Asian Longhorned Beetle *Anoplophora glabripennis* (Motschulsky): Lessons Learned and Opportunities to Improve the Process of Eradication and Management

Michael T. Smith, Jean J. Turgeon, Peter De Groot, and B. Gasman

Geographic Range. *Anoplophora glabripennis* (Motschulsky) (Coleoptera: Cerambycidae), native to China (Wu and Jiang 1998) and the Korean peninsula (Peng and Liu, 1992, Lingafelter and Hoebeke 2002, Williams et al. 2004), is among the recent non-indigenous invasive species to North America and Europe. Locations of the known infestations of *A. glabripennis* in North America (year found) include New York City and Long Island, NY (1996), Chicago, IL (1998), Jersey City, NJ (2002), Toronto, Canada (2003), Carteret, NJ (2004), Linden, NJ (2006), and Prall Island and Staten Island, NY (2007). In addition, adult *A. glabripennis* were discovered in Sacramento, CA (June 2005), thereby putting at risk various tree species in the western United States. Locations of the known infestations of *A. glabripennis* in Europe (year found) include Austria: Braunau am Inn (2001) (Tomiczek et al. 2002, 2007); France: Gien (Loiret) (2003) (Cocquempot et al. 2003) and Sainte-Anne-sur-Brivet (Loire Atlantique) (2004); (Herard et al. 2005) Germany: Neukirchen am Inn (Bavaria) (2004) (Benker et al. 2004, Tomiczek et al. 2007); and Italy: Corbetta (Milano) (2007) (Maspero et al. 2007). Cargo infested by *A. glabripennis* has also been discovered and eradicated in warehouses in at least 17 states across the United States, as well as in Canada, Italy, Austria, Germany, France, and Poland. Given the known pathways for *A. glabripennis* introduction, via solid wood packing material used in international trade, it is not surprising that the known infestations are typically at ports of entry or within the surrounding areas, particularly along routes of transportation leaving from these areas.

Host Range. In China, *A. glabripennis* is a primary wood borer pest of many deciduous broadleaf tree species (Xiao 1992), where feeding by larvae in the cambium and xylem causes widespread tree mortality (Yang et al. 1995). Broadly, its hosts include *Populus* spp., *Salix* spp., *Ulmus* spp. and *Acer* spp. (Xiao 1992). In addition, while *Tilia* and *Eleagnus* species are reported to be attacked by *A. glabripennis*, eggs fail to hatch and larvae die before boring into the xylem, respectively (referred to as dead-end hosts). Finally, *Melia azedarach* L. is reported to be repellent (Gao and Zhong. 1998; Sun *et al.* 1990). The known host species of *A. glabripennis* in North America, in which it has successfully developed and emerged, include *Acer* (maple), including *A. platanoides* (Norway maple), *A. saccharum* (Sugar maple), *A. saccharinum* (Silver maple), *A. rubrum* (Red maple), *A. negundo* (Box-elder or Manitoba maple); *Salix* (willow), including *S. alba* (White willow), *S. babylonica* (Weeping willow), *S. discolor* (Pussy willow) and *S. nigra* (Black willow); *Ulmus* (elm); including *U. americana* (American elm); *U. pumila* (Siberian elm) and/or *U. parvifolia* (Chinese elm); *Betula* (birch), including *B. occidentalis* (Water birch), *B. papyrifera* (White birch) and *B. populifolia* (Gray birch); *Aesculus*, including *A. hippocastanum* (Horsechestnut) and *A. glabra* (Ohio Buckeye); *Sorbus americana* (Mountain Ash); and *Platanus x acerifolia* (London Plane-Tree) (Ric et. al. 2007). The known host species of *A. glabripennis* in Europe include *A. platanoides, A. negundo, A. saccharinum, A. pseudoplatanus, Platanus* sp., *Fagus sylvatica "asplenifolia", Betula pendula*, *Aesculus hippocastanum, Populus* sp., *Salix* sp. and *Prunus* sp. (Hérard et al. 2005, Maspero et al. 2007; Sawyer 2009). Therefore, while *A. glabripennis* attacks a broad range of host genera, *Acer* species are by far the species of choice of *A. glabripennis*, both within and outside its countries of origin.

