stand locality, and stored at –10° C (13° F).

Test Procedures

Seeds were soaked 36 hours in aerated water at 25° C (77° F), dipped 1 minute in 0.4 percent captan fungicide, drained 20 minutes, and chilled 90 days at 1° C (34° F) in polyethylene bags (Krugman and Jenkinson 1974). Chilled seeds were sown in prepared beds in February, March, April, and May. The soil had been fumigated with methylbromide:chloropicrin (67:33) at a rate of 325 lbs per acre (364 kg per hectare) in August of the previous year, and had been amended with triple super phosphate (NPK 0-45-0) in November, at a rate to supply 225 lb phosphorus (P) per acre (252 kg P per hectare).

Design of the experiment consisted of four replications of a randomized complete block of split-split plots. The blocks measured 15 m (50 ft) long and 1.5 m (5 ft) wide, and were located 0.8 m (2.5 ft) apart, side by side in four adjacent beds. Sowing-date plots were split once for disease treatment and again for seed source. Each source plot held six rows of 20 spots each. Rows were lined across the beds, and spots were set 7.5 cm (3 in) apart within and between rows.

Disease treatment plots in the first test (*I*) were drenched with two different fungicides. Plots were sprayed with 3.06 g benomyl and 1.37 g etridiazole in 2.04 liters water per square meter just before sowing.

Disease treatment plots in the second test (*II*) were inoculated with a known pathogenic culture of *Fusarium oxysporum* f. sp. *pini* at time of sowing. A large quantity of moist, 0.5-mm (0.2-in) pieces of sterilized barley straw was inoculated with the culture, incubated at room temperature until colonization was complete, air-dried, and stored at 10° C (50° F). Infested straw was evenly spread on the treatment plots and raked into the surface 3 cm (1 in) of soil.

The sowings were not mulched, and the germinants were not shaded. The beds were watered as needed until seedling emergence was complete, then deep-irrigated twice weekly until rains ended the summer drought. Seedlings were fertilized with granular ammonium phosphate sulfate (NPS 16-20-13) in early July. Soil between rows was scarified with a cultivating fork, and granules were spread at a rate to supply 100 lb nitrogen (N) per acre (112 kg N per hectare).

Data Collection and Analysis

Seedling emergence and mortality were recorded twice weekly. Emergence of each seedling was recorded after its hypocotyl crook had broken through the bed surface. Seedling mortality continued until autumn. To confirm the presence of Fusarium, dead and dying seedlings were collected biweekly and assayed in a plant pathology laboratory in Berkeley. First-year seedling height and stem diameter just above ground line were measured in November, after root elongation had ceased.

Effects of seed source, sowing date, and Fusarium disease on seedling emergence, mortality, first-year height, and stem diameter were assessed by analysis of variance (Scheffé 1959). Coefficients of determination were calculated to assess the relation of 1–0 seedling height, Y, to sowing date, X, using $Y = a + b(\ln X) + c(\ln X)^2$, and to onset of emergence, Z, using $Y = a + Bz$ (Ryan and others 1981).

Results

Seedling emergence was not significantly affected by seed source, sowing date, or Fusarium disease in either nursery year. Emergence averaged 98 to 99 percent for sowings in the first test, which included the fungicide drench treatment, and 96 to 98 percent for those in the second test, which included the Fusarium inoculation treatment.

Early Sowing and Fungicide Drench (I)

Sowing date significantly affected the time elapsed from seed sowing to onset of seedling emergence, and seed source and sowing date significantly affected first-year seedling height (*table 2*).

Seedling emergence and growth—The time elapsed before seedlings began to emerge increased with earlier sowing and averaged 57 days for sowings on February 1 compared to 19 days for those on May 3 (*table 3*). Yet, sowing early captured up to 8 critical weeks of the growing season, as measured from onset of emergence in the nursery to cessation of root elongation in the beds in November. Sowing on February 1, March 1, and April 5 captured an average of 54, 44, and 15 days, respectively, at the front end of the growing season, compared to sowing on May 3.

