

Chinese Coccinellidae for Biological Control of the Hemlock Woolly Adelgid: Description of Native Habitat

Michael E. Montgomery¹, Defu Yao², Hongbin Wang²

Abstract

The hemlock woolly adelgid, *Adelges tsugae* Annand, is generally believed to be native to Asia and is known to occur in India, Japan, and China. In China, there are approximately four species of hemlock that grow in 14 provinces. We explored regions of the Southwestern Plateau in Yunnan, Sichuan, and Shaanxi Provinces for the adelgid and its natural enemies. The montane- forests of this region are largely in their natural state and noted for their biological diversity. We found the hemlock woolly adelgid in all three provinces and on each hemlock species examined (*Tsuga dumosa* (D. Don) Eichler, *T. forrestii* Downii, and *T. chinensis* (Franch.) Pritz.). More than 9 families of natural enemies were found in association with *A. tsugae* in China. One family, the Coccinellidae, is exceptionally diverse and seems to have an important role in maintaining the adelgid at low population densities. Of the 50+ species of lady beetles found on hemlock, at least 25 are new to science. Nine species are known to feed on HWA and three have been imported for further evaluation as biological control agents. The biodiversity of the lady beetles is discussed in relation to the habitat and climate of their native range compared with potential release sites in the United States.

Introduction

The hemlock woolly adelgid, *Adelges tsugae* Annand, is a non-native invasive pest of hemlock in the eastern United States. The adelgid is native to Asia and has been found in India, Japan, and China, including the island of Taiwan (Blackman and Eastop 1994). Its first recognition as a species was based on specimens from Oregon and British Columbia (Annand 1928).

The first reports of *A. tsugae* in the eastern United States was in Virginia in the 1950s. By the mid-1980s it had spread to the eight mid-Atlantic states from Virginia to Rhode Island, and had become a serious forest pest (Souto et al. 1995).

The hemlock woolly adelgid is considered a pest only on the hemlocks that grow in eastern North America—*Tsuga canadensis* L. (Carrière) and *T. caroliniana* Engelman. The vulnerability of eastern hemlock to *A. tsugae* is probably the consequence of a lack of natural enemies and an intolerance to adelgid feeding (McClure 1987). There are only a few native and introduced predators that attack the hemlock woolly adelgid in the eastern United States

(Montgomery and Lyon 1996) and these do not have significant impact on *A. tsugae*. In Japan, McClure (1995) found five predators that killed 96 percent of *A. tsugae* in forest sites. One of these, an oribatid mite, did not feed directly on the adelgid but destroyed up to 91 percent of the adelgid eggs by dislodging them from the egg mass. Insects preying on *A. tsugae* in Japan were a lady beetle, a green lacewing, a midge fly, and a flower fly. Both the mite and lady beetle were imported and released in the United States and the lady beetle, *Pseudoscymnus tsugae* Sasaji and McClure (1997) has demonstrated good potential as a biological control agent of *A. tsugae* (Cheah and McClure 1996).

Extensive field exploration in China from 1996 to 1998 of hemlock forests in Yunnan, Sichuan, and Shaanxi Provinces found predaceous insects in eleven families that are potential natural enemies of *A. tsugae* (Wang et al. 1997). The families are Coccinellidae, Cecidomyiidae, Syrphidae, Hemerobiidae, Chrysopidae, Derodontidae, Anthocoridae, Miridae, Inocellidae, Staphylinidae, and Labaiduridae. The coccinellids (lady beetles) seem especially promising for biological control of hemlock woolly adelgid.

This report discusses the environment in China in which these lady beetles were found. The objective is to increase understanding of the habitat and climate of an area where an extraordinary diversity of lady beetles associated with *A. tsugae* occurs. This information will facilitate establishment of effective biological control of the adelgid in the eastern United States.

