



Biology, impact, management and potential distribution of *Aromia bungii*, a major threat to fruit crops around the world

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Abstract

Aromia bungii Faldermann (Coleoptera: Cerambycidae) is an emerging invasive pest of economically important *Prunus* species that is native to China, Mongolia, the Russian Far East, Korea, and Vietnam. It was recently introduced to Japan, Germany, and Italy, where it is spreading and damaging crops and ornamental trees. It exhibits an adaptable lifecycle, a high reproductive output, and the larvae live concealed under the bark of infested trees, which are traits that promote its invasiveness. Detection and monitoring of *A. bungii* currently rely upon visual identification of infested trees that are usually already damaged, which is inefficient and not target-specific. Current control methods rely primarily upon the labour-intensive physical removal of infested trees. Although native parasitoid natural enemies of *A. bungii* provide control in Chinese orchards, none are appropriate for classical biological control in invaded areas due to biosafety concerns surrounding their broad host ranges. However, entomopathogenic fungi and nematodes may provide viable options for biological control in invaded ranges. Recent advancements in semiochemical baited traps may provide sustainable, target-specific, and efficacious methods to monitor and control *A. bungii*. There remains much to learn about the biology and control of *A. bungii*, and continued advancements in the study of sustainable control tools are needed for the management of this emerging pest.

Keywords Red-necked longicorn beetle · Wood-boring pest · Emerging pest · Biological invasion · Potential distribution · Biological control

Key message

- *Aromia bungii* is a pest of economically important *Prunus* species.
- It has recently invaded Japan, Germany and Italy.
- Aspects of its biology and ecology promote its invasiveness.
- Current detection, monitoring, and control of *A. bungii* are labour-intensive and inefficient.
- Advancements in target-specific tools provide a positive outlook for future management options.

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Introduction

Aromia bungii Faldermann (Coleoptera: Cerambycidae) is a wood-boring beetle native to eastern China, Mongolia, the Russian Far East, Korea, and Vietnam (Zhang and Zhao 1996; Kim et al. 2006; Byun et al. 2009; GBIF 2022). Throughout its native range, *A. bungii* primarily infests trees in the genus *Prunus*, including economically important crop species such as apricots, cherries, peaches, and plums (Liu et al. 1999; Tian et al. 2008; Zhao et al. 2009; Zhao et al. 2019), resulting in extensive damage. For instance, damage rates of up to 90% have been reported within apricot orchards in China (Liu et al. 1999; Li et al. 2018). Recently, *A. bungii* has invaded Germany (Burmeister et al. 2012; EPPO 2012a, 2020), Italy (EPPO 2012b, 2013a; Garonna et al. 2013), and Japan (Kano et al. 2014; Tamura and Shoda-Kaguya 2022). Due to its economic importance throughout its native range, this expanding global distribution has triggered concern regarding the potential biosecurity threat posed by *A. bungii* worldwide, and especially for Europe (EPPO 2014; De la Peña et al. 2019; Russo et al. 2020; Tamura and Shoda-Kaguya 2022), where it is included in the list of quarantine pests to the Union territory and regulated as a priority pest (EU 2019). Despite its continued spread, the pest is officially under eradication and containment in both Germany (EPPO 2023) and Italy (EPPO 2022).

Aromia bungii is polyphagous (Song et al. 2010; Jin et al. 2014; Zhao et al. 2019) and exhibits a long life cycle of which a significant portion is spent as a larva that bores tunnels inside tree trunks, feeding on the xylem and phloem (Wang et al. 2007). This inhibits the physiological functions of infested trees, eventually causing their death (Meng et al. 1985). In China, the management of this pest relies on a variety of phytosanitary, physical, chemical, and biological control approaches (Zhang et al. 1991; Wang et al. 2015; Niu et al. 2018; Han et al. 2019). However, most of the current knowledge about *A. bungii* is documented in Chinese, and to some extent Japanese, literature. In this review, we cover the biology, impact, management, and current distribution of *A. bungii* by drawing upon the Chinese, Japanese, and English literature. Searches were conducted in the China National Knowledge Infrastructure and J-STAGE databases to obtain relevant Chinese and Japanese literature, respectively, whereas Google Scholar and Web of Science were used to obtain English literature. We also discuss the potential global distribution of *A. bungii* through the development of a bioclimatic MaxEnt (Phillips et al. 2006) model. Reviewing these elements will provide scientists, industry, and policymakers with a reference to the current state of information regarding *A. bungii*

to inform preparedness, future research, and responses in the face of this escalating global threat.

Biology of the pest

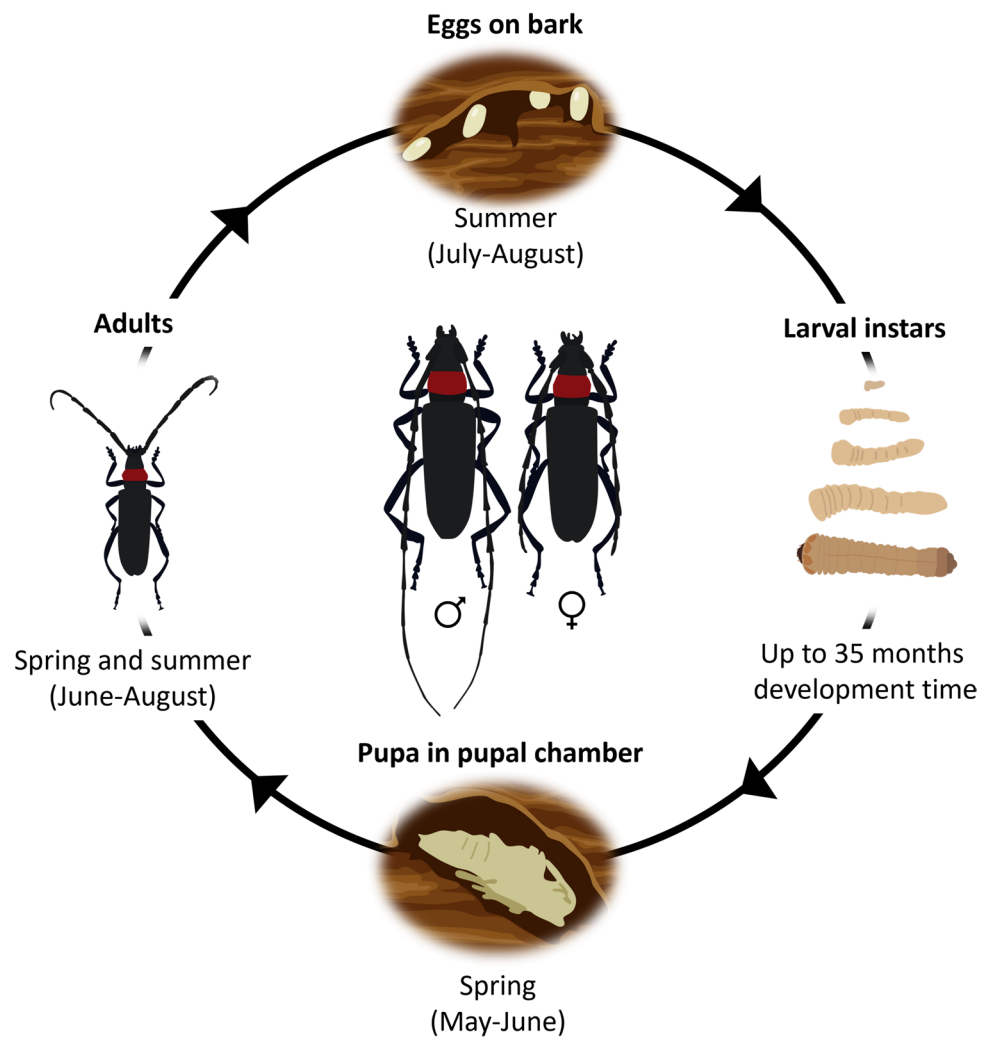
Life cycle, development, and reproduction

The life cycle and development of *A. bungii* (Fig. 1) were investigated in a Chinese study (Liu 1982). In China, the time taken to complete one generation is dictated by the climatic conditions and varies between 1 and 3 years (Iwata 2018). A 1-year life cycle is limited to the warmer regions, for example Sichuan Province (Zhang et al. 2000). In Anhui Province, the population exhibits a mixture of both 1- and 2-year life cycles (Yu and Gao 2005), whereas further north, the life cycle is completed in either 2 or 3 years (Li 1995; Lu 1995; Wang et al. 2007; Iwata 2018).

Laboratory observations demonstrated that the egg stage duration of *A. bungii* averages 8.70 days (Russo et al. 2020). In Shanxi Province, China, larvae emerge from early July to September (Li 1995). Here, the larval stage is reported to last for 34–35 months, with periods of overwintering and development until the larvae form a pupal chamber in which they overwinter and finally pupate in the following spring (Li 1995; Ma et al. 2007). In Anhui Province, where *A. bungii* exhibits a 2-year life cycle, the larval stage lasts for 21.50 months (Liu 1982). Although there is no information on the development time of larvae, in the Japanese prefecture of Tochigi, larvae were found to complete the formation of pupal chambers between late June and August. The mature larva then overwinters in the pupal chamber and pupates in mid-May of the following year (Haruyama et al. 2021a). We were unable to find more data describing the timing and duration of the larval stages of *A. bungii* outside of China. Hatching larvae immediately drill through the outer bark of the tree (Liu 1985; Zhang et al. 2000; Yu and Gao 2005) and feed on the outer surface of the xylem (Yamamoto et al. 2020). When frass (sawdust and faeces) begins to accumulate within the feeding tunnels, the larva pushes it out of the borehole. Due to this behaviour, the presence of large larvae is indicated by reddish brown frass accumulating at the base of the tree trunk, which is used for the visual detection of *A. bungii* presence (Liu et al. 1999; Zhang et al. 2000). Feeding damage has therefore usually already been exerted upon infested trees before *A. bungii* is detected (Yasui et al. 2019).

As larvae mature, they tunnel into the xylem directly, where they continue to feed before forming the pupal chamber (Hong 2011; Yamamoto et al. 2020). Larvae predominantly feed near the base of the main stem, or within the main branches close to the main stem (Wang et al. 2015). This pattern of feeding behaviour described for both

Fig. 1 Life cycle of *Aromia bungii* as reviewed from the Chinese and Japanese literature



immature and mature larvae is consistent amongst different host trees (Yamamoto et al. 2020).