Table 2—***Variance analyses of seed source, sowing date, and fungicide drench effects on emergence, mortality, and first-year growth of sugar pine in the Sierra Nevada (I)***

Source of variation	Error term	Degrees freedom	Variance (mean square) for: Days to emerge	Mortality (pct)	Height (mm)
Seed source, S	SB	1	0.14	1.129	7982.8**
Sowing date, D	DB	3	3956.93**	3.474*	4915.5†
Fungicide, T	TB	1	6.89*	.788	237.7
Block, B	DB	3	1.10	.432	1770.2
SD	SDB	3	.14	.834	226.7*
ST	STB	1	.14	.114	.8
DT	DTB	3	2.22	.120	116.4
SB	SDTB	3	.39	.936	22.0
DB	a	9	3.43	.668	1785.9
TB	DTB	3	.31	.210	502.4*
SDT	SDTB	3	.81	1.085	81.2
SDB	SDTB	9	.84	.525	51.3
STB	SDTB	3	.31	.318	62.0
DTB	b	9	1.31	.600	102.3
SDTB	c	9	.64	.714	58.1

†, *, ** Significant at $p < 0.10$, $p < 0.05$, $p < 0.01$

Table 3—***Seed source and sowing date effects on emergence, mortality, and first-year growth of sugar pine in the Sierra Nevada (I)***[1]

Seedling trait, Seed source and elevation (*ft*)	Nursery sowing date: Feb 1	Mar 1	Apr 5	May 3
Emergence, *pct*	98.9	99.1	98.8	98.2
Days to emerge	56.6	39.4	32.5	18.9
Mortality, *pct*	1.0	1.2	1.0	.2
1–0 height, *cm*				
CC 4600	16.9	16.1	14.2	12.1
UT 5600	14.1	13.2	12.3	10.8

[1] Means are averages of fungicide and check plots for sources CC and UT. See *tables 1* and *2*.

Sowing on February 1 increased seedling height by 40 percent and 31 percent for the sources from 4600 ft and 5600 ft of elevation, respectively, compared to sowing on May 3. Seedlings of the 4600-ft source grew taller than those of the 5600-ft source, by 20, 22, 16, and 12 percent in the February, March, April, and May sowings, respectively (sowing date significant at $p < 0.10$), and the differences between sources increased with earlier sowing (interaction of seed source and sowing date significant at $p < 0.05$).

Fusarium disease—Fusarium disease was practically absent. Seedling mortality averaged about 1 percent in the fungicide and check plots and was unaffected by sowing date. Fungicide applications delayed emergence slightly (1 day) and reduced first-year height in earlier sowings in three of the four test blocks (interaction of fungicide treatment and test block significant at $p < 0.05$). Seedlings in the fungicide plots were visibly shorter and slightly chlorotic compared to those in the check plots.

Early Sowing and Fusarium Inoculation (II)

Seed source and sowing date significantly affected seedling emergence, mortality, first-year height, and stem diameter (*table 4*).

Seedling emergence and growth—Sowing date had substantially greater effects than seed source (*table 5*). The time elapsed before seedlings began to emerge increased with earlier sowing, and averaged 60 days for sowings on February 6 compared to 21 days for those on May 22. Sowing on February 6, March 14, and April 10 captured an average of 66, 55, and 30 days at the front end of the growing season, respectively, compared to sowing on May 22. Increase in rate of emergence with later sowing was slightly

Table 4—*Variance analyses of seed source, sowing date, and Fusarium inoculation effects on emergence, mortality, and first-year growth of sugar pine in the Sierra Nevada (II)*

Source of variation	Error term	Degrees freedom	Variance (mean square) for			
			Days to emerge	Mortality (pct)	Height (mm)	Diameter (mm)
Seed source, S	SB	2	37.5**	128.5**	37564**	1.059**
Sowing date, D	DB	3	6417.3**	2501.0**	51952**	1.732**
Fusarium, T	TB	1	.0	2972.6*	139	.004
Block, B	DB	3	29.2**	286.0	12809**	.764**
SD	SDB	6	15.1**	6.4	1031**	.011
ST	STB	2	2.5	20.8	102	.004
DT	DTB	3	1.9	432.8*	268	.017
SB	SDTB	6	1.0	9.0	174*	.049*
DB	a	9	3.6	178.6	1090	.061
TB	DTB	3	8.7*	132.3	783	.046
SDT	SDTB	6	1.3	40.2	75	.024
SDB	SDTB	18	2.2	32.1	150*	.019
STB	SDTB	6	3.2	21.4	213*	.045
DTB	b	9	2.8	82.5	479	.071
SDTB	c	18	1.8	21.2	57	.017

*, ** Significant at $p < 0.05$, $p < 0.01$

faster for the source from 3400 ft of elevation than for those from 6250 ft and 6700 ft (interaction of seed source and sowing date significant at $p < 0.05$).

