Finding a Replacement for the Eastern Hemlock: Research at the Arnold Arboretum

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This specimen of Tsuga chinensis *was collected by E. H Wilson in Hubei Province, China in 1910 It is now growing at the Arnold Arboretum.*

The hemlock woolly adelgid (*Adelges tsugae*, hereafter HWA) is an introduced insect from Asia that was first discovered feeding on eastern (or Canadian) hemlock *(Tsuga canadensis)* in Virginia in the 1950s.[1] It did not become a serious problem on the East Coast until the 1980s, when it started killing entire populations of both wild and cultivated trees in the mid-Atlantic region. HWA is now well established in the eastern portion of the range of eastern hemlock, from New Hampshire south to North Carolina,[2] as well as in most of the range of Carolina hemlock *(T. caroliniana)*.

While considerable research has been directed toward developing chemical and biological controls for HWA on eastern and Carolina hemlock,[3] relatively little work has been done to determine the resistance of other hemlock species. In one experiment, McClure[4] found that one Japanese species, *T. diversifolia* (northern Japanese hemlock), and two species from western North America, *T. heterophylla* and *T. mertensiana* (western hemlock and mountain hemlock) showed more resistance to HWA than Carolina and eastern hemlock when all five species were cultivated outdoors in Connecticut for one year. Subsequent fieldwork on native hemlock populations in Asia has shown that HWA occurs only infrequently in natural populations of *T. diversifolia* and *T. sieboldii* in Japan[5] and in a subspecies of *T. chinensis* (Chinese hemlock), in China.[6] These results have been attributed to

a combination of host resistance and the presence of natural predators. Bentz et al.[7] reported that cultivated specimens of northern Japanese hemlock and Chinese hemlock growing in close proximity to infected eastern hemlock in Washington, D.C., and in Philadelphia, Pennsylvania, showed strong resistance to HWA over an eight-year period of exposure, while a second Japanese species, *T. sieboldii* (southern Japanese hemlock), showed variable levels of damage. The existing literature on HWA resistance of various hemlock species is summarized in Table 1.

At the Arnold Arboretum we have been studying the Chinese hemlock as a possible replacement for eastern hemlock in landscape settings.

Species	Range	Shade tolerance	Relative growth rate	Hardiness to USDA zone 6	HWA resistance
Tsuga canadensis	Eastern North America	Yes	Fast	Yes	**No**
Tsuga caroliniana	Southern Appalachian Mountains	Yes	Moderate	Yes	**No**
Tsuga chinensis	Central and western China	Yes	Fast	Yes	**Yes**
Tsuga diversifolia	Central and northern Honshu, Japan	Yes	Slow	Yes	**Yes**
Tsuga heterophylla	Northwestern North America	Yes	Fast	Questionable	Questionable
Tsuga mertensiana	Northwestern North America	Unknown	Slow	Yes	Unknown
Tsuga sieboldii	Central and southern Honshu, Japan	Yes	Moderate	Yes	Questionable

Table 1. Comparison of the environmental tolerance factors of various Tsuga *species cultivated at the Arnold Arboretum.*

Source	Collection no and (date)	Collection location	Altitude (m)	Arnold Arboretum accession no	No. living plants (2004)
Veitch China Exp (1899-1902)	EHW #952 (1901)	Xing Shan, Hubei Province	2,130	6851 (Nov 1907)	0 (died 1921)
Arnold Arboretum Exp (1910-1911)	EHW # 4453 (1910)	Fang Xian, Hubei Province	2,300-3,000	17569 (= 6851-1) (Feb. 1911)	1 (grounds)
Botanic Garden, Sun Yat-Sen Memorial Park (Nanjing)	(1932, 1934)	Sichuan Province	—	394-32, 534-34	0
Chinese Academy of Forestry	(1979, 1980)	Sichuan Province (31°N;103°E)	1,000-1,300	1291-79, 481-80	0
Shanghai Botanical Garden	(1980)	Zhejiang Province	—	664-81	0
Quarryhill Botanical Garden	(1991, 1992)	Sichuan Province	2,070-2,500	466-95;92-93	0
U S National Arboretum	(1992)	Wild source	—	233-2003	5 (nursery)
Sheffield Seed Co.	China Natl Tree Seed Co (1992)	Wild source	—	100-94	75 (grounds)
Xian Botanical Garden	(1994, 1996)	Ningshaan, Shaanxi Province	1,600-1,900	503-94, 65-96	10 (grounds)
NACPEC Exp (Qingling Mts)	QLG-013, 188, 190, 193 216, 217 (1996)	Ningxi Reserve, Shaanxi Province	1,800-2,200	20-99; 21-99, 227 to 232-2003	13 (grounds); 26 (nursery)
Cui and Ma (Xian Botanical Garden)	CUI 97-053, 97-054 (1997)	Shaanxi Province	—	242, 243-2000, 307, 308-2000, 225, 226-2003	28 (grounds), 14 (nursery)
USDA Forest Service	(2002)	Wenbishan, Yunnan Province	2,650	439-2003	Greenhouse
USDA Forest Service	(2002)	Ningshan Co , Shaanxi Province	1,800	440-2003	Greenhouse

