Current Forestry Reports
https://doi.org/10.1007/s40725-024-00230-8

FOREST ENTOMOLOGY (B CASTAGNEYROL, SECTION EDITOR)

The Ecology, Economics, and Management of *Agrilus* Beetles

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Accepted: 12 August 2024
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Abstract

Purpose of Review The invasion of North America by the Asian beetle *Agrilus planipennis* has caused severe economic and ecological damage to ash (*Fraxinus*) tree populations. *Agrilus planipennis* has recently entered eastern Europe and is spreading there. Many other *Agrilus* species can potentially become invasive pests due to the cryptic nature of their immature stages that can be inconspicuously transported within infested plant material. We review the ecology, economic impacts, and management strategies of *Agrilus* worldwide and highlight research gaps.

Recent Findings Much has been learned in recent decades about the basic biology and control tactics for a few *Agrilus* species, especially *A. planipennis*.

Summary The genus *Agrilus* has over 3,341 described species, making it the largest genus in the Animal Kingdom. Most *Agrilus* are univoltine and have a narrow host range. Chemical, tactile, and visual cues of host plants are used by adult *Agrilus* to select suitable hosts for consumption by adults and larvae. Most *Agrilus* larvae develop within the cambial region, constructing galleries that effectively girdle the host plant. Mechanisms of host plant resistance are being explored. Diverse groups of natural enemies attack all life stages of *Agrilus* species, with some coevolved specialist parasitoids being introduced successfully to suppress *A. planipennis* in North America. Climate change, leading to warmer and drier conditions, will influence the distribution and population dynamics of many *Agrilus* species. Many research gaps still exist in the areas of biocontrol, host plant resistance, and sustainable management strategies for this important group of plant pests.

Keywords Buprestidae · Invasive species · Woodborers · Natural enemies · Biological control · Integrated pest management

Introduction

Worldwide, the genus *Agrilus* (Coleoptera: Buprestidae) has over 3,341 described species, making it the largest genus in the Animal Kingdom [1]. Among these species, ~ 39% (1,292 species) occur in the Americas, 36% (1,189) in Asia, 23% in Africa (753), 4% in Oceania (135), and 2% in Europe (79) [1]. *Agrilus* are found in boreal, temperate, subtropical, and tropical zones [1, 2]. New *Agrilus* species are being described annually, indicating their real diversity is even greater than currently realized [1, 3].

Almost all *Agrilus* develop in eudicot angiosperms [3, 4], with the one known exception being a species (*A. schwerdtfegeri*) reared from *Pinus* in Guatemala [5]. Most *Agrilus* larvae develop in a single plant genus or a few genera of the same plant family [3]. Although several *Agrilus* are pests that damage agricultural crops and forest trees, some are beneficial, such as *A. hyperici* (Fig. 1J), a biocontrol agent against the weed St. John's wort (*Hypericum perforatum*) [6].

The Asian species *A. planipennis* (emerald ash borer, EAB, Figs. 1A, 2A, E) has caused the most damage of any *Agrilus*, especially in North America, where it was first discovered in 2002 [7]. Since its discovery, EAB has spread to 36 USA states and five Canadian provinces, killing millions of North American ash (*Fraxinus*) trees in both managed and unmanaged forests [8]. EAB was likely introduced inadvertently from China to North America via infested wood

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Published online: 24 September 2024

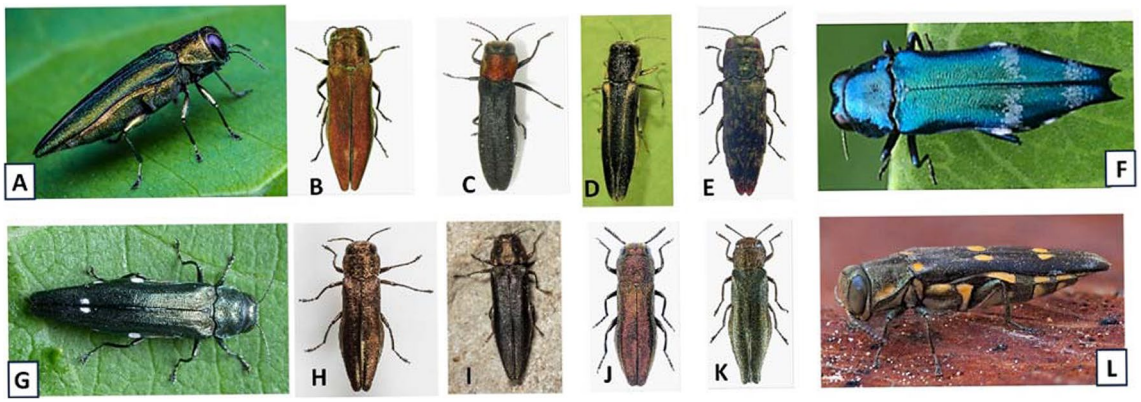

Fig. 1 Adults of several of the *Agrilus* species discussed in this paper. **A** *Agrilus planipennis* (Photo William Ravlin). **B** *A. sinuatus* (Gilles San Martin). **C** *A. ruficollis* (Chris Rorabaugh). **D** *A. bilineatus* (Robert Haack). **E** *A. occipitalis* (Eduard Jendek). **F** *A. acutus* (Subash Jeyan). **G** *A. biguttatus* (Trevor and Dilys Pendleton). **H** *A. mali* (A. V. Kovalev). **I** *A. anxius* (Tom Murray). **J** *A. hyperici* (U. R. Schmidt). **K** *A. viridis* (U. R. Schmidt). **L** *A. auroguttatus* (Mike Lewis)

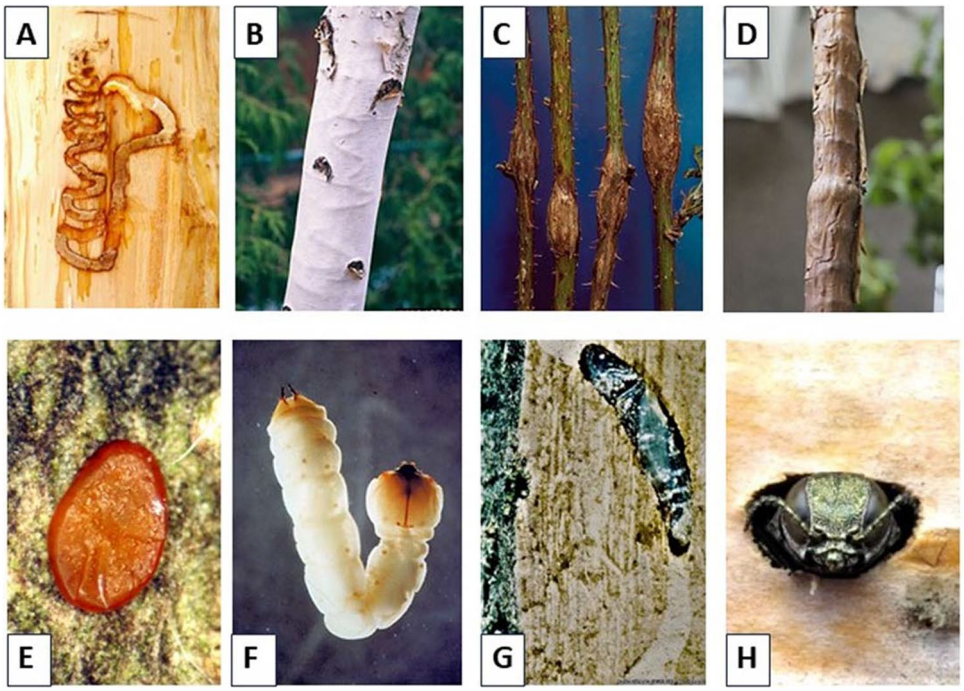

Fig. 2 **A** Typical meandering larval gallery of *A. planipennis* on sapwood surface of *Fraxinus* tree (JJD). **B** Trunk of *Betula* tree indicating callus formation of the sapwood surface along the larval galleries of *A. anxius* (Steven Katovich). **C** Gall formation on stems of *Rubus* plants at the site of infestation by *A. ruficollis* larvae (James Solomon). **D** Spiral larval gallery pattern of *A. cuprescens* along stem of a *Rubus* plant (Justin O'Dea). **E** Egg of *A. planipennis* on bark of a *Fraxinus* tree. Eggs turn golden-brown with age (Houping Liu). **F** Typical shape of an *Agrilus* larva when removed from its fully completed pupal cell (Robert Haack). **G** Pupa of *A. bilineatus* that has nearly transformed to an adult within its pupal cell that was constructed in the thick outer bark (Robert Haack). **H** Typical D-shaped exit hole constructed by *Agrilus* adults as they emerge from their host plant (Deborah Miller)

packaging materials in the 1990s [9, 10]. Due to the severe damage caused by EAB, it has become the most studied *Agrilus* species in the world [11].

Many other *Agrilus* have caused notable economic and ecological damage, such as the bronze birch borer (*A. anxius*, Figs. 1I, 2B, H) on *Betula*, goldspotted oak borer (*A. auroguttatus*, Fig. 1L) on *Quercus*, oak splendor beetle (*A. biguttatus*, Fig. 1G) on many tree species, twolined chestnut borer (*A. bilineatus*, Figs. 1D, 2F, G) on *Quercus*, rose stem girdler (*A. cuprescens*, Fig. 2D) on *Rosa* and *Rubus*, and apple jewel beetle (*A. mali,* Fig. 1H) on *Malus* (Table 1). The rising pest status of several *Agrilus* species worldwide has

Table 1 Global summary of prominent *Agrilus* pest species, including scientific and common names, acronyms as used in this paper, major native plant hosts, native and known invaded ranges of each *Agrilus* species, respective pest status and host plant genera most impacted, and references associated with the table information

Scientific name (common name, acronym used herein)	Major host plant genera	Native range of *Agrilus* species; pest status	Expanded range of *Agrilus* species; introduced pest status	References
Agrilus acutus (Spiral stem borer)	*Carica, Hibiscus*	Bangladesh, South India, Indonesia, Papua New Guinea, Sri Lanka; primarily pest of cultivated *Hibiscus* crops, but also *Abelmoschus*, *Corchorus*, *Malachra* and *Urena*	Andhra Pradesh (India); pest of cultivated *Hibiscus* crops	[1, 11–15]
Agrilus anxius (Bronze birch borer)	*Betula*	Eastern North America (USA and Canada); intermittently impactful outbreaks in forests on *Betula,* pest of introduced Eurasian *Betula*	Western USA; pest of introduced Eurasian *Betula*	[2, 16, 17]
Agrilus auriventris (Citrus flatheaded borer)	*Citrus*	China, Southeast Asia, Japan; pest of cultivated *Citrus* crops	Polynesia[a]; pest of *Citrus* crops	[1, 18, 19]
Agrilus auroguttatus (Goldspotted oak borer)	*Quercus*	Arizona (USA), Northern Mexico; not known as a pest	California (USA), serious pest of multiple native *Quercus* tree species	[20–22]
Agrilus biguttatus (Oak splendor beetle)	*Fagus*, *Castanea*, *Quercus, Tilia, Populus, Ulmus*	Europe; intermittently impactful outbreaks in forests on *Quercus*	No range expansion reported	[23–25]
Agrilus bilineatus (Twolined chestnut borer)	*Castanea, Quercus*	Eastern North America (USA and Canada); intermittently impactful outbreaks in forests on *Quercus,* historical pest of *Castanea*	Established in Turkey, pest status is not known	[26–28]
Agrilus cuprescens (Rose stem girdler)	*Rubus, Rosa*	Eurasia; intermittently serious pest of cultivated *Rubus* and *Rosa* crops	North America (USA and Canada), intermittently serious pest of cultivated *Rubus* and *Rosa* crops	[1, 29–31]
Agrilus fleischeri (Spotted poplar borer)	*Populus, Salix*	East Asia; intermittent pest of native *Populus* trees, localized outbreaks on introduced *Populus* in China	No range expansion reported	[32–34]
Agrilus mali (Apple jewel beetle)	*Cydonia, Malus, Pyrus, Prunus, Emmenopterys*	Eastern Asia; intermittent pest of *Malus* and *Pyrus* in orchards	Northwest China, serious pest of native wild *Malus sieversii* trees	[2, 33, 35, 36]
Agrilus occipitalis (Citrus bark borer)	*Citrus*	Southeast Asia, Indonesia; pest of cultivated *Citrus* crops	Micronesia[a], pest of cultivated *Citrus* crops	[1, 65]
Agrilus planipennis (Emerald ash borer, EAB)	*Fraxinus, Chionanthus*	Northeast Asia; intermittent pest of native *Fraxinus* trees, pest of introduced *Fraxinus*	North America (USA and Canada), significant pest of all *Fraxinus* trees	[37–40]
Agrilus prionurus (Soapberry borer)	*Chionanthus, Sapindus*	Northern Mexico; pest status unknown	Texas (USA), serious pest of western soapberry trees (*Sapindus saponaria var. drummondii*)	[2, 41]
Agrilus pseudocoryli (Hazel stem borer)	*Corylus*	North America (USA and Canada); emerging pest of cultivated hybrid *Corylus americana x Corylus avellana*	No range expansion reported	[42]

