

INTRODUCTION AND CULTIVATION OF CHINESE HEMLOCK (*TSUGA CHINENSIS*) AND ITS RESISTANCE TO HEMLOCK WOOLLY ADELGID (*ADELGES TSUGAE*)

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Abstract. Chinese hemlock (*Tsuga chinensis*) is native to mountainous regions in eastern, central, and southwestern China. Interest in the species has recently increased because of its potential resistance to hemlock woolly adelgid (HWA) (*Adelges tsugae*), an introduced insect that has been killing eastern hemlock (*T. canadensis*) in the eastern portions of its range since the 1980s. Despite the fact that Chinese hemlock was introduced into cultivation in 1901, its environmental tolerances are still largely unknown. This study reports on the performance of Chinese hemlock seedlings planted within a native stand of eastern hemlock (*T. canadensis*) at the Arnold Arboretum in Boston, Massachusetts, U.S., that was heavily infested with HWA. In comparison with a control group of eastern hemlock, Chinese hemlock seedlings were completely resistant to HWA damage after 4 years of exposure. The results of our investigation indicate that *T. chinensis* is fully hardy in USDA zone 6 and is a suitable replacement for *T. canadensis* in landscape situations because of its rapid growth rate, tolerance of shade, and resistance to HWA.

Key Words. *Adelges tsugae*; host resistance; integrated pest management (IPM); plant health; *Tsuga canadensis*; *Tsuga chinensis*.

The hemlock woolly adelgid (*Adelges tsugae* Annand) (HWA) is an introduced insect from Asia that was first discovered feeding on eastern (Canadian) hemlock (*Tsuga canadensis* (L.) Carrière) in Virginia, U.S., in the 1950s (Gouger 1971). 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 of the United States. HWA is now well established in the eastern portion of the range of eastern hemlock, from New Hampshire south to North Carolina (McClure 1990; Orwig et al. 2002), as well as in most of the range of Carolina hemlock (*T. caroliniana* Engelm.).

While there has been considerable research on the chemical and biological control of HWA on eastern and Carolina hemlock (McClure 1995; McClure et al. 2000), relatively little work has been done on the question of the resistance of other hemlock species to the insect. In one experiment, McClure (1992) found that one Japanese species (*T. diversifolia* (Maxim.) Mast.) and two species from western North America (*T. heterophylla* (Raf.) Sarg. and *T. mertensiana* (Bong.) Carrière) showed resistance to HWA relative to *T. canadensis* and *T. caroliniana* when all five species were cultivated outdoors in Connecticut for 1 year. Subsequent fieldwork on native hemlock populations in Asia has shown that HWA occurs at relatively low densities in natural populations of *T. diversifolia* and *T. sieboldii* Carrière in Japan (McClure et al. 2000) and *T. chinensis* (Franch.) E. Pritz. in China (Montgomery et al. 2000), observations that are explained by a combination of host resistance and the presence of natural predators. Bentz et al. (2002) reported that cultivated specimens of *T. diversifolia* and *T. chinensis* growing in close proximity to infected plants of *T. canadensis* in Washington, D.C., and Philadelphia, Pennsylvania, showed strong resistance to HWA over an 8-year period of exposure, while a second Japanese species, *T. sieboldii*, showed variable levels of damage. The existing literature on HWA resistance of various hemlock species is summarized in Table 1.

Table 1. Comparison of the environmental tolerance factors of various *Tsuga* species cultivated at the Arnold Arboretum, including shade tolerance, relative growth rate (compared to other hemlocks), cold hardiness, and HWA resistance.

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

Attention in this paper is focused on Chinese hemlock, *T. chinensis*, which has been little studied outside its native habitat because of limited commercial availability. Active research on Chinese hemlock has been underway at the Arnold Arboretum for the past 10 years to assess its suitability as a replacement for *T. canadensis* in landscape situations. The present study has three primary goals: to (1) reconstruct the history of introduction of *T. chinensis* into cultivation in North America, (2) document its resistance to HWA and (3) delineate its environmental tolerances.