In the colder latitudes of *A. bungii*'s distribution in China, adults emerge from pupae between mid-June and mid-August and exhibit a longevity of around 53 days (Li 1995), whereas in warmer latitudes adult emergence occurs between early June and late July (Liu 1982). Investigations in both Osaka and Tochigi Prefectures, Japan, demonstrated that adult beetles were fully formed in the pupal chambers in early June, but emerged from trees in mid- to late June (Haruyama et al. 2021a; Yamamoto and Kaneko 2022). During an outdoor cage experiment with infested *Prunus x yedoensis* (Yoshino cherry) in Ibaraki Prefecture, Japan, adults emerged between mid-June and late July. Here, male longevity averaged 60 days, whereas female longevity was 79 days (Urano et al. 2022). However, in laboratory conditions at 20 °C, Russo et al. (2020) observed an average adult male longevity of 62.70 days, whereas ovipositing females lived for 34.70 days at 25 °C. The differences in seasonal phenology between *A. bungii*

populations throughout China and Japan exemplify the adaptability of its life cycle to diverse climatic conditions, which is a trait that benefits invasive species, and further highlight the invasive potential of *A. bungii* (Crowley and Hopper 2015; Orlova-Bienkowskaja and Bienkowski 2016).

Aromia bungii adults emerge sexually mature from host trees during the day (Cao and Li 1995; Wang et al. 2007). Findings from both China and Japan have demonstrated that adult sex ratio early in the season is heavily male biased, but gradually reduces to around 50%, indicating that the majority of males emerge before females (Huang 2009; Yamamoto and Kaneko 2022). This allows males to mate with females as they emerge. An approximately 50% sex ratio has also been reported amongst *A. bungii* populations in both Italy and Japan (Russo et al. 2020; Urano et al. 2022).

Recent evidence indicates that mate location is mediated by pheromonal communication. Compounds observed from the antennal secretions from sensilla basiconica, and antennal chemoreceptivity to a range of volatile organic

compounds, in both males and females strongly suggest a role of olfactory-mediated mate recognition (Di Palma et al. 2019; Germinara et al. 2019). Furthermore, a sex-aggregation pheromone, produced only by males, has been identified and demonstrated to elicit antennal responses and field attraction in both males and females (Xu et al. 2017; Yasui et al. 2019; Zou et al. 2019). It is reported from China that mating predominantly occurs when temperatures reach at least 28 °C, and that males exhibit mate-guarding behaviour post copulation (Liu et al. 1982). Although knowledge on the mating behaviour of *A. bungii* is incomplete, an understanding of pheromonal communication is useful for the development of semiochemical-based control tools (Yasui et al. 2019).

Laboratory experiments found that female *A. bungii* began ovipositing an average of 2.10 days after emergence and mating, with an average oviposition period of 22.10 days (Russo et al. 2020). Field observations in China have reported variable pre-ovipositional periods ranging between 2–5 days after mating (Li 1995; Wang et al. 2007; Huang 2009). Females use their ovipositors to search the surfaces of tree trunks for appropriate crevices or lesions in the bark, into which eggs are laid (Huang 2009). Females prefer to oviposit on older trees, given their tendency to feature coarser surfaces compared to their younger counterparts (Urano et al. 2022; Yamamoto et al. 2022). Usually, single eggs are laid inside cracks, but occasionally groups of two to five eggs have been observed (Hong 2011). In the laboratory, female *A. bungii* had an average lifetime fecundity of 587.50 eggs, with 50% laid within the first week following emergence, and an average oviposition rate of 24.20 eggs per day (Russo et al. 2020). The average hatching rate was 75.60% and was higher for eggs laid earlier during the oviposition period, indicating that fertility decreases with adult female age (Russo et al. 2020). Female fecundity in field populations in China is lower than what is reported in the laboratory, but also highly variable. For instance, Wang et al. (2007) observed that females lay 91–734 eggs during their lifetime (average 325–357), whereas Hong (2011) observed 112–362 eggs per female, though the number of replicates was not reported. Lifetime fecundity also differs depending on the tree species from which adults emerge, suggesting that nutritional conditions experienced during larval development can impact reproductive fitness in adult females (Urano et al. 2022). Current knowledge on lifetime fecundity of *A. bungii* females suggests that it is much greater than that of the European congeneric *Aromia moschata* L. (Coleoptera: Cerambycidae) (Russo et al. 2020) and other wood-boring pests belonging to the same subfamily, for example *Trirachys sartus* Solsky (Coleoptera: Cerambycidae) and *Osphranteria coerulescens* Redtenbacher (Coleoptera: Cerambycidae) (Sharifi et al. 1970; Mazaheri et al. 2007). In addition to its short pre-oviposition period, this indicates

that *A. bungii* exhibits a high reproductive potential, allowing it to rapidly establish invasive populations, which in turn impedes successful eradication and long-term management (Myers et al. 2000; Russo et al. 2020; Osawa et al. 2022).

For a detailed review on the morphology of each life stage of *A. bungii*, refer to Appendix 1 of the Supplementary Materials.

Dispersal ecology

The dispersal ecology of *A. bungii* is not well understood. Fukaya et al. (2017) demonstrated that oriented flight behaviour from females was stimulated by the upstream presence of conspecific males inside wind tunnels, suggesting that adult dispersal may be partially influenced by mate-location behaviour. In terms of dispersal capacity, females can fly a distance of 10–60 m when threatened, whereas males tend to crawl away (Huang 2009; Chen et al. 2023). Similarly, Liu (1982) reports that adult flight events typically cover 40–70 m.

Since the establishment of *A. bungii* was first confirmed in Japan in 2012, its range has expanded rapidly (Osawa et al. 2022), possibly suggesting a strong dispersal capacity. Osawa et al. (2022) developed an expansion-predicting model for *A. bungii*, concluding that habitat continuity (i.e. continuity of host plant presence) would allow for effective dispersal. The widespread planting of flowering cherry trees throughout Japan has therefore likely accelerated dispersal and establishment (Urano et al. 2022). However, genetic evidence suggests that its non-contiguous distribution throughout Japan is the result of multiple independent introductions from China (Tamura and Shoda-Kaguya 2022), and that its current distribution is not solely explained by natural dispersal. The scarcity of knowledge on the dispersal ecology of *A. bungii* highlights an important knowledge gap. An empirical understanding of dispersal mechanisms helps to ascertain the spread dynamics of invasive populations, which in turn informs management (O'Reilly-Nugent et al. 2016; Bosco et al. 2020).

Host plants in the native and invaded range

The host range of *A. bungii* falls predominantly within the Rosaceae family (Table 1), but with particular preference towards the genus *Prunus* (Wang et al. 2007; Iwata 2018). However, it is possible that the reported preference for *Prunus* is an artefact of biased study effort due to their importance as agricultural crops. Nevertheless, 16 plant species from 12 families have been reported as hosts of *A. bungii* in China, in addition to the 12 rosaceous host species. It is unclear how these reports of non-rosaceous

host plants were attributed to *A. bungii*, and it is therefore not possible to infer their validity or status as major or minor hosts. Furthermore, in Germany, Italy, and Japan, *A. bungii* has only been observed infesting *Prunus* species, which casts further doubt upon these reports on host plants in China.

Economic impact

The economic impacts of *A. bungii* in China are limited to reports of damages, with estimates of financial consequences lacking. These impacts are of particular importance to peaches, as their production substantially outweighs that of other *Prunus* crops in China, for which there are limited reports (Iwata 2018; FOAG 2023). Generally, peach trees live for about 30 years, but this is reduced to approximately 10 years for trees that have been damaged by *A. bungii* (Niu et al. 2018), though death can occur within 2–3 years after initial infestation (Zhou 2015). Given that susceptibility to infestation increases with tree age, so does its susceptibility to damage (Li et al. 2018; De la Peña et al. 2019; Urano et al. 2022). For example, the percentage of 12 year-old peach trees damaged by *A. bungii* infestation within an orchard in Hebei Province was 88.90%, whereas that of 6–7 year-old peach trees was 6.50% (Wang et al. 2007). However, survey results of orchards throughout Beijing showed that the average damage rate of 7–8 year-old fruit trees was 44.90% (Liu et al. 1996). Similarly, a field study in Inner Mongolia demonstrated that the percentage of wild peach trees damaged by *A. bungii* was only 8% for those with a diameter at breast height (DBH) of < 10 cm, but 100% for those with a DBH of 21–25 cm (Xue et al. 2011). Within orchards in Hunan Province, the percentage of 19–20 year-old peach trees damaged by *A. bungii* was over 90% (Li et al. 2018). Many other studies have reported similarly devastating levels of damage to peach orchards throughout the distribution of *A. bungii* in China (Liu 1982; Meng et al. 1985; Zhou 1986; Liu et al. 1999; Zhang et al. 2000; Yu and Gao 2005; Yu et al. 2005; Huang 2009; Shi et al. 2009; Cheng et al. 2016).

Numerical reporting on the damages caused by *A. bungii* in Japan is limited, and we are not aware of any estimates of financial losses. However, the results of surveys conducted after discoveries of outbreaks provide insight into the severity of damages as *A. bungii* continues to spread in Japan. Nakano (2018) provides an overview of the damages caused during an outbreak of *A. bungii* in Tokushima Prefecture that was first discovered in

2015. Subsequent surveys of 30 peach orchards revealed that 56.67% of these orchards contained infestations, with 15.03% of the sampled trees showing signs of *A. bungii* damage. In 2016, the percentage of damaged trees increased to 21.73% of those sampled, and in the worst affected orchard, two thirds of the trees died. Shoda-Kagaya (2018) also reported that after the 2016 discovery of *A. bungii* adults in Tochigi Prefecture, 9.67% of peach and plum trees surveyed were damaged. However, most of the damage in Japan has been exerted upon *P. yedoensis*, which has significant cultural importance (Urano et al. 2022). For example, the spring cherry blossom festival (Hanami) is an important cultural tradition and attracts substantial tourism (Tamura and Shoda-Kagaya 2022). The impacts of *A. bungii* in Japan could therefore also extend to culture and the tourism sector. These reports highlight the extensive damage that *A. bungii* has caused to stone fruit crops and *P. yedoensis* in the early stages of invasion in Japan, and the potential for these damages to spread and progress rapidly.

Although *A. bungii* remains under containment within relatively small areas in Italy and Germany, survey results from inside the demarcation zones in Italy demonstrate its potential to incur serious economic impacts if it were to spread throughout Europe. For example, a 2018 survey within the demarcation zone in Campania, where *A. bungii* was first discovered in 2012, found 210 infested *Prunus* trees that were subsequently destroyed (EPPO 2012b, 2019). Subsequent surveys in 2020 and 2021 identified a further 231 and 298 infested *Prunus* trees, respectively (EPPO 2021, 2022). These findings demonstrate that *A. bungii* exhibits the capacity to readily infest and damage *Prunus* crops in Italy. If eradication and containment efforts were to be unsuccessful, this suggests the potential for severe economic consequences for several European countries. For example, Greece, Spain, Italy, and France have significant peach markets, comprising 31.30%, 30.90%, 30.30%, and 3.80% of the total peach production within the EU, respectively (EU 2022).