Table 1 (continued)

Scientific name (common name, acronym used herein)	Major host plant genera	Native range of *Agrilus* species; pest status	Expanded range of *Agrilus* species; introduced pest status	References
Agrilus ribesi (Currant borer)	*Ribes*	Europe; West-central Asia; pest of cultivated *Ribes* crops	North America (USA and Canada); pest of cultivated *Ribes* crops, damage attributed to *A. cuprescens* until 2015	[43]
Agrilus ruficollis (Red-necked cane borer)	*Rubus*	Eastern North America; intermittently serious pest of cultivated *Rubus* crops	Introduced to New Zealand as biocontrol for feral *Rubus*, but did not establish	[44–47]
Agrilus sexsignatus (Varicose borer)	*Eucalyptus*	Indonesia, Philippines, Melanesia; pest of cultivated *Eucalyptus* crops	No range expansion reported	[48, 49]
Agrilus sinuatus (Sinuate pear borer)	*Crataegus, Pyrus, Malus, Mespilus, Prunus, Sorbus*	Southern and Central Europe; primarily intermittent pest of *Pyrus*	Northern Europe, UK, North America, Japan; regional intermittent pest of *Pyrus*	[50, 51]
Agrilus viridis (Beech splendour beetle)	15 genera, see Jendek and Polakova 2014	Eurasia; intermittent pest of cultivated *Corylus*	No range expansion reported	[3, 52]
Agrilus zanthoxylumi	*Zanthoxylum*	Southern-Central China; pest of cultivated *Zanthoxylum* crops	Shandong province (China) pest of cultivated *Zanthoxylum* crops	[53]

[a]Suspected introduction via infested *Citrus* nursery crop plant material

raised concerns about their potential damage to both forests and agricultural crops worldwide, particularly if introduced outside their native ranges.

Previous reviews on *Agrilus* beetles have examined their morphology and general biology [54], larval host plants [3], and native geographic distribution [1]. Specific reviews of individual pest species addressed *A. anxius* [16], *A. cuprescens* [29], and EAB [55, 56]. The aim of the current review is to examine both historical and recent literature on the ecology, economic significance, and management strategies for all *Agrilus* and highlight research needs to help develop sustainable management strategies. In many cases, we will focus on recent EAB research, given that it has been the focus of many studies in Asia, Europe, and North America [11, 56].

Ecology

Agrilus Biology and Life History

Voltinism In temperate latitudes, most *Agrilus* are univoltine [57–59]. At times, two years is required to complete one generation, especially in cooler climates, when developing in vigorous hosts, or when developing from eggs laid in late summer [20, 23, 60, 61]. However, some *Agrilus* in temperate areas are typically semivoltine, such as *A. guerini, A. horni*, *A. pensus*, and *A. torquatus* [57–59, 62]. Multivoltinism may occur in some subtropical and tropical species (e.g., *A. acutus* Fig. 1F, *A. occipitalis* Fig. 1E, and A. *viridissimus*), given that generation times of only 2–4 months have been reported [63–65].

Adult Emergence, Seasonality, Diurnal Activity, and Food As *Agrilus* adults emerge from their host, they chew a characteristic D-shaped exit hole [58, 66] Fig. 2H]. Adults can fly several kilometers [67], but likely disperse short distances when suitable host plants are nearby [10]. In temperate latitudes, *Agrilus* adults are active throughout the summer months, starting in late spring, peaking in early to mid-summer, and ending in late summer. For species with a broad geographic range, emergence can begin 1–2 months earlier in warmer regions compared to cooler regions [58, 59]. The sex ratio of most *Agrilus* is 1:1 [18, 32, 68–70]; however, more female-biased sex ratios have been reported [48, 71].

Agrilus adults are most active from late morning through the afternoon and prefer sun-exposed hosts [31, 72]. Adults typically feed for 1–2 weeks before mating and laying eggs [20, 31, 32, 44, 57, 66, 73–75], although some may require 3–4 weeks to become sexually mature [58]. Adults usually consume foliage of the larval host plant but can feed on other plants [73, 76]. *Agrilus* adults usually live 2–5 weeks [31,

32, 44, 60, 66, 68, 69, 73, 74, 77, 78], but some can survive as long as 10–11 weeks [20, 79].

Mating, Oviposition, Fecundity, Eggs Adults typically mate on the trunk, branches, or foliage of the larval host plant. Mating is common during late morning and afternoon, with oviposition peaking in early afternoon [57, 80]. On woody hosts, females can lay eggs on smooth bark but often deposit eggs within bark cracks or under bark flakes [20, 28, 32, 57, 58, 77, 81, 82]. Some *Agrilus* lay eggs singly [Fig. 2E], especially on small diameter hosts [29, 31, 58, 63, 82, 83], or in small clusters [58, 62, 80]. Clusters with up to 28 eggs have been documented in *A. macer* [84] and 30 eggs in *A. biguttatus* [23]. Females often deposit a semi-transparent substance over the eggs, which cements the eggs to the bark and slows desiccation [74, 77, 84].

Eggs usually hatch in 1–2 weeks, but 3–4 weeks has been reported [31, 32, 44, 58]. Total fecundity is difficult to determine in nature. However, under favorable laboratory conditions mean lifetime fecundity was 23–110 eggs per female for various *Agrilus* [85–89], with as many as 614 eggs laid by a single *A. fleischeri* [32].

Larval Development *Agrilus* larvae enter the host through the side of the egg in contact with the host tissue. In woody plants, larvae tunnel through the outer bark to the cambial region and construct galleries that score both the inner bark (phloem) and outer sapwood (xylem) (Fig. 2A). *Agrilus* larvae use their terminal processes (urogomphi) to pack their frass behind them as they feed [54, 57 Fig. 2A, F]. Most larvae construct individual galleries [58], however, *A. macer* larvae feed gregariously [84]. *Agrilus* larvae have four [54, 68, 82, 90, 91] or five instars [23, 57, 63, 74, 92–94].

In woody plants, *Agrilus* larvae often depart the cambial region and enter the sapwood to molt or in response to high host resistance such as rapid callus formation [57, 7895 Fig. 2B-D]. With *Agrilus* of shrub hosts such as *A. cuprescens*, the larva will leave the cambium and tunnel into stem's pith by autumn [31]. In some root (*A. horni* and *A. vittaticollis*) and branch-infesting (*A. mali*) species, larvae initially tunnel in the cambial region and then in the xylem [57, 77, 79, 94].

The linear length of *Agrilus* larval galleries is often under 1 m, but some galleries have measured 1.5–2 m in length [23, 48, 77, 79]. Host conditions can influence the shape of a larval gallery, being longer and more sinuate in high-vigor hosts versus shorter and straighter in low-vigor hosts [57, 60, 74, 95].

Overwintering Most temperate *Agrilus* species overwinter as last-instar larvae in pupal cells constructed in the sapwood, outer bark, pith, or roots [20, 31588283 Fig. 2G]. If larvae of some species fail to reach their final instars (mostly J-shaped larvae, Fig. 2F) before winter, they typically overwinter in the cambial region and resume feeding the following spring, and then pass a second winter before pupating and transforming to adults. However, in China, *A. mali* overwinters as early larval instars and then completes development and emerges as adults the following summer [94]. Some *Agrilus,* such as *A. subcinctus*, which develops in recently dead ash twigs, overwinter as pupae [82].

As larvae construct their pupal cells, they often extend their gallery to near the outer bark surface, and then use this same path later when they emerge as adults [77, 7928 Fig. 2G]. If bark is sufficiently thick, pupal cells are usually constructed in the outer bark, or in the sapwood if the bark is too thin [20, 23, 71]. On small diameter branches and stems, pupal cells are usually in the xylem or pith [29, 82].

Pupation Pupation usually occurs in late spring and early summer in temperate areas. Pupation typically takes 1–4 weeks [23, 28, 31, 32, 44, 58, 66, 77]. Newly formed adults remain in the pupal cell for a few days to a week before they chew out of the host [68].

Insect-Plant Interactions

Host Plant Selection by Adults Upon emergence, *Agrilus* adults must feed, find mates, and select host plants suitable for oviposition. These tasks are facilitated by chemical, physical or tactile, and visual stimuli associated with host plants and conspecifics [96–103]. Understanding how these environmental stimuli influence *Agrilus* behavior can lead to novel management strategies.

At longer distances, when adults are in flight, host plant selection is likely driven by plant-produced volatile compounds that are often particular to a plant species or host condition [104, 105]. For *Agrilus* considered to be secondary pests, volatiles associated with stressed plants, such as alcohols and green-leaf volatiles from foliage or sesquiterpenes from bark, often elicit strong antennal responses [106, 107] and are attractive to *Agrilus* adults [68, 102, 108–110]. Evidence from EAB suggests that newly emerged females only respond to foliage volatiles until they complete maturation-feeding, after which they shift to volatiles associated with oviposition locations [102, 111]. This behavioral sequence may reflect a general pattern within the *Agrilus*, where their response to host cues is regulated by internal physiological changes [111].

At short distances, when the adults are near or have landed on a potential host plant, visual cues associated with the color and shape of the host plant influence adult behavior. For example, studies using traps of various colors found that more adults of EAB, *A. egeniformis*, *A. egenus* and *A. subcinctus* were captured on green or yellow traps

compared with purple or white traps [112–114]. Green or yellow color has the spectrum of reflective light (540–560 nm) corresponding to the reflectance of host foliage as well as the spectral sensitivity of many *Agrilus* [112, 113]. The strong response to green is found in many *Agrilus* adults that feed on foliage or use foliage as a cue to locate oviposition locations [115]. For *Agrilus* adults that feed on flowers or pollen, traps colored with floral colors such as blue, yellow, and white often are attractive [116–118]. Altogether, these findings should be considered carefully because relatively few of the world's 3,341 *Agrilus* species have been evaluated, and some studies have indicated differences in response by males and females of the same species [112–114].