CHINESE HEMLOCK IN CULTIVATION

While *T. chinensis* has a widespread distribution in mountainous regions of eastern, central, and southwestern China between 1,000 and 3,500 m (3,282 to 11,487 ft) (Wu and Raven 1999), the species is poorly represented in North American botanical gardens. E.H. Wilson is credited with the introduction of Chinese hemlock into cultivation with seed he collected in Xing Shan, Hubei Province in October 1901 (collection # 952), while working for the Veitch Nursery Company of Chelsea, England (Sargent 1913–1917, 2:38; Rehder 1940; Clausen and Hu 1980; Howard 1980). One of the very few specimens of *T. chinensis* of known provenance is growing at the Arnold Arboretum of Harvard University, under accession #17569. Wilson collected this plant as a seedling in Fang Xian, Hubei Province, China, in September 1910 and sent it to the Arnold Arboretum, where it arrived in February, 1911 (Sargent 1913–1917, 3:446; Howard 1980). As of winter 2004, Wilson's tree was 15 m (49.2 ft) tall with a diameter at breast height (dbh) of 37 cm (14.4 in.) and a branch spread of 12 m (39.4 ft), and showed no sign of adelgid infestation.

Over the years, Arnold Arboretum staff had propagated both seedlings and cuttings from the Wilson tree and distributed them to various botanical gardens and nurseries in the United States. Between 1915 and 1945, arboretum records show at least 16 separate distributions of *T. chinensis* #17569, involving a total of 28 plants. Many of the older Chinese hemlocks now growing in botanical collections in the United States are the direct descendants of Wilson's Hubei seedling.

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

SITE CONDITIONS, PLANT MATERIALS, AND METHODOLOGY

The Hemlock Hill portion of the Arnold Arboretum consists of approximately 10 ha (22 ac). The north-facing slope is covered with a nearly pure stand of *T. canadensis*. Bedrock is close to the surface on much of Hemlock Hill, and the soils that overlay it are well-drained and nutrient poor. Four soil samples collected from the north-facing slope of Hemlock Hill were analyzed in May 2003 and showed pH levels between 4.2 and 4.5, organic matter content between 11.3% and 19.5%, and high levels of ammonium and low levels of nitrate (Del Tredici et al. 2003).

HWA was first discovered on Hemlock Hill in April of 1997, and the pest has spread rapidly throughout the hemlock population, which consisted of some 1,905 individuals with dbh's greater than 5 cm (2 in.). The entire population was labeled, mapped, and qualitatively assessed for condition and HWA damage during the winter of 1997–1998. Eastern hemlocks 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. Eastern hemlocks growing on the interior portions of Hemlock Hill have been left untreated and are now in a serious state of decline. When the entire population was recensused during the winter of 2002–2003, 263 trees were found to have been removed (all were either dead or near death), and those remaining had lost foliage and were in poor health (Del Tredici et al. 2003). Table 3 shows the dramatic decline in the condition of the hemlocks that occurred between 1998 and 2002 as a result of the HWA infestation.

The senior author undertook a study of the resistance of *T. chinensis* to HWA using seedlings that were raised from a lot of seed purchased from Sheffield Seed Company in Locke, New York, in February 1994 (lot # 9101, received from the China National Seed Company in March 1992). The senior author determined that the seed, while of unknown provenance, was collected from trees growing in the wild. At the Arnold Arboretum, the Sheffield seed was accessioned under #100-94 and given a 3-month cold-stratification period, after which it was sown in a warm greenhouse. In April 1999, 74 five-year-old seedlings were planted out on the arboretum grounds. At the time, they were growing in 12 L (3 gal) containers and were between 60 and 110 cm (23.4 and 42.9 in.) tall. To specifically test the resistance of *T. chinensis* to HWA, some 42 of the seedlings were planted on the interior portions of the Hemlock Hill section of the arboretum in groups of three to six individuals in scattered light-gaps. The canopy for all the seedlings consisted of eastern hemlocks that were badly infected with HWA.

Table 2. List of *Tsuga chinensis* accessions received by Arnold Arboretum that originated in China between 1901 and 2002. See text for details.

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 3. Comparison of the condition ratings of the 1,905 eastern hemlocks [with dbh's greater than 5 cm (2 in.)] growing on Hemlock Hill at the Arnold Arboretum between 1998 and 2002. Condition ratings were performed both years by the same staff members.

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.