Seedling size increased markedly with earlier sowing, and stem height and diameter were consistently greater for the source from lower elevation. Seedlings in the February sowings averaged 114 percent taller and 18 percent greater in stem diameter than those in May sowings. Seedlings of the 3400-ft source averaged 30, 39, 34, and 32 percent taller than those of the 6250-ft source in the February, March, April, and May sowings, respectively, and 49, 64, 50, and 55 percent taller than those of the 6700-ft source. Overall, seedlings of the 3400-ft source averaged 34 percent and 55 percent taller than those of the 6250-ft and 6700-ft sources. Differences in height and stem diameter between seedlings of different sources were greatest in the March sowing (interaction of seed source and sowing date significant at $p < 0.05$).

Fusarium disease—Seedling mortality in the second test was 3 to 33 times greater than in the first test (*table 6*). Mortality in the inoculated plots averaged 21 percent. Mortality in the check plots averaged 10 percent, indicating that Fusarium reinvaded after soil fumigation. With or without inoculation, mortality was five times higher in the May sowings than in the February ones. Seedlings in three of the four sowings averaged 1 cm (0.4 inch) shorter in inoculated plots than in check plots, suggesting Fusarium infection in the survivors. Increase in mortality with later sowing seemed slightly higher for the 3400-ft source (but seed source was not significant at $p < 0.10$).

Table 5—*Seed source and sowing date effects on emergence, mortality, and first-year growth of sugar pine in the Sierra Nevada (II)*[1]

Seedling trait, Seed source and elevation (*ft*)	Nursery sowing date			
	Feb 6	Mar 14	Apr 10	May 22
Emergence, *pct*	97.6	98.4	95.8	97.6
Days to emerge				
SP 3400	61.0	33.4	30.2	20.0
MC 6250	59.5	36.1	33.4	22.5
BH 6700	59.9	37.1	34.2	21.4
Mortality, *pct*				
SP 3400	7.5	9.6	25.7	26.6
MC 6250	4.0	7.0	20.4	22.9
BH 6700	3.0	6.7	22.8	24.6
1–0 height, *cm*				
SP 3400	24.1	23.0	17.1	11.5
MC 6250	18.6	16.6	12.8	8.7
BH 6700	16.2	14.0	11.4	7.4
1–0 stem diam, *mm*				
SP 3400	4.1	4.1	3.8	3.5
MC 6250	3.9	3.7	3.6	3.3
BH 6700	3.8	3.7	3.6	3.2

[1] Means are averages of Fusarium-inoculated and check plots. See *tables 1* and *4*.

Table 6—*Sowing date and Fusarium inoculation effects on mortality and first-year growth of sugar pine in the Sierra Nevada (II)*[1]

Seedling trait, Bed treatment	Nursery sowing date			
	Feb 6	Mar 14	Apr 10	May 22
Mortality, *pct*				
Check	3.2	5.5	12.8	16.5
Inoculated	6.6	10.0	33.1	32.8
1–0 height, *cm*				
Check	20.2	17.8	14.4	9.7
Inoculated	19.1	18.0	13.2	8.8

[1] Means are averages for sources SP, MC, and BH. See *tables 1* and *4*.

Discussion

Sowing fully chilled seeds in late winter or early spring consistently produced first-year seedlings of sugar pine that were mostly free of disease and large enough to use as 1–0 planting stock (*fig. 2*).