Description of Habitat

Forests in China

Forests in China are similar to those in the United States in many respects. The land area of China is slightly greater than that of the U.S., including Alaska. The forests are more concentrated in the eastern half of the country and much of the western part is grassland, desert, or mountains above timberline. There are six major types of natural forest in China that are organized in broad latitudinal bands or narrow altitudinal gradients (Wang 1961). The forest types from north to south are: (1) boreal coniferous; (2) mixed northern hardwood; (3) temperate, deciduous broad-leaved; (4) mixed mesophytic; (5) sclerophyllous, evergreen broad-leaved; and (6) rain forest. These extant types originally formed a remarkably unbroken expanse of forest from the Arctic to below the Tropic of Cancer (Wang 1961). Extensive land clearing for agriculture and establishment of secondary forests of pine and, to a lesser extent, poplar, have disrupted the continuity and little of the lowland natural forest remains. Because of their ruggedness and isolation, the forests in the mountains of southwestern China are in a remarkably intact, natural condition. In a day's journey from 800 m to 4,000 m, the forest can change from rainforest to evergreen

¹USDA Forest Service, Northeastern Center for Forest Health Research, 51 Mill Pond Road, Hamden, CT 06514

²Chinese Academy of Forestry, Research Institute of Forest Environment and Protection, Beijing 100091, People's Republic of China

Table 1. Species and varieties of *Tsuga* occurring in China

Species/Variety	Cheng 1983			Fargon 1990		
	Sp.	Var.	Syn.	Sp.	Var.	Syn.
<i>T. chinensis</i> (Franchet) Pritzel in Diels	x			x		
<i>T. oblongisquamata</i> (Cheng et Fu) Cheng et Fu	x				x	
<i>T. chinensis</i> var. <i>robusta</i> Cheng et Fu		x			x	
<i>T. tchekiangensis</i> Flous	x					x
<i>T. formosana</i> Hayata	x					x
<i>T. forrestii</i> Downie	x			x		
<i>T. dumosa</i> (D. Don) Eichler	x			x		
<i>T. yunnanensis</i> (Franchet) Pritzel			x			x
<i>T. longibracteata</i> Cheng	x					x*

* placed in a new genus as *Nothotsuga longibracteata* (Cheng) Hu ex C.N. Page

sclerophyllus broad-leaved, to deciduous broad-leaved, to montane coniferous, to alpine scrub. In this area, the montane-boreal forests often occur as isolated "islands" (Wang 1961). Hemlock is common at the lower elevations in the fog belt where boreal coniferous forest merges with broad-leaved forest.

Hemlocks in China

There are approximately 20 previously described species of hemlock in China, but no more than 7 are considered valid species by modern authorities (Table 1). Only 3 of the 7 species of *Tsuga* in C[Z]heng (1983) are listed as true species by Fargon (1990). One of the species, *T. longibracteata* Cheng, has been placed in a distinct new genus, *Nothotsuga* (Page 1988). The common name of this species, bristlecone hemlock, refers to the unusually large and bristly cones that distinguish it from *Tsuga* species. The classification of the *T. chinensis* group varies among authorities with the Chinese maintaining more species than Western botanists (see following discussion about *T. chinensis*). The nomenclature in Table 2 is not meant to be authoritative to but provide an identity meaningful to both Chinese and North American entomologists for the various "hemlocks" found in China. All of the taxons in Table 2 except *Tsuga dumosa* (D. Don) Eich. occur only in China.

Tsuga dumosa occurs in a relatively narrow range of latitude across the southern Himalayan Mountain Range from northeastern Pakistan, northern Myanmar (Burma), to northwestern Yunnan and southwestern Sichuan in China. It is a common species in the transition zone between boreal coniferous forests and deciduous hardwoods. Chinese specimens in herbariums and local usage are often called *T. yunnanensis* (Franchet) Pritzel, but both Chinese and Western authorities (Cheng and Fu 1978, Fargon 1990) regard it and *T. dumosa* as the same species. Its common name is Himalayan hemlock, but it is called Yunnan tieshan in Chinese. In Yunnan, *T. dumosa* usually is found at elevations between 2,600 and 3,000 m. Precipitation is over 1,000 mm/yr, with most falling during the growing season.