Table 2. This list of Tsuga chinensis *accessions received by Arnold Arboretum and originating in China between 1901 and 2002 documents the Arboretum's persistence in introducing specimens from diverse parts of* T. chinensis's *native range. See text for details.*

Our ten-year research project has focused on three primary goals: reconstructing the history of the introduction of Chinese hemlock into cultivation in North America; documenting its resistance to HWA; and delineating its environmental tolerances.

CHINESE HEMLOCK IN CULTIVATION IN NORTH AMERICA

Chinese hemlock is widely distributed at elevations between 3,282 and 11,487 feet (1,000 and 3,500 m) in mountainous regions of eastern, central, and southwestern China.[8] E. H. Wilson is credited with introducing the species into cultivation in North America with seed he collected in Xing Shan, Hubei Province (collection #952), in October 1901, while working for the Veitch Nursery Company of Chelsea, England.[9] Despite this early introduction, Chinese hemlock remains poorly represented in North American botanical gardens. One of the very few specimens of known provenance was collected by Wilson as a seedling in Fang Xian, Hubei Province, China, in September 1910. He sent it to the Arnold Arboretum, where it arrived in February 1911.[10] As of the winter of 2004, Wilson's tree was growing under accession #17569 and was 49.2 feet (15 m) in height with a diameter at breast height of 14.4 inches (37 cm) and a branch spread of 39.4 feet (12 m). It showed no sign of HWA infestation.

Over the years, the Arboretum's staff has propagated both seedlings and cuttings from the Wilson tree and distributed them to various botanical gardens and nurseries throughout the United States; records show at least sixteen separate distributions involving twenty-eight plants between 1915 and 1945. Many of the older Chinese hemlocks now growing in botanical collections in the United States are direct descendants of Wilson's Hubei seedling.

Apart from Wilson's collections in 1901 and 1911, wild-collected germplasm of Chinese hemlock appears not to have entered North America again until 1979 and 1980, when visiting delegations of Chinese botanists presented their hosts with seed from the Chinese Academy of Forestry. Since then, numerous American and European expeditions to China have collected and distributed seeds from wild populations growing at altitudes between 3,282 and 8,697 feet (1,000 and 2,650 m) in the provinces of Sichuan, Hubei, Shaanxi, Fujian, Zhejiang, and Yunnan (Table 2).

Year sampled	Excellent*	Good	Fair	Poor	Dead or removed
1998	249	1,406	163	87	—
2002	10	68	422	1,142	263

*Excellent = outstanding specimen, good = healthy specimen, no evidence of disease or physical damage, fair = specimen in decline, evidence of disease or physical damage, poor = specimen in poor condition, more dead branches than living

Table 3. Changes in the condition ratings of the 1,905 eastern hemlocks (i.e., those with dbh's greater than 2 inches [5 cm]) growing on Hemlock Hill at the Arnold Arboretum between 1998 and 2002. Plant condition was rated both years by the same staff members.

THE ARBORETUM'S RESEARCH PROJECT

The north-facing slope called Hemlock Hill consists of approximately 22 acres (10 ha) covered with a nearly pure stand of eastern hemlock. Bedrock is close to the surface on much of the hill, and the soils that overlay it are well drained but poor in nutrients. When HWA was first discovered there in April of 1997, the hemlock population numbered 1,905 individuals with diameters at breast height greater than two inches (five cm). Since then the pest has spread rapidly. The entire population was labeled, mapped, and qualitatively assessed for condition and HWA damage during the winter of 1997–1998. The trees along the base of Hemlock Hill have been sprayed annually in the fall with dormant oil since 1997, which has effectively protected them from HWA, but those in the out-of-reach interior portions have been left untreated and are now in a serious state of decline. By the winter of 2002–2003, when the entire population was recensused, 263 trees had been removed (all were either dead or nearly dead), and those remaining had lost foliage and were in poor health.[11] Table 3 shows the dramatic decline in the hemlocks' condition that occurred between 1998 and 2002 as a result of the HWA infestation.