The shape of a plant, as well as the light spectra reflected from different plant tissues, may also play a role in host location. For example, EAB adults can distinguish between a live and an artificial host plant when in view, but not when hidden from view and required to use only host-associated volatiles [119]. Further, EAB can differentiate between leaves of different sizes, preferring larger leaves for consumption [119].

After landing on a potential host, adult *Agrilus* must assess host plant suitability for their own consumption as well as for oviposition or larval development. It is presumed that volatiles from the entire host plant, or the portion they consume, are correlated with a plant's suitability as a food source. In laboratory studies, EAB adults showed differences in consumption of foliage between coevolved and non-coevolved hosts [120], as well as between different species of non-coevolved hosts [121]. These findings may be related to variation in nutrients and defensive compounds in plant tissues [102, 122, 123], and thereby can influence consumption and adult fitness [123]. Within a host plant, these same factors, as well as moisture content can influence *Agrilus* larval feeding [123, 124].

Female *Agrilus* likely use multiple cues to find suitable oviposition sites. Specific cues that stimulate or discourage *Agrilus* oviposition are poorly known. Studies with other wood- and stem-boring insects indicate that short-range, chemical cues can reflect host tissue condition, presence and quantity of conspecifics and competitors, and frass from current or previous occupants [125]. In addition, vibrational cues may correspond to differences in density or structure of plant tissues, as well as chewing by both feeding conspecifics or competitors [126, 127]. Lastly, tactile cues such as the amount of resistance detected by female's ovipositor could predict the degree of protection their offspring would have from natural enemies, or whether a neonate larva is likely to bore into its preferred plant tissue [128]. A deeper understanding of these cues may allow for improved methods to monitor and manage *Agrilus* pests [103].

Larva-Plant Interactions *Agrilus* larvae have an intimate relationship with their host plants given that larvae develop over 1–2 years in the meristematic cambial region of their host (Fig. 2A-D). Therefore, the physiological condition of the host often has a strong influence on survival and fitness of *Agrilus* larvae (see Host Plant Resistance).

Agrilus utilize many plants as larval hosts, including herbaceous perennials, vines, shrubs, and trees. In a review of all known larval hosts for the world's *Agrilus* [3], host records were only found for 686 *Agrilus* species (22%), with the most complete records being for the Nearctic and Palaearctic *Agrilus*. The top 10 genera of host plants worldwide are *Acacia* (used by 133 *Agrilus* species), *Quercus* (98), *Celtis* (46), *Salix* (35) *Prosopis* (24), *Populus* (22), *Albizia* (21), *Ulmus* (21), *Carpinus* (17), and *Juglans* (17). About 50% of *Agrilus* use a single plant species as a larval host, 64% use a single plant genus, and 75% use a single plant family. However, some *Agrilus* have a large host range, including *A. viridis* (Fig. 1K) reared from 49 plant species, *A. roscidus* from 23 plant genera, and *A. roscidus* from 10 plant families [3].

Multiple *Agrilus* species can infest the same host plant concurrently in some woody plants [24, 129, 130]. In these situations, smaller species tend to colonize the crown branches, while larger species favor the trunk. For *Agrilus* species that infest both the branches and trunk of a tree, infestation usually begins in the branches and upper trunk and then proceeds downward along the trunk in subsequent years, with tree death occurring in 2–4 years [24, 61, 68, 74, 78]. In contrast, root-feeding *Agrilus* oviposit along the lower trunk or stem, near groundline [58, 77]. Shrub-infesting *Agrilus* such as *A. cuprescens* and *A. ruficollis* (rednecked cane borer, Figs. 1C, 2C) commonly oviposit near the base of a stem on younger stems, but further up on older stems which may have multiple infestation points; *A. ruficollis* has also been observed to uniquely prefer ovipositing near leaf axils [29].

Factors Affecting *Agrilus* Population Dynamics and Outbreaks

Both biotic and abiotic factors can affect *Agrilus* population dynamics. Outbreaks of many *Agrilus* pests in both their native and invaded ranges are often associated with variation (or lack thereof) in host plant conditions (i.e., susceptibility or resistance), natural enemies, and climatic factors.

Host Plant Resistance Most *Agrilus* that attack live plants prefer plants that are weakened or stressed. Vigorous hosts can kill young larvae by flooding larval galleries with plant exudates or overgrowing the larvae with callus tissue [57, 95]. However, in situations where an *Agrilus* species

encounters a naïve host plant, i.e., where the plant and insect did not coevolve, the naïve host may lack resistance mechanisms, which can favor successful infestation of apparently health plants.

An encounter with a naïve host can occur when a host plant is moved to a new continent such as when Asian and European *Betula* are planted in North America and then infested by native *A. anxius* [16, 131] or when North American *Fraxinus* were planted in China and infested by native EAB [37, 132]. A similar situation can occur when an *Agrilus* species is moved to a new continent such as when EAB was introduced to North America [133]. At times, both the plant and insect can be moved, such as when North American *Fraxinus* that were planted in European Russia and Ukraine were infested by EAB after its introduction there from Asia [134], or *A. cuprescens* introduction to North America in infested *Rosa* nursery stock (14). These novel encounters can also occur in the same country, such as when the *Quercus*-infesting *A. auroguttatus* was moved from Arizona to California, USA [20], or when the *Malus*-infesting *A. mali* was moved from eastern to western China [35].

Outbreaks of several *Agrilus* species often follow successive years of drought or defoliation [16, 19, 23, 60, 80, 116, 135–139]. By contrast, some root-infesting *Agrilus* prefer vigorous host plants [6, 57]. Some *Agrilus* pests such as *A. auriventris* (citrus flatheaded borer) have been noted to prefer older plants [19], while others such as *A. sinuatus* (sinuate pear borer, Fig. 1B) or *A. cuprescens* will readily attack young plants or young stems [29, 138]. It is not known if or to what degree stress events are associated with recent outbreaks of several *Agrilus* species that have been introduced to other regions, such as *A. cuprescens* [29] and *A. auroguttatus* in North America [21, 140], and *A. mali* and *A. fleischeri* in China [32, 33, 35, 141].

With the arrival of EAB in North America, several field studies have explored host plant resistance in Asian and North American *Fraxinus* species. Asian species such as *F. chinensis*, *F. mandschurica* and *F. rhynchophylla* are the coevolved hosts and thus more resistant than North American *Fraxinus* to EAB [37, 133, 142, 143]. However, among the non-coevolved North American *Fraxinus* species, some species such as *F. americana*, *F. nigra*, and *F. pennsylvanica* are more often killed by EAB than others such as *F. quadrangulata* [144]. More recently, certain surviving *F. pennsylvanica* trees (often termed as "lingering ash") have shown the genetic capacity to tailor their response to EAB infestation by killing enough EAB larvae to prevent lethal damage to their vascular tissues [145]. Tree resistance to EAB likely involves multiple mechanisms, including higher constitutive and inducive concentrations of bark lignans, coumarins, proline, tyramine, defensive proteins, secoiridoids, and other phenolic compounds that reduce adult feeding and oviposition, as well as larval feeding and survivorship [146–149]. Although host resistance has been well studied in EAB, similar advances are lacking for nearly all other *Agrilus* species.

Natural Enemies There are diverse groups of natural enemies that attack all life stages of *Agrilus* species, primarily parasitoids, but also avian predators, and pathogens. As of this review, approximately 15 species of hymenopteran parasitoids are known to attack *Agrilus* eggs, and at least 51 hymenopteran (36 genera) and 3 coleopteran (3 genera) species attack *Agrilus* larvae in Asia, Europe, and North America (Table 2). Most egg parasitoids are Encyrtidae, while the larval parasitoids are members of seven hymenopteran families: Braconidae, Ichneumonidae, Eulophidae, Eupelmidae, Eurytomidae, Bethylidae and Chalcididae. The rate of parasitism varies with the species of *Agrilus* and parasitoid, as well as the geographic area where parasitism occurs (Table 2). The highest rates of *Agrilus* egg parasitism (ca. 50%) were by encyrtid wasps (4 species) in North America, Asia, and Europe. In contrast, the highest rates of *Agrilus* larval parasitism (> 50%) were caused by species of two braconid genera (*Atanycolus* in North America; [150, 151] and *Spathius* in Asia [152, 153], North America [154], and Europe [155], and two eulophid genera: *Tetrastichus* and *Baryscapus* in Eurasia [142, 156–158] and in North America [159, 160]. *Agrilus* larval parasitism by ichneumonids was frequently reported in North America and Asia, but generally at low rates (< 10%).

The primary predators of tree-infesting *Agrilus* are woodpeckers (Picidae), which often feed on the overwintering larval stages, causing up to 60% larval mortality [151, 154]. More recently, pathogenic fungi and microsporidian species were also isolated from several pest *Agrilus* adults, including *A. anxius*, *A. cuprescens,* and EAB [188–190].

Climate Change *Agrilus* populations dynamics will be directly and indirectly affected by climate change and these effects can be positive or negative depending on the climate event, host plant species impacted, and world region affected. Warming climates will speed *Agrilus* development times, especially at the cooler extremes of their range, allowing a higher proportion of the population to be univoltine rather than semivoltine [191–193]. For northern temperate *Agrilus* species, populations may expand northward with a warming climate if suitable hosts are present [192, 193]. By contrast, near the southern edge of an *Agrilus* species' range, populations may recede northward if winter temperatures do not provide sufficient cold periods needed to complete obligatory diapause [29, 191, 194]. Increased occurrences of severe polar vortexes could increase winter mortality of some *Agrilus* [191, 195], while extreme heat events could negatively impact development rates [196].

Table 2 Parasitoids associated with *Agrilus* species (adapted from and updated since Taylor et al. 2012). x = level of parasitism undetermined/not found in the literature