Control options in China

Phytosanitary control

Developmental stages of *A. bungii* can easily be transported long distances via human-mediated pathways, particularly during the transportation of nursery stock (Zhang et al. 2000; Bai et al. 2017). Because current detection methods do not favour rapid-detection (Liu et al. 1999; Fujiwara-Tsujii and Yasui 2023), it is recommended that host seedlings of *A. bungii* be subject to strict quarantine measures before being distributed to nurseries, and that any potential host plants

Table 1 Known host plant species of *Aromia bungii* in its native and invaded ranges

Country	Family	Species	References
China	Rosaceae	<i>Eriobotrya japonica</i> (loquat)	Peng et al. (2010)
		<i>Malus</i> sp. (crabapple)	Song et al. (2010); Gui et al. (2019)
		<i>Malus domestica</i> (apple)	Lu (2017); Gao (2018); Song et al. (2010);
		<i>Prunus armeniaca</i> (apricot)	Fang (2001)
		<i>Prunus avium</i> (cherry)	Fu et al. (2007); Zhang et al. (2009); Song et al. (2010)
		<i>Prunus japonica</i> (Japanese bush cherry)	Hong (2011); Gao (2018)
		<i>Prunus mume</i> (Chinese plum)	Si and Hu (2002); Lu (2017)
		<i>Prunus persica</i> (peach)	Chen and Jia (2006); Deng and Wang (2013); Jin et al. (2014)
		<i>Prunus pseudocerasus</i> (Chinese sour cherry)	Tian et al. (2008)
		<i>Prunus salicina</i> (Japanese plum)	Liu (1982); Wang et al. (2007); Zhao et al. (2019)
		<i>Pyrus</i> spp. (pear)	Hong (2011)
		<i>Rubus corchorifolius</i> (raspberry)	Bai et al. (2017)
	Aquifoliaceae	<i>Ilex chinensis</i> (holly)	Song et al. (2010)
	Ebenaceae	<i>Diospyros kaki</i> (persimmon)	Hong (2011)
	Fabaceae	<i>Albizia julibrissin</i> (Persian silk tree)	Song et al. (2010)
		<i>Robinia pseudoacacia</i> (black locust)	Song et al. (2010)
	Fagaceae	<i>Castanea mollissima</i> (Chinese chestnut)	Tang et al. (1988)
	Juglandaceae	<i>Juglans regia</i> (walnut)	Hong (2011)
	Lythraceae	<i>Punica granatum</i> (pomegranate)	Wang et al. (2002)
	Moraceae	<i>Morus alba</i> (mulberry)	Zhang et al. (1995)
	Rutaceae	<i>Zanthoxylum bungeanum</i>	Ma et al. (2001)
	Salicaceae	<i>Populus</i> spp. (poplar)	Song et al. (2010)
<i>Salix babylonica</i> (weeping willow)		Song et al. (2010); Lu (2017)	
<i>Xylosma racemosum</i> (oak wood)		Bai et al. (2017)	
Sapindaceae	<i>Koelreuteria</i> spp. (Chinese lantern tree)	Kang (2017); Liu and Liu (2018)	
Theaceae	<i>Camellia sinensis</i> (tea)	Peng et al. (2010)	
Ulmaceae	<i>Ulmus pumila</i> (elm)	Song et al. (2010); Mou et al. (2013)	
Japan	Rosaceae	<i>Prunus mume</i> (Chinese plum)	Urano et al. (2022)
		<i>Prunus persica</i> (peach)	Urano et al. (2022)
		<i>Prunus salicina</i> (Japanese plum)	Urano et al. (2022)
		<i>Prunus yedoensis</i>	Urano et al. (2022)
Germany	Rosaceae	<i>Prunus avium</i> (cherry)	LfL (2023)
		<i>Prunus cerasifera</i> 'Nigra' (cherry plum)	LfL (2023)
		<i>Prunus cerasus</i> (sour cherry)	LfL (2023)
		<i>Prunus domestica</i> (plum)	LfL (2023)
		<i>Prunus domestica</i> subsp. <i>domestica</i> (prune plum)	LfL (2023)
		<i>Prunus domestica</i> subsp. <i>insititia</i> (damson plum)	LfL (2023)
		<i>Prunus domestica</i> subsp. <i>italica</i> (greengage)	LfL (2023)
		<i>Prunus domestica</i> subsp. <i>syriaca</i> (mirabelle plum)	LfL (2023)
		<i>Prunus padus</i> (bird cherry)	LfL (2023)
		<i>Prunus persica</i> (peach)	LfL (2023)
	<i>Prunus serrulata</i> (Japanese cherry)	LfL (2023)	

Table 1 (continued)

Country	Family	Species	References
Italy	Rosaceae	<i>Prunus armeniaca</i> (apricot)	EPPO (2012a, 2012b, 2019, 2021)
		<i>Prunus avium</i> (cherry)	EPPO (2012a, 2012b, 2019, 2021)
		<i>Prunus cerasifera</i> (cherry plum)	EPPO (2012a, 2012b, 2019, 2021)
		<i>Prunus cerasus</i> (sour cherry)	EPPO (2012a, 2012b, 2019, 2021)
		<i>Prunus domestica</i> (plum)	EPPO (2012a, 2012b, 2019, 2021)
		<i>Prunus laurocerasus</i> (cherry laurel)	EPPO (2012a, 2012b, 2019, 2021)
		<i>Prunus persica</i> (peach)	EPPO (2012a, 2012b, 2019, 2021)
		<i>Prunus serotina</i> (black cherry)	EPPO (2012a, 2012b, 2019, 2021)

should be treated with insecticides to avoid planting infested seedlings (Zhang et al. 2000; Bai et al. 2017). However, it is not clear how widely these measures are implemented in China.

Various phytosanitary approaches are also undertaken within *Prunus* orchards in China to limit tree damage. Considering that weaker host trees are more susceptible to infestation (Yamamoto et al. 2022), the application of fertilisers such as nitrogen, phosphorus, and potassium, and an increasing use of organic fertilisers, to strengthen the overall health and vigour of trees is suggested to improve resistance to infestation (Han et al. 2019). Pruning and the thinning of flowers and fruits are also employed to reduce the ineffective consumption of nutrients and improve tree ventilation, thereby maintaining tree vigour and resistance to infestation (Han et al. 2019).

Because older trees are more susceptible to infestation (Yamamoto et al. 2022), it is recommended that trunks are cleaned in a timely manner (Fan 2018). Considering the timing of adult emergence, old bark is often removed to limit the availability of oviposition sites. Old bark infested with larvae is also often manually removed and burned (Niu et al. 2018). Additionally, damaged branches are removed, but severely damaged trees that no longer produce fruit are felled and burnt to reduce the pest population in the orchard (Han et al. 2019). After all infested trees and branches have been removed, regular inspections for re-infestation are recommended (Fan 2018). However, these approaches are time-consuming and labour-intensive, and data are lacking on how effective these phytosanitary measures are in controlling *A. bungii* infestations and reducing damage in Chinese orchards.

Physical control

Physical control methods remain widely used to manage *A. bungii* within orchards in China. This includes rudimentary manual control options that involve directly capturing and/

or killing the various life stages of *A. bungii*. Collection of adults is often undertaken by shaking branches using a pole, causing beetles to fall to the ground where they can be readily collected (Niu et al. 2018). To catch and kill larvae, the age and feeding depth of larvae within the trunk is firstly distinguished by the colour of frass deposited at exit holes (Dong and Zhu 1987). Consequently, to kill shallow-feeding larvae, the bark is cut with a sharp knife (Niu et al. 2018). To kill deeper-feeding larvae, the frass inside the borehole is removed with tweezers and a wire is inserted to remove the larvae (Niu et al. 2018). To physically destroy *A. bungii* eggs, trunks are checked frequently for the presence of eggs during the oviposition period. Eggs are then scraped off or killed with a mallet (Niu et al. 2018). Finally, sealing adult emergence holes with cement or mud is conducted to suffocate adults inside pupal chambers and prevent their emergence (Lu 1995). Despite these methods being commonly reported, data are lacking on their effectiveness in preventing infestations and damages.

Physical tree protection by trunk whitening is the most well-reported alternative to manual removal methods in Chinese orchards. This involves painting a lime-sulphur mixture onto the main trunk and the base of branches, with a contact insecticide also often included. The mixture contains a sulphur, lime, and water ratio of 1:10:40, with the addition of a small amount of salt (Niu et al. 2018). The first whitening is done in autumn when trees have shed their leaves, to kill overwintering larvae. The second whitening is conducted before adult emergence, as the filling of cracks and rough surfaces on the bark limits the availability of suitable oviposition surfaces. It has also been suggested that the white colour of this mixture has some repellent effect on *A. bungii* adults, though it is not clear whether this has been experimentally investigated (Niu et al. 2018). Chen (2016) demonstrated that trunk whitening resulted in a 30.64% reduction of infested trees. However, a polyvinyl alcohol whitening mixture has also been tested, with a lime, water, phoxim (organophosphate), and salt ratio of 3:30:120:1. This

mixture exhibits strong adhesion and rain resistance, and the coating can remain for up to 3 months, which spans the period of adult activity (Lu 1995; Wang et al. 2007; Yamamoto and Kaneko 2022). It was shown to reduce oviposition by 23–85.10% and survival of larvae by 67.10–16.70% (Lu 1995). The availability of data to support the efficacy of the trunk whitening method may justify further investigation and implementation in invaded countries until more target-specific, and less labour-intensive, methods become available.

Another method of physical trunk protection involves tightly covering oviposition-susceptible areas of tree trunks, such as deep cracks or wounds, with gauze nets or plastic film, which is reportedly effective in preventing oviposition (Lu 1995; Wang et al. 2015). It is similarly reported that grass is wrapped around the trunk during the period of adult activity to prevent emerging larvae from drilling into the bark (He et al. 2007; Tian et al. 2008). However, no data are available on the effectiveness of tree wrapping techniques in China.