Landscapes. In China, *A. glabripennis* is a pest of man-made landscapes, including windbreaks, greenbelts, ornamental plantings in urban areas, and plantations or shelter-forests, where they undergo cyclical outbreaks (Hsiao 1982). These landscapes are typically monocultures or of very limited species diversity, often composed of fast-growing non-native tree species introduced from Europe and other countries. In contrast, *A. glabripennis* is not a pest in South Korea, but is rare and limited to riparian species-rich habitats (Williams et al. 2004). Unlike China, the introduction and widespread planting of monocultures of non-native tree species has not typically been used in South Korea. In North America, *A. glabripennis* is a pest of urban, industrial, and residential areas, infesting street and yard trees, as well as trees within cemeteries, parks, and woodlots or nature preserves. Infested trees are largely open-grown or along edges of closed canopy landscapes. Likewise, *A. glabripennis* is limited to trees within urban environments in Europe (Hérard et al. 2005). Not unlike areas in China where *A. glabripennis* is a pest, these landscapes are also largely manmade and limited in species diversity. To date, there is little or no evidence that *A. glabripennis* is a pest within natural forests.

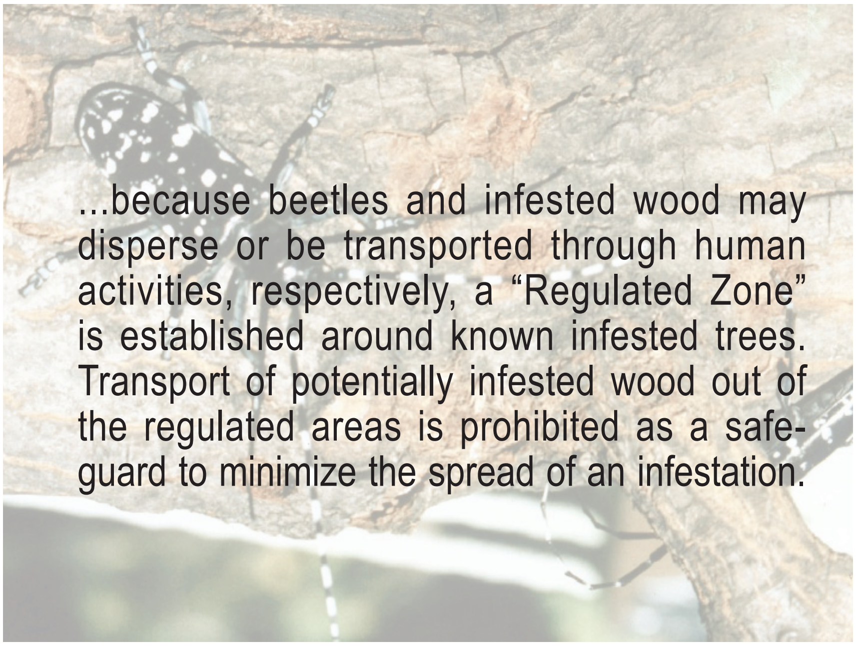
Impact. Based on a study of urban forests in nine large American cities, it was estimated that *A. glabripennis* could destroy as much as 30% of the trees (1.2 billion trees) and 35% of their canopy cover, collectively valued at $669 billion (Nowak et al. 2001). Additionally, *A. glabripennis* would impact property values, fall foliage tourism, forest products industry, maple syrup production, and aesthetics, as well as significantly reducing the environmental benefits provided by trees (e.g. cleaning air; cleaning water within many urban landscape watersheds; and energy-conserving shade) (GAO 2006). To date, the realized costs associated with invasive populations of *A. glabripennis* include costs of eradication and costs resulting from the loss of tree cover. In the United States, the Animal Plant Health Inspection Service (APHIS) estimated the costs of eradication from 1998 to 2006 at $249

Table 1. Impact of Asian Longhorned Infestations Outside its Countries of Origin (as of December 2007).

		No. Trees Removed [a]		No. Trees [c]	
	Location	Infested [b]	High-Risk	Surveyed (%)	Treated
United States [d]					
New York	New York City & Long Island	6,203	11,942	48,100 (6%)	65,928
New Jersey	Middlesex/Union Co.	616	20,903	11,603 (7%)	31,970
New Jersey	Hudson Co.	113	348	4,669 (97%)	0
Illinois	Chicago	1,551	220	8,727 (100%)	0
Canada [e]					
Ontario	Toronto	600	25,000	na	0
Europe [f]					
Austria	Braunau am Inn	95	—	—	—
France	Gien (Loiret)	42	—	—	—
France	Sainte-Anne-sur-Brivet (Loire Atlantique)	55	—	—	—
Italy	Corbetta (Milano)	4	—	—	—
Germany	Neukirchen am Inn (Bavaria)	16	—	—	—

[a] Cumulative since first year infested trees were discovered
[b] Trees showing signs or symptoms of attack, including those infested in the current year and all previous years.
[c] Only pertains to 2007
[d] Markham 2007
[e] Estimates
[f] Hérard et al. 2005; Maspero et al. 2007

million (GAO 2006), including the costs for survey and detection, tree removal, public outreach, and prophylactic treatment of landscape trees. The actual loss of tree cover resulting from removal of trees in North America and Europe is provided in Table 1 (Markham 2007). It is important to note that in 2007, trees continue to be removed in the New York infestation, including 98 trees showing signs and symptoms of attack by *A. glabripennis* and 10,070 trees considered at high risk of attack, especially *Acer* species.