On June 25 and 26, 2003, the authors evaluated the growth and resistance of 38 of the 42 Chinese hemlocks that had been planted on Hemlock Hill in 1999. Four individuals were left out of the study because they were not able to be located at the time of the evaluation. As a "control" group, the authors tagged some 33 seedlings of *T. canadensis* that were growing spontaneously on the north-facing slope of Hemlock Hill, adjacent to the planted Chinese hemlocks. The fact that only 33 seedlings could be located on the north-facing slope is testament to the paucity of natural hemlock regeneration and explains why some of the plants used in this study were larger than optimal [up to 380 cm (148.2 in.) tall]. The major differences between the two trial groups were as follows: The *T. chinensis*

seedlings had 4 years of exposure to HWA, while the *T. canadensis* seedlings had 6; and the majority of *T. chinensis* seedlings (68%) were growing in light gaps that received some direct sunlight during the day, while the majority of *T. canadensis* seedlings (94%) were growing in understory positions that did not receive any direct sunlight.

The authors measured the heights of the 38 *T. chinensis* and 33 *T. canadensis* seedlings and recorded their canopy position, which was rated 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 infestation with HWA, two branches on opposite sides of each tree were selected at random, and the six top-most shoots on each branch, consisting of growth from both 2002 and 2003, were selected for evaluation. For each of the 12 shoots per tree, the authors (1) measured its length to the nearest millimeter, (2) counted the number of HWA egg sacs, (3) noted the presence or absence of new (2003) growth, and (4) noted the presence or absence of spider mite damage. The cottony HWA egg sacs were counted with the naked eye on the undersides of the 2002 shoots, and spider mite damage was assessed by looking for the characteristic leaf stippling on the uppersides of the 2002 shoots (Montgomery 2003).

The senior author recensused the 38 Chinese hemlock seedlings on March 9, 2004, in order to obtain final height

Table 4. Means and standard deviations for shoot length, HWA egg sacs, percentage of new growth, and mite damage on matched populations of *Tsuga chinensis* and *T. canadensis* growing at the Arnold Arboretum.

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				
<i>Tsuga chinensis</i>	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)
<i>Tsuga canadensis</i>	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.

measurements for the 2003 growing season and to assess their survival following an extremely cold winter when the temperature at the arboretum reached a low of -22.5°C (-8.5°F) on January 16.

RESULTS AND DISCUSSION

Results of this study are summarized in Table 4. The most dramatic finding was the total absence of HWA egg sacs on any of the 38 *T. chinensis* seedlings in comparison to a mean of 45.9 egg sacs per 12-shoot sample for *T. canadensis*. Another indicator of *T. chinensis* resistance to HWA was the difference in new growth between the two species. One hundred percent of the terminal buds on sampled shoots of *T. chinensis* produced new growth compared with only 45% for *T. canadensis*. Lastly, the mean shoot length for *T. chinensis* was 10.3 cm (4 in.), more than twice the 4.9 cm (1.9 in.) length recorded for *T. canadensis*. These results clearly indicate that Chinese hemlock possesses a high degree of resistance to HWA under conditions that were optimal for infestation of eastern hemlock. This conclusion supports anecdotal reports of Chinese hemlock's resistance to HWA (Montgomery et al. 2000; Bentz et al. 2002).

The remeasurement of the 38 Chinese hemlocks on March 9, 2004, showed them to be 17% taller than they were in the summer, when their shoot tips were drooping, with an average height of 197.8 ± 50.7 cm (77.1 ± 19.8 in.). Given that the seedlings averaged between 80 and 90 cm (31.2 and 35.1 in.) tall when they were planted out in April 1999, the average increase in height for *T. chinensis* over four growing seasons has been over a meter (Figure 1). This was a remarkable figure given the shady conditions on Hemlock Hill, the thin soil, and the minimal after-care the plants received. Finally, it should 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.

The results of this study indicate that *T. chinensis* is fully hardy in USDA zone 6 and is a suitable replacement for *T. canadensis* in landscape situations because of its relatively rapid growth rate, tolerance of shade, and resistance to HWA.



Figure 1. 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.