Trapping is reported to be commonly used in China. *Aromia bungii* adults, particularly the males, show a strong attraction towards traps baited with brown sugar, wine, and vinegar at a ratio of 1:0.5:1.5. When adult beetles begin to emerge during spring, such traps are hung 1.5 m above the ground in the shade of trees between orchard rows. New liquid is added every 3–5 days (Zhou 1986). The efficacy of this method is unclear. However, these attractants are commonly used to attract a wide variety of insects, whereas species-specific baits, such as semiochemicals, would likely be required for effective detection, monitoring, and control using traps (Xu et al. 2017; Yasui et al. 2019).

One interesting approach to the physical control of *A. bungii* reported in China is microwave exposure, which raises their body temperature to a lethal level (40–70 °C). The upper lethal temperature threshold of the beetle larvae is reported to be 5–10 °C lower than that of the host tree, meaning that the larvae can be killed without damaging the tree. The optimal combination and application are a microwave frequency of 915 MHz, at a power of 400 W, with bidirectional radiation and omni-directional scanning for 6–8 min. The effective penetration depth of this combination can reach up to 35 cm. The concealment of *A. bungii* larvae under the bark therefore does not affect microwave control of *A. bungii* (Jian et al. 1991). However, data are also lacking on the efficacy of this approach. Furthermore, microwaves can cause mutations in organisms and may have lethal effects on other native and/or beneficial species (Jian et al. 1991), which may suggest its suitability for phytosanitary treatment of logs and wood packing materials as opposed to within-orchard control (Nzokou et al. 2008; Makoviny et al. 2012; Payette et al. 2015; Pawson et al. 2019).

Chemical control

A multitude of chemical control options are suggested against *A. bungii* and other long-horned beetles on fruit trees in China (e.g. reviewed by Wang et al. 2007; Huang et al. 2012). As a wood-boring beetle, only adults, eggs, and freshly hatched larvae can be reached by spraying insecticides. For larvae tunnelling in the wood, other application methods have to be employed. Here, we provide an overview on different methods that have been used in China against different life stages of *A. bungii*.

Control of adults

Chemical compounds that have been used as sprays to control adult *A. bungii* include dichlorvos (organophosphate), fenitrothion (organophosphate), deltamethrin (pyrethroid), phoxim (organophosphate), and fipronil (phenylpyrazole). The following compounds have also been used in microcapsule formulation: deltamethrin, fenitrothion, diflubenzuron (benzoylurea), cypermethrin (pyrethroid), and fenvalerate (pyrethroid) (Huang et al. 2012). An example of a microencapsulated insecticide is Green Wei Lei, a contact insecticide based on 8% cypermethrin, which can be diluted 300–400 times and sprayed directly on the trunk. The microcapsules rupture when adult beetles step on them, causing the pesticide to stick to the beetle's feet and eventually enter its body. The capsules remain active for at least 52 days, killing more than 90% of adults within 40 days (Du 2011).

Control of eggs

During the period of egg laying to larval hatching, different chemicals have been recommended for spraying: a 1000–2000-fold dilution of 75% thiodicarb (carbamate); a 1000–3000-fold dilution of 2.5% cyhalothrin (pyrethroid); a 1000–2000-fold dilution of 10% lambda cypermethrin; an 800–1500-fold dilution of 5% fluorobenzamide; a 1000–1500-fold dilution of 20% tebufenozide (moulting hormone); a 3000–4000-fold dilution of 15% imidacloprid (neonicotinoid) or an 800-fold dilution of 40% chlorpyrifos (organophosphate). For direct spraying during the peak period of egg laying, a solution of 20% acetamiprid or 5% imidacloprid (diluted 1500–2000 times) has been recommended (Huang 2009). Other chemical compounds that have been used to control eggs and newly hatched larvae include fenitrothion, carbaryl (carbamate), dimethoate (organophosphate) and parathion (organophosphate) (Huang et al. 2012; EPPO 2014). The insecticides are recommended to be sprayed once every 7–10 days directly onto the trunks and branches within 15 m above the ground (Niu et al. 2018). However, the efficacy of controlling eggs with insecticide sprays is unclear.

As mentioned in the section on physical control, trunk whitening can be used in combination with chemical insecticides to prevent adult beetles from laying eggs on a tree (Wang et al. 2007).

Control of larvae

The following chemical compounds have been applied in China against *A. bungii* larvae using various application methods: the organophosphates dimethoate, omethoate, triazophos, malathion, fenitrothion, and dichlorvos; the pyrethroid deltamethrin; the neonicotinoid imidacloprid; as well as the inorganic compounds zinc phosphide, aluminium phosphide, and sulfurly fluoride (Huang et al. 2012).

One form of insecticide application against *A. bungii* larvae is the treatment of boreholes. For example, a 10% imidacloprid solution can be applied directly to the borehole using a brush. To increase the permeability of the insecticide, diesel oil can be added at a ratio of 1:0.5. The control effect has been shown to range from 90–100% after 5 days (Huang 2009). When a bore hole with fresh frass is detected, the hole is first cleaned and then treated with either aluminium phosphide, an 80% dichlorvos solution, cotton wool dipped in phoxim, or isofenphos-methyl (organophosphate). After the treatment, the boreholes should be sealed to prevent the larvae from escaping lethal insecticide exposure (Wang et al. 2009; Niu et al. 2018). The control effect of treating boreholes on fruit trees in this manner can reach up to 95% (Zhuang et al. 1994). An alternative treatment of boreholes that is practiced in China is the insertion of camphor balls (= mothballs). Larval mortality through this method was found to be 96% (Chen et al. 1992).

Instead of applying insecticides individually to boreholes, trees can also be fumigated by applying an insecticide on the trunk under a plastic wrapping. For ideal results, a foam wrapping should first be installed on the upper end of the trunk for better sealing. Then, the trunk should be wrapped with a double layer of plastic film and additionally tightened with a rope. After adding the insecticide, the lower part of the plastic film should be buried and compacted with soil. Using this method, 3 days of fumigation with 12–52 g of aluminium phosphide per 1 m³ has been shown to cause 91% larval mortality. The mortality can be increased to 98% by doubling the fumigation time to 6 days (Meng et al. 1985, Song et al. 1988).

Alternatively, tree trunks can be treated by coating them with a mix of mud and insecticides. For example, dichlorvos can be mixed with soil and water at a ratio of 1:40 to produce a fine mud. The mud can then be spread on the surface of infested trunks and wrapped in plastic film. Experiments have shown a 90% larval mortality after 15 days of insecticide application in this manner (Chen and Shao 1993).

Systemic insecticides are also being used against *A. bungii* infesting fruit trees in China. A relatively simple approach has been published by Liu (2010): approximately 10 cm above ground a small hole of 3 cm depth should be drilled into the trunk. A mix of the organophosphate methamidophos and 500 ml saline solution is prepared and injected into the drill hole so that the insecticide solution can be absorbed by the tree. Advantages of this application method are that it functions regardless of weather conditions and can be applied relatively easily compared to other insecticide applications against *A. bungii* larvae (Liu 2010). Applications of systemic insecticides have been proven successful against the beetle, such as the direct injection of a 1.80% matrine nicotine and 5% abamectin solution, which can achieve control effects of more than 95% (Wei 2018).

Outlook for chemical control of *Aromia bungii* in invaded areas

The fact that the larval stages of *A. bungii* are concealed makes chemical control of this species difficult, and laborious application processes have to be employed for successful control. Such treatments are probably not feasible in large-scale fruit production. Likewise, systemic insecticides, which are arguably easier to apply, are rather suited for single ornamental trees and may not be permitted for use in fruit trees in many countries. Spraying against adults and eggs may not lead to successful control as the flight period of adults is relatively long (Yamamoto and Kaneko 2022). Additionally, some of the described methods of chemical control seem to be anecdotal and may need further scientific investigation to validate their efficacy and risks for humans and the environment. Finally, several of the above-described insecticides are restricted or even banned in other countries (e.g. EPPO 2014). For example, as described in detail below, in Italy only one substance is currently registered for use against *A. bungii* in crop systems. Thus, chemical insecticides may only be a solution in individual cases. As described in the sections above and below, more promising control options are available and care should therefore be taken to use chemical insecticides that are compatible in the context of Integrated Pest Management.

Biological control

Entomopathogenic fungi

Several species of entomopathogenic fungi have been investigated for their potential use as biological control agents for *A. bungii*. Of the entomopathogens, *Beauveria bassiana* Vuill. is the most common cause of insect disease and is known from over 700 insect species (De Faria and Wraight

2007). The pathogenicity of *B. bassiana* on *A. bungii* was investigated by Shi et al. (2009), who demonstrated that exposure of larvae to *B. bassiana* spores under laboratory conditions at 23 °C for 25 days resulted in a 100% infection rate and 70% mortality. As *B. bassiana* is used as a biocontrol agent for many different insect pests worldwide, it may be of interest to investigate strains already registered for use in invaded areas to determine the potential to develop a biological control strategy for this pest in the event of establishment.

Entomopathogenic nematodes

Field studies on the use of entomopathogenic nematodes (EPNs) for control of *A. bungii* larvae in peach and apricot trees in China demonstrated that *Steinernema carpocapsae* Weiser (MK, A₂₄, and Beijing strains) provided the most effective control of *A. bungii* at a dose of 30,000–50,000 nematodes per/ml (Liu et al. 1998). When the three different strains were applied separately, the control efficiency after 1 month varied between 58.30% and 100%, but was not significantly different with dosages of 40,000 nematodes/ml as recommended against *A. bungii* in fruit orchards (Liu et al. 1997). *Steinernema longicaudum* Shen & Wang (CB-2y strain), *Steinernema bibionis* Bovien (OTIO strain), and two strains of *Steinernema feltiae* Filipjev (Mexican and Agriotos strains) have also been tested for their efficacy against *A. bungii*. *Steinernema longicaudum* (CB-2y) injected into feeding tunnels can remain infective for several days, with mortality of *A. bungii* larvae observed within 6 days of injection and increasing thereafter. Mortality reached 48% on the 13th day and 64.40% on the 30th day (Liu 1993). The two strains of *S. feltiae* and *S. bibionis* all caused more than 70% mortality within 20 days of application. However, *S. feltiae* (Mexican strain) exerted up to 90% mortality. The efficacy of control varied between seasons, with optimal control in summer when compared to spring and autumn, when nematode activity is reduced due to lower temperatures (Liu et al. 1993).