For our study of Chinese hemlock's resistance to HWA, we used seedlings that were raised from a seed lot purchased in February

Species	No seedlings sampled	Mean plant height (cm)	Exposure			Mean shoot length (cm)*	Mean no HWA egg sacs per shoot	Mean % shoots w/new growth	Mean % shoots w/mite damage
			Sun	Gap	Shade				
Tsuga chinensis	38	169 0 ± 38 0 (range = 84 to 240 cm)	8	18	12	10 3 ± 3 5 (range = 5 5 to 17 2)	0	100	8 7 ± 24 7 (range = 0 to 92)
Tsuga canadensis	33	182 6 ± 94 5 (range = 45 to 380 cm)	2	——	31	4 9 ± 1 2 (range = 2 7 to 8)	3 8 ± 4 (range = 0 to 14 7)	45 4 ± 38 8 (range = 0 to 100)	20 9 ± 27 6 (range = 0 to 100)

*Based on samples of 12 shoots per tree

Table 4 Performance of Tsuga chinensis *versus* T. canadensis *in the Arnold Arboretum study.*

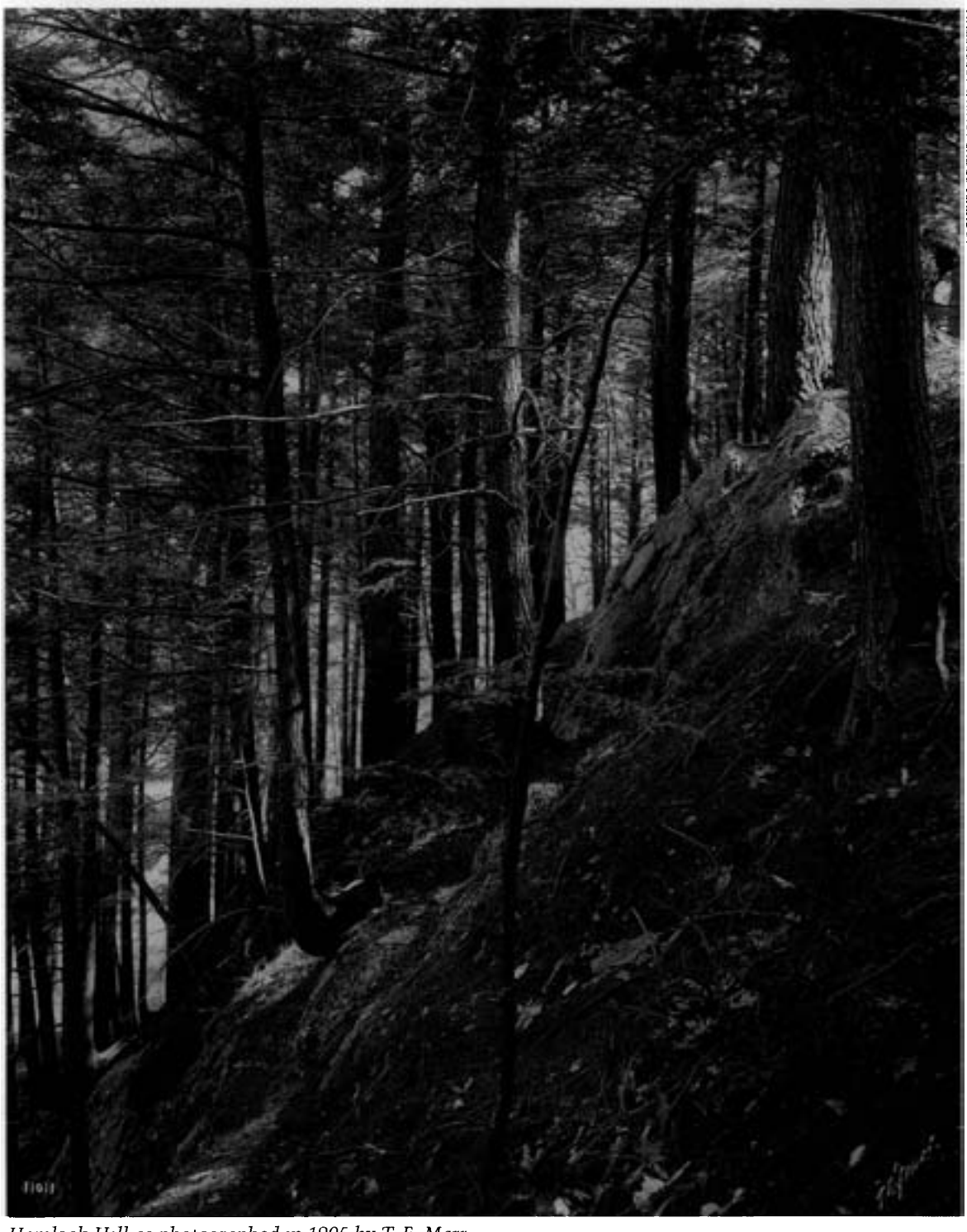
1994 and known to have been collected in China in the wild (AA accession #100-94). After a three-month period of cold stratification, seed was sown in a warm greenhouse. In April 1999, when the five-year-old seedlings were between 23.4 and 42.9 inches (60 and 110 cm) tall, we planted 42 of them in scattered light gaps of the interior portions of Hemlock Hill, in groups of three to six individuals. The canopy for all the seedlings consisted of eastern hemlocks that were badly infected with HWA. At the same time, we established a control group by tagging 33 seedlings of eastern hemlock that were growing spontaneously on the north-facing slope of Hemlock Hill, adjacent to the newly planted Chinese hemlocks. Unlike the majority (68 percent) of the Chinese hemlock seedlings, which were growing in light gaps with at least some direct sunlight during the day, the majority of eastern hemlock seedlings (94 percent) were in understory positions that received no direct sunlight at all.