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- Acknowledgments.** The authors would like to thank Arnold Arboretum staff members Tom Akin, Julie Coop, John DelRosso, Bob Ervin, Susan Kelley, Jim Papargiris, and Kyle Port, whose work on the Hemlock Hill project made this study possible; Mike Montgomery of the USDA Forest Service, Northeast Region, for providing details on protocols for counting HWA; and Nathan Havill for his helpful comments on a draft of the manuscript.
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Résumé. La pruche de Chine (*Tsuga chinensis*) est originaire des régions montagneuses de l'Est, du Centre et du Sud-Ouest de la Chine. L'intérêt envers cette espèce s'est accru récemment en raison de son potentiel de résistance au puceron lanigère de la pruche (*Adelges tsugae*), un insecte introduit qui tue les pruches du Canada (*T. canadensis*) dans les régions orientales de son aire de distribution depuis les années '80. En dépit du fait que la pruche de Chine a été introduite en culture depuis 1901, sa tolérance environnementale est toujours encore méconnue. Cette étude traite de la performance des semis de pruche de Chine plantés au sein d'un peuplement indigène de pruches du Canada (*T. canadensis*) de l'arboretum Arnold de Boston au Massachusetts et qui a été lourdement infesté par le puceron lanigère en question. Comparativement avec une groupe-témoin de pruches du Canada, les semis de pruche de Chine étaient totalement résistants aux dommages causés par le puceron lanigère de la pruche, et ce après quatre ans d'exposition. Les résultats de notre étude indiquent que *T. chinensis* est pleinement rustique en zone 6 du USDA et constitue un remplaçant approprié pour *T. canadensis* dans les aménagements paysagers en raison de sa croissance rapide, de sa tolérance à l'ombre et de sa résistance au puceron lanigère de la pruche.

Zusammenfassung. Die chinesische Schierlingtanne *Tsuga chinensis* ist in den Bergregionen von Ost-, Zentral- und Südwestchina beheimatet. Das Interesse an dieser Art hat kürzlich zugenommen wegen ihrer potentiellen Resistenz gegenüber der Wollschildlaus *Adelges tsugae*, einem eingeführten Schadinsekt, welches an der östlichen Schierlingtanne *T. Canadensis* seit den 80er Jahren zu großem Absterben geführt hat. Trotz der Tatsache, dass die chinesische Schierlingtanne um 1901 in die Kultivierung eingeführt wurde, sind ihre Umwelttoleranzen noch

weitgehend ungekannt. Diese Studie berichtet über die Leistung von Sämlingen der chinesische Schierlingtanne an dem heimischen Standort von der östlichen Schierlingtanne am Arnold Arboretum in Boston, USA, welche heftig von den Schadinsekten befallen sind. Im Vergleich zu einer Kontrollgruppe von östlichen Schierlingtannen waren die chinesische Schierlingtannen über einen Zeitraum von 4 Jahren vollkommen resistent gegenüber den Insekten. Die Ergebnisse unserer Untersuchung weisen darauf hin, dass *Tsuga chinensis* in den USA in der Zone 6 völlig immun ist und wegen seiner schnellen Wachstumsrate, Schattentoleranz und Widerstand gegen *Adelges tsugae* ein geeigneter Ersatz für *T. canadensis* ist.

Resumen. El abeto chino (*Tsuga chinensis*) es nativo de las regiones montañosas del este, centro y suroeste de China. El interés en esta especie ha aumentado debido a su resistencia potencial al aldedido (*Adelges tsugae*), un insecto introducido que ha estado matando desde 1980 al abeto del este (*T. canadensis*) en la porciones orientales de su rango. A pesar del hecho de que el abeto chino fue introducido como cultivo en 1901, sus tolerancias ambientales son aún en gran parte desconocidas. Este estudio reporta el comportamiento de brinzales de abeto chino plantados en rodales nativos de abetos del este (*T. canadensis*) en el Arboretum Arnold en Boston, MA, que estuvo fuertemente infestado con el aldedido. En comparación con un grupo de control de abeto del este, los brinzales de abeto chino fueron completamente resistentes al daño de *Adelges tsugae* después de cuatro años de exposición. Los resultados de nuestra investigación indican que *T. chinensis* es resistente en la zona 6 de la USDA y es un reemplazo en el paisaje aceptable para *T. Canadensis* debido a su tasa rápida de crecimiento, tolerancia a la sombra y resistencia a *Adelges tsugae*.