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REVIEW

Current and future control of the wood-boring pest *Anoplophora glabripennis*

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Abstract The Asian longhorn beetle (ALB) *Anoplophora glabripennis* is one of the most successful and most feared invasive insect species worldwide. This review covers recent research concerning the distribution of and damage caused by ALB, as well as major efforts to control and manage ALB in China. The distribution and destruction range of ALB have continued to expand over the past decade worldwide, and the number of interceptions has remained high. Detection and monitoring methods for the early discovery of ALB have diversified, with advances in semiochemical research and using satellite remote sensing in China. Ecological control of ALB in China involves planting mixtures of preferred and resistant tree species, and this practice can prevent outbreaks. In addition, strategies for chemical and biological control of ALB have achieved promising results during the last decade in China, especially the development of insecticides targeting different stages of ALB, and applying *Dastarcus helophoroides* and *Dendrocopos major* as biocontrol agents. Finally, we analyze recommendations for ALB prevention and management strategies based on native range and invasive area research. This information will hopefully help some invaded areas where the target is containment of ALB.

Key words *Anoplophora glabripennis*; biocontrol; ecological control; management; wood-boring pest

Introduction

The Asian longhorn beetle (ALB), *Anoplophora glabripennis* Motschulsky (Coleoptera: Cerambycidae), is a wood-boring pest native to most of mainland China and the Korean peninsula which requires international quarantine and has been introduced into North America and Europe, principally *via* solid wood packing material (SWPM) used in international cargo (Cavey *et al.*, 1998; Wu, 2018). This species has become a global forest quarantine pest and has attracted great attention in North America and Europe.

Over the past few decades, research on ALB has sparked interest among scientists worldwide, and topics ranging from its biology to control and management strategies have been widely reviewed in North America and Europe (Haack *et al.*, 2010; Branco *et al.*, 2021). However, in its native range in China, despite being well studied, most of the pertinent literature is poorly reported outside of China due to the accessibility of the research, and the availability of Chinese journals since only a small

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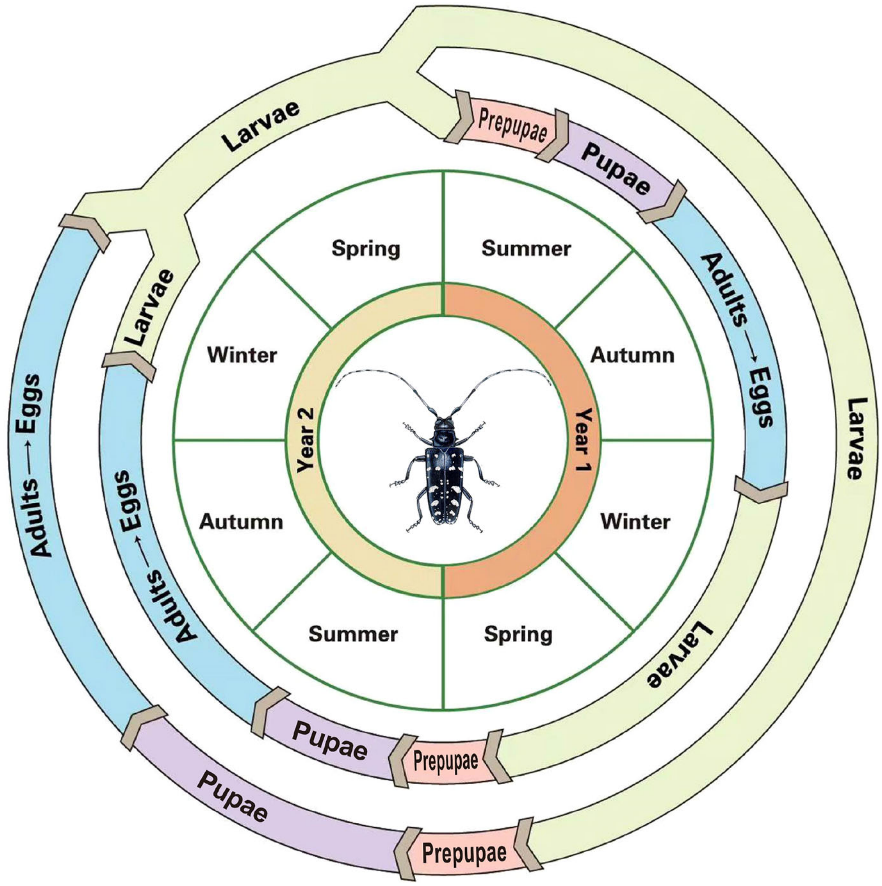

Fig. 1 Conceptual representation of the life cycle of Asian longhorn beetle (ALB), which can be 1 or 2 years depending on host vigor and the rate of degree-day accumulation.

proportion of scientists from the rest of the world can read Chinese. Therefore, in this review, we cover research on the distribution and damage caused by ALB, as well as recent progress in monitoring, detection, control, and management of ALB in China. Finally, we discuss existing and potential future prevention and management strategies.

Distribution and damage caused by ALB

In its native range, ~80% of individuals are estimated to complete their development within 1 year and <20% require 2 years (Fig. 1) (Wang, 2004; Li, 2017). The egg stage/period of ALB is ~16 d, and newly hatched larvae do not enter the xylem but feed on decomposed phloem at the edge of the oviposition pit (Fig. 2E). The 2nd instar larvae begin boring into the xylem and heartwood to feed, resulting in S- or U-shaped larvae tunnels (Geib *et al.*, 2010; Wu *et al.*, 2010; Fan, 2013) (Fig. 2F). ALB adults usually remain in the pupal chamber for more than a week (Fig. 2H) after they emerge and start to exit from a new emergence hole (about 1 cm in diameter) chewed with their mouthparts (Fig. 2I) (Luo & Li, 1999; Wang, 2004). ALB adult females undergo a period of obligatory maturation feeding for ovarian maturation. Adult beetles live on 2-to-3-year-old twigs, petioles, and leaf veins for maturation feeding (Fig. 2B). Adults walk from the crown to tree trunks to find ovipositing sites after ovarian maturation. Females use their sense of touch and vision to detect the bark of host species before oviposition and to judge whether it is suitable to lay eggs (Li & Liu, 1997). Females begin to chew bark in a head-downwards position to prepare an oviposition pit as soon as they find the right place on a host tree (Fig. 2A). Studies in its native range showed that adults males live for 3–50 d, and females live for 14–66 d (Hu *et al.*, 2009; Guo, 2020). Most ALB beetles fly up to ~30 m at a time, and the dispersal distance of the first generation is generally less than 200 m if hosts are continuously distributed (He & Huang, 1993).