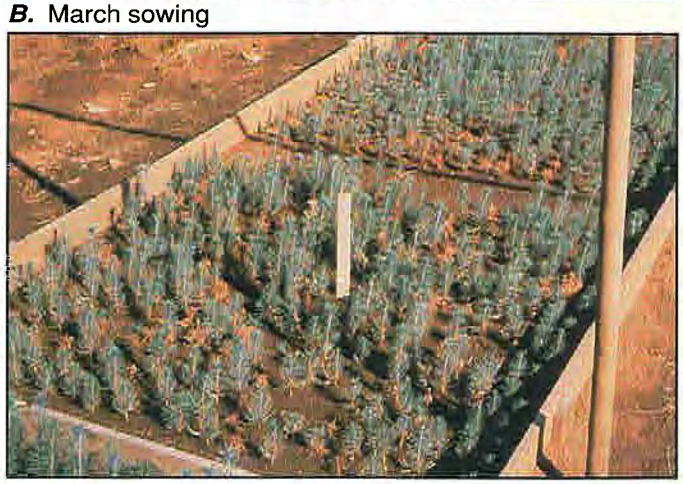
Nursery Sowing Windows for 1–0 Sugar Pine

In the western Sierra Nevada, nursery sowing windows for efficient production of large and healthy 1–0 sugar pine include late winter and early spring (*fig. 3*). Seedlings in our February and March sowings averaged from 14 to 24 cm in height and 3.7 to 4.1 mm in stem diameter, depending on seed source. Sowing late within the

A. February sowing

B. March sowing

C. April sowing



D. May sowing

E. May sowing in soil inoculated with Fusarium

Figure 2—Sugar pine seedlings after one growing season in a test (***II***) of February, March, April, and May sowings in the Institute of Forest Genetics nursery (***A–E***). Sowing in February–March efficiently produces 1–0 planting stock. Traditional May sowings are highly susceptible to Fusarium disease and consistently yield stunted first-year seedlings.

window caused modest decreases in seedling height, that is, 8 to 9 percent for sources from low and middle elevations (3400, 4600, 5600 ft), and 13 to 14 percent for those from high elevations (6250, 6700 ft). Sowing in April, just outside the window, sacrificed up to 31 percent of potential height growth. Sowing in May, the traditional month, sacrificed up to 54 percent of potential and precluded raising sugar pine to plantable size in one growing season.

Integrating seedling height and radial growth dramatizes the practical effects of early sowing. Estimates of average seedling stem volumes using the equation $0.1\pi d^2 h$, where d is stem diameter and h is height (*table 5*), show that, for all sources, February–March sowings produce seedlings that have up to four times the stem volume of those produced in the traditional May sowings.

First-year growth of sugar pine from sources at low, middle, and high elevations depends largely on nursery sowing date (*fig. 3*). Coefficients of multiple determination (R^2) between first-year seedling height and sowing date were 0.98 and higher. Seedling height decreases directly with later sowing and with later onset of emergence (*fig. 4*). Simple coefficients of determination (r^2) ranged from 0.95 to 0.99. Rate of decrease in seedling height with later sowing varies with source and year. Height increases as elevation of seed source decreases, and differences between seedlings from different sources are greater with earlier sowing and emergence.

Extended seed chilling and early sowing markedly increase first-year growth not only of sugar pine, but of Douglas-fir (Sorensen 1978). In the USDA Forest Service's Humboldt Nursery, situated at 250 ft (76 m) of elevation on California's north coast, seedlings may have ninefold greater stem volumes in February sowings than in May sowings (Jenkinson and Nelson 1986). Field testing has repeatedly shown that February and March sowings yield 1–0 Douglas-fir of high survival and growth potential for seed sources from coastal and inland regions in western Oregon and northern California (Boughton 1989, Jenkinson 1989, Jenkinson and Nelson 1983).

Nursery sowing windows are synchronous with the resumption of seedling root growth. In the Institute of Forest Genetics nursery, 1–0 seedlings of ponderosa and Jeffrey pines resume root elongation in late February to early March, when soil in the beds is daily warming above 10° C (50° F) at a depth of 8 cm (3 in). Similar threshold temperatures are observed for sugar pine in the Institute nursery and for Douglas-fir in Humboldt Nursery (Jenkinson 1980, Jenkinson and Nelson 1986).