Parasitoid guild	Order: Family	Species	*Agrilus* host/Host's food plants (genus)	Regions where parasitism was reported	Levels of parasitism reported	References
Egg parasitoids	Hym: Aphelinidae	*Ablerus* sp.	*A. anxius/Betula*	USA, Canada	< 0.2%	[90]
	Hym: Encyrtidae	*Oobius* (=*Avetianella*) sp.	*A. anxius/Betula*	USA, Canada	< 3.5%	[90]
		Coccidencyrtus sp.	*A. liragus/Populus*	USA, Canada	~ 55%	[80]
		Ooencyrtus erionotae	*A. sexsignatus/Eucalyptus*	Philippines	32—57%	[161]
		Ooencyrtus sp.	*A. anxius/Betula*	USA, Canada	< 2.4%	[90]
		Oobius agrili	*A. planipennis/Fraxinus*	China	> 50%	[162, 163]
		Oobius zahaikevitshi	*A. viridis/Corylus*	Italy	8—58%	[164]
		Oobius minusculus	*A. subcinctus/Fraxinus*	USA	8.6–9.4%	[82, 164]
			A. egenus/Robinia			
		Oobius whiteorum	*A. anxius/Betula*	USA	x	[164]
		Oobius primorskyensis	*A. planipennis/Fraxinus*	Russian Far East	23–44%	[165, 166]
		Oobius saimaensis	*A. fleischeri/Populus*	China	6—48%	[32, 167]
		Oobius fleischeri	*A. fleischeri/Populus*	China	6—48%	[32, 167]
		Orianos brazai	*A. sexsignatus/Eucalyptus*	Philippines	x	[168]
		Signichorini tribe	*A. anxius/Betula*	USA, Canada	< 1%	[90]
	Hym: Signiphoridae	*Thysanus* sp.	*A. liragus/Populus*	USA, Canada	~ 12%	[74]
Larval parasitoids	Hym: Braconidae	*Atanycolus charus*	*A. anxius/Betula*	USA, Canada	0.3—52%	[74, 80]
			A. liragus/Populus			
		Atanycolus cappaerti	*A. planipennis/Fraxinus*	USA, Canada	9—71%	[71, 150]
			A. liragus/Populus			
			A. bilineatus/Castanea, Quercus			
			A. sulcicollis/Quercus			
		Atanycolus simplex	*A. liragus/Populus*	USA, Canada	< 1%	[74, 169]
			A. bilineatus/Castanea, Quercus			
		Atanycolus hicorie	*A. planipennis/ Fraxinus*; other native *Agrilus* wood borers	USA, Canada	< 2%	[170, 171]
		Atanycolus tranquebaricae	*A. planipennis/Fraxinus*	USA	< 1%	[172]
		Atanycolus disputabilis	*A. planipennis/Fraxinus*	USA	< 1%	[172]
		Atanycolus nigropopyga	*A. planipennis/Fraxinus*;	USA	< 3%	[173]
		(=A. disputabilis)	other native *Agrilus* wood borers			
		Atanycolus nigriventris	*A. planipennis/ Fraxinus*	Russian Far East	< 50%	[167]
		Atanycolus ivanowi	*A. mali/Malus*	China	~ 27%	[174]
		Bracon sp.	*A ruficollis/Rubus*	USA	5%	[58, 175]
		Microbracon xanthostigmus	*A. ruficollis/Rubus*	USA	x	[47, 58]
		Doryctes farthus	*A. anxius/Betula*	USA, Canada	< 0.1%	[169]
			A. liragus/Populus			
		Doryctes rufipes	*A. anxius/Betula*	Northeastern US/Canada	< 0.1%	[169]
			A. liragus/Populus			
		Doryctes atripes	*A. anxius/Betula*	Northeastern US/Canada	< 0.1%	[169]
		Doryctes undulatus	*A. mali/Malus*	China, Xinjiang province	x	[174]

Table 2 (continued)

Parasitoid guild	Order: Family	Species	*Agrilus* host/Host's food plants (genus)	Regions where parasitism was reported	Levels of parasitism reported	References
		Ecphylus sp.	*A. subcinctus/Fraxinus*	USA	x	[82]
		Heterospilus sp.	*A. subcinctus/Fraxinus*	USA	x	[49]
		Iphiaulaz impostor	*A. biguttatus/Populus*	Europe	~13%	[176]
		Leluthia astigma	*A. planipennis/Fraxinus*	USA	~2.1%	[71, 177–179]
			A. difficilis/Gleditsia;			
			A. bilineatus/Quercus			
			A. sulcicollis/Quercus			
			A, cuprescens/Rosa & Rubus			
			Other *Agrilus* sp.			
		Spathius sp.	*A. auriventris/Citrus*	Japan, China	7%	[20, 180]
		Spathius agrili	*A. planipennis/Fraxinus*	Northern China	60—90%	[181]
		Spathius galinae	*A. planipennis/Fraxinus*	Vladivostok, Russia	~64%	[172, 182]
		Spathius curvicaudis	*A. biguttatus/Quercus*	Europe	~25%	[176, 183]
		Spathius floridanus	*A. planipennis/Fraxinus*; other North American native wood-borers	USA	< 0.5%	[173]
		Spathius laflammei	*A. planipennis/Fraxinus;* other North American native wood-borers	USA	< 1%	[173]
		Spathius simillimus	*A. anxius/Betula*	USA, Canada	< 0.5%	[71, 171]
			A. liragus/Populus			
			A. planipennis/Fraxinus			
			A. bilineatus/Quercus			
			A. sulcicollis/Quercus			
		Spathius polonicus	*A. planipennis/ Fraxinus*; other European native wood borers	Russia/Europe	~50%	[155]
		Spathius sinicus	*A. mali/Malus*	China	x	[174]
		Spathius brevicaudis	*A. mali/Malus*	China	x	[174]
		Polystenus rugosus	*A. mali/Malus*	China/Europe	< 1%	[32, 174]
			A. flecheri/Populus			
		Paramblynotus sp	*A. flecheri/Populus*	Northeast China	~52%	[32]
		Pareucorystes varinervis	*A. mali/Malus*	China/Europe	x	[174]
		Wroughtonia (Helconidea) ligator	*A. planipennis/Fraxinus*	Northeastern US/Canada	< 1%	[74, 169]
			A. liragus/Populus			
			A. bilineatus/Castanea, Quercus			
	Hym: Bethylidae	*Sclerodermus pupariae*	*A. planipennis/Fraxinus*	Northern China	~13%	[153]
	Hym: Chalcididae	*Phasgonophora sulcata*	*A. anxius/Betula*	US/Canada	< 20%	[67, 80, 90, 184]
			A. liragus/Populus			
			A. bilineatus/Quercus			
			A. planipennis/Fraxinus			
	Hym: Cleonymidae	*Cleonymus magnificus*	*A. cuprescens/Rosa & Rubus*	North America (US)	14%	[58, 175, 179]
			A. ruficollis/Rubus			

Table 2 (continued)

Parasitoid guild	Order: Family	Species	*Agrilus* host/Host's food plants (genus)	Regions where parasitism was reported	Levels of parasitism reported	References
		Tetrastichus nr. *rugglesi*	*A. anxius/Betula; A. planipennis/Fraxinus*	US/Canada	< 0.1%	[74, 80]
	Hym: Eulophidae	*Barysapus* nr. *endemus*	*A. cuprescens/Rubus & Rosa*	Europe	58%[b]	[157]
		Tetrastichus agrili	*A. sinuatus/Pyrus*	North America (US)	< 49%[b]	[179]
			A. cuprescens/Rosa			
		Tetrastichus heeringi	*A. sinuatus/Pyrus*	Europe	43—93%	[51, 157, 158]
			A. cuprescens/Rosa & Rubus			
			A. ribesi/Ribes			
		Tetrastichus sp.	*A. sexignatus/Eucalyptus*	Philippines	2—50%	[161]
		Tetrastichus planipennisi	*A. planipennis/Fraxinus*	China, Russian Far East	22—40%	[142]
		Baryscapus (Tetrastichus) rugglesi	*A. arcuatus/Quercus*	USA, Canada	≥ 9%	[44, 80, 160]
			A. champlaini/Ostrya			
			A. cuprescens/Rubus & Rosa			
			A. ruficollis[a]			
			A. liragus/Populus[a]			
		nr. *Hadrotrichodes*	*A. subcintus*	USA	x	[82]
	Hym: Eupelmidae	*Balcha indica*	*A. planipennis/Fraxinus*	USA, Asia	< 4%	[71, 185]
			A. sulcicollis/Quercus; other Asian and North American woodborers			
		Eupelmus pini	*A. planipennis/Fraxinus*	USA	< 0.2%	[186]
	Hym: Metapelmatidae	*Metapelma* sp.	*A. planipennis/Fraxinus*	China	< 4%	[185]
	Hym:	*Metapelma* sp.	*A. subcinctus/Fraxinus*	USA	x	[82]
		Metapelma schwarzi	*A. cuprescens/Rosa & Rubus*	USA	x	[179]
		Metapelma spectable	*A. bilineatus/Quercus*	USA	x	[71]
			A. sulcicollis/Quercus			
	Hym: Eurytomidae	*Bephratoides agrili*	*A. anxius/Betula*	USA, Canada	< 1%	[74, 169]
		Eurytoma rosae	*A. cuprescens/Rosa & Rubus*	USA, Europe	x	[157, 179]
			A. bilineatus/Castanea			
		Eurytoma sp.	*A. anxius/Betula*	USA, Canada	< 1%	[74, 169]
	Hym: Ichneomonidae	*Cubocephalus* sp.	*A. planipennis/Fraxinus*	USA	< 0.2%	[186]
		Dolichomitus messorperlongus	*A. anxius/Betula*	USA, Canada	< 0.4%	[74, 169]
			A. liragus/Populus			
		Dolichomitus vitticrus	*A. planipennis/Fraxinus*	USA	< 0.2%	[186]
		Ephialtes sp.	*A. anxius/Betula*	USA, Canada	< 0.4%	[80]
			A. liragus/Populus			
		Glypta sp.	*A. anxius/Betula*	USA, Canada	< 1%	[169]
		Ichneumon sp.	*A. anxius/Betula*	USA, Canada	< 1%	[169]
		Olesicampe sp.	*A. anxius/Betula*	USA, Canada	< 1%	[169]
		Orthizema sp.	*A. anxius/Betula*	USA, Canada	< 1%	[169]
		Pimploterus sp.	*A. anxius/Betula*	USA, Canada	< 1%	[169]
		Baruchnemon sp.	*A. ruficollis/Rosa*	USA	x	[187]

Table 2 (continued)

Parasitoid guild	Order: Family	Species	*Agrilus* host/Host's food plants (genus)	Regions where parasitism was reported	Levels of parasitism reported	References
		Xorides sp.	*A. planipennis/Fraxinus*	Northeast China	< 10.6%	[185]
	Hym: Stephanidae	*Foenatopus* sp.	*A. sexsignatus/Eucalyptus*	Southeast Asia (Philippines)	< 50%	[161]
	Hym:Pteromalidae	*Oodera* sp.	*A. subcinctus/Fraxinus*	USA	x	[82]
	Col: Cleridae	*Tenerus* sp.	*A. planipennis/Fraxinus*	Northeast China	< 21%	[185]
	Col: Trogossitidae	*Xenoglena quadrisignata*	*A. planipennis/Fraxinus*	Northeast China	< 1.2%	[185]

x = estimated of level of parasitism undetermined/not found in literature

[a]Ill-defined identity or association with associated parasitoid, unconfirmed

[b]Stated level of parasitism unconfirmed or lacking specificity to species

Because *Agrilus* populations are strongly driven by bottom-up forces, the effects of climate change on host plants will likely have significant indirect effects on *Agrilus* population dynamics. Warmer climates and higher CO^2 levels will increase primary growth and secondary production of defensive compounds for many plant species, which could make some hosts less vulnerable to *Agrilus* attack [197–199]. However, warmer climates may reduce growth and vigor for plant species that are more adapted to cooler climates, such as *Betula papyrifera*, making them more susceptible to *Agrilus* attack [16, 136, 200]. This effect is expected to be most pronounced near the southern geographic distribution of heat sensitive plant species in the northern hemisphere. More frequent and pronounced droughts, and other extreme weather events, including fluctuating winter temperatures, late season frosts, extreme heat, and high winds, can also reduce plant vigor and increase their vulnerability to *Agrilus* attack [201, 202].

Effects of climate change on natural enemies will also affect top-down pressures on many *Agrilus*. For example, several *Agrilus* larval parasitoids are multivoltine and require a proportion of the *Agrilus* population to be semivoltine, so suitable larval hosts are available when adult parasitoids emerge in the spring of every year [203]. As the proportion of semivoltine *Agrilus* declines in warming climates, host-parasitoid synchrony will likely decrease [193]. Also, some parasitoids may be more adapted to cooler climates compared to their host, such as the EAB egg parasitoid *Oobius agrili* [204]. Like many insect species, extreme weather events may negatively affect parasitoid survival and development, but parasitoids may be more sensitive than their *Agrilus* hosts. For example, overwintering *Tetrastichus planipennisi* and *Spathius galinae* suffered higher mortality from an extreme cold weather event compared to EAB larvae [191].