Tsuga chinensis (Franch.) Pritzel, is the most widely distributed hemlock species in China occurring from eastern Xizang (Tibet) west to the island of Taiwan, and from Gansu south to Yunnan. The species is often divided into several varieties, but there is not a consensus on the varieties or whether some species are distinct from *T. chinensis*. An earlier publication (Cheng and Fu 1978) classified *T. oblongisquamata* Cheng et Fu and *T. tchekiangensis* Flous as varieties of *T. chinensis* (Franch.) Pritz. Only the variety *T. chinensis* var. *robusta* seems to be universally recognized. A hemlock restricted to Taiwan, *T. formosa* Hayata, is considered a species by Cheng and Fu (1978), but Fargon (1990) believes that it does not have sufficient consistent differences to regard it as a variety of *T. chinensis*. *Tsuga chinensis*, including its varieties, usually occurs at elevations of 1,200 to 3,200 m. Soils may be red, yellow, or podzols (Fargon 1990). Climate usually is temperate and relatively moist. It occurs in mixed mesophytic forests and montane boreal forests. The common name is Chinese hemlock and in Chinese it is simply hemlock (tieshan).

Tsuga forrestii Downie is a species with morphological characteristics intermediate between *T. dumosa* and *T. chinensis* (Fargon 1990). Some authorities consider it a subspecies of *T. dumosa*, others a subspecies of *T. chinensis*. The range of *T. forrestii* is limited to the mountains near the border of northwestern Yunnan and southwestern Sichuan where the two former species meet. *Tsuga forrestii* is known as a high mountain species occurring between 2,000 and 3,500 m. The Chinese name for this species, Lijiang tieshan, reflects its principal locality. We found *T. forrestii* above 2,800 m in close proximity to *T. dumosa* when collecting lady beetles in Lijiang Prefecture, Yunnan, and could easily distinguish them.

The Chinese species tend to have broader, more flat crowns than the North American species. They have pendulous leaders and branch tips, similar to *T. heterophylla* (Raf.) Sargent. Like the North American species, the Chinese hemlocks are usually the most shade tolerant and oldest species in a forest. The largest hemlock we observed was almost 40 m tall with a diameter greater than 3 m.

Table 2. Distribution of hemlocks in China

Taxon	Province														
	Xizang	Gansu	Yunnan	Sichuan	Shaanxi	Guizhou	Guangxi	Hunan	Hubei	Henan	Guangdong	Jiangxi	Anhui	Fujian	Taiwan
<i>Tsuga dumosa</i> (D. Don) Eich.	x		x	x											
<i>T. forrestii</i> Downie			x	x											
<i>T. chinensis</i> (Franch.) E. Pritz.	x	x	x	x	x	x			x	x					
<i>T. c. oblongisquamata</i> Cheng et Fu				x					x						
<i>T. c. tchekiangensis</i> (Flous) Cheng et Fu	x						x	x			x	x	x	x	
<i>T. c. robusta</i> Cheng et Fu				x					x						
<i>T. c. formosana</i> Hayata															x
<i>Nothotsuga longibracteata</i> (Cheng) ex page						x	x	x			x	x		x	

General Characteristics of the Hemlock Forest

In China, *Tsuga* species usually are a minor component of the forest (Wang 1961). They usually are scattered among other species and are more abundant on steep, north-facing slopes at lower altitudes and south slopes at higher altitudes. Hemlock forest is a transitional zone between the montane coniferous forest and the hardwood forest zones. In the upper Yangtze Valley it is the upper limit of the mixed mesophytic forest. No tree species dominates this forest. What is most striking is the extraordinary diversity of tree species. Besides *Tsuga*, there are species in the genera *Abies*, *Aesculus*, *Carpinus*, *Cercis*, *Chamaecyparis*, *Clethra*, *Corylus*, *Ilex*, *Juglans*, *Juniperus*, *Lindera*, *Magnolia*, *Malus*, *Prunus*, *Picea*, *Pinus*, *Pseudotsuga*, *Sorbus*, *Taxus*, *Tilia*, and *Ulmus*. There are also species in other genera not present in North America such as *Castanopsis*, *Cercidiphyllum*, *Schima*, *Cunninghamia*, and *Keteleeria*. This assemblage of a large number of tree species with the crown layer shared by several species with no species or groups predominate is a characteristic of the mixed mesophytic forest type. This forest type is extensive in the hilly country of the Yangtze River Basin and also occurs in the Southern Appalachians of eastern North America.