Four years later, on June 25 and 26, 2003, we evaluated the growth and extent of HWA infestation of the control group and of 38 of the 42 Chinese hemlocks that had been planted in 1999. By this time the Chinese hemlock seedlings had had four years of exposure to HWA and the eastern hemlock seedlings six years. We measured the heights of all the seedlings in both groups and rated their canopy positions as "sun" (growing in a large canopy gap with moderate amounts of direct sun), "gap" (growing in a small canopy gap with minimal amounts of direct sun), or "shade" (growing in complete shade). To assess the level of HWA infestation, we selected at random two branches on opposite sides of each tree, taking for evaluation the six topmost shoots on each branch (consisting of growth from both 2002 and 2003). The following was then recorded for all the shoots: (1) shoot length to the nearest millimeter; (2) the number of HWA egg sacs found on the undersides of the 2002 shoots; (3) the presence or absence of new (2003) growth; and (4) the presence or absence of spider mite damage, assessed by looking for the characteristic leaf stippling on the upper sides of the 2002 shoots.[12]

The 38 Chinese hemlock seedlings were recensused on March 9, 2004, to obtain final height measurements for the 2003 growing season and to learn how many had survived after an unusually cold winter that saw the temperature at the Arboretum reaching a low of –8.5 degrees Fahrenheit (–22.5 degrees centigrade) on January 16.

RESULTS OF THE STUDY

Results of the study are summarized in Table 4. The most dramatic finding was the total absence of HWA egg sacs on all of the 38 Chinese hemlock seedlings, in contrast to a mean of 45.9 egg sacs per 12-shoot sample for eastern hemlock. Another indicator of Chinese hemlock's resistance to HWA was found in the measurement of new growth: 100 percent of the terminal buds on the sampled shoots of Chinese hemlock had produced new growth in 2003, compared with only 45 percent for eastern hemlock. Finally, the mean shoot length for Chinese hemlock was 4 inches (10.3 cm), more than twice the 1.9 inches (4.9 cm) recorded for eastern hemlock. These results clearly show that Chinese hemlock possesses a high degree of resistance to HWA when growing in conditions that are optimal for infestation of eastern hemlock.



ARCHIVES OF THE ARNOLD ARBORETUM

Hemlock Hill as photographed in 1905 by T. E. Marr

One of the Tsuga chinensis *seedlings (AA #100-94) growing in a canopy gap on Hemlock Hill at the Arnold Arboretum, photographed in summer 2003.*

The remeasurement of the 38 Chinese hemlocks on March 9, 2004, showed them to be 17 percent taller than they had been the previous summer when their shoot tips were drooping, with an average height of 77.1 inches (197.8 cm) within a range of 57.3 to 96.9 inches (147.1 to 248.5 cm). The seedlings had averaged between 31.2 and 35.1 inches (80 and 90 cm) in height when they were planted out in April 1999; their average growth over four growing seasons was therefore more than a meter. This is a remarkable figure, considering the stressful conditions on Hemlock Hill and the minimal aftercare the plants received. It should also be noted that the plants showed very little winter damage at the time of the March resurvey, despite the low temperatures recorded in January 2004.