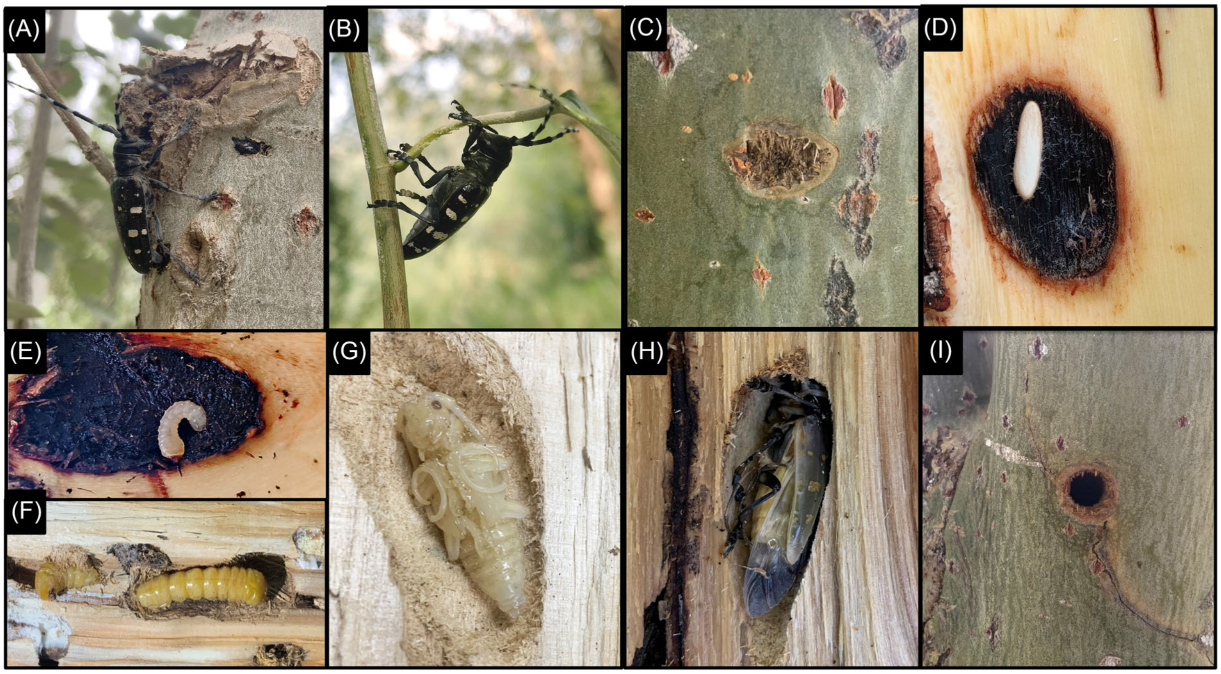

Fig. 2 Biological characteristics of Asian longhorn beetle (ALB). (A) Female adult laying eggs. (B) Feeding damage by adults on petioles. (C) A typical ALB oviposition pit. (D) An ALB egg laid beneath the bark in the cambial region. *Fusarium solani* surrounds and covers the egg and grows on wood. (E) A young larva in the cambial region. (F) General shape of a full-grown larva. (G) General shape of a pupa. (H) After emergence, adults stay in the pupal chamber for ~10 d. (I) Circular exit holes.

In China, ALB is recorded throughout most of the country, except Taiwan, Hong Kong, and Macao (Li *et al.*, 2020a; Cui *et al.*, 2022). ALB has caused extensive damage since the 1980s, especially north of the Yangtze River. This was especially true during the first phase project of the world-famous "Three North" shelter forest system, which is dominated by *Populus* and *Salix*; this area has almost been completely destroyed by this beetle, and more than 200 million trees were lost (Luo, 2005; Wang *et al.*, 2018). Among them, nearly 50 million floodplain trees in Ningxia alone have been cut down to manage ALB infestations. Potential losses in compensatory value resulting from a widespread ALB outbreak could exceed US$1.5 billion, equal to approximately 12% of the total economic losses caused by forest pests and diseases (Golec *et al.*, 2018). Losses caused by ALB in terms of ecological and social benefits are incalculable. However, because control and management strategies have been actively implemented recently, a full-blown ALB disaster has been avoided. The distribution of ALB is sporadic in southern China but widespread in northern China, and disasters have been avoided in most areas. Currently, ALB is only rampant in the Hexi Corridor of Gansu Province (Wang *et al.*, 2022). Moreover, Korea is the only native habitat where ALB has not become a pest and their populations are relatively small (Lee *et al.*, 2020).

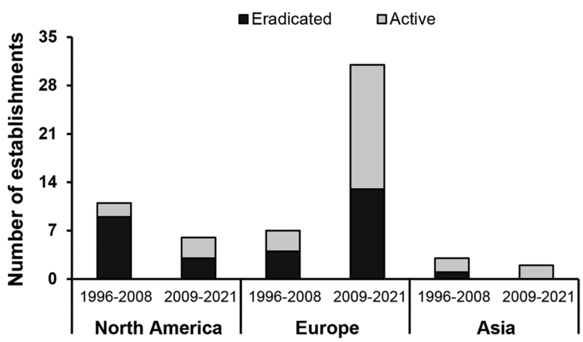

Fig. 3 Number of Asian longhorn beetle (ALB) establishments detected over different time periods in different geographical areas.

From 1996 to 2021, 60 ALB establishments were detected outside the native range across 20 countries/regions (Fig. 3), including 5 establishments in Asia, 17 in North America, and 38 in Europe (Haack *et al.*, 2010; Sjöman *et al.*, 2014; Branco *et al.*, 2021). As of December 2020, approximately half of all detected ALB establishments have been successfully eradicated worldwide (Fig. 3). The criteria to declare eradication seems to be the same in different countries; that is, no new damage by this beetle has been detected within 5 years. ALB has been discovered in Asia in Xinjiang (2000) and Tibet (2002) in China, Japan (2002), and Lebanon (2015) (Moussa & Cocquempot, 2017); however, there have been no reports of significant disasters when these countries/regions implemented the necessary controls. More recently, an established population has again been reported in Hyogo Prefecture in Japan (Akita *et al.*, 2021).

In North America, breeding populations of ALB were first found in *Acer* in Brooklyn, New York, USA in 1996 (Haack *et al.*, 1996), followed by Illinois (1998), New Jersey (2002), Massachusetts (2008), Ohio (2011), and South Carolina (2020) (Coyle *et al.*, 2021). The cost of eradication campaigns conducted in the United States between 1996 and 2013 was estimated to be more than \$537 million (Eyre & Haack, 2017). ALB was first discovered in 2003 in a commercial warehouse area in Ontario, Canada, and the Canadian Food Inspection Agency subsequently led eradication work by establishing a 152 km^2 control area and felling ~27 400 trees, which averted a disaster. However, ALB reappeared 10 km east of the control area in 2013, and another 8 600 trees were removed from this area in 2014 (Turgeon *et al.*, 2015). In North America, a high rate (70%) of successful eradications was also achieved.