The areas we explored for natural enemies of the hemlock woolly adelgid are located in northwestern Yunnan, southwestern Sichuan, and southern Shaanxi (Fig. 1). We examined hemlock growing between between 2,500 and 3,000 m altitude in forest with deciduous broad-leaved species with intrusions of montane-boreal conifers from higher altitudes, and evergreen sclerophyllous broad-leaved species from lower altitudes. The areas where we made collections were reminiscent of the forest where hemlock occurs in Great Smoky Mountain National Park, USA, an

area also noted for its biodiversity. The most common fir and spruce species in the areas where we found the hemlock woolly adelgid were *Abies fabri* (Masters) Craib, *A. delavayi* Franch., *A. forrestii* C. Coltm Rodgers, *Picea brachtyla* (Franch.) Pritz., and *P. likiangensis* (Franch.) Pritz. Other conifers present, besides hemlock, include *Pinus armandii* Franch., *P. yunnanensis* Franch., *Keteleeri evelyniana* Masters, *Cunninghamia lanceolata* (Lamb.) Hook, *Larix potaninii* Batalin and *Taxus chinensis* (Pilg.) Reg. Among the deciduous hardwood trees, species of *Acer*, *Alnus*, *Betula*, and *Populus* were most common. Evergreen oaks were common in Yunnan. *Rhododendron* spp. were prevalent in the understory in all areas. Mountain bamboo, *Arundinaria* spp., was common in the understory in Sichuan.

The montane-coniferous forests of the region have about 24 species and varieties of *Abies* and *Picea* (Wang 1961), although the taxonomic status of many of these is unclear. There are 3 species of hemlock with one species found nowhere else. It seems that speciation in many tree genera in the region remains active; both polymorphic species and incipient genera are not uncommon.

Climate

All areas where hemlock occurs in China are very moist during the growing season. Monsoon rains extend to the collection area in northwestern Yunnan and influence the weather further north. The narrow band of altitude where hemlock grows is a fog belt. The tree trunks in this forest are covered with mosses and lichens and long strands of the lichen, *Usnea longissima*, hang from the crowns.

The Perfecture of Lijiang, in Yunnan Province, was the most southerly and highest in elevation of the three collecting