Economic and Ecological Impacts

Economic and ecological damage has been reported from multiple *Agrilus* species (Table 1). Much of this damage is caused by *Agrilus* that have been accidentally introduced to areas where a naïve (non-coevolved host) occurs or vice versa. Generally, many *Agrilus* pests characteristically cause damage in an intermittently severe pattern when populations flare up and reach outbreak levels and then decline again. For several of these *Agrilus* (e.g., *A. anxius*, *A. biguttatus*, and*A. bilineatus*), intermittent widespread mortality to their coevolved hosts appears to be partially driven by preceding periods of environmental stress [25, 136, 202]. Given these threats, many world regions have heightened their awareness or enacted stricter quarantines on certain plant species or plant products that could harbor high-risk *Agrilus* pests [33, 34, 141].

Of all the *Agrilus* species worldwide, EAB is by far the most damaging species, especially in its invaded range of North America. An early cost projection for EAB remediation in just 25 northeastern USA communities for one decade (2009–2019), which covered treatment, removal, and replacement of landscape ash trees, was US$25 billion [205], making it the costliest wood-boring insect to have invaded the USA [206]. In addition to economic damage, EAB has negatively impacted many ash-dependent biodiversity and degraded North American forest ecosystem functions and services [162, 207–212]. In the invaded range of European Russia and Ukraine, EAB may negatively impact European ash, *F. excelsior* [213]. Throughout its native range in East Asia, however, EAB rarely reaches outbreak levels, but has killed Asian ash that are stressed [37]. However, EAB outbreaks are common in areas where North American ash species have been planted in China [37, 66, 69, 142, 214] and the Russian Far East [152]. Currently, North American ash

is only planted in China as monoculture plantations or as landscape and street trees [132].

Of the many *Agrilus* pests, *A. cuprescens* is the most globally widespread [1]. It is a pest of cultivated *Rubus* and *Rosa* crops, both in its native range of Eurasia and in North America where it was introduced [29]. *A. cuprescens* remains an economically important pest in Eurasia [158, 215, 216] and North America, where it has caused losses up to ~ 90% of *Rubus* crops and nursery closures for *Rosa* production [29]. *A. cuprescens* spread from northeastern North American in the 1910s-1920s, to the Great Lakes region in the 1920s-1940s, then to Utah in the 1950s-1980s, and then to the Pacific Northwest in the 1990s, where it has become a serious pest of concern in *Rubus* production [29]. *Agrilus cuprescens* was also observed to ecologically impact native Canadian prairie *Rosa* stands [217, 218].

The Nearctic *A. ruficollis* has been a pest of cultivated *Rubus* throughout eastern North America since the mid-1800s [219] and remains a pest today [45]. Crop losses of up to 72% have been reported for *A. ruficollis* [220]. Damage from both *A. cuprescens* and *A. ruficollis* vary widely (Fig. 2C, D), and it is not understood whether outbreaks of these pests are preceded by environmental stress or heavily influenced by population fluctuations of their larval parasitoids [158, 160, 220].

In citrus crop production in Asia and Oceania, *A. auriventris* is a serious orchard pest [38, 221]. During an 8-year outbreak of *A. auriventris* in Japan, estimated ~ 70 K *Citrus* trees were killed [19]. Many of the infested trees were older, and drought was considered a precursor to the outbreak. Moreover, recent outbreaks of *A. auriventris* in China [222], and its current classification as quarantine pest in Western Australia illustrate its ongoing economic relevance. In addition, the six species of the Asian *A. angulatus* species group are also known citrus pests and could cause economic damage if introduced to other citrus growing regions of the world [223].

Agrilus sinuatus is a European species that primarily impacts *Pyrus* production and remains economically relevant today in multiple European countries [50]. This species was introduced to North America in the late 1800s, where it became a devastating pest of *Pyrus* production in the Northeast [73, 138] and intermittently remains a regional pest.

Agrilus mali is another economically damaging *Agrilus* that intermittently impacts cultivated *Malus* in eastern China and Korea [224]. More recently, *A. mali* became established in western China where it is now a serious pest of wild *Malus* [33, 35]. The rate of spread and severity of damage caused by *A. mali* in western China is like EAB, with near complete infestation of wild *Malus* forests and 40–50% tree mortality [35, 94, 225].

Like *A. mali, A. auroguttatus* and *A. prionorus*, are pests recently introduced to regions proximal to their native range, where outbreaks have caused damage to native *Quercus* in California and *Sapindus* in Texas USA, respectively. Forest products of some major tree pests such as *A. anxius*, *A. biguttatus*, and *A. bilineatus* have been quarantined by multiple countries to reduce the risk of introduction and thereby safeguard local forest and horticultural industries and environments.

Other more recently emerging *Agrilus* pests of concern to crops include *A. viridis* as a native pest of cultivated *Corylus avellana* nut trees in Europe [226], *A. pseudocoryli* as a native pest of cultivated hybrid *Corylus americana* × *Corylus avellana* in North America [42], and introduction of *A. acutus* into a major Hibiscus-producing region in India [13].

Alternatively, some *Agrilus* have been employed as biocontrol agents of invasive plants. *Agrilus hyperici* was intentionally introduced to Australia and the USA to control *H. perforatum*. It successfully established in North America and contributed significantly to *H. perforatum* control [83, 227] but did not significantly suppress *H. perforatum* in Australia [6]. *Agrilus ruficollis* was also introduced to New Zealand as a biocontrol agent for feral, invasive *Rubus* [228], although it did not become established. *A. cuprescens* was assessed for *Rosa multiflora* control in North America but was not found to be highly impactful [186]. In the future, it is possible that other *Agrilus* species will be used for weed biocontrol.

Management

Management of many native *Agrilus* within their historical geographic range is infrequent. This is largely because most damage caused by native *Agrilus* occurs to stressed forest trees, where active management is not practical, and outbreaks subside when tree vigor returns. By contrast, active control methods, including eradication efforts, are often undertaken for invasive tree-killing *Agrilus* species, like EAB. Alternatively, *Agrilus* pests of cultivated small trees or shrubs (crops) may be more readily managed. For example, cultural practices were developed against *Agrilus* pests of *Rosa* and *Rubus* prior to use of pesticides [219, 229]. These practices include pruning out infested stems before adult *Agrilus* emergence, followed by destruction (usually burning) and remain relevant today [30, 225, 230]. Other methods, such as those developed for *A. sinuatus* centered on using physical barriers or repellents to prevent or deter oviposition [73].

Several advances in management strategies for *Agrilus* pests of healthy plants have been developed in recent decades following the discovery of EAB in North America. These have focused on setting quarantine boundaries, survey methods, eradication, spread prevention, biological control, host plant resistance, silvicultural practices, insecticide treatments, and area-wide integrated pest managements [37, 142, 144, 154, 203, 231–234]. Unlike EAB, many *Agrilus* species are native and considered secondary pests that primarily colonize stressed host plants [202]. Therefore, a key strategy

to manage these secondary *Agrilus* species is through prevention, i.e., by maintaining good plant health. Avoiding soil compaction, watering during dry periods, and harvesting overmature trees are often effective in preventing attack by secondary *Agrilus* pests. However, for *Agrilus* crop pests, regular scouting, cultural practices, and chemical control may be necessary to prevent significant economic damage. For some *Agrilus* crop pests, insecticide controls have been transformative, such as the account of insecticides effectively ending a major outbreak of *A. auriventris* in Japan [19]. In the following sections, we will discuss several management strategies that were developed primarily for EAB but are likely applicable to many other *Agrilus* species.

Early Detection and Eradication or Prevention An eradication strategy was initially implemented in the USA and Canada following the EAB discovery in Michigan and Ontario in 2002 [235]. However, the eradication effort was later abandoned because of difficulties detecting EAB at low population densities, primarily due to the lack of effective monitoring tools. In subsequent years, many advances were made in trap designs [113, 236], host-plant based lures [96, 110], and sex pheromones [100, 101]. The improved traps were used to detect and delineate the leading edge of the EAB invasion [237]. Although the detection efficacy of current traps and lures is still limited at low EAB population levels, these traps have been useful for monitoring EAB spread and have been used to capture other *Agrilus* species in other countries [238, 239].

Considering the severe negative impacts of the EAB invasion in North America, it is still prudent to adopt pest prevention strategies in regions where EAB and other potentially invasive *Agrilus* have not yet established. For example, proactive research efforts have been recently initiated in Europe to develop a preparedness toolbox to deal with the potential arrival of EAB, *A. anxius* and other buprestids [31, 240, 241]. Similar proactive efforts have been developed in Europe for other potentially invasive species such as *A. anxius*, *A. bilineatus*, *A. fleischeri*, and *A. mali* [26, 34]. Likewise, in agricultural pest control, trapping is a key component of determining management action thresholds for IPM (Integrated Pest Management) programs, and have been explored for *A. cuprescens*, *A. ruficollis,* and *A. sinuatus* [29, 45, 223]. Colored sticky traps or funnel traps have not yet proven to be effective for *A. cuprescens* [29]. However, Kim et al. [45] found that 542 nm, 49% reflectance green funnel traps that are used for EAB were also effective for trapping *A. ruficollis*. Similarly, light green and transparent sticky traps were effective for trapping *A. sinuatus* [223].

Biological Control Although many natural enemies are considered important biological control agents of *Agrilus* pests, few studies have quantified their role within IPM programs except for EAB [151, 154, 159, 242], *A. cuprescens* [158, 160] and *A. ruficollis* [175]. In the case of EAB, a classical biological control program was initiated in 2007 after US federal and state regulatory agencies approved release of three parasitoids from China: *Oobius agrili* (Encyrtidae), *Spathius agrili* (Braconidae), and *Tetrastichus planipennisi* (Eulophidae) A fourth EAB parasitoid, *Spathius galinae* (Braconidae) from Russia, was approved for release in the USA in 2015. By fall of 2023, one or more of these four biocontrol agents had been released in over 32 USA states and three Canadian provinces [154, 243]. Field studies have documented successful establishment at numerous release sites of the egg parasitoid *O. agrili* and the larval parasitoids *S. galinae* and *T. planipennisi*. Long-term life table studies have demonstrated that *S. galinae* and *T. planipennisi*have significantly suppressed EAB populations within 3 – 5 years after release [151, 154, 159, 191]. Moreover, suppression of EAB is likely to expand in North America geographically as these parasitoids spread to new areas. Development of such large-scale biological control programs for other invasive *Agrilus* pests will require foreign exploration for specialized natural enemies, assessment of native natural enemies for conservation, and long-term support for large-scale rearing and release programs.

Host Plant Resistance Host plant resistance has been recognized as an ideal management tool for many insect pests of trees [244, 245] and crops [29]. Planting pest-resistant plants would reduce insecticide usage, which often has inadvertent off-target effects and may be limited to high value trees in forests or ornamental contexts. This has been suggested as a strategy for reducing *A. anxius* infestations of *Betula* trees in urban forests and ornamental landscapes [16, 246]. Research is currently underway to develop EAB-resistant *Fraxinus* cultivars, including hybridizing coevolved (e.g., *F. mandshurica*) and naïve North American ash species, as well as crossing with naïve hosts that show high levels of natural EAB resistance [144, 145]. Due to the intermittent nature of many *Agrilus* crop pests, investment in developing new resistant cultivars may not always be justifiable, but selection of existing cultivars may be useful. Multiple past reports and studies have attempted to discern patterns of cultivar resistance in *Rubus* crops for *A. cuprescens* or *A. ruficollis* [31, 44, 158, 220, 247] but considerable variability has been observed [29].