Parasitoids

Several parasitoid species have been documented from *A. bungii* in its native range. However, many appear to have a fairly broad host range. The parasitic beetle, *Dastarcus helophoroides* Fairmaire (Coleoptera: Bothrideridae) is a generalist parasitoid that attacks pupae of various wood-boring beetles of economic importance in Asia (Rim et al. 2018). Some evidence suggests that subpopulations of *D. helophoroides* may specialise on different Cerambycidae species (Wei et al. 2009; Yang et al. 2014). In fact, one such subpopulation was critical in a biological control programme targeting *Monochamus alternatus* Hope (Coleoptera:

Cerambycidae) (Yang et al. 2014). The behavioural responses of *D. helophoroides* to frass odours from different longhorn beetle species reveal that subpopulations of the parasitoid were most attracted to frass from their original host species (Wei et al. 2009). Wei et al. (2009) discussed the possibility of different biotypes of *D. helophoroides*, but regardless suggested that *D. helophoroides* could be considered a habitat specialist. Men et al. (2017) tested several subpopulations of this parasitoid on *A. bungii* and demonstrated significant differences in their parasitism of this host, with mortality ranging from approximately 11–53% depending on the original host species. Subpopulations originally reared from *Batocera horsfieldi* Hope (Coleoptera: Cerambycidae) and *M. alternatus* were significantly attracted to frass of *A. bungii*, whereas other subpopulations were not. To better understand the potential impact of *D. helophoroides* on *A. bungii*, Wang et al. (2018) tested the control efficiency, and suggested a release ratio of 8–10 parasitoids per *A. bungii* larvae achieved approximately 72% parasitism. However, it is unclear whether a particular subpopulation was selected for this research and whether this would have an impact on the control efficacy. It has since been suggested that host-specificity and efficiency of different subpopulations be tested to determine whether there is potential for classical biological control of various invasive wood-boring beetles in their invaded ranges or whether the host range is too broad to be considered acceptable (Rim et al. 2018). In particular, it is important to note that previous literature suggests that this species can also parasitise wood-boring Hymenoptera and Lepidoptera (Philips and Ivie 2002), suggesting limited potential as a classical biological control agent, and again supporting the suggestion of Wei et al. (2009) that this parasitoid is more likely a habitat specialist than a host specialist.

Another parasitoid, *Sclerodermus guani* Xiao and Wu (Hymenoptera: Bethyridae), is an ectoparasitoid of longhorn beetle larvae and has shown some promise in laboratory and field experiments. Zhang et al. (1991) showed that under laboratory conditions of 25–28 °C, parasitism of *A. bungii* larvae was 80.25%, and when released in the field, parasitism rates of *A. bungii* larvae under bark ranged from 10.53–13.33%, whereas parasitism of larvae feeding in the xylem was 31.15%. The control efficacy of *S. guani* was lower for *A. bungii* larvae that were newly hatched and fully mature, and when the host-parasitoid ratio was 1:3, average parasitism was 68.30% (Zhang et al. 1991). When 10,000 *S. guani*/km² were released in the Jiangsu Rudong Orchard, parasitism reached 52.86% (Jiang et al. 2001). Similarly, releases of *S. guani* to control *A. bungii* in an orchard in Shanghai for two consecutive years achieved average larval parasitism levels of approximately 70% (Guan 2004). In the light of these promising results, Men et al. (2019) investigated the potential of three species of *Sclerodermus* (*S. guani*, *S. sichuanensis*, and *S. pupariae*)

as candidate biological control agents for *A. bungii*, in particular focusing on host location and parasitism levels under laboratory conditions. *Sclerodermus sichuanensis* was only attracted to *A. bungii* frass when it was reared on *A. bungii* and not on other (substitute) hosts, while *S. guani* was also attracted when reared on *Tenebrio molitor* (Coleoptera: Tenebrionidae). Despite these differences in olfactory response in the laboratory, parasitism levels in *A. bungii*-infested peach logs were similar for all three species in no-choice tests under semi-field conditions (43% for *S. guani*, 36% for *S. sichuanensis*, and 34% for *S. pupariae*), with additional mortality inflicted through parasitoid host-feeding behaviour. Based on these results, and because rearing methodology is already well-developed for *S. guani* in China, Men et al. (2019) suggest further research on the biological control potential of *S. guani* in the field to optimise mortality levels in *A. bungii* when used in augmentative biological control in Asia. However, *S. guani* is a generalist that can attack and develop in a range of Coleoptera (Families Cerambycidae, Curculionidae, Tenebrionidae, Buprestidae), Hymenoptera (Families Pamphiliidae and Aphidae), and Lepidoptera (Families Pyralidae, Gelechiidae, and Sesiidae) (Men et al. 2019). As such, this species is unlikely to be considered as a classical biological control agent for *A. bungii* due to a high likelihood of non-target effects on native fauna in invaded regions.

As regulatory approval for the introduction of exotic biological control agents has become increasingly stringent, and Asian parasitoids of *A. bungii* seem to have a broad host range, natural enemies of native, closely related or ecologically equivalent species present in areas invaded by *A. bungii* may provide an alternative option for inundative biological control. Native representatives of the genus *Aromia* are not present in North America. However, *A. moschata* is the

only representative of the genus that is native to Europe. It is widespread and common throughout most of continental Europe and North Africa, where it primarily develops in willow trees. Larvae of the *A. moschata* are attacked by at least eleven ichneumonid species, and one tachinid (Table 2). Similar to the parasitoids known from *A. bungii*, most of the species associated with *A. moschata* are generalists attacking a wide variety of Cerambycidae (Gima 2011). Although not coevolved with *A. bungii*, it is likely that some of these species may also attack it, but further studies are needed to clarify whether it would be a suitable host. Only one other species of *Aromia* is known, *Aromia malayana* Hayashi (Coleoptera: Cerambycidae), which is also from Asia. Very little is known about this species, and it is unlikely to be a promising source for additional natural enemies for classical biological control of *A. bungii*.

Predators

Native predators in the native area of *A. bungii* may provide some ecological services by consuming eggs, larvae, and adults. For example, the woodpeckers *Dendrocopos major* L. and *Yungipicus canicapillus* Blyth may have some control effect on *A. bungii*, and it has been suggested that artificial bird nests can be hung in orchards to attract and retain woodpeckers (Sun et al. 2002). Furthermore, laboratory studies and field surveys in Japan demonstrated the potential of native ant species to inflict mortality on *A. bungii* eggs and hatchlings before they burrow into the bark (Sunamura et al. 2020).

Biopesticides

Daphne genkwa Siebold & Zucc. is a deciduous shrub that is often used in traditional Chinese medicine. Wan et al. (2009)

Table 2 Parasitoids associated with the Eurasian musk beetle, *Aromia moschata*

Family	Subfamily	Species	References
Ichneumonidae	Campopleginae	<i>Rhimphoctona megacephalus</i> (Gravenhorst) [syn. <i>Pyracon austriacus</i>]	Panin and Săvulescu (1961)
		Pimplinae	<i>Dolichomitus messor</i> (Gravenhorst)
	<i>Dolichomitus tuberculatus</i> (Geoffroy)		Panin and Săvulescu (1961); Aliyev and Maharramova (2009)
	<i>Perithous divinator</i> (Rossi),		Panin and Săvulescu (1961); Pisičá (2001)
	<i>Perithous scurra</i> (Panzer)		Ghahari and Gadallah (2017)
	<i>Rhyssella approximator</i> F		Campadelli and Scaramozzino (1994)
	Xoridinae	<i>Deuteroxorides elevator</i> (Panzer),	Fitton et al. (1988)
		<i>Ischnoceros caligatus</i> (Gravenhorst)	Pisičá (2001)
		<i>Ischnoceros rusticus</i> (Geoffroy)	Campadelli and Scaramozzino (1994)
		<i>Xorides indicatoris</i> Latreille	Campadelli and Scaramozzino (1994)
Tachinidae	Dexiinae	<i>Xorides praecatorius</i> (F.)	Panin and Săvulescu (1961); Pisičá (2001)
		<i>Billaea adelpha</i> (Loew)	Campadelli (1986); Cerretti and Tschorsnig (2010)

describe the use of this plant in the control of wood-boring beetles in apricot trees, with 97% mortality when used as follows: stems (3–6 cm) of *D. genkwa* should be placed directly into boreholes and sealed with mud. When temperatures reach 32–39 °C in July and August, toxic substances in the stems of the *D. genkwa* essentially fumigate the tunnels of larvae, killing the pest in the process.

Two species of Agaricales fungi have been investigated for their use on *A. bungii* based on the insecticidal toxins they produce. Evidence suggests that liquid, fermented *Lepiota helveola* Bres. (Agaricales: Agaricaceae) is effective against *A. bungii* eggs and first-instar larvae, causing 84.20% and 68.50% mortality, respectively (Hong and Yang 2010a). More specifically, after ultrasonic crushing and centrifugation, the mycelial suspension of *L. helveola* (concentration 5–20%) caused between 33.90 and 87.50% mortality of larvae when injected directly into the boreholes (Hong and Yang 2010a). The highest mortality level (85.71%) was achieved when a dose of 10 ml was injected and boreholes were sealed (Hong 2011). Similarly, a liquid suspension made from *Amanita phalloides* Vaill. ex Fr. (Agaricales: Agaricaceae) with a concentration of the supernatant > 15% after ultrasonic treatment, resulted in a mortality rate of 68.33% when injected into larval boreholes, again due to the insecticidal activity of the toxins produced by this species (Hong and Yang 2010b).

Outlook for biological control of *Aromia bungii* in invaded areas

Although biological control alone is unlikely to eradicate or drastically reduce populations of *A. bungii* in invaded areas, it may be an important component of an integrated pest management (IPM) strategy to reduce the damage caused by this pest. The introduction of currently known Asian natural enemies (parasitoid and predators) is unlikely to be approved due regulatory concerns regarding their broad host range. However, additional surveys in Asia may reveal the occurrence of more host-specific parasitoids. Conservation of native predators (e.g. ants) and inundative releases of native parasitoids of related host species could contribute to population reduction, alongside other control methods. Based on previous research in Asia, the most promising approach for biological control would be the use of entomopathogenic fungi (e.g. *B. bassiana*) and entomopathogenic nematodes (e.g. *S. carpocapse* and *S. feltiae*), in particular those already registered for other insect pests in invaded countries, as recommended by EPPO (2014). However, screening and testing of existing EPN and entomopathogenic fungi formulations on *A. bungii* prior to establishment in areas at high risk of invasion would be necessary in order to take a proactive approach in developing an IPM strategy that incorporates biological control. Further, research on multi-pronged

approaches combining biological control with other control methods to develop the most effective IPM strategy would be advantageous prior to the establishment and spread of *A. bungii* in other territories worldwide.