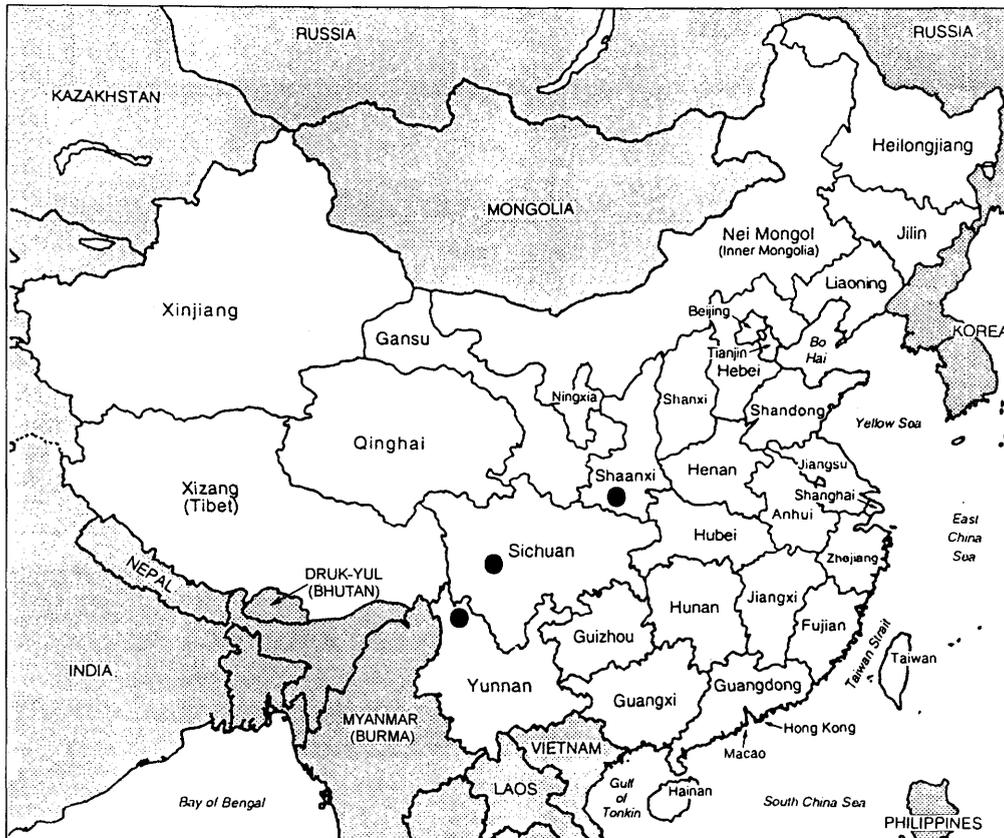


Figure 1.—Map of the provinces of China showing the areas explored (solid circles) for natural enemies of the hemlock woolly adelgid.

areas. Monthly temperature and precipitation means for Lijiang are compared to Shenandoah National Park, Virginia, U.S.A. (Fig. 2). The weather station in Lijiang is located near the city at an altitude of 2,400 m. We adjusted these temperatures to 2,800 m, where the hemlock grows, by applying a lapse rate of 0.5°C per 100 m (Yoshino 1975). The weather station in Shenandoah National Park is at 1,100 m and 38.5°N latitude. The longitude of Lijiang is 27.1°N; this is about the same as Miami, Florida (Lijiang is much colder because it is 8,000 ft higher in elevation).

Although the climate in Lijiang is mild, temperatures frequently drop to -10°C during the winter. Snowfall is heavy, especially in early winter and late spring. We experienced a >5 cm snowfall at 2,900 m during the afternoon in late April.

The Chinese hemlocks, like most *Tsuga* species, grow where the humidity is high and the soil is moist throughout the growing season. They do not extend in altitude to the tree line and are not as cold tolerant as spruce and fir. The temperature range for *T. diversifolia* in Japan, *T. heterophylla* in western North America, and *T. dumosa* in China are similar; not below -10°C or above 20°C, January and July monthly means, respectively (Fargon 1990). It appears that all the Asian species exist in climates that are warmer than the extremes at which the North American species, *T. canadensis* and *T. mertensiana* (Bong.) Carrière can occur.

Lady beetles on Chinese hemlocks

To date, we have collected 54 species of lady beetles from hemlocks in China. Most species were found in Yunnan (45), whereas only 11 and 5 species were found in Sichuan and Yunnan, respectively. Only eight of the species were found in more than one location and no species was found in all three locations. A listing of the 54 species collected from hemlock, including descriptions for 20 new species, can be found in Yu et al. (in press).

There are several reasons why more species of lady beetles were collected in Yunnan; some are logistical and others are habitat related. Much more collecting effort was made in Yunnan. A greater diversity of accessible hemlock habitats existed near our base in Lijiang City, Yunnan. Extensive stands of both *T. dumosa* and *T. forrestii* were within a one-half day drive. *Pinus armandii* was more prevalent in our collecting areas in Lijiang than in the other two provinces. This 5-needle white pine was infested by an undetermined adelgid in the genus *Pineus*. Several of the lady beetles, including those that were most abundant, were collected also from the white pine.

The majority of lady beetles we collected from hemlock in China are in the tribe Scymnii. Members of this tribe are predators of homopterous insects, mostly aphids, adelgids, and scales (Pang and Gordon 1986). Of the nine species we