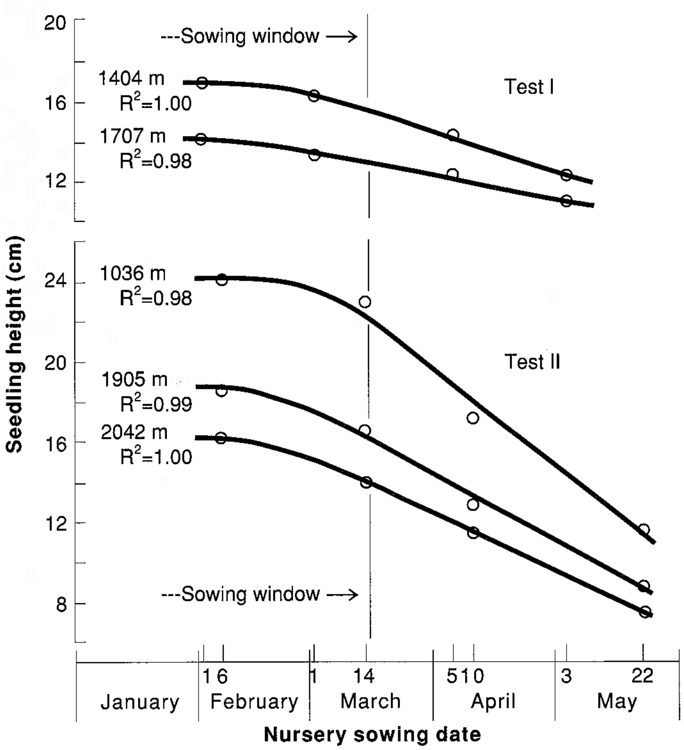


Figure 3—Nursery sowing date explains 98 to 100 percent (R^2 = 0.98 to 1) of the variation in first-year height of sugar pine from seed sources at low, middle, and high elevations in the Sierra Nevada. Seedlings in February–March sowings escape Fusarium disease and produce 1–0 planting stock.

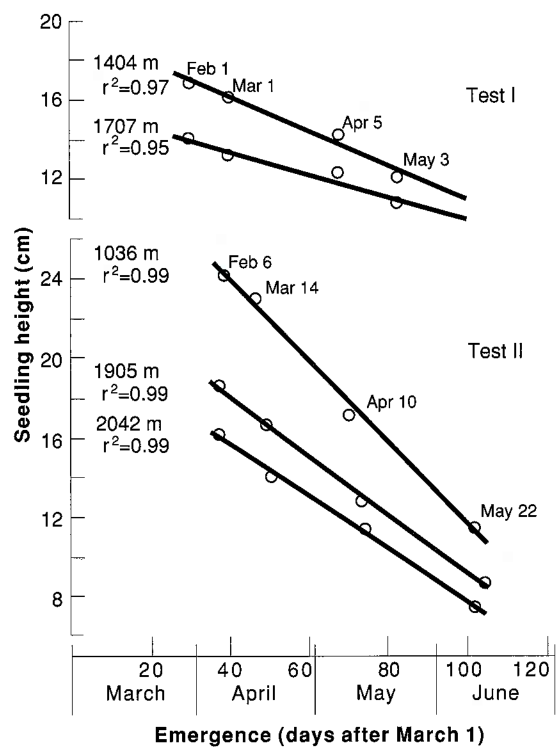


Figure 4—Onset of seedling emergence explains up to 99 percent (r^2 = 0.99) of the variation in first-year height of sugar pine from seed sources at low, middle, and high elevations in the Sierra Nevada. Seedlings in February–March sowings are double the height of those in traditional May sowings.

Because winter sowing anticipates early emergence in cool soils, seeds must be able to germinate at relatively low temperatures. To attain uniform and complete emergence in cool conditions, seeds require extended chilling at 1° C (34° F). Like sugar pine, Douglas-fir from western Oregon and northern California emerged completely and grew best in winter sowings of seeds that had been chilled 90 days (Jenkinson and Nelson 1986). Arboreal associates of sugar pine, that is, ponderosa pine, Jeffrey pine, California red fir, and white fir, emerged and grew well in spring sowings of seeds that had been chilled 60 days (Hallgren 1984, Jenkinson 1980). When fully chilled seeds were tested on thermal-gradient bars, ponderosa pine reached 50 percent germination at 5° C (41° F) in 30 to 60 days, white fir germinated completely at 3° C (38° F) in 50 to 60 days, and Shasta red fir germinated completely at 5° C in 27 days (Jenkinson, data on file; Jenkinson and Nelson 1991).