In Europe, the first breeding population was discovered in Braunau am Inn, Austria, close to the border with Germany, in 2001, and further outbreaks have occurred in Austria (2001), France (2003), Germany (2004), Italy (2007), The Netherlands (2010), Switzerland (2011), England (2012), Montenegro (2015), and Finland (2015) (Hérard *et al.*, 2006; Loomans *et al.*, 2013; Straw *et al.*, 2015; Pajović *et al.*, 2017; Riikka *et al.*, 2018; Javal *et al.*, 2019). Most outbreaks in these countries have been relatively mild, with >50 trees attacked in only 5 outbreaks: Braunau am Inn, Neukirchen in Germany, Cornuda in Italy, Winterthur in Switzerland, and Kent in southern England. However, a lot of human resources and money were expended by implementing eradication programs in these countries to prevent the spread of ALB. For example, in Lombardy, Italy alone, the costs of *Anoplophora* (predominantly ALB) eradication campaigns between 2008 and 2013 totaled almost 20 million Euros (Cavagna *et al.*, 2013). ALB has been eradicated through various measures in some of the above countries during the past decade. However, it continues to spread and destroy trees in Italy, Germany, and France (Hamit *et al.*, 2014). By contrast, eradication success rates of ALB in Europe were lower than in North America (Fig. 3). However, the survey methods of ALB are mainly based on visual surveys. It is difficult to observe naturally occurring ALB by visual surveys in forests with low ALB density and a complex environment. Therefore, it is unclear whether eradication has really occurred in some areas.

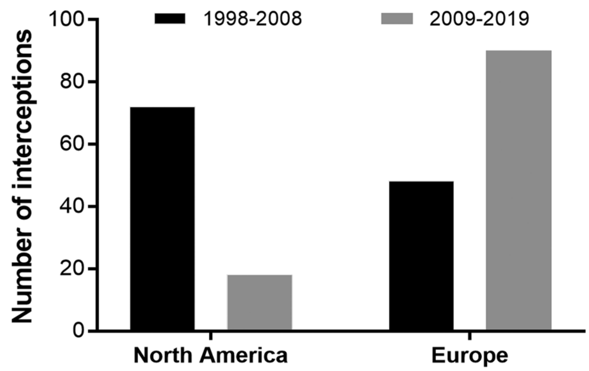

Fig. 4 Number of Asian longhorn beetle (ALB) interceptions in Europe and North America during different time periods.

We follow the definition of interception provided by Haack *et al.* (2010). ALB has been intercepted 130 times worldwide, including 120 times in North America and Europe, between 1998 and 2008 (Fig. 4) (Haack *et al.*, 2010). In North America and Europe, ALB was intercepted 140 and 90 times, respectively, from 1998 to 2019 (Branco *et al.*, 2021). For the periods from 1998 to 2008 and from 2009 to 2019, the number of ALB interceptions decreased in North America, with 72 *versus* 18 cases, whereas the number of ALB interceptions almost doubled in Europe (48 *vs*. 90 cases; Fig. 4). For the period spanning 2009–2019, ALB was intercepted from 18 countries in Europe (16 times) and North America (twice), all from infested consignments arriving from China. ALB interceptions were associated with SWPM in 96% of cases (mostly linked to stone and tile products) and only once to an object with wooden parts (Branco *et al.*, 2021). Notably, despite the adoption of the International Standards for Phytosanitary Measures (ISPM) 15 in 2002, and the strict standards this set for heat treatment and fumigation of SWPM to be used in international trade, in North America, the number of reported interceptions involving wood packaging has significantly decreased, but in Europe, the number has increased (Haack *et al.*, 2014). Therefore, there is a long way to go to strengthen the interception and quarantine of borers in SWPM for import and export, and multidisciplinary participation is needed to establish a safe and effective quarantine and inspection technology system (Gao *et al.*, 2016).

Monitoring and detection in China

In the past decade, the monitoring and detection of ALB have significantly advanced. A survey is carried out in each demarcated area at least once per year in China to identify infested trees and potential host tree species that could be infected. To minimize the chances of ALB populations becoming established, Europe and North America have implemented similar measures. Beetles are mainly detected in public parks, street trees, shelterbelts, and natural reserve areas. Mainly methods based on semiochemicals, visual surveys, and other detection methods have been employed in China. Recent advances in alternative monitoring and detection methods are described below.

The ability of ALB to respond to volatile organic compounds (VOCs) released by host trees plays a vital role in host selection and reproduction (Li *et al.*, 1999). In China, researchers found that VOCs released from highly susceptible host trees can attract ALB within 100 m to forage (Wen *et al.*, 1999). Green-colored paperboard was found to enhance the ALB response to host plant odor cues when the combination of forest green-colored paperboard and host tree odor was attractive to adults (Lyu *et al.*, 2021). Additionally, stressed host trees are susceptible to ALB attack. The contents of some volatile compounds in drought-stressed trees increase, such as butyl alcohol, pentyl alcohol, and *cis*-3-hexanol, which are more attractive to ALB than to non-stressed ones (Jin *et al.*, 2004). Further, drought-stressed trees have low resistance to attack by ALB. For example, healthy *Populus tremulagigas* can kill eggs by filling the oviposition pit with fluid, while drought-stressed *P. tremulagigas* cannot do this effectively, and so are killed by ALB more easily (Deng, 2009). For example, the Hexi Corridor (part of the Silk Road Economic Belt) has less rainfall than many other regions of China, and destruction by ALB is consequently more severe (Huang *et al.*, 2021; Wang *et al.*, 2022).

There has been great interest in identifying pheromones of ALB to facilitate their early detection. Zhang *et al.* (2002) revealed that 2 dialkyl ether volatiles, 4-(*n*-heptyloxy)-butanal and 4-(*n*-heptyloxy)-butan-1-ol, are secreted by males at a 1 : 1 ratio, and they are strongly attractive to adults in the laboratory. However, male pheromone-based trapping systems mainly attract virgin females (Wickham *et al.*, 2012; Nehme *et al.*, 2014; Xu & Teale, 2021). Compared with male pheromones, female-produced pheromones may be more beneficial for ALB monitoring (Xu *et al.*, 2020). Five monounsaturated compounds are secreted by females that can effectively elicit copulatory behavior in males. These compounds were identified as the alkenes (*Z*)-9-tricosene, (*Z*)-7-pentacosene, (*Z*)-9-pentacosene, (*Z*)-7-heptacosene, and (*Z*)-9-heptacosene, and they are present at a relative ratio of 1 : 2 : 2 : 1 : 8 (Zhang *et al.*, 2003). The pheromone and host chemical cues elicit behavioral responses of ALB in the laboratory, but a limited attraction in field bioassays (Xu *et al.*, 2020; Lyu *et al.*, 2021). We believe there are many reasons for this phenomenon. In fact, pheromones or host volatiles can attract ALB by complex mixed-signal cues in the field, but additional visual and chemical cues in the close range may also be involved, such as plant color, shape, texture, and non-host plant volatile substances; these can interfere with the behavior of ALB (Lyu *et al.*, 2015; Xu & Teale, 2021). Therefore, it is important to understand the factors affecting ALB behavior in the field environment, and further research is needed to develop insect-attracting devices based on the manipulation of visual and olfactory cues (Lyu *et al.*, 2021). The gene sequences of the sex pheromone-binding proteins AglaPBP1 and AglaPBP2 have also been obtained at the molecular level. This lays a foundation for further study of the function of these genes and the molecular mechanisms underlying insect olfaction in general (Wang *et al.*, 2019).