Eradication Approaches. The approaches used to address invasive populations of *A. glabripennis* in the United States. (GAO 2006), Europe (Hérard et al. 2005) and Canada (Ric et al. 2007, Turgeon et al. 2007) were recently summarized. As one might expect, the approaches have evolved from one invasion event to the next as more is learned during the process of each eradication program, and as development of alternative approaches have come to fruition. While the approaches and their respective strategies have often differed among the invasive populations and among the landscapes infested, there have been certain unifying components among the eradication programs. First, because beetles and infested wood may disperse or be transported through human activities, respectively, a "Regulated Zone" is established around known infested trees. Transport of potentially infested wood out of the regulated areas is prohibited as a safeguard to minimize the spread of an infestation. Additional components common to the eradication programs include survey and detection; treatment of trees showing signs and symptoms of attack and trees at high risk of attack; technologies for implementing eradication strategies; and public outreach.

Detection of infested trees has been limited to visual surveys for trees showing signs and symptoms of *A. glabripennis* attack. These surveys have included extensive inspection of trees by ground crews equipped with high-resolution binoculars, and intensive inspection of trees by tree climbers and other personnel using ladders and bucket trucks. APHIS estimates visual surveys to be 30–66% efficient in the United States (Milius 1999). To increase the efficiency of visual surveys for *A. glabripennis*-infested trees, the *A. glabripennis* eradication program in Canada expanded visual surveys to include a wider range of tree species. Furthermore, a training guide for detecting of the signs and symptoms of attack by *A. glabripennis*, including images that encompass the extensive variation in their appearance and a protocol for visual surveys, was recently published (Ric et al. 2007). Additional methods under development for detection of infested trees include acoustic technology for detection of the vibrations caused by *A. glabripennis* larvae as they feed on and break wood fibers within infested trees (Mankin et al., 2008).

Methods for detecting and monitoring of adult *A. glabripennis* are under development. Pheromones produced by female and male *A. glabripennis* have been the focus of several investigations by APHIS, State University of New York (SUNY) and USDA Agricultural Research Service (ARS). While both male and female volatiles have been identified (Zhang et al. 2002, 2003), attraction of *A. glabripennis* in field studies has not been reported. Sentinel trees for detection of adult *A. glabripennis* have also been investigated, and *Acer mono* has been reported to be highly attractive under natural field conditions (Smith 2003, Smith et al. 2007b). Potted *A. mono* and/or *A. truncatum* sentinel trees have been used by the California Department of Food and Agriculture (CDFA) (2005–2006), and jointly by the Canadian Food Inspection Agency (CFIA) and Canadian Forest Service (CFS) in the Toronto eradication program. In the United States, the New York Department of Environmental Conservation and the City of Chicago are exploring the use of potted *A. mono* trees in their eradication programs, and as landscape trees during post-eradication phase. It is worth noting that in 2007, an incipient invasive population of Agrilus planipennis Fairmaire, the Emerald Ash Borer, was successfully detected in Maryland using potted sentinel trees. An artificial lure based upon *A. mono* trees for detection of adult *A. glabripennis* is also under development and results to date are encouraging (Smith et al. 2007b).

A variety of treatment methods have been used in the eradication programs, including: (1) removal of trees that are suspected to be infested, as well as trees considered to be at risk of attack (Wang et al. 2000, Turgeon et al. 2007); (2) prophylactic application of systemic insecticides applied by trunk or soil injection to trees considered to be at high risk of attack (Poland et al. 2006a,b). While this approach primarily targets free-living adult *A. glabripennis* during their feeding, it has limited larval activity depending on timing of application; and (3) application of an encapsulated contact insecticide shown to be highly effective against adult *A. glabripennis* (>99% adult mortality for at least 60 d) when applied to landscape trees for population suppression or as a prophylactic treatment to prevent initiation of attack (Smith et al. 2007c). The insecticide is currently approved for use against *A. glabripennis* in the United States, and the CDFA has applied the insecticide to potted sentinel trees for use in detection of adult beetles. APHIS has considered using the contact insecticide for niche application in the United States to either control of free-flying adult *A. glabripennis* on currently infested trees before felling to prevent dispersal, or as a prophylactic application on small-diameter trees where systemic insecticides would be impractical or in wooded landscapes with limited environmental and public exposure.