Winter Sowings Avoid Fusarium Disease

Nursery soils in the Sierra Nevada are normally warm from midspring to late autumn, and seedlings have to be irrigated frequently. These moist, warm conditions are conducive to the development of root diseases. Sowing seeds in winter to early spring takes advantage of soil temperatures that are warm enough to permit germination, but too cool for lethal Fusarium activity. Germinants thereby escape early infection, and seedlings have time to develop secondary tissues and mycorrhizal associations that protect against Fusarium disease.

Our second nursery sowing test was heavily colonized by Fusarium. Yet seedling mortality in check plots averaged only 3.2 percent in the February sowings, which had been installed when the soil was still cold, and only 5.5 percent in the March sowings, which had been installed shortly after the soil was daily warming above 10° C (50° F), temperatures warm enough to permit root elongation (*fig. 2*). Even in plots inoculated with *F. oxysporum* f. sp. *pini*, mortality was held to 6.6 percent by sowing in February, and to 10 percent by sowing in March. By contrast, seedling losses in May sowings, which had been installed after the soil was daily warming above 15° C (59° F), were five times greater than those in February sowings. Mortality in the May sowings averaged 17 percent in the check plots and 33 percent in the inoculated plots.

Unlike root pathogens, mycorrhizal fungi and favorable soil bacteria probably are most active when the nursery soils are cool (see Jenkinson and Nelson 1986, and references therein). In California forests, summer drought confines peak activities of the beneficial rhizoflora to early spring and autumn, when soil water and temperature regimes are most favorable for root growth. Thus, sowing in winter to early spring, when the nursery soil is cool, permits seed germination and seedling emergence in conditions that both enhance mycorrhizal formation and limit pathogen activity.

Seedling cultural regimes that begin with early sowings take advantage of environmental conditions like those found during germination, emergence, and early growth in natural habitats. Early-sow regimes consistently yield first-year sugar pines that are uniformly large and practically free of Fusarium disease. Such seedlings ensure successful 1–0 planting stock. By contrast, regimes that begin with late sowings risk high mortality and severe stunting, ensure small first-year seedlings, and force the nursery to produce 2–0 planting stock.

Conclusion and Application

Whatever the mechanism, nursery management of sugar pine is most successful when the environmental conditions for seed germination, seedling emergence, and early growth match those of natural growth rhythms in native environments. First-year seedlings in winter sowings (February, March) are healthy and sufficiently large for 1–0 planting stock. First-year seedlings in late sowings (May) may be plagued by Fusarium disease, are mostly too small for 1–0 planting stock, and are necessarily carried for a second growing season to produce 2–0 planting stock.

High survivals in field tests have repeatedly demonstrated the merit of 1–0 sugar pine for tree planting programs. In 1982, 1–0 seedlings of diverse seed sources in April sowings in Placerville Nursery were lifted in winter, held in standard cold storage, and planted in spring on cleared sites in the seed zones of origin in the North Coast Range and Sierra Nevada (USDA Forest Service 1982). First-year survivals reached 83 to 94 percent for middle- and low-elevation sources on the Mendocino, Plumas, and Stanislaus National Forests, and 62 percent for a high-elevation source on the Sierra National Forest. In 1984, 1–0 seedlings of rangewide seed sources in an early-April sowing in the Institute of Forest Genetics nursery were lifted in winter, held in cold storage, and successfully planted in spring in common-garden tests at low and high elevations in the western Sierra Nevada. In 1988, 1–0 seedlings in a February sowing of most of those same sources were similarly lifted, stored, and planted in common-garden tests in the Coast Range and Klamath Mountains of southwest Oregon. First-year survivals averaged 86 and 94 percent in the low- and high-elevation Sierra Nevada plantations, and 98 and 82 percent in the coastal and inland Oregon plantations (Jenkinson 1994).

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PSW–RP–219

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