Containment, eradication, and control measures in invaded countries

Japan

Information pertaining to current containment, eradication, and control measures against *A. bungii* outbreaks in Japan is patchy and limited in detail, and a holistic explanation cannot be provided. Shoda-Kagaya (2018) provides a general overview of the approaches used to control infestations across Japan, revealing some overlap with methods applied in China. The author posits that felling, and immediately incinerating or chipping, infested trees is currently the most effective method, and is conducted during the adult emergence period to prevent the spread of adults. The stump and roots are also removed to eliminate any larvae remaining below ground. The efficacy of this approach remains unclear as no data are provided.

However, the economic value of *Prunus* fruit trees, and especially the cultural value of cherry blossom trees, frequently renders felling infeasible due to public perception (Kiryama et al. 2015; Shoda-Kagaya 2018). In this instance, the tree wrapping technique, as described for China, is applied to infested trees before adult emergence. This prevents their spread, but requires regular visitation to kill the emerged adults before they mate and oviposit on the tree from which they emerged (Nakano 2018; Shoda-Kagaya 2018). A 3 year study on the efficacy of control methods for *A. bungii* in infested peach orchards in Tochigi Prefecture (Haruyama et al. 2021b), revealed that in orchards where tree wrapping was applied, 30–80% of captured adults were those contained within the net. This provides evidence for the efficacy of this technique. However, both Nakano (2018) and Shoda-Kagaya (2018) argue that this is labour-intensive and time-consuming and therefore unlikely to retain efficacy at the larger spatial scales required to contain the spread of *A. bungii*.

In a 3-year study on the control methods being used against *A. bungii* in peach orchards in Tochigi Prefecture, Haruyama et al. (2021b) found that the average adult beetle density in orchards using chemical spray was 0.70 per tree, whereas that for control (abandoned) orchards was 21.90 per tree. This apparently provides evidence for the high efficacy of insecticide sprays against *A. bungii* in Japanese orchards, though unfortunately, this study did not provide details on the type of insecticides that were applied, or how they were administered. To find a solution against *A. bungii* attacking

flowering ornamental cherry trees, Yamamoto et al. (2022) studied the efficacy of the dinotefuran (neonicotinoid) formulation “Wood-Star”, which was directly injected into the stem of the tree. The method seems promising, as an 88% decrease of actively feeding larvae for at least four weeks was observed in treated trees. Although more studies exist on the efficacy of insecticides against *A. bungii* in Japan, their scope is focused on research towards identifying effective control methods for potential future application, as opposed to the assessment of currently applied control tools.

Interestingly, biological control of *A. bungii*, through egg and hatchling predation by native ants, has also been considered in Japan. Sunamura et al. (2020) demonstrated in the laboratory that three out of the four native ant species tested exhibited predation of *A. bungii* eggs. Furthermore, two of the ant species predated upon *A. bungii* hatchlings, causing fatal damage. The authors also reported that field surveys revealed a correlative lower number of *A. bungii* frass-ejection holes on tree trunks with higher ant density, and suggest that native ants may contribute to the overall control of *A. bungii* in Japan. Other types of natural enemies of *A. bungii* have not been studied in Japan.

Italy

Following the initial outbreak in Southern Italy in 2012 (EPPO 2012b), rigorous actions were undertaken to limit the spread of *A. bungii* and work towards its eradication, while also monitoring its territorial expansion. The geographical extension of *A. bungii*, initially confined to the Campania region and subsequently identified in Lombardy (Northern Italy) (EPPO 2013a), necessitated the introduction of specific legislation for the purposeful management of this pest. In fact, this situation has arisen not solely due to *A. bungii* capacity for dispersal, but also because of the fragmented nature of agricultural lands and the prevalence of many private gardens typical of the infested area, making monitoring a challenging task (Garonna et al. 2013; Russo et al. 2020). In June 2020 and June 2023, *A. bungii* infestations were also detected in the Lazio and Tuscany regions, respectively, where required management is also being applied (EPPO 2020a; Drosera 2023). Details on further detections and spread of *A. bungii* within these regions can be found in EPPO (2012b), EPPO (2017), Azzoni (2019), EPPO (2019), Carella (2019), Carella (2021), EPPO (2021), Azzoni (2022), EPPO (2022), Carella (2022), and Bianchi (2023).

The EU Decision 2018/1503 (EU 2018) outlines a comprehensive framework of measures designed to proactively prevent the continued introduction and proliferation of *A. bungii* within European territories. In cases where the presence of *A. bungii* was confirmed, a demarcation area was established. This area is determined by the sum of

both the infested zone (characterised by the presence of plants either infested by the pest or displaying symptoms attributable to *A. bungii*) and a buffer zone of at least 2 km wide that surrounds the infested area (increased to 4 km after 4 years of positive surveys).

Within the infested zone, obligatory measures include the removal of trees infested by or exhibiting symptoms associated with *A. bungii*, as well as *Prunus* plants within a 100 m radius surrounding the infested host plant. During the insect's flight period, confirmed infested plants must be cut down following technical precautions to prevent further spread. The collected material from the cut trees should be either chipped or thermally treated on-site. If on-site treatment is not possible, it should be carefully packaged and transported for subsequent treatment. In the specified buffer zone, a comprehensive monitoring programme is established to vigilantly oversee all vulnerable plant species, including ornamental *Prunus* species, across a range of environments, such as agricultural fields, private gardens, and public parks.

Monitoring activities primarily rely on trapping methods during the flight period of the adults (e.g. plastic traps baited with sweet and sour liquids, such as those used in China), as well as visual signs of infestation, such as deterioration of the plant or the presence of frass and adult exit holes on the bark. When symptoms are evident, the presence of larvae should be confirmed by removing the bark and finding larvae or tunnels, and using morphological or DNA-based methods to confirm whether the damage is due to *A. bungii* or other wood-boring beetles that produce similar damage to host plants (EPPO 2015; De la Peña et al. 2019; Rizzo et al. 2020; Rizzo et al. 2021; also see section on “[Research and development for future control options](#)”).

Observation of *A. bungii* activity is important in the determination of optimal timing for potential insecticide interventions. At present, Italy only has one registered active ingredient, deltamethrin, for crop use against *A. bungii*. The use of the product is authorised on plants of *Prunus* species and *Olea europaea* L., with localised trunk treatments and a prescribed limit of three applications per year. However, this molecule may not effectively eliminate emerging adults due to their extended emergence period and prolonged lifespan (Russo et al. 2020).

Germany

In Germany, an *A. bungii* infestation was officially confirmed for the first time in Kolbermoor, Rosenheim, Bavaria in 2012 (EPPO 2012a). As Germany must act according to the same EU Implementing Decision (EU 2018) as Italy, the measures took place according to the previously described pattern. Despite further infestations being discovered around Kolbermoor, no *A. bungii* have been found in Rosenheim

city itself since 2016, and the total demarcated area was recently decreased (EPPO 2023). The delimited area created according to the regulations covers just under 100 km² as of 2023 (LfL 2023).

In addition to visual monitoring, an experiment on the efficacy of a pheromone for *A. bungii*, newly developed in China, was tested in Kolbermoor. The scientific underpinning and published literature on the use of this pheromone for monitoring and control is reviewed in detail in “*research and development for future control options*”. However, a trial of its efficacy against an active outbreak in Germany is pertinent to the progress of the ongoing containment and eradication response. The attractant is composed of the male sex-aggregation pheromone (E)-2 cis-6,7-epoxynonal (Xu et al. 2017). It attracts both males and females, but acts more strongly on females.

Across the entire infestation zone, 18 pheromone traps were set up in an even grid. Cross barrier traps (impact traps) were used, each equipped with a pheromone dispenser. To ensure safe trapping and preservation of the beetles within the two-week control cycle, a container with salt solution was included at the bottom of the trap.

The first traps were placed in 2022, though no beetles were caught due to the late delivery of the pheromones. However, in 2023, traps were placed in the same locations in mid-July, and five beetles were recorded in three different locations between July and October. Further trials involving pheromone trapping are required to assess the potential contribution of this method to ongoing monitoring efforts in Germany.

Research and development for future control options

Although there is evidence to indicate efficacy for some of the current control measures employed against *A. bungii* in China and Japan, continued spread and damage throughout its invaded ranges has necessitated recent research towards the development of more effective and target-specific tools. Amongst these, semiochemical-based control options have received significant research interest. Evidence for a male-produced airborne sex pheromone was first presented by Fukaya et al. (2017) using wind tunnel experiments. This pheromone was soon identified as the novel compound (E)-2-cis-6,7-epoxynonal, which can occur as two enantiomers in a racemic mixture. When extracted and used as a lure in traps during field experiments in China and Japan, it attracted both sexes, indicating it as a sex-aggregation pheromone that could be applied to improve surveillance, detection, and control of *A. bungii* (Xu et al. 2017). Both the racemic mixture, and both enantiomers individually, were later synthesised (Mori 2018). Males naturally only produce

one enantiomer, and although it was determined that this and the racemic mixture are equally attractive to both sexes, the unnatural enantiomer did not attract either sex (Yasui et al. 2019). This finding has promising implications for the application of this pheromone, because the racemic mixture is significantly cheaper to synthesise than either enantiomer individually. This lure has been further optimised with the addition of a minor male-produced volatile component, (2E,6Z)-nona-2,6-dienal, which doubled trap catches (Zou et al. 2019). Moreover, the longevity of pheromone emission has been doubled from seven to 14 days, with sustained attraction, by adjusting the solvent volume and surface area of the lure (Yasui et al. 2021). The development and optimisation of a pheromone lure for *A. bungii* provides an option that could soon become available for cost-effective, target-specific, large-scale monitoring and control, which could substantially improve management efforts (Zou et al. 2019). However, Germinara et al. (2019) demonstrated that *A. bungii* adults possess the ability to detect various host volatiles, and their antennae house multiple types of olfactory receptors (Di Palma et al. 2019), implying the potential presence of other semiochemicals involved in chemical communication, both within its species and with other species.

Recent research has additionally proposed another potential semiochemical-based control tool. Rose oxide is a major component of volatiles secreted by *A. bungii* (Wei et al. 2013), and this pungent compound is deployed as a defensive allomone (Chen et al. 2023). Interestingly, rose oxide also has an intraspecific effect, whereby conspecifics of both sexes were significantly repelled by high concentrations in y-tube olfactometer experiments (Chen et al. 2023). Despite the recency of this research, it potentially has significant implications for the future control of *A. bungii*. Rose oxide is already commercially available at low cost, and Chen et al. (2023) suggest that its repellent effect could be applied to improve sex-aggregation pheromone trapping using a push–pull strategy. This approach could employ rose oxide to repel adults away from host trees, while being simultaneously attracted to pheromone traps (Cook et al. 2007; Chen et al. 2023).