Technologies have been developed for implementing survey and treatment strategies. First, empirical studies of *A. glabripennis* dispersal resulted in development of models of *A. glabripennis* dispersal rate, population spread, and individual daily movement (Smith et al. 2001b, 2004; Smith 2003; Bancroft and Smith 2005). These models have been integrated as a key component in eradication of *A. glabripennis* by the regulatory agencies in the United States, Canada and Europe, specifically to establish boundaries for survey and detection, as well as for the tree removal and prophylactic insecticide treatment approaches discussed above. Second, empirical studies of adult *A. glabripennis* emergence from infested trees resulted in development of an accumulated degree-day model of adult *A. glabripennis* seasonal phenology (Smith et al. 2004). This model was subsequently linked with a historical climatological database (North Carolina State University Aphis Plant Pest Forecasting System, NAPPFAST) to generate probability maps for predicting the seasonal emergence phenology of *A. glabripennis,* and thereby provide a practical method for timing the implementation of eradication, survey, and treatment strategies that target adult beetles, as well as surveying for signs and symptoms of attack. The model and probability maps have been used in the eradication programs of invasive populations of *A. glabripennis*, as well as in management and research programs in China.

Research and development of biological control for *A. glabripennis* within the United States and Europe was recently reviewed (Smith et al. 2003), and efforts include: (1) development of fungal bands (Dubois et al. 2004a,b; Hajek et al. 2006, 2007a,b); (2) exploration for natural enemies within the countries of origin, including *Scleroderma guani* (Hymenoptera: Bethylidae) and *Dastarcus helophoroides* (Coleoptera: Colydiidae) (Smith and Yang 2001a; Smith et al. 2003; Yang et al. 2004); (c) exploration and development of natural enemies native to the United States. To date, three native parasitoid species have been found to parasitize and complete F_1 development on *A. glabripennis* (Smith et al. 2007a).

The importance of public outreach to the success of the *A. glabripennis* eradication programs in the United States, Canada, and Europe cannot be overemphasized. The numerous benefits reaped from partnering with the public are beyond the scope of this paper. GAO (2006) provides a more detailed discussion of the importance and approaches of public outreach utilized in the U.S. eradication programs. A few highlights are noteworthy. For example, in most cases, it was an informed and engaged public that provided the early detection of *A. glabripennis* or trees showing signs of attack. In the eradication efforts in Europe, not unlike those in North America, local partners participated in monitoring and eradication (Hérard et al. 2005). In addition to early detections, partnering at the local and regional levels also contributed to the rapid response efforts. Again, a number of factors involved, including those unique to each eradication effort, greatly influenced the approaches employed in conducting the public outreach programs.

Summary. Known infestations of *A. glabripennis* occur largely within man-made landscapes of limited species diversity, including those in China, North America, and Europe. Infested trees are typically open grown and along edges. While *A. glabripennis* has not been documented as a pest of species-rich natural forests within and outside its countries of origin, its threat to natural forest ecosytems remains untested. Therefore, it is prudent to maintain vigilance at all levels, including those to: (1) minimize potential pathways for new introductions, (2) maintain public awareness, and (3) continue development of methods for early detection and rapid response. However, without the evolution of alternative and improved approaches for implementation of these three efforts, successful eradication will be compromised. In addition, since introductions may inevitably escape successful eradication, it is important to consider proactive approaches that limit the likelihood of establishment and spread, including those to: (1) increase species diversity within landscapes at risk; (2) limit fragmentation, (3) select and plant species adapted to respective landscapes (sites), and (4) improve and maintain species health. Finally, increased understanding of the process of invasion will improve early detection and rapid response to introductions of *A. glabripennis*, as well as innumerable other potential invasive species, including both exotic and native species. Efforts to census the *A. glabripennis* infestation in Toronto, Canada, as an integral component of the eradiation program, is unique among the invasive populations of *A. glabripennis,* and should serve as a model for future invasions.

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Michael T. Smith is a Research Entomologist of over 30 years, and is a lead Scientist on Invasive Insect Species, with emphasis on insect behavior and ecology, USDA-Agricultural Research Service, Beneficial Insects Introduction Research Unit, Newark, DE. 19713; email: Michael.Smith@ars.usda.gov. **Jean J. Turgeon**, is a senior research scientist with 26 years of experience in biology and management of forest insect pests, and is Chair of the International Science Subcommittee for the Eradication of the Asian Longhorned Beetle in Canada, Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, Ontario, CANADA P6A 2E5, jturgeon@nrcan.gc.ca. **Peter De Groot** is a senior research scientist with 34 years of experience in several fields of forest entomologist, Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, Ontario, CANADA P6A 2E5; and **B. Gasman**, Canadian Food Inspection Agency, Toronto, Ontario CANADA M3J 2E2, pdegroot@nrcan.gc.ca.