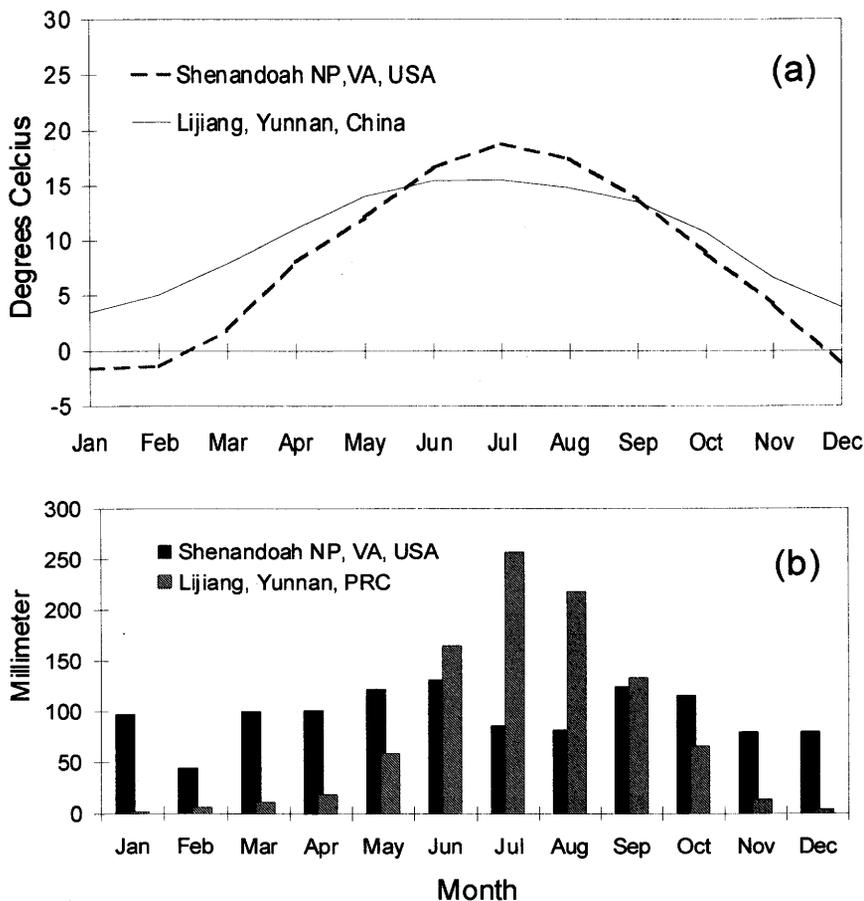


Figure 2.—Comparison of monthly mean temperature (a) and precipitation (b) between growing sites of hemlock in southwestern China and southeastern United States.

Table 3.—Number and percent of the total of lady beetles in different sites in Lijiang County, Yunnan Province

Species of beetle	Wenbi Shan Temple		Yulong, Snow Mountain		Heyuan Forest Farm	
<i>Scymnus (Neopullus) sinuanodulus</i>	67	65%	21	22%	11	16%
<i>Scymnus (Neopullus) camptodromus</i>	2	2%	71	74%	18	27%
Other <i>Scymnus</i> spp.	15	15%	5	6%	26	39%
All other	19	18%	1	1%	12	18%

confirmed to feed on *A. tsugae*, five are in the genus *Scymnus* (Yu et al., in press). Three of the others (*Oenopia billieti* (Mulsant), *Adalbia conglomerata* (L.), and *Calvia championorum* Booth) are widespread and feed on other Homoptera besides adelgids. The genus *Scymnus* is the largest genus in the family Coccinellidae and has been divided into five subgenera.

Whenever we made collections, we found a member of the subgenus *Scymnus (Neopullus)* to be the most common

lady beetle on hemlock infested with *A. tsugae*. *Scymnus (Neopullus) camptodromus* Yu et Liu was the only member of the subfamily found in more than one province. The relative distribution of members of the subfamily varied among collecting areas in the same country (Table 3). The elevation of the Yulong site is 2,900 m, 200 m higher than the other two sites. *Tsuga dumosa* was at each site, but Heyuan also had *T. forrestii*.

End Remarks

As with the tree species, the lady beetles in the hemlock forests of southwestern China are exceptionally diverse. The steep, broken mountains where hemlock is most abundant in China may have fostered speciation of the hemlock and other trees, their pests, and the natural enemies of the pests. The *Scymnus* lady beetles especially are diverse, with many localized species. It has, historically, been difficult to grow Chinese hemlocks in North America. It may be equally difficult to transplant the lady beetles that feed on *A. tsugae* in China. Attempts to establish lady beetles should give special care to climate matching.

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¹The preferred spelling is Zheng, C. J. in Pinyin, the system adopted in 1979 by PRC for transliterating Chinese ideograms into the Latin alphabet. Cheng is used here to maintain consistency with the nomenclature author of some *Tsuga* species.