These results show that Chinese hemlock is fully hardy in USDA Zone 6 and is a suitable replacement for eastern hemlock in landscape situations thanks to its relatively rapid growth rate, its tolerance of shade, and its resistance to HWA.

Endnotes

[1] R. J. Gouger. 1971. Control of *Adelges tsugae* on hemlock in Pennsylvania. *Sci Tree Topics* 3 1–9.

[2] M. S. McClure. 1990. Role of wind, birds, deer, and humans in the dispersal of hemlock woolly adelgid (Homoptera: Adelgidae). *Environ Entomol* 20: 258–264, D. A. Orwig, D. R. Foster, and D. L. Mausel. 2002. Landscape patterns of hemlock decline in New England due to the introduced hemlock woolly adelgid. *Journal of Biogeography* 29:1475–1488.

[3] McClure. 1995. Managing hemlock woolly adelgid in ornamental landscapes. *Bulletin of the Connecticut Agriculture Experiment Station # 925.* New Haven, CT; McClure, C. A. Cheah, and T. C. Tigner. 2000. Is *Pseudoscymnus tsugae* the solution to the hemlock woolly adelgid problem? An early perspective, pp 89–96. In K. A. McManus, K. S. Shields, and D. R. Souto, eds. *Proceedings. Symposium on Sustainable Management of Hemlock Ecosystems in Eastern North America,* 22–24 June 1999, Durham, NH. GTR-NE-267. USDA Forest Service, Northeastern Research Station, Newtown Square, PA.

[4] McClure. 1992. Hemlock woolly adelgid. *American Nurseryman* 175(6): 82–89.

[5] McClure et al. 2000.

[6] M. E. Montgomery, D. Yao, and H. Wang. 2000. Chinese Coccinellidae for biological control of the hemlock woolly adelgid: Description of native habitat, pp 97–02. In K. A. McManus et al. 1999.

[7] S. E. Bentz, L. G. H. Riedel, M. R. Pooler, and A. M. Townsend. 2002. Hybridization and self-compatibility in controlled pollinations of eastern North American and Asian hemlock *(Tsuga)* species. *Journal of Arboriculture* 28(4): 200–205.

[8] Z.-Y. Wu and P. H. Raven, eds. 1999. *Flora of China,* Vol. 4. Science Press, Beijing, China, and Missouri Botanical Garden Press, St. Louis, MO.

[9] C. S. Sargent, ed. 1913–1917. *Plantae Wilsonianae An Enumeration of the Woody Plants Collected in Western China for the Arnold Arboretum of Harvard University During the Years 1907, 1908, and 1910 by E H. Wilson* Cambridge University Press, Cambridge, MA; A. Rehder. 1940. *Manual of Cultivated Trees and Shrubs,* 2nd ed. Macmillan, New York, NY; K. S. Clausen and S. Y. Hu. 1980. Mapping the collecting localities of E. H. Wilson in China. *Arnoldia* 40(3): 139–145, R. A. Howard. 1980. E. H. Wilson as a botanist (part I). *Arnoldia* 40(3): 102–138.

[10] Sargent 1913–1917, 3:446; Howard 1980

[11] P. Del Tredici, T. Akin, J. Coop, J. DelRosso, R. Ervin, S. Kelley, A. Kitajima, J. Papargiris, and K. Port. 2003. Proposed Hemlock Hill Management Plant. Arnold Arboretum Living Collections Department, internal report. Jamaica Plain, MA.

[12] M. E. Montgomery. 2003. Research scientist, USDA Forest Service, Camden, CT. Personal communication.

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Peter Del Tredici is a senior research scientist at the Arnold Arboretum. Alice Kitajima now coordinates plant records at Descanso Gardens in La Cañada Flintridge, California. This article is adapted from "Introduction and Cultivation of Chinese Hemlock *(Tsuga chinensis)* and Its Resistance to Hemlock Woolly Adelgid *(Adelges tsugae),*" published in *Journal of Arboriculture* (2004) 30(5): 282–287.