Cultural Control Cultural practices such as planting selective host plant species, as well as thinning, pruning, watering, and fertilizing trees have all been promoted in North America and Europe against several *Agrilus* pests, including *A. anxius*, *A. bilineatus*, *A. cuprescens*, *A. mali* and *A. ruficollis.* For *A. cuprescens* and *A. ruficollis*, destruction of infested canes before adult emergence is effective [30, 230] and can often be integrated with routine cane pruning and trellising activities [29]. Other practices that maintain tree

health, such as matching the tree's hardiness and sun requirements to the planting location, irrigating during drought, proper mulching, and preventing severe defoliation, are all important components of plant health care programs for landscape trees [246, 248–250]. However, although fertilization is commonly recommended, there is no evidence it increases tree resistance to BBB [251].

In forest situations, increasing stand age diversity is recommended for reducing susceptibility of *B. papyrifera* to *A. anxius* [252]. In the case of EAB, some have recommended preemptive logging of ash during the initial EAB invasion, combined with planting non-host trees of EAB [253–255]. Other cultural practices should be explored to lessen the impact of both native and invasive *Agrilus* [256].

Chemical and Gene-Based Control Historically, many insecticides have been used to protect plants against *Agrilus* attack. Many of these products were aimed at the adult beetles. These applications must be timed to be active after adult emergence and before oviposition to be effective. Models predicting adult emergence of EAB [257, 258], and *A. cuprescens* [29, 259] have been used to time insecticide applications. Many insecticides have shown good control, but multiple applications are often required for species that emerge over several weeks. Many insecticides have been tested against *Agrilus* adults and larvae [16, 18, 29, 51, 55, 260–264]. Many have proven effective, but a number of older products such as lead arsenate and dichlorodiphenyltrichloroethane (DDT) have since been phased out and may not be approved in many countries. Some more current effective, non-systemic products that are more widely approved include multiple pyrethroids, carbaryl, malathion, and neem oil [233, 263, 265]. More recently, several systemic insecticides (e.g., azadirachtin, dicrotophos, dimethoate, dinotefuran, emamectin benzoate, and imidacloprid) when applied via soil drench, bark basal spray, or trunk micro-injection have shown multi-year control against both *Agrilus* larvae and adults [261, 266–269].

Among the systemic insecticides, emamectin benzoate appears very effective against EAB, providing control for 2–3 years [233, 268]. Recent economic analyses have revealed that treating landscape ash trees with systemic insecticides is less costly than the cost of tree removal [233]. Moreover, simulation studies suggest that treating large-diameter *Fraxinus* trees with systemic insecticides can slow the spread of EAB in individual forest stands [232, 234, 270]. More importantly, the trunk micro-injection technique directly places the insecticide within the tree and thus reduces contamination to the surrounding environment [271]. Although nontarget organisms such as insects that directly feed on treated trees can be adversely affected by systemic insecticides, direct exposure to predators and parasitoids of target *Agrilus* pests is largely eliminated [272–274]. That said, off-target effects of systemic insecticides may be impractical for *Agrilus* pests of some food crops. For instance, effective timing of systemic insecticides for *A. cuprescens* control in *Rubus* crops simultaneously poses unacceptable risks to humans via high levels of pesticide residues on harvested fruit and unacceptable insecticide exposure to pollinators [30, 194].

Since many insecticides often have inadvertent off-target effects on the environment, this warrants exploration of alternative control strategies [273, 274]. For instance, research has recently begun developing RNA interference (RNAi) technology for EAB control [275–279]. The mode of action of RNAi products involves "silencing" specific target genes that can lead to species-specific pest control. However, this technology is still in the early stages of development, and its efficacy and safety remain untested; currently no commercial products of RNAi technology have yet been developed for EAB or any other *Agrilus* species.

Areawide Integrated Pest Management (IPM) An areawide IPM strategy has been recently explored for managing EAB in North America [231, 280–282]. This strategy integrates EAB monitoring, selective treatments of trees with trunk injection of systemic insecticides to minimize adverse effects on natural enemies, and use of girdled *Fraxinus* trap trees, along with biological control and has been shown to slow and reduce EAB impacts at both small (local) and large (regional) scales [114, 234, 282]. However, success of this areawide IPM strategy is strongly influenced by the initial condition of the ash trees and EAB densities, tree species composition and proximity to insecticide-treated ash trees [234, 282]. Usage of such areawide IPM programs for other *Agrilus* pests remains to be studied.

Conclusions

The genus *Agrilus* is the most speciose genus in the Animal Kingdom [1]. By far, EAB has been the most destructive and costly *Agrilus* species, especially in its invaded range of North America and Europe. Several other *Agrilus* species occasionally reach outbreak levels, especially during periods of drought, or when they encounter naïve hosts, causing widespread plant mortality. Several *Agrilus* species have become established in areas outside their native range, likely the result of inadvertent movement of infested solid wood packaging, nursery plants, and firewood [283]. More *Agrilus* species could be moved in future years, both within and between countries, and thereby threaten local economies and ecosystems. Climate change will likely exacerbate the pest status of many *Agrilus* species by altering their geographic range and voltinism, as well as by altering host susceptibility to *Agrilus* infestation [284]. Moreover, the dynamic interplay of how *Agrilus* species' natural enemies and climate change will alter *Agrilus* population dynamics

is poorly understood. Much more basic biology needs to be learned for the vast majority of *Agrilus* species worldwide, as exemplified by the fact that the larval host plants are unknown for about 78% of the world's *Agrilus* [3]. Similarly, although many advances have been made in chemical control of *Agrilus* pest species, much more remains to be learned about host plant resistance, the chemical ecology of *Agrilus* and their natural enemies, and how such findings can be incorporated into future management strategies.

Acknowledgements We thank Jonathan Schmude for assistance in formatting the manuscript and reference list. Work is partly funded by USDA ARS and USDA FS appropriated base funds.

Author Contributions All authors contributed equally to drafting and reviewing the manuscript. JJD and JO contributed to construction of Tables 1 and 2.

Funding USDA appropriated base funds (8010–22000-031D).

Data Availability No original datasets were generated or analyzed during the current study.

Compliance with Ethical Standards

Competing Interests The authors declare no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

1. Jendek E, Grebennikov VV. Summary of native geographic distribution of all 3,341 species of the most speciose animal genus *Agrilus* (Coleoptera: Buprestidae). J Insect Biodivers. 2023;39(2):32–78. https://doi.org/10.12976/jib/2023.39.2.1.
2. Ruzzier E, Haack RA, Curletti G, Roques A, Volkovitsh MG, Battisti A. Jewels on the go: exotic buprestid around the world (Coleoptera: Buprestidae). NeoBiota. 2023;84:107–35. https://doi.org/10.3897/neobiota.84.90829.
3. Jendek E, Poláková J. Host plants of world *Agrilus* (Coleoptera, Buprestidae)-A critical review. Cham: Springer; 2014. p. 706. https://doi.org/10.1007/978-3-319-08410-7.
4. Fisher WS. A Revision of the North American Species of Buprestid Beetles Belonging to the Genus *Agrilus*. Smithsonian Institute United States National Museum, 1928; i–v: 1–347. United States Government Printing Office, Washington, DC, USA. https://doi.org/10.5479/si.03629236.145.1
5. Jendek E. *Agrilus schwerdtfegeri* Schwerdtfeger, the first proven *Agrilus* developing in conifer, with an analysis of authorship and synonymy. Stud Rep Taxonomical Ser. 2013;9:473–6.
6. Briese D. Current status of *Agrilus hyperici* (Coleoptera: Buprestidae) released in Australia in 1940 for the control of St John's Wort: lessons for insect introductions. Biocontrol Sci and Techn. 1991;1:207–15. https://doi.org/10.1080/09583159109355200.
7. Haack RA, Jendek JE, Liu H, Marchant KR, Petrice TR, Poland RM, Ye H. The emerald ash borer: a new exotic pest in North America. Newslett Mich Entomol Soc. 2002;47:1–5.
8. EAB Information. Emerald ash borer information network. 2024. Available online: https://www.emeraldashborer.info/. Accessed 30 Apr 2024.
9. Bray M, Bauer LS, Poland TM, Haack RA, Cognato AI, Smith JJ. Genetic analysis of emerald ash borer (*Agrilus planipennis* Fairmaire) populations in Asia and North America. Biol Invas. 2011;13:2869–87.
10. Siegert NW, McCullough DG, Liebhold AM, Telewski FW. Dendrochronological reconstruction of the epicentre and early spread of emerald ash borer in North America. Divers and Distrib. 2014;20:847–58. https://doi.org/10.1111/ddi.12212.
11. Jendek E. A statistical overview of the research history of the superfamily Buprestoidea (Coleoptera). J Insect Biodivers. 2024;45:28–40. https://doi.org/10.12976/jib/2024.45.2.1.
12. Jendek E. Revision of *Agrilus acutus* (Thunberg, 1787) and related species (Coleoptera: Buprestidae). Zootaxa. 2004;507(1):1–19. https://doi.org/10.11646/zootaxa.507.1.1.
13. Kumar VM, Kumar KM, Harisatyanarayana N, Rao NV. Infestation of *Agrilus* sp. on mesta (*Hibiscus cannabinus* and *H. sabdariffa*) in Andhra Pradesh, India. Plant Protect Asso India. 2015;43(4):526–7.
14. GBIF. Global Biodiversity Information Facility Backbone Taxonomy. Checklist dataset of *Agrilus acutus* (Thunberg, 1787) in in GBIF Secretariat. 2023; https://doi.org/10.15468/39omei. Accessed via GBIF.org on 2024–05–08.
15. Jendek E, Nakládal O. Taxonomic, distributional and biological study of the genus Agrilus (Coleoptera Buprestidae). III Zootaxa. 2021;4963(1):58–90. https://doi.org/10.11646/zootaxa.4963.1.3.
16. Muilenburg VL, Herms DA. A review of bronze birch borer (Coleoptera: Buprestidae) life history, ecology, and management. Environ Entomol. 2012;41(6):1372–85. https://doi.org/10.1603/EN12238.
17. EPPO. *Agrilus anxius*. EPPO Bulletin 2011;41:409–13. https://doi.org/10.1111/j.1365-2338.2011.02510.x
18. Ohgushi R. Ecological studies on the citrus flat-headed borer, *Agrilus auriventris* Saunders. I. Season of emergence. Jpn J Appl Entomol Z. 1966;10:55–63. https://doi.org/10.1303/jjaez.10.55.
19. Ohgushi R. On an outbreak of the citrus flat-headed borer, *Agrilus auriventris* E. Saunders in Nagasaki prefecture. Res Popul Ecol. 1978;9:62–74. https://doi.org/10.1007/BF02521397.
20. Coleman TW, Seybold SJ. Goldspotted oak borer in California: invasion history, biology, impact, management, and implications for Mediterranean forests worldwide. In: Paine TD, Lieutier F, editors. Insects and Diseases of Mediterranean Forest Systems. Cham, Switzerland: Springer International Publishing; 2016. p. 663–697. https://doi.org/10.1007/978-3-319-24744-1_22.
21. Coleman TW, Seybold SJ. Previously unrecorded damage to oak, *Quercus* spp., in southern California by the goldspotted oak borer, *Agrilus coxalis* Waterhouse (Coleoptera: Buprestidae). Pan-Pac Entomol. 2008;84:288–300.
22. Coleman TW, Seybold SJ. Verification of a useful character for separating the sexes of the goldspotted oak borer, *Agrilus coxalis* auroguttatus (Coleoptera: Buprestidae). Pan-Pac Entomol. 2010;86:57–61.
23. Brown N, Inward DJG, Jeger M, Denman S. A review of *Agrilus biguttatus* in UK forests and its relationship with acute oak decline. For: Int J For Res. 2015;88(1):53–63. https://doi.org/10.1093/forestry/cpu039.
24. Moraal LG, Hilszczanski J. The oak buprestid beetle, *Agrilus biguttatus* (F.) (Col., Buprestidae), a recent factor in oak decline in Europe. J Pest Sci. 2000;73:134–8. https://doi.org/10.1007/BF02956447.
25. Sallé A, Nageleisen LM, Lieutier F. Bark and wood boring insects involved in oak declines in Europe: current knowledge and