As the most basic survey method for monitoring ALB, visual surveys typically involve examination of potential host trees looking for signs of infestation (e.g., branch dieback, adult emergence holes, larval frass on the ground, and oviposition pits) in shelterbelts and urban/suburban trees in China. Wen *et al.* (1999) showed that host bark roughness affects the oviposition location of ALB female adults. If the bark of the host plant is rough, then ALB can oviposit throughout the trunk and branches (e.g., *Populus gansuensis*); if the bark of the host plant is smooth, then eggs are mostly laid at bifurcations of the trunk (e.g., *Populus alba* var. *pyramidalis*). ALB surveys are usually conducted by observers on the ground equipped with binoculars to detect known signs and symptoms of an attack on the upper parts of the trunk. Furthermore, the environment in which trees are located also affects detectability; infested street trees or trees in public parks are more easily detected than infested farmland shelterbelts or woodland. Therefore, professional investigation teams in China have been set up to survey different environmental conditions. In addition to surveys carried out inside demarcated areas, specific surveys are also randomly conducted outside demarcated areas at high-risk sites. In addition, because of the lower density of ALB in some areas, their infestation is difficult to observe; therefore, sentinel trees should be deployed to these places to help investigate the occurrence of ALB (Wang, 2006; Eschen *et al.*, 2019).

Recent studies have used satellite remote-sensing imaging to assess the damage of wood-boring pests to individual trees in China (Luo *et al.*, 2022). Zhou *et al.* (2021a) developed a novel approach of combining Multispectral WorldView-2 imaging data and tree physiological factors for the semiautomatic classification of 3 stages of poplar damage from ALB infestation (green, yellow, and gray). This approach was also used to determine if the canopy color was abnormal, which could be directly assessed by remote-sensing images at the tree level to predict tree damage. The overall accuracy of detecting the degree of damage to poplar is promising. Accurate and up-to-date location and health information at the single tree scale with a high spatial resolution (0.5 m) can be provided, which is important for managing tree damage due to ALB infestation in northwest China. Moreover, different physiological factors underlying the damage stages (green, yellow, and gray) can also be clarified, reducing the cost of field data collection and increasing management measure accuracy and applicability (Zhou *et al.*, 2021a). The generated maps represent the spatial and single tree damage data required to implement prevention and control measures, thereby reducing the large-scale harm from ALB in the shelter forest in northwest China.

Management/control in China

Damage caused by ALB can be severe, and outbreaks are characterized by concealment, latency, repetitiveness, and destructiveness; hence, management and control must be long-term and complex. Comprehensive and effective prevention and control measures are needed to prevent ALB from spreading and endangering invaded areas with established populations and its native range. In recent years, various control strategies have been implemented to prevent the spread and damage of ALB in China. These measures include forestry practices and chemical, physical, and biological control. Progress in management and control methods is described below.

Forest management

ALB has caused the most significant damage to poplar and willow species in China. The Chinese government has promoted the establishment of plantations of poplar to counteract desertification in northwest China; the “Three-North Shelterbelt Program” launched in 1978 has a goal of 23 million ha of plantations by 2050. Poplar and willow trees are the main tree species extensively planted in China along roadsides and in cities as ornamental trees. Therefore, in China, outbreak populations of ALB since the 1980s have been linked to forest composition. For most establishments in invasion sites, the first trees to be infested were *Acer* spp. (mainly *A. platanoides* and *A. pseudoplatanus*), which corresponded to 90% of ALB infestations. However, *Salix* sp., *Ulmus* sp., and *Aesculus hippocastanum* were also commonly infested. A list of species ranked in order of host susceptibility to ALB is reported in Table 1 for China and other invaded countries.

However, huge variability in host preference is possible within a single genus (e.g., *Populus* spp.). In Ningxia Province, populations of ALB drastically decreased after the monoculture poplar forest was changed to a mixed forest by replacing susceptible tree species with resistant species. Furthermore, the best effect of tree resistance to ALB in shelterbelts was a combination of non-host tree species, resistant tree species (tree species with good ecological and economic benefits), and susceptible tree species (trap tree species) at a 4.5 : 4.5 : 1.0 ratio implemented *via* strip or row planting (Luo, 2005). Yan *et al.* (2008) considered testing 10%–20% of trap tree species (e.g., *A. negundo*) among street trees dominated by resistant tree species to effectively manage ALB. It should be noted that the insect resistance of host trees will change with the stand structure and geographical location. For example, a pure *P. alba* var. *pyramidalis* forest is susceptible to ALB, but the damage is rare when mixed with *P. gansuensis* (Wang *et al.*, 2022). Therefore, in order for this mixed forest strategy to be effective long term, ALB attracted by trap trees should be killed using insecticides. Otherwise, the trap tree will die from ALB overfeeding, and then ALB will transfer from the trap tree to the resistant tree species.

Tree species can attract adult ALB to oviposit eggs, but eggs and larvae may not normally develop; for example, some bait and kill hosts (*Elaeagnus angustifolia* and *Tilia tuan*) (Table 1) have been employed in forest management measures for ALB in recent years. Currently, planting bait and kill hosts in existing poplar and willow shelterbelts is under way. These measures can avoid ALB disasters without incurring the cost of changing tree species (Wang & Luo, unpublished data). In addition, the smoothness of bark is an important physical factor affecting ALB oviposition. For example, *P. hopeiensis* makes the oviposition of eggs difficult for ALB because its bark is smooth (Wu, 2018). Pruning dead branches and cutting weeds in forest areas have been applied to improve the health of tree species and the cleanness and smoothness of bark, and to create conditions that are not ideal for wood borers such as ALB (Wu, 2018). In Gansu and Inner Mongolia, a practice called “high trunk truncation” has been

Table 1 Worldwide categorization of Asian longhorn beetle (ALB) host trees species.

Host category	Degree of resistance	Tree species
Non-host trees	–	*Ailanthus altissima*, *Gleolitsia sinensis*, *Pyrus betulaefolia*, *Paulownia fortune*, *Rhus typhina*, *Ginkgo biloba*, *Olea europaea*, *Citrus reticulata*, *Armeniaca* spp., *Juglans* spp., Pinaceae, Cupressaceae
Potential hosts	–	*Acacia farnesiana*, *Robinia pseudoacacia*, *Sophora japonica*, *Casuarina equisetifolia*, *Jacaranda mimosifolia*, *Albizia julibrissin*, *Tilia* spp., *Pyrus* spp., *Oaks* spp.
Resistant hosts	High resistant hosts	*Populus alba*, *Fraxinus americana*, *Fraxinus Sogdiana*, *Populus hopeiensis*, *Populus tremuloides*, *Broussonetia papyrifera*, *Melia azedarach*, *Cercis chinensis*
	Low resistant hosts	*Populus balsamifera*, *Populus deltoides*, *Populus pruinose*, *Populus davidiana*, *Populus tomentosa*, *Populus alba* var. *pyramidalis*, *Populus euphratica*, *Celtis sinensis*, *Quercus* spp., *Morus* spp., *Alnus* spp., *Malus* spp., *Carpinus* spp., *Prunus* spp., *Cercidiphyllum* spp.
Preferred hosts	Susceptible hosts	*Populus* spp., *Acer* spp., *Salix* spp., *Ulmus* spp., *Betula* spp., *Platanus* spp., *Aesculus* spp., *Quercus rubra*, *Fraxinus pennsylvanica*, *Acer platanoides*, *Acer pseudoplatanus*
	Highly susceptible hosts (trap tree species)	*Acer negundo*, *Acer buergerianum*, *Acer mono*, *Acer saccharum*, *Acer truncatum*, *Aesculus hippocastanum*, *Acer rubrum*, *Populus opera*, *Populus nigra* var. *thevestina*, *Populus simonii*, *Populus gansuensis*, *Populus cathayana*
Bait and kill hosts	Susceptible hosts	*Elaeagnus angustifolia*, *Tilia tuan*, *Populus tremula*

used to help the economy and the environment. This involves cutting off badly damaged trunks 1.5–2 m above the ground by mechanical operation when the leaves develop in spring (Hu *et al.*, 2009). This measure is mainly done to cut off young tree trunks with serious ALB damage. The remaining tree trunks are nutritious enough to promote the resprouting of new branches on the cut-off surface, and the environmental benefits are restored in the next year. In China, in areas seriously harmed by ALB, "controlling points and protecting areas" measures are enforced to completely remove damaged trees and potential host tree species around damaged trees to control the spread of ALB.

Chemical control measures

Numerous studies on developing and applying high-efficiency insecticides targeting different stages of ALB have been reported (Table 2). For ALB adults, an 8% cypermethrin easy-burst microcapsule insecticide with an average diameter of 10–20 μm was made in China to spray on the trunks or leaves of infested trees. This was done to make the pesticide treatments last longer and have less of a negative effect on the environment (Liu *et al.*, 1999). When ALB adults contact the microcapsules, they easily break, releasing the effective ingredient, cypermethrin. The insecticide sticks to the feet of the beetles and is absorbed into their bodies. Capsules that are not stepped on remain intact, which prevents the waste caused by repeated insecticide use.

Currently, the most widely adopted method for controlling high populations of ALB in China consists of spraying 8% cypermethrin or 2% thiacloprid in the canopies of host trees twice a year, and this is very effective for killing adults (Liu *et al.*, 1999; Yu *et al.*, 2021). However, the cost of these insecticides is expensive, and spraying a large area will cause economic pressure. In addition, various pesticides can be mixed to spray canopies and effectively kill adults (Table 2). Wu (2018) found that a 100-fold dilution of 50% sumithion, 50% carbaryl, and 20% fenitrothion had a powerful controlling effect on ALB adults. The field experiment demonstrated efficient control of ALB by spraying chemosterilant CS II (wettable powder) during the main period of eclosion. The total mortality of eggs and recently hatched larvae was 72.08% (Tang *et al.*, 2001). Nevertheless, spraying insecticide on tree crowns during the adult stage may cause significant

Table 2 Control effects of insecticides on different stages of Asian longhorn beetle (ALB).

Insecticide name	Stage of control	Methods of control	Effect of control	Reference
Aluminum phosphide	Egg	Insert oviposition pit	100%	Hu *et al.* (2009)
10% Imidacloprid	Larvae	Injection trunk	99%	Wang *et al.* (2017)
4% imidacloprid + 80% 2,2-dichlorovinyl dimethyl phosphate	Larvae	Injection trunk	91.9%	Tang *et al.* (2007)
10% imidacloprid + 10% acetamiprid	Larvae	Injection trunk	88.8%	Zhou *et al.* (2017)
Methamidophos	Larvae	Injection trunk	90%	Zhu *et al.* (1998)
Emamectin benzoate	Larvae	Injection trunk	98%	Wang *et al.* (2020)
Methyl bromide	Larvae and pupae	Fumigation	100%	Barak *et al.* (2005)
Cyanide	Larvae and pupae	Fumigation	99.5%	Ren *et al.* (2006)
Sulfuryl fluoride	Larvae and pupae	Fumigation	100%	Wang *et al.* (2003)
40% omethoate + kerosene	Larvae and adult	Coat trunk	Good	Qin *et al.* (2009)
40% omethoate + 10% imidacloprid	Larvae and adult	Coat trunk	Good	Huang (2020)
8% cypermethrin	Adult	Spray tree canopy	Very good	Liu *et al.* (1999)
2% thiacloprid	Adult	Spray tree canopy	Very good	Yu *et al.* (2021)
50% sumithion + 50% carbaryl + 20% fenitrothion	Adult	Spray tree canopy	Good	Wu (2018)
Chemosterilant CS II	Adult	Spray tree canopy	72.08%	Tang *et al.* (2001)

negative externalities, such as killing a large number of non-target insects, biodiversity loss, ground and surface water contamination, and directly or indirectly affecting the growth and development of other organisms.

In the egg stage, blocking the oviposition pit with aluminum phosphide pellets or inserting wooden sticks containing aluminum phosphide (generating phosphine) can kill ALB eggs (Hu *et al.*, 2009). In the larval stage, injection of systemic insecticides into the trunks of infested trees is an effective measure with a low environmental impact. Four neonicotinoid systemic insecticides, thiacloprid, dinotefuran, imidacloprid, and thiamethoxam, can be toxic to ALB larvae when injected into tree trunks or soil (Wang *et al.*, 2005). Among these, imidacloprid is the most effective agent for controlling ALB larvae (Wang *et al.*, 2017). According to other studies, the control effect on larvae is enhanced when imidacloprid is combined with other insecticides. Injecting a mixture of 4% imidacloprid and 80% dichlorvos controls 91.9% of longhorn beetle larvae (Tang *et al.*, 2007). Zhou *et al.* (2017) found that, when 10% imidacloprid and 10% acetamiprid were injected into tree trunks to get rid of ALB larvae, the population dropped by 88.8%, compared with 86.4% when imidacloprid was used alone. Other insecticides have also been tested for killing larvae, and it has been demonstrated that ~90% of larvae and 65% of adults are killed by injecting methamidophos into poplar tree trunks (Zhu *et al.*, 1998). Moreover, 3 months after injection, the mortality of adults feeding on these treated poplars remained at 70%–80% (Xu *et al.*, 1999). Emamectin benzoate was injected into an infested willow forest in China, and this compound proved effective at reducing ALB larval populations by 89% in the first spring after application and by >99% during the second year. Reinfestation only occurred in the 3rd year after application (Wang *et al.*, 2020). A thin mud made of 40% omethoate mixed with 10% imidacloprid or kerosene can be brushed on the base of a trunk below 30−60 cm from the ground, killing adults, and newly hatched larvae (Qin *et al.*, 2009; Huang, 2020). Injections of systemic insecticides into the trunks of infested trees and the application of trunk-coating insecticides comprise effective measures with a low environmental impact and this approach is still widely used in China. However, this measure only applies to single trees or specific areas, such as gardens, street trees, and public parks. Moreover, it is difficult and takes a lot of time to conduct in forests seriously damaged by ALB, which makes this measure economically expensive. In addition, according to the operation standard of ISPM 15, chemical fumigation of wood packaging and infested logs is very effective for killing ALB larvae and pupae, and the compounds used mainly include methyl bromide and cyanide (Wang *et al.*, 2003; Barak *et al.*, 2005; Ren *et al.*, 2006). Additionally, heat treatment is also one of the major disinfestation methods. When the central temperature of wood reaches 56 °C for at least 30 min, ideal pest control effect can also be achieved (Ren *et al.*, 2006).

Physical control measures

At present, physical control of ALB involves removing severely damaged trees and replacing susceptible trees with resistant species, artificial killing (eggs, larvae, and adults), and hammering egg-laying sites. In Ningxia and Gansu Provinces in China, local forestry departments allowed students to capture adult and hatched larvae with incentives; nearly 500 000 beetles were captured in Ningxia alone in 2007, and a drastic decline in the ALB population was recorded 1 year later (Hu *et al.*, 2009). In the early stages of oviposition, tree trunks 1.5–2 m from the ground can be painted white (with 8% sulfur, 88% quicklime, 2% salt, and 2% trichlorfon evenly mixed) or straw ropes can be tied to prevent adult females from laying eggs from crown to trunk by walking, thereby blocking the ALB reproductive cycle (Yu & Zhao, 2016). From June to September, ALB lay eggs between the phloem and xylem, and ovipositing grooves are readily identified by their gelatinous secretions. It is easy to find and knock oviposition pits at the base of the tree trunk to crush the eggs inside the pits or to dig iron wire into the oviposition pits to kill the larvae. These physical control measures can be effective for maintaining the ALB population below pest thresholds, especially in young trees and urban areas. However, measures for physical control are very laborious, expensive, and time-consuming.

Biological control measures

ALB eradication and management strategies in its native and invaded ranges have primarily involved pesticide treatment and removal of infested trees, which are both economically and environmentally expensive. Therefore, an effective alternative and sustainable control method, such as biological control *via* specialized natural enemies, is needed. Biological control may achieve long-term control of ALB, using parasitoids, predators (e.g., birds), and/or entomopathogens (e.g., fungi and bacteria).

Dastarcus helophoroides (Coleoptera: Bothrideridae) is distributed in mainland China and Japan and is currently the most promising parasitic insect enemy of ALB in China. Female adults lay eggs near the boreholes of ALB and the number of eggs laid at one time is 100–200. The newly hatched larvae mainly parasitize on larvae and pupae of ALB (Golec *et al.*, 2018; Wang *et al.*, 2021). Indoor rearing techniques for this insect are well established; the parasitism rate against ALB gradually accelerates with advancing generations of *D. helophoroides*. When using *D. helophoroides* to control ALB, the population density of ALB should be considered; the levels of parasitism could reach 50%–70% when the ratio of ALB to *D. helophoroides* was approximately 1 : 1.2 (Huang *et al.*, 2008). In addition, different host tree species affect the parasitism rate of *D. helophoroides*, and control effects were excellent when *D. helophoroides* was released on willows and poplars (Cao, 2020). The infected rate of ALB was dramatically reduced from 100% to 23.46% in Shaanxi Province after continuous introduction of *D. helophoroides* for 5 years (Niu *et al.*, 2012). In Gansu Province, the parasitic rate of *D. helophoroides* on ALB was 45% the year it was introduced (Wei *et al.*, 2021a). This pollution-free biological control technology has created a new way to prevent and control ALB in China.

Sclerodermus guani (Hymenoptera: Bethylidae), another efficient ectoparasitoid of ALB early larvae, is mainly distributed in north and central China (Yang *et al.*, 2018). The female adult first stabs into the larvae of ALB with the venom needle and injects the venom to paralyze the larvae, then lays several eggs on the surface of the larvae of ALB. Recent field studies in China indicated that mass-rearing and releasing of 2 generalist insect parasitoids, *S. guani* and *D. helophoroides*, can sometimes effectively control ALB on plantations or urban trees (Huang *et al.*, 2008; Wei *et al.*, 2011; Gao *et al.*, 2013; Yang *et al.*, 2018). However, many studies have shown they have significant effects only when populations are continually augmented (Niu *et al.*, 2012; Yang *et al.*, 2018; Wang *et al.*, 2021). In addition, *D. helophoroides* and *Sclerodermus* spp. native to Asia that attack ALB have broad host ranges, and their release as biological control agents is unlikely to be approved in Europe or North America because of their potential effects on native species (Meng *et al.*, 2015; Gould *et al.*, 2018). In a recent survey using test logs harboring ALB larvae, *Oxysychus* sp. and *Bracon planitibiae* were the most abundant parasitoid species recovered in China (Li *et al.*, 2020b). Further studies are underway to assess their potential as biological control agents against ALB. In addition to ALB, *D. helophoroides* and *S. guani* are important parasitic natural enemy insects of *Monochamus alternatus*, *Semanotus bifasciatus*, *Apriona swainsoni* (Hope), and *Massicus raddei* in China (Luo *et al.*, 2018).

Pathogenic fungi such as *Peacilomyees farinosus*, *Metarhizium* sp., and *Beauveria* sp. can exert good control of ALB (Li, 2017). A mixture of *B. bassiana* Z28 and *P. farinosus* Z26 was used to plug oviposition holes, and this achieved good control of ALB within 0.5 m of holes (Luo *et al.*, 2018; Li *et al.*, 2020b). However, this research is still in the experimental stage, and applying fungi by hand to oviposition holes would be very expensive and unlikely to be feasible on a large scale.

Non-woven fiber bands containing cultures of entomopathogenic fungi with surfaces covered with infective spores are applied around trunks or branches of trees in China and Japan (Higuchi *et al.*, 1997; Luo *et al.*, 2018). Evaluations of the efficiency of *M. anisopliae* and *Beauveria* spp. applied in fiber bands have been carried out in confined areas (Xu *et al.*, 2003). Bands impregnated with *M. anisopliae* and *B. bassiana* were shown to be effective against ALB in open field conditions, even 63 d after treatment (Hajek *et al.*, 2003). It has been demonstrated that *B. bassiana* applied as fungal bands could spread up to 50 m in natural forest conditions (Hu *et al.*, 2005). However, microbial control of ALB requires a suitable external environment. The germination rate, storage period, and pathogenicity of spores are different under different temperatures and humidity. In addition, the fiber bands may be only applicable to the control of ALB in street trees and landscape trees, which has certain limitations for control of ALB in large areas of damaged forests.

In addition, among predators, the Chinese woodpecker *Dendrocopos major* has been shown to play an important role in reducing both larval and adult populations of ALB. Using woodpeckers to control ALB larvae has achieved good results in several places in the Inner Mongolia Autonomous Region, with a predation rate of 62.3%–80% (Yang, 2006). The effective control area for *Picus canus* and *D. major* was 3 133 hm^2, and the predation rate reached 54%–60% (Zhu, 2002). To prevent and control ALB, *P. canus* and *D. major* were successfully recruited to Jiuquan City, Gansu Province. After 1 winter, the insect removal rate reached more than 60% with good results, and the ALB population density was effectively controlled within 3 years (Wan *et al.*, 2008; Wei *et al.*, 2021b). It is important that they will stay and form a permanent solution once they have been recruited to a region. However, woodpeckers have very high requirements for habitat, which makes them very difficult to recruit and needs to be implemented by professionals, so they can only be used in a fraction of the areas infested with ALB.

Suggestions for future control and management

Predicting the potential occurrence of ALB worldwide using several models showed that ALB could inhabit parts of all continents except Antarctica. Among continents, regions with favorable conditions were mainly Europe, eastern Asia (mainly China), eastern North America (mainly southeastern Canada and eastern USA), southern Africa, and southern South America (Zhou *et al.*, 2021b). However, the distribution range of ALB around the world is likely to expand under global warming, but whether ALB will be found in more locations remains unknown. Therefore, early warning and prevention of ALB must remain a priority in the future.

By 2006, all countries listed in Fig. 1 had implemented ISPM 15; all SWPM arriving as imports in these countries in recent years should have been treated. In 2009, maximum size limits for residual bark in SWPM were changed by revising ISPM 15 to further reduce the prevalence of live pests (Food and Agriculture Organization, 2009). However, ALB was intercepted 126 times in North America between 2009 and 2019, and ALB populations became established in many countries, including Finland and Lebanon. It is unclear if the presence of live insects in SWPM carrying the ISPM 15 stamp indicates treatment failure, tolerance of insects to treatment, post-treatment infestation, unintentional noncompliance, or fraudulent use of the ISPM 15 mark (Haack *et al.*, 2010). Future international standards could establish clear quality control guidelines for exporting countries, such as using pest-free mother stock, isolating introduced plant material, implementing standard operating procedures, strict record keeping, and internal audits. Once infected materials are found, they should be destroyed in place. In addition, wood-based panel packaging materials are the result of deep processing of wood, which can gradually replace SWPM. Currently, wood-based panel packaging materials have become the primary materials for wood packaging in developed countries, such as oriented strand board.

ALB has typically been introduced into more urban areas, not native forests, making eradication more feasible. Although eradication programs to control ALB have proved successful in Europe and North America, they have caused significant economic and ecological losses. In addition, it is still possible that ALB will invade and become established in new areas because difficulties in detecting these beetles are a major concern for eradication efforts. In the past decade, detection methods for ALB have significantly developed in Europe. For example, “sniffer dogs” have been trained and used in several European countries to identify infested trees through the specific odors released by ALB larvae and their frass. This method has achieved good results in Austria, France, Italy, Switzerland, and Germany (Hoyer-Tomiczek *et al.*, 2016; EFSA *et al.*, 2019). Still, detection is difficult because of the habitat, and this beetle is always found breeding in trees long after its introduction; therefore, the semiochemicals and satellite remote-sensing imaging recently studied in China are important measures for early warning and prevention. In addition, it is still necessary to train professional forest investigators. New progress has been achieved by a proposed method that applies neural network and sound identification techniques to automatic monitoring of larvae boring vibrations in China, such as *S. bifasciatus* and *Eucryptorrhynchus brandti*, which can improve the possibility for early warning of ALB larvae (Sun *et al.*, 2020).

Since the outbreak of ALB in the 1980s, working on approaches to controlling ALB has not stopped, and the ongoing management efforts have generally succeeded in preventing damaging outbreaks of ALB in China. Methods for physical, chemical, and biological control have been developed in China and are being investigated in invaded areas. In particular, ecological management work in China is important for maintaining ALB populations below the economic threshold density (Luo, 2005). Rich forest communities are less susceptible; that is, populations of ALB drastically decreased after a pure poplar forest was changed to mixed forest in which the preferred tree species (trap tree species) were grown together with resistant tree species (Table 1). Similarly, attractive trees species can be planted together with repellent species to create a "push and pull" effect in the forest and thus avoid the creation of outbreak populations that can decimate forests (Luo *et al.*, 2003; Faccoli *et al.*, 2015).

Based on the native range and invasive area research, we have divided the areas inhabited by this beetle into 3 zones (Table 3): old occurrence areas (invasion occurring for more than 5 years), new occurrence areas (invasion occurring for less than 5 years), and nonoccurrence areas (no invasion occurring or there was successful eradication) according to the National Forestry and Grassland Administration of China (2011). In countries where ALB populations have been established, zones can be based on the characteristics of different regions to achieve sustainable control of this beetle through specific measures, such as implementing classified policies and zoning management consistent with local conditions.

In the native range, ALB is found in old occurrence areas. In slightly damaged areas of the native range, such as in southern China and Korea, artificial visual surveys and attractants (host VOCs and pheromones) are used to accurately explore the population dynamics of this beetle, as well as support forest management and biological control measures (e.g., the release of parasitic enemy insects) to keep ALB populations below the economic threshold. Severely damaged areas of the native range mainly include planted forests in the "Three North" of China (shelterbelts). These areas were mostly planted with tree species sensitive to ALB based on destruction information. Luo (2005) considered that ALB is an important part of artificial forest ecosystems, and the relationship between this beetle and host tree species should be considered, along with natural enemies and the living environment. Ecological control measures are required to prevent beetle-inflicted disasters. First, strengthening the management and pest control in declining trees and mature forests should be a priority. These forests are dominated by regeneration and transformation, which requires measures for rationally planting multiple tree species to resist ALB disasters (Table 1). Second, depending on the ALB population density and the ratio of harmed trees in young and middle-aged forests, chemical control is the primary measure, supplemented by forest management (pollarding and clearing infested wood), and physical and biological measures can be implemented to achieve comprehensive management.

In invasion areas, eradication programs (including cutting and burning infested trees, uprooting stumps, and destroying all host plants in a certain radius) are the most important measures to eliminate ALB populations and prevent their movement and spread. In old occurrence zones of invasion areas, ALB eradication measures are still needed, even though they are challenging. Treatment of trees with chemical control measures is considered an important component of the control and management of ALB in severely damaged areas such as New York, where large economic losses occur. Detection and monitoring measures should be frequently carried out in mildly damaged zones of ALB invasion areas, such as in Europe. In addition, biological control measures and forest management should be implemented in old occurrence zones of ALB invasion areas. All new occurrence zones are mildly damaged areas, including Lebanon (2016), South Carolina (2020), and Japan (2021), where eradication measures were implemented in time to eliminate ALB populations and prevent their movement and spread. In addition, these measures should be purposefully supplemented by preventive treatment, with insecticides (such as drilling and drug injection or soil irrigation) applied to each host around infested trees; this has already been employed in several areas, with good results in Illinois, New Jersey, Canada, Austria, and The Netherlands. Additionally, in nonoccurrence ALB areas, where quarantine measures (ISMP 15) should be strengthened, supplementing detection and monitoring measures, and focusing on eradicated areas and those areas adjacent to occurrence areas, should be performed to achieve early detection and early eradication.

Table 3 Asian longhorn beetle (ALB) management and control strategies for zones with different degrees of damage in the native range and invaded areas.

Distribution	Classification	Criteria	Damage degree	Control suggestions	Country/region	Reference
Native range	Old occurrence areas	Occurrence of ALB for more than 5 years	Mild damage	Detection and monitoring measures, coordinated biological control measures, forest management	South China Tibet, China Xinjiang, China Korea	Liu (2016) Wang (2004) Wang (2004) Williams *et al.* (2004)
			Severe damage	Forest replacement (debilitating forest and overmature forest) Chemical control measures and supporting forest management, physical control, biological control (young forest and medium-age forest)	North China	Luo *et al.* (2003); Huang *et al.* (2008); Wang *et al.* (2018); Li *et al.* (2020a); Wang *et al.* (2021)
Invasion area	Old occurrence areas	Invasion of ALB for more than 5 years	Mild damage	Eradication measures Detection and monitoring measures, biological control measures, forest management	France Italy Germany Ohio, USA	CABI (2014) Faccoli and Gatto (2016) Schröder *et al.* (2005) NAPPO (2017)
			Severe damage	Eradication measures Chemical control measures, biological control, forest management	New York, USA Massachusetts, USA	Poland *et al.* (2006) Shatz *et al.* (2013)
	New occurrence areas	Invasion of ALB for ≤5 years	Mildly damaged	Eradication measures Preventive treatment with insecticide	South Carolina, USA Japan Lebanon	Coyle *et al.* (2021) Akita *et al.* (2021) Moussa and Cocquempot (2017)
	Non-occurrence areas	Eradicated and other risk areas	–	International Standards for Phytosanitary Measures 15, coordinated detection and monitoring measures	Finland Netherlands Austria England Switzerland Montenegro Canada	Riikka *et al.* (2018) Loomans *et al.* (2013) Hérard *et al.* (2006) Straw *et al.* (2015) Tsykun *et al.* (2019) Pajović *et al.* (2017) Turgeon *et al.* (2015)

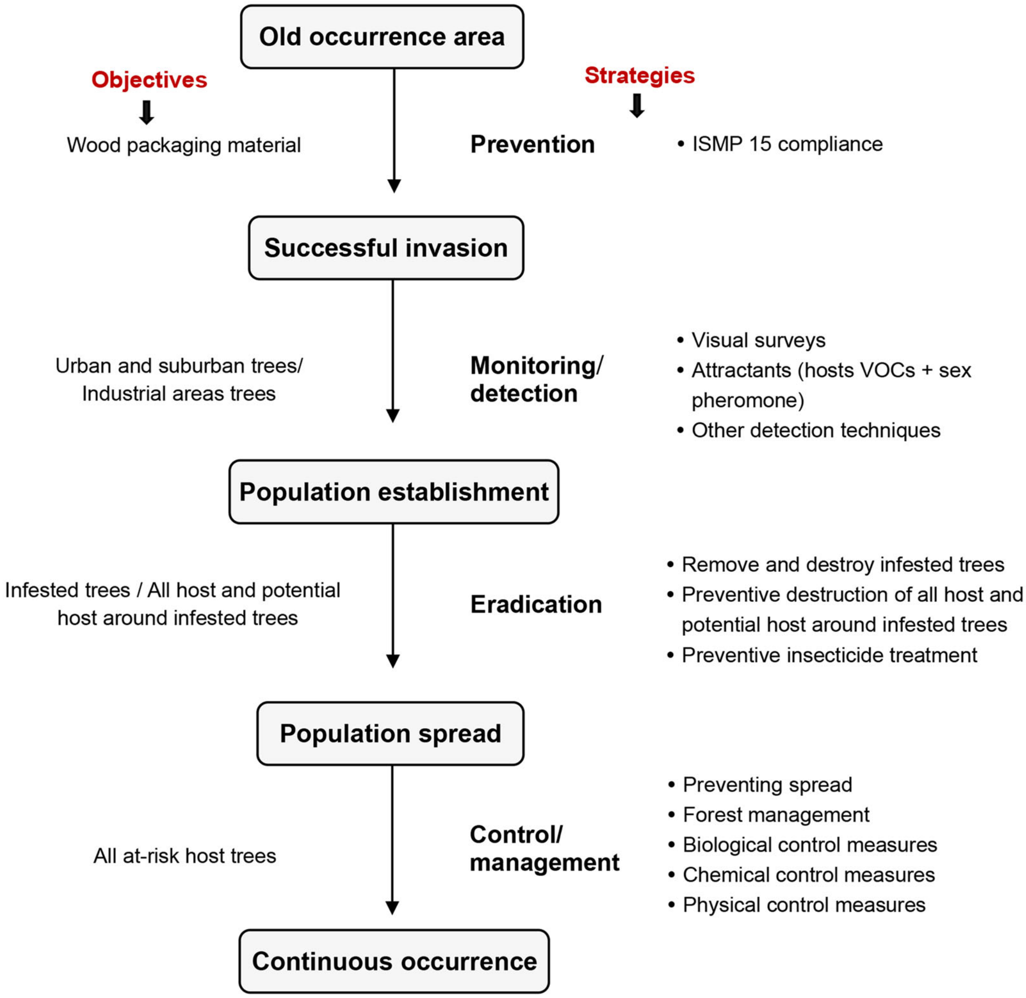

Fig. 5 Summary of Asian longhorn beetle (ALB) management objectives and strategies during different stages.

Conclusion

Based on ALB management strategies employed over the past 30 years, future strategies should include 4 steps. In the first step, SWPM should be strictly quarantined in accordance with ISMP 15 standards, especially SWPM from old ALB occurrence areas. The second step is to monitor beetles and assess trees in the urban/suburban forests (private gardens, street trees, public parks) and commercial areas involved in importing SWPM to avoid invasion of adult ALB in the case of ISMP 15 interception failures. Third, if ALB is found during monitoring and detection work, an eradication project should be implemented in a timely manner in accordance with the relevant laws and regulations of the local government. Fourth, if eradication fails, additional control and management strategies should be implemented in all ALB occurrence areas and potential occurrence areas, which will become a long-term task (Fig. 5).

Despite advances in the last decade, prevention and management of ALB remains challenging (Branco *et al.*, 2021). With the continuous development of world trade and ongoing global climate change, whether ALB will be found in more locations remains unknown. The effective management of ALB is based on accurate detection and forecasting of pest invasion. Effective monitoring systems should be established in medium- and high-risk countries (including countries in which established populations have been eradicated) to prevent the occurrence of ALB where necessary, and should include the use of semiochemicals, satellite remote sensing, or a sentinel host (Meng *et al.*, 2014; Zhou *et al.*, 2021a). However, highly effective semiochemicals have not yet been discovered, and identifying highly effective semiochemicals requires joint efforts of researchers from various countries. In addition, ALB and *Fusarium solani* have established a stable symbiotic relationship (Scully *et al.*, 2014; Mason *et al.*, 2019; Wang *et al.*, 2022), and whether this symbiotic fungus can provide new possibilities for the management of ALB also requires further research.

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Disclosure

The authors declare there is no conflict of interest/competing interests. This study does not contain any experiments using any animal species that require ethical approval.

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