A number of sensitive molecular approaches for rapid identification of *A. bungii* frass are also being developed. Current detection of infestations relies upon the visual inspection of ejected frass, which is common amongst wood-boring larvae and not limited to *A. bungii*, leading to misidentification and necessitating the collection of larvae, which further damages the tree (Liu et al. 1999; De la Peña et al. 2019; Fujiwara-Tsujii and Yasui 2023). Rizzo et al. (2020) developed two diagnostic protocols that utilise PCR (Probe and SYBR Green) to amplify the low concentrations of DNA extracted from frass, which is then used for identification of *A. bungii*. All samples from both protocols were discriminable from 100% of reference sequences from

other wood-boring species, with 96.10% and 97.30% diagnostic sensitivity for the SYBR Green and Probe protocols, respectively. A later study developed a loop-mediated isothermal amplification (LAMP) protocol, another DNA-based technology, for the rapid identification of *A. bungii* frass (Rizzo et al. 2021). This protocol demonstrated no response to the amplification reaction from frass samples of closely related species, and comparable diagnostic sensitivity to the aforementioned PCR-based protocols. However, LAMP technology is field-friendly and does not require a laboratory environment or specialist skills, suggesting a higher analytical sensitivity compared to the PCR-based protocols. A similar PCR-based approach, using a CAPS marker, has also been developed (Haruyama and Kurihara 2022). Further development of the rapid-detection of *A. bungii* frass was achieved by Fujiwara-Tsujii and Yasui (2023), who conducted a GC–MS analysis demonstrating that a specific hydrocarbon makeup within frass can be used to discern the species. The benefit of this method is that hydrocarbons are much more stable and resistant to degradation compared to DNA, enabling the identification of frass that may have been exposed to adverse conditions (Fujiwara-Tsujii and Yasui 2023). These developments in sensitive and target-specific protocols for the diagnosis of *A. bungii* frass could expedite the detection of infestations and promote a non-invasive, more targeted response to the spread of this pest (Brockerhoff et al. 2010; Rizzo et al. 2020).

Potential global distribution

The potential global distribution of *A. bungii* was estimated using MaxEnt models. Data for the native distribution of *A. bungii* were retrieved from a comprehensive search in the China National Knowledge Infrastructure (CNKI 2022), Wanfang Data (2022), and Chongqing VIP (CQVIP 2022) databases for relevant articles, reports, and theses. Online news and reports on the geographical distribution of *A. bungii* in China were also researched. For the global distribution, information was retrieved from the EPPO global database and EPPO reporting Service (EPPO 2012a, 2012b, 2013a, 2013b, 2017, 2019, 2020, 2021, 2022), the CABI compendium, regional decrees available online (Regione Lombardia 2019; Servizio fitosanitario Lombardia 2019; Giunta Regionale della Campania 2022), online entomological bulletins (Burmeister et al 2012), journal articles in the English literature (Byun et al. 2009; Iwata 2018; Lee et al. 2021; Tamura and Shoda-Kagaya 2022) and GBIF. The final dataset of the current distribution of *A. bungii*, which was used to model its potential global distribution, encompassed 896 occurrence points (Fig. 2).

Several MaxEnt models of the potential distribution of *A. bungii* were created using different combinations

of variables and parameters (modelling methodology is described in the Supplementary Materials). The model that was considered best (M1) according to evaluation statistics and expert opinion is presented hereafter. A similarly good performing model (M2) calibrated with the same modelling parameters but different explanatory variables is presented in the Supplementary Materials.

Model M1 was created with MaxEnt (Phillips et al. 2006) using the R package ENMeval (Kass et al. 2021) and 70% of the available occurrence points (the remaining 30% were used for evaluation), hinge-linear-quadratic features, a beta multiplier of 0.2, background absences randomly chosen across the globe, and the following bioclimatic variables: Bio2—mean diurnal range of temperature, Bio3—isothermality, Bio7—temperature annual range, Bio11—mean temperature of coldest quarter, Bio15—precipitation seasonality, Bio17—precipitation of driest quarter, Bio18—precipitation of warmest quarter, and Bio19—precipitation of coldest quarter.

Performance statistics reveal that model M1 exhibits high correlation between predicted and original values (train.cor = 0.892), an excellent overall accuracy (train.AUC = 0.994), and a very good balance between sensitivity (proportion of correctly modelled presences) and specificity (proportion of correctly modelled absences) (train.TSS = 0.956). This remains true when evaluating the model on the test dataset (30% of the data set apart for evaluation): test.cor = 0.886, test.AUC = 0.991 and test.TSS = 0.950, which attests to the robustness of the model.

The variables that contribute the most in explaining *A. bungii*'s distribution in model M1 are Bio18 (50.5% contribution), Bio11 (28.5%), and Bio15 (11.2%). Bio18 and Bio11 relate to limiting factors of the availability of water during hot periods and the average temperature during cold periods. Bio15 is a measure of precipitation variability during the year.

Spatial patterns of the predicted probabilities of occurrence of *A. bungii* obtained with this model show the highest probabilities of occurrence for the species in China and Korea (native range), Japan (invaded range), Northern Myanmar, Butan, Nepal, and Northern India. Lower probabilities are shown for Europe, North and South America, and to an even lesser extent for South Africa and Australia (Fig. 3).

To ascertain the potential distribution of the pest, the predicted probabilities of occurrence can be translated into presence/absence using a threshold. We used the threshold for which all original occurrences are predicted as presences (no-omission) (Fig. 4A) and the threshold that maximises the true skill statistic TSS (maximises the true positive but also the true negative rate) (Fig. 4B). Threshold choice can lead to different predictions of potential distribution. The prediction obtained with the no-omission threshold can be

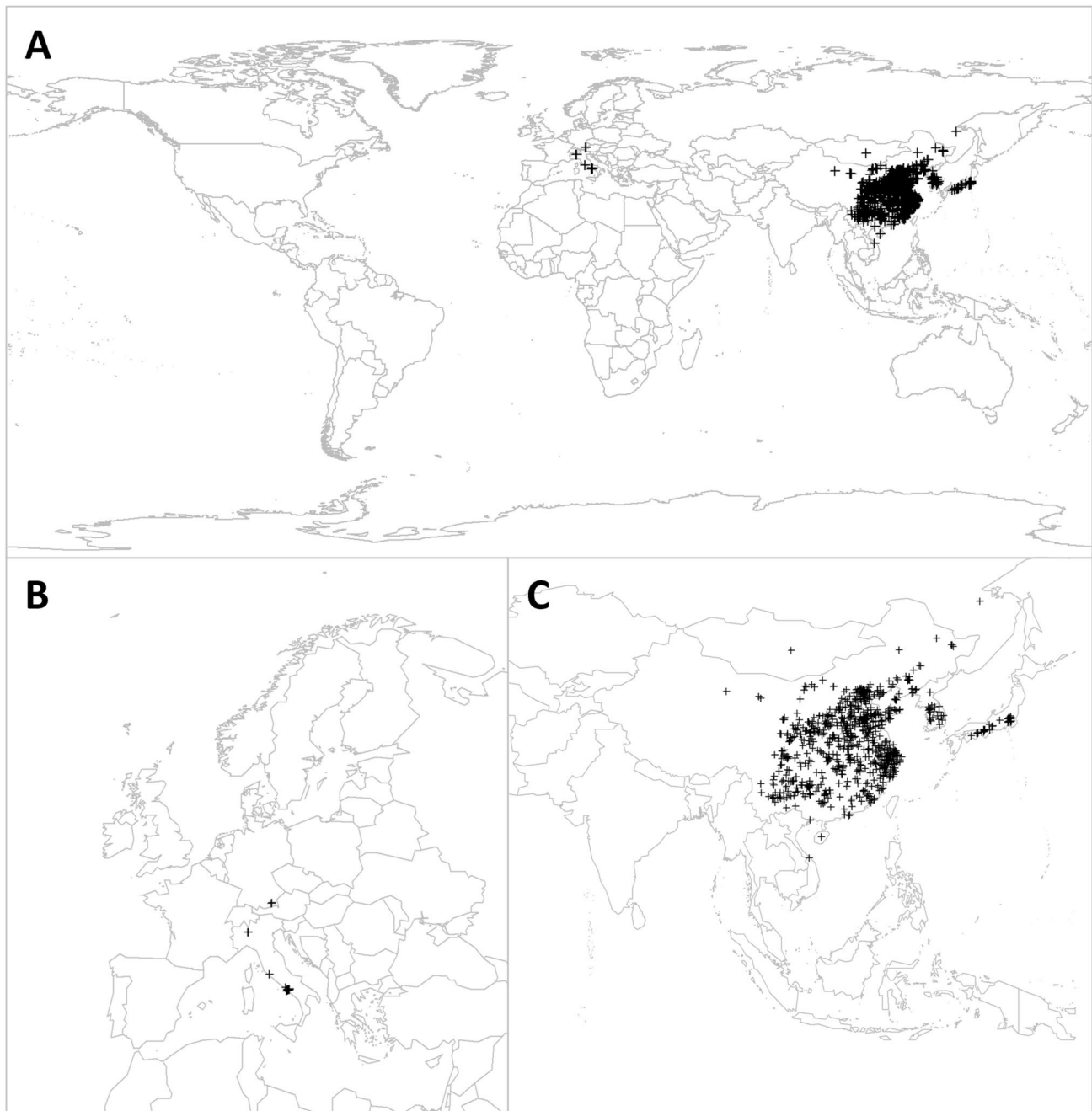


Fig. 2 Occurrence points (black crosses) of *Aromia bungii* retrieved from different sources (see text) and used for the modelling of its potential distribution across the globe. **A** known global distribution; **B** current distribution in Europe; **C** current distribution in its native range

large since it encompasses all climatic conditions for which even a single occurrence of *A. bungii* was detected. The prediction obtained by instead maximising TSS is more restricted since it tries to balance the omission (presences predicted as absences) and commission errors (absences predicted as presences). For high-risk pests, the prediction obtained with the no-omission threshold may be prioritised for a 'safe' decision. This model predicts favourable conditions for *A. bungii* that extend over a much larger area than

its current invasive range. This suggests that the pest may continue to spread through northern Japan, and that several European countries are at risk of further spread of *A. bungii*, particularly those of southern and eastern Europe, southern Germany, and Austria. Significant portions of the USA and southern Canada are also predicted to be climatically favourable for *A. bungii*, highlighting the risk posed to North America.

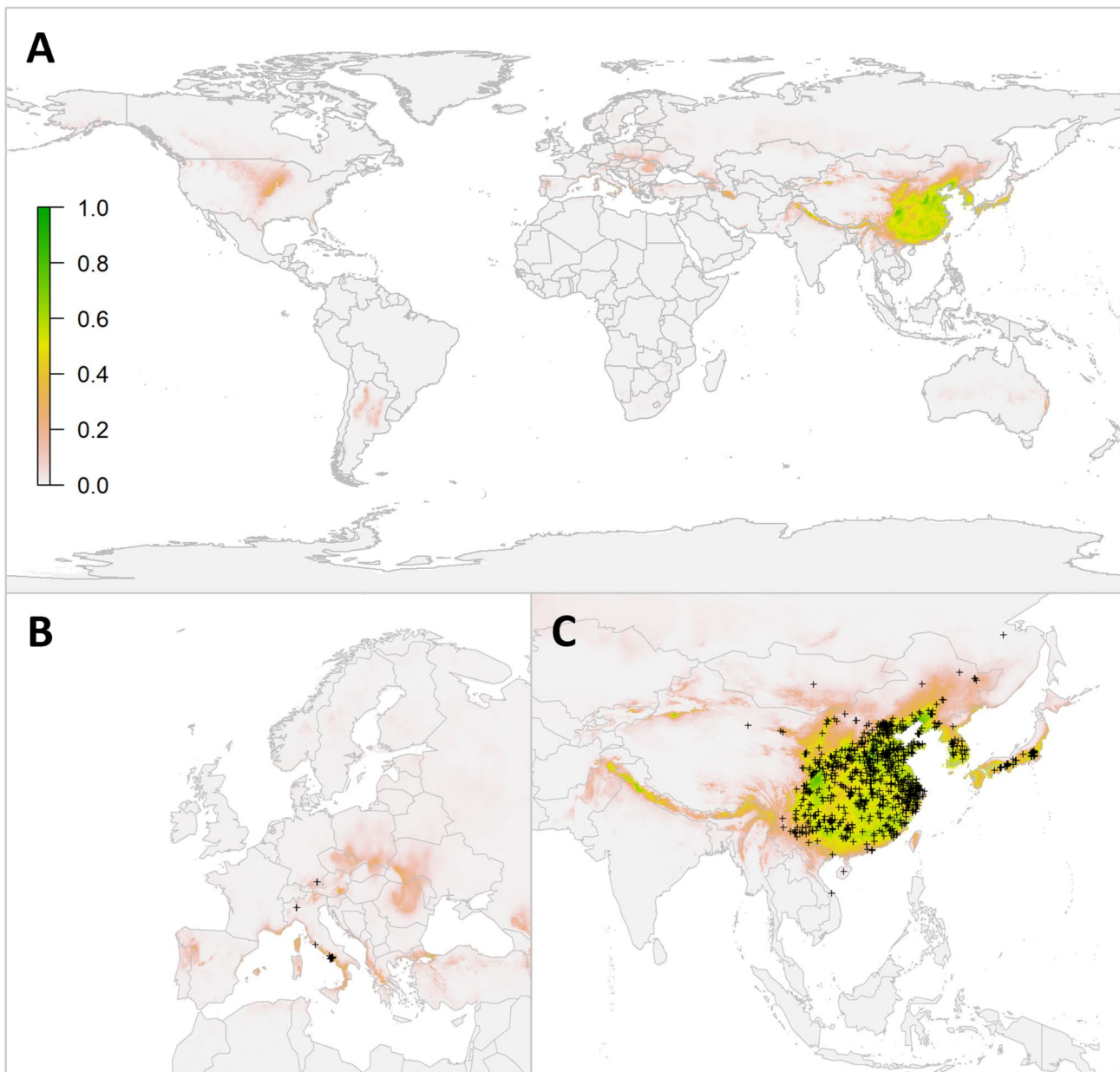


Fig. 3 Spatial patterns of the predicted probabilities of occurrence of *Aromia bungii* according to model M1. **A** global occurrence probabilities; **B** occurrence probabilities in Europe; **C** occurrence prob-

abilities in its native range. Black crosses represent the original data (occurrences) used for the modelling

This type of output map is very sensitive to the threshold employed to transform probabilities into presence/absence, but also, more generally, to the data, variables and parametrisation used to create the model. For comparison, Fig. 5A illustrates the predicted presence of *A. bungii* using the same model calibrated with a beta multiplier of 1 (MaxEnt parameter), which generally provides a model that follows less closely the distribution data than a beta multiplier of 0.2. Figure 5B illustrates the predicted presence of the same model obtained with the totality of the data

(896 occurrences) instead of only the calibration subset (627 occurrences). These models predict a much wider distribution throughout both Europe and North America. Considering the northern distributional limit of *A. bungii* in its native range (Fig. 2), climatic suitability predictions for subarctic areas (Kottek et al. 2006), such as Alaska and northern Scandinavia, should be viewed with caution. However, the flexible lifecycle of *A. bungii* promotes adaptability to a wide range of climatic conditions (Li 1995; Ma et al. 2007; Crowley and Hopper 2015), and the lack of physiological data on

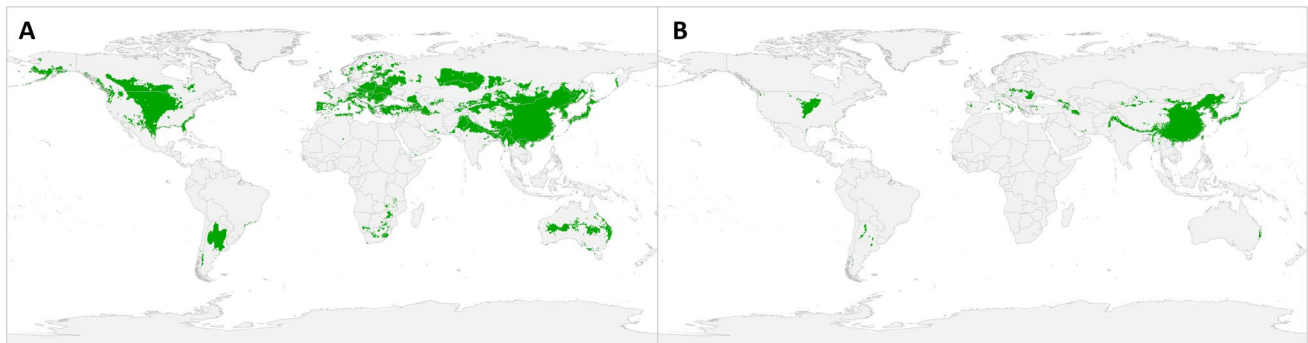


Fig. 4 Potential distribution of *Aromia bungii* according to model M1, obtained by applying two different thresholds to the predicted probabilities of occurrence: **A** no-omission threshold; **B** threshold that maximises TSS. The predicted presence is shown in green

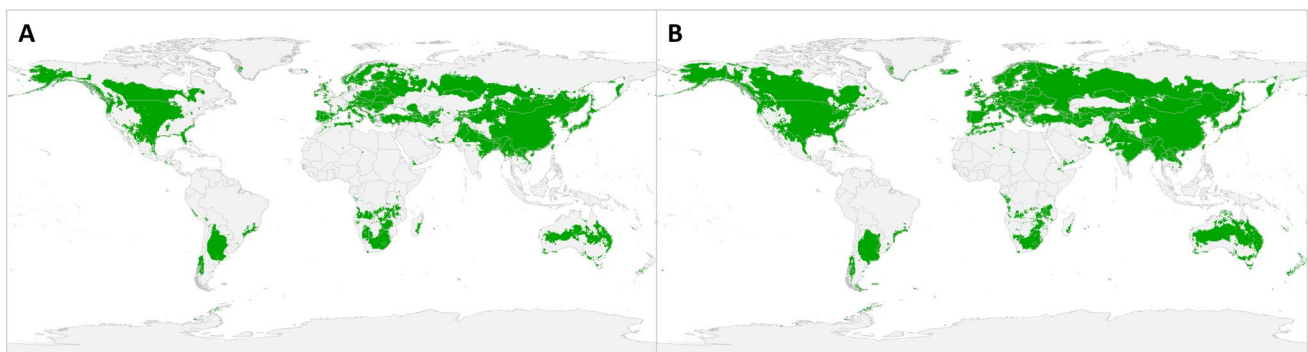


Fig. 5 Potential distribution of *Aromia bungii* obtained by applying a no-omission threshold to the probabilistic map of model M1 calibrated with a beta multiplier of **A** 1, or with **B** the totality of the data. The predicted presence is shown in green

temperature thresholds for development and mortality makes inferences surrounding distributional limits challenging and hampers the use of more sophisticated (semi)-mechanistic models based on physiological rather than occurrence data. While it is acknowledged that species distribution modelling approaches such as MaxEnt can sometimes perform poorly in non-equilibrium situations involving extrapolation to novel environmental conditions not used for training the model (e.g. dispersal during a biological invasion), such models should be considered for risk assessment until additional data become available that enables further refinement of estimates of potential distribution. However, the presented models solely consider the climatic potential for the species, but other factors currently not considered can also strongly influence distribution, such as the critical limiting factor of host plant presence, which is particularly important for wood-boring pests that develop in a habitat that is partially protected from external climate (Dang et al. 2021).

Conclusion

Our review provides an overview of the current knowledge on the biology, impact, potential distribution, and management of *A. bungii* and discusses implications within the context of *A. bungii* as an emerging pest. A substantial portion of available information appears to be observational field assessments, with a paucity of experimental studies available. However, invigorated scientific interest in *A. bungii* in response to its emergence as an invasive pest is helping to fill such knowledge gaps, improving our understanding of its invasiveness and potential management options. Recent advancements have been made in the development of target-specific and efficient tools for detection, monitoring, and control, with particular promise shown for semiochemical-based traps. However, classical biological control against *A. bungii* may not be viable due to biosafety risks, but targeted natural enemy surveys would provide greater clarity on the potential for this approach. This review ultimately provides a source of reference for *A. bungii* that can be used by scientists, regulatory agencies, and industry to direct future research and implementation of management options.

Author contributions

KH, TH, TG, LS, JC, JZ, JC, RM, XX, FN, and AG wrote the manuscript. JZ and JC reviewed and translated the Chinese literature. RM, XX and KH collected distribution data. RM developed the MaxEnt models. All authors read and approved the manuscript.

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Data availability All data generated or analysed during this study are included in this published article.

Declarations

Conflict of interest All authors declare that there is no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals (vertebrates) performed by any of the authors.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent to publish Consent was obtained from all individual participants included in the study.

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