future prospects in a context of climate change. For Ecol Manag. 2014;328:79–93. https://doi.org/10.1016/j.foreco.2014.05.027.
26. EPPO. *Agrilus bilineatus*. EPPO Bulletin. 2019;50(1):158–65. https://doi.org/10.1111/epp.12641.
27. Hizal E, Arslangündoğdu Z. The first record of two-lined chestnut borer *Agrilus bilineatus* (Weber, 1801) (Coleoptera: Buprestidae) from Europe. Entomol News. 2018;127(4):333–5. https://doi.org/10.3157/021.127.0404.
28. Chapman RN. Observations on the life history of *Agrilus bilineatus*. J Agric Res. 1915;3:283–97.
29. O'Dea JK. A review of *Agrilus cuprescens* (Ménétries, 1832), the rose stem girdler, in North America. Agric For Entomol. 2024; 1-18. https://doi.org/10.1111/afe.12622.
30. Davis DW, Raghuvir NN. The control of the rose stem girdler on raspberries in Utah. J Econ Entomol. 1963;56(5):674–7.
31. Davis DW, Raghuvir NN. The biology of the rose stem girdler, *Agrilus rubicola communis*, on raspberries in Utah (Coleoptera Buprestidae). Ann Entomol Soc Am. 1964;57(2):154–9.
32. Zang K, Wang XY, Yang ZQ, Wei K. JJ Duan: Biology and natural enemies of *Agrilus fleischeri* (Coleoptera: Buprestidae), a newly emerging destructive buprestid pest in Northeast China. J Asia-Pac Entomol. 2017;20:47–52. https://doi.org/10.1016/j.aspen.2016.11.010.
33. Volkovitsh MG, Kovalev AV, Orlova-Bienkowskaja MJ. Current distribution and diagnostic features of two potentially invasive Asian buprestid species: *Agrilus mali* Matsumura and *A. fleischeri* Obenberger (Coleoptera: Buprestidae). Insects. 2020;11(8):493. https://doi.org/10.3390/insects11080493.
34. EPPO. *Agrilus fleischeri*. EPPO Bulletin. 2020;50(1):166–9. https://doi.org/10.1111/epp.12642.
35. Bozorov TA, Luo Z, Li X, Zhang D. *Agrilus mali* Matsumara (Coleoptera: Buprestidae), a new invasive pest of wild apple in western China: DNA barcoding and life cycle. Ecol Evol. 2019;9:1160–72. https://doi.org/10.1002/ece3.4804.
36. Yi Z, Liu D, Cui X, Shang Z. Morphology and ultrastructure of antennal sensilla in male and female *Agrilus mali* (Coleoptera: Buprestidae). J Insect Sci. 2016;16(1):1–10. https://doi.org/10.1093/jisesa/iew073.
37. Liu H, Bauer LS, Gao R, Zhao T, Petrice TR, Haack RA. Exploratory survey for the emerald ash borer, *Agrilus planipennis* (Coleoptera: Buprestidae), and its natural enemies in China. Great Lakes Entomol. 2003;36:191–204. https://www.fs.usda.gov/treesearch/pubs/12798.
38. Jendek E. Studies in the East Palaearctic species of the genus *Agrilus* Dahl, 1823 (Coleoptera: Buprestidae). I Entomol Prob Bratislava. 1994;25(1):9–25.
39. Kurosawa Y. Buprestid fauna of eastern Asia (3). Tokyo Nat. Sci. Mus. Bul. (n.s.) 1956;3:33–41.
40. Institute of Zoology, Chinese Academy of Science. *Agrilus marcopoli* Obenberger, Agriculture insects of China (Part. I). Beijing, China: China Agric Press; 1986. p. 445.
41. Billings RF, Grosman DM, Pase HA. Soapberry borer, *Agrilus prionurus* (Coleoptera: Buprestidae): An exotic pest threatens western soapberry in Texas. Southeastern Nat. 2014;13:105–16. https://doi.org/10.1656/058.013.s510.
42. Perish PK, Shanovich HN, Koch AN, Lindsey ARI, Aukema BH. The hazel stem borer, *Agrilus pseudocoryli* (Coleoptera: Buprestidae), as a pest of hybrid hazelnuts. J Econ Entomol. 2023;116(2):496–504. https://doi.org/10.1093/jee/toad023.
43. Jendek E, Grebennikov V, Bocak L. Undetected for a century: Palaearctic *Agrilus ribesi* Schaefer (Coleoptera: Buprestidae) on currant in North America, with adult morphology, larval biology and DNA barcode. Zootaxa. 2015;4034(1):112–26. https://doi.org/10.11646/zootaxa.4034.1.5.
44. Mundinger FG. Two buprestid cane-borers of brambles with experiments on control. J Econ Entomol. 1941;34(4):532–7.
45. Kim SHS, Trammel CE, Lewis BA, Johnson DT. Comparison of color attractiveness for *Agrilus ruficollis* (Coleoptera: Buprestidae): potential for a simple trap. J Econ Entomol. 2016;109(4):1799–806. https://doi.org/10.1093/jee/tow142.
46. Cameron P J, Hill RL, Bain J, Thomas WP (eds). A Review of Biological Control of Invertebrate Pests and Weeds in New Zealand 1874 to 1987. 1989. pp. xiii+-424.
47. Chittenden FC. The red-necked raspberry cane-borer. United States Department of Agriculture Farmer's Bulletin 1922;1286:1–5.
48. Braza RD. Biology of the varicose borer, *Agrilus sexsignatus* (Fisher), on bagras Eucalyptus deglupta Blume. Philippine Entomol. 1988;7:351–8.
49. Braza RD. Control of varicose borer in PICOP's bagras plantation. Canopy Int. 1988;14(2):7–9.
50. Matula E, Bozsik G, Muskovits J, Ruszák C, Jávorszky L, Bonte J, Paulin M, Vuts J, Fail J, Tóth Á, Egri Á. The optimal choice of trap type for the recently spreading jewel beetle pests *Lamprodila festiva* and *Agrilus sinuatus* (Coleoptera, Buprestidae). Insects. 2023;14(12):961. https://doi.org/10.3390/insects14120961.
51. Jancke O. Der Birnprachtkäfer (*Agrilus sinuatus* Oliv., Buprestidae), [The pear Buprestid (*A. sinuatus*)], Anzeiger für Schädlingskunde. 1949;22(4):51–7, https://doi.org/10.1007/BF02097111.
52. Pellegrino I, Curletti G, Liberatore F, Cucco M. Cryptic diversity of the jewel beetles *Agrilus viridis* (Coleoptera: Buprestidae) hosted on hazelnut. European Zool J. 2017;84(1):465–72. https://doi.org/10.1080/24750263.2017.1362050.
53. Wu H. Bionomics and control of *Agrilus zanthoxylumi*. Chinese Bull Entomol. 2006;43(2):236–9.
54. Chamorro ML, Lourdes M, Jendek E, Haack RA, Petrice TR, Woodley NE, Konstantinov AS, Volkovitsh MG, Yang X-K, Grebennikov VV, Lingafelter SW. Illustrated guide to the emerald ash borer *Agrilus planipennis* Fairmaire and related species (Coleoptera, Buprestidae). Sofia-Moscow: Pensoft; 2015.
55. Herms DA, McCullough DG. Emerald ash borer invasion of North America: history, biology, ecology, impact, and management. Ann Rev Entomol. 2014;59:13–30. https://doi.org/10.1146/annurev-ento-011613-162051.
56. Sun JH, Koski TM, Wickham JD, Baranchikov YN, Bushley KE. Emerald ash borer management and research: decades of damage and still expanding. Annu Rev of Entomol. 2024;69:239–58. https://doi.org/10.1146/annurev-ento-012323-032231.
57. Carlson RW, Knight FB. Biology, taxonomy, and evolution of four sympatric *Agrilus* beetles (Coleoptera: Buprestidae). Contrib Am Entomol Inst. 1969;4:1–105.
58. Solomon JD. Guide to insect borers in North American broadleaf trees and shrubs. Washington, DC: USDA Forest Service, Agriculture Handbook AH-706; 1995.
59. Bílý S. Summary of the bionomy of the buprestid beetles of Central Europe (Coleoptera: Buprestidae). Acta Ent Mus Nat Pra. 2002;10:1–104.
60. Dunbar DM, Stephens GR. The bionomics of the two-lined chestnut borer. In: Anderson JF, Kaya HK, editors. Perspectives in forest entomology. New York: Academic Press; 1976. p. 73–83.
61. Cappaert D, McCullough DG, Poland TM, Siegert NW. Emerald ash borer in North America: A research and regulatory challenge. Am Entomol. 2005;51:152–65. https://doi.org/10.1093/ae/51.3.152.
62. Nelson GH, Hespenheide HA. A re-evaluation of some *Agrilus* Curtis species (Coleoptera: Buprestidae). Coleops Bull. 1998;52:31–4. https://www.jstor.org/stable/4009319
63. Dutt DK. Bionomics of *Agrilus acutus* (Thnb) (Col, Buprestidae) on mesta (*Hibiscus cannabinus*) in India. B Entomol Res. 1969;58(3):421–30. https://doi.org/10.1017/S0007485300057187.

64. Roberts H. DPI Entomology Bulletin: No. 45. Forest insect pests of Papua New Guinea 1. Under-bark borers of kamarere and terminalias - *Agrilus* beetles. Harvest. 1987;12:59–64.
65. Hawkeswood TJ, Turner JR. A note on the biology and behaviour of *Agrilus occipitalis* Eschscholtz (Coleoptera: Buprestidae) in Papua New Guinea. Jewel Beetles. 1994;3:14–8.
66. Wang XY, Yang ZQ, Gould JR, Zhang YN, Liu GJ, Liu ES. The biology and ecology of the emerald ash borer, *Agrilus planipennis*, in China. J Insect Sci. 2010;10:128. https://doi.org/10.1673/031.010.12801.
67. Taylor RAJ, Bauer LS, Poland TM, Windell KN. Flight performance of *Agrilus planipennis* (Coleoptera: Buprestidae) on a flight mill and in free flight. J Insect Behav. 2010;23:128–48. https://doi.org/10.1007/s10905-010-9202-3.
68. Haack RA, Benjiamin DM. The biology and ecology of the two-lined chestnut borer, *Agrilus bilineatus* (Coleoptera, Buprestidae) on oaks, *Quercus* spp, in Wisconsin. Can Entomol. 1982;114:385–96. https://doi.org/10.4039/Ent114385-5.
69. Wei X, Wu Y, Reardon R, Sun TH, Lu M, Sun JH. Biology and damage traits of emerald ash borer (*Agrilus planipennis* Fairmaire) in China. Insect Sci. 2007;14:367–73. https://doi.org/10.1111/j.1744-7917.2007.00163.x.
70. Haack RA, Petrice TR, Zablotny JE. The first report of the European oak borer, *Agrilus sulcicollis* (Coleoptera: Buprestidae), in the United States. Great Lakes Entomol. 2009;42:1–7. https://doi.org/10.22543/0090-0222.2194.
71. Petrice TR, Haack RA. Biology of the European oak borer in Michigan, United States of America, with comparisons to the native twolined chestnut borer. Can Entomol. 2014;146:36–51. https://doi.org/10.4039/tce.2013.58.
72. Jennings ED, Taylor P, Duan JJ. The mating and oviposition behavior of the invasive emerald ash borer (*Agrilus planipennis),* with reference to the influence of host tree condition. J Pest Sci. 2014;81:71–8. https://doi.org/10.1007/s10340-013-0539-1.
73. Glasgow H. The feeding habits of the sinuate pear borer in relation to control practices. In: Bulletin 648. Geneva: New York State Agricultural Experiment Station; 1934. pp. 1–31.
74. Barter GW. Studies of the bronze birch borer, *Agrilus anxius* Gory, in New Brunswick. Can Entomol. 1957;89:12–36. https://doi.org/10.4039/Ent8912-1.
75. Ohgushi R. Development of ovary and pre-oviposition period of citrus flat-headed borer, *Agrilus auriventris auriventris* S. Saunders under laboratory conditions. Jpn J Appl Entomol Z. 1963;7:92–6. https://doi.org/10.1303/jjaez.7.92.
76. Akers RC, Nielsen DG. Spatial emergence pattern of bronze birch borer, (Coleoptera: Buprestidae) from European white birch. J Entomol Sci. 1990;25:150–7. https://doi.org/10.18474/0749-8004-25.1.150.
77. Brooks FE. Apple root borer. J Agric Res. 1914;3:179–86.
78. Balch RE, Prebble JS. The bronze birch borer and its relation to the dying of birch in New Brunswick forests. Forestry Chron. 1940;16:179–201. https://doi.org/10.5558/tfc16179-3.
79. Nord JC, Knight FB, Vogt GB. Identity and biology of an aspen root girdler *Agrilus horni*. For Sci. 1965;11:33–41. https://doi.org/10.1093/forestscience/11.1.33.
80. Barter GW. Survival and development of the bronze poplar borer *Agrilus liragus* (Coleoptera: Buprestidae). Can Entomol. 1965;97:1063–8. https://doi.org/10.4039/Ent971063-10.
81. Loerch CR, Cameron EA. Within-tree distributions and seasonality of immature stages of the bronze birch borer, *Agrilus anxius* (Coleoptera: Buprestidae). Can Entomol. 1984;116:147–52. https://doi.org/10.4039/Ent116147-2.
82. Petrice TR, Haack RA, Strazanac JS, Lelito JP. Biology and larval morphology of *Agrilus subcinctus* (Coleoptera: Buprestidae), with comparisons to the emerald ash borer *Agrilus planipennis*. Great Lakes Entomol. 2009;42:173–84.
83. Campbell CL, McCaffrey JP. Population trends, seasonal phenology, and impact of *Chrysolina quadrigemina*, *C. hyperici* (Coleoptera: Chrysomelidae), and *Agrilus hyperici* (Coleoptera: Buprestidae) associated with *Hypericum perforatum* in northern Idaho. Environ Entomol. 1991;20:303–15. https://doi.org/10.1093/ee/20.1.303.
84. Poole EM, Ulyshen MD, Horn S, Cram M, Olatinwo R, Fraedrich S. Biology and distribution of *Agrilus macer* LeConte (Coleoptera: Buprestidae), a species associated with sugarberry (*Celtis laevigata* Willd.) mortality in the southeastern USA. Ann For Sci. 2019;76:7. https://doi.org/10.1007/s13595-018-0794-7.
85. Brooks FE. Life history of the hickory spiral borer *Agrilus arcuatus* Say. J Agric Res. 1926;33:331–8.
86. Akers RC, Herms DA, Nielsen DG. Emergence and adult biology of *Agrilus difficilis* (Coleoptera: Buprestidae), a pest of honeylocust, *Gleditsia triacanthos*. Great Lakes Entomol. 1986;19(1):1552. https://doi.org/10.22543/0090-0222.1552.
87. Rutledge CE, Keena MA. Mating frequency and fecundity in the emerald ash borer *Agrilus planipennis* (Coleoptera: Buprestidae). Ann Entomol Soc Am. 2012;105:66–72. https://doi.org/10.1603/AN11037.
88. Rutledge CE, Keena MA. Mating frequency and fecundity in *Agrilus anxius* (Coleoptera: Buprestidae). Ann Entomol Soc Am. 2012;105:852–8. https://doi.org/10.1603/AN12025.
89. Petrice TR, Bauer LS, Miller DL, Poland TM, Ravlin FW. A phenology model for simulating *Oobius agrili* (Hymenoptera: Encyrtidae) seasonal voltinism and synchrony with emerald ash borer oviposition. Environ Entomol. 2020;50(2):280–92. https://doi.org/10.1093/ee/nvaa169.
90. Loerch CR, Cameron EA. Natural enemies of immature stages of the bronze birch borer, *Agrilus anxius* (Coleoptera: Buprestidae), in Pennsylvania. Environ Entomol. 1983;12:1798–801. https://doi.org/10.1093/ee/12.6.1798.
91. Haavik LJ, Coleman TW, Flint ML, Venette RC, Seybold SJ. *Agrilus auroguttatus* (Coleoptera: Buprestidae) seasonal development within *Quercus agrifolia* (Fagales: Fagaceae) in southern California. Ann Entomol Soc Am. 2013;106:189–97. https://doi.org/10.1603/AN12112.
92. Gul H, Chaudhry MI. Studies on the application of Dyar's rule to the larval stages of shisham bark borer *Agrilus dalbergiae* Thery (Buprestidae: Coleoptera). Bull Zool. 1983;1:27–31.
93. Wei SJ, Zheng HH, Huangfu WG, Shi ZH, Chen XX. Division of larval instars of the citrus borer, *Agrilus auriventris* Saunders (Coleoptera Buprestidae). Acta Entomol Sinica. 2006;49:302–9.
94. Cui ZJ, Zhang YL, Zhang X, Luo ZH, Zhang P, Golec J, Poland TM, Zalucki MP, Han P, Lu ZZ. Life history and mortality factors of *Agrilus mali* Matsumura (Coleoptera: Buprestidae) in wild apples in Northwestern China. Agric For Entomol. 2019;21:309–17. https://doi.org/10.1111/afe.12333.
95. Anderson RF. The relation between host condition and attacks by the bronzed birch borer. J Econ Entomol. 1944;37:588–96. https://doi.org/10.1093/jee/37.5.588.
96. Crook DJ, Mastro VC. Chemical ecology of emerald ash borer *Agrilus planipennis*. J Chem Ecol. 2010;36:101–12.
97. Poland TM, Chen Y, Koch J, Pureswaran D. Review of the emerald ash borer (Coleoptera: Buprestidae), life history, mating behaviours, host plant selection, and host resistance. Can Entomol. 2015;147(3):252–62. https://doi.org/10.4039/tce.2015.4.
98. Silk PJ, Roscoe LE, Brophy M, Price J, Ryall KL. Influence of light on sound production behaviors in the emerald ash borer *Agrilus planipennis*. Entomol Exp Appl. 2008;166:844–53.
99. Silk PJ, Ryall K, Mayo P, Lemay M, Grant G, Crook D, Cossé A, Fraser I, Sweeney JD, Lyons DB, Pitt D, Scarr T, Magee D. Evidence for a volatile pheromone in *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae) that increases attraction to a host foliar volatile. Environ Entomol. 2011;40(4):904–16.

100. Silk P, Ryall K. Semiochemistry and chemical ecology of the emerald ash borer *Agrilus planipennis* (Coleoptera: Buprestidae). Can Entomol. 2015;147(3):277–89. https://doi.org/10.4039/tce.2014.58.
101. Silk PJ, Ryall K, Mayo P, MaGee DI, Leclair G, Fidgen J, Lavallee R, Price J, McConaghy J. A biologically active analog of the sex pheromone of the emerald ash borer *Agrilus planipennis*. J Chem Ecol. 2015;41:294–302. https://doi.org/10.1007/s10886-015-0562-1.
102. Silk PJ, Mayo P, Ryall K, Roscoe L. Semiochemical and communication ecology of the emerald ash borer, *Agrilus planipennis* (Coleoptera: Buprestidae). Insects. 2019;10:323.
103. Duan JJ. A novel oviposition trap for studying the egg-laying behavior of emerald ash borer. J Pest Sci. 2024. in press. https://doi.org/10.1007/s10340-024-01770-5.
104. Anulewicz AC, McCullough DG, Cappaert DL, Poland TM. Host Range of the emerald ash borer (*Agrilus planipennis* Fairmaire) (Coleoptera: Buprestidae) in North America: results of multiple-choice field experiments. Environ Entomol. 2008;37(1):230–41. https://doi.org/10.1603/0046-225X.
105. Rigsby CM, Muilenburg V, Tarpey T, Herms DA, Cipollini D. Oviposition preferences of *Agrilus planipennis* (Coleoptera: Buprestidae) for different ash species support the mother knows best hypothesis. Ann Entomol Soc Am. 2014;107(4):773–81. https://doi.org/10.1603/AN13185.
106. Rodriguez-Saona C, Poland TM, Miller JR, Stelinski LL, Grant GG, de Groot P, Buchan L, MacDonald L. Behavioral and electrophysiological responses of the emerald ash borer, *Agrilus planipennis*, to induced volatiles of Manchurian ash, *Fraxinus mandshurica*. Chemoecology. 2006;16:75–86. https://doi.org/10.1007/s00049-005-0329-1.
107. Vuts J, Woodcock CM, Sumner ME, Caulfield JC, Reed K, Inward DJG, Leather SR, Pickett JA, Birkett MA, Denman S. Responses of the two-spotted oak buprestid, *Agrilus biguttatus* (Coleoptera: Buprestidae), to host tree volatiles. Pest Manag Sci. 2016;72(4):845–51. https://doi.org/10.1002/ps.4208.
108. Dunn JP, Kimmerer TW, Nordin GL. Attraction of the twolined chestnut borer, *Agrilus bilineatus* (Weber) (Coleoptera: Buprestidae) and associated borers to volatiles of stressed white oak. Can Entomol. 1986;118(6):503–9. https://doi.org/10.4039/Ent118503-6.
109. Dunn JP, Kimmerer TW, Nordin GL. The role of host tree condition in attack of white oaks by the twolined chestnut borer, *Agrilus bilineatus* (Weber) (Coleoptera: Buprestidae). Oecologia. 1986;70:596–600. https://doi.org/10.1007/BF00379911.
110. Crook DJ, Krimian A, Francese J, Fraser I, Poland TM, Sawyer AJ, Mastro V. Development of a host-based semiochemical lure for trapping emerald ash borer *Agrilus planipennis* (Coleoptera: Buprestidae). Environ Entomol. 2008;37:356–65.
111. Ryall KL, Dutkiewicz D, Silk PJ, Antunes PM, Ochoa I. Ovarian development of *Agrilus planipennis*: effects of age and mating status and influence on attraction to host volatiles. Entomol Exp Appl. 2013;149(1):77–84. https://doi.org/10.1111/eea.12112.
112. Crook DJ, Francese JF, Zylstra KZ, Fraser I, Sawyer AJ, Bartels D, Lance DR, Mastro VC. Laboratory and field response of the emerald ash borer, *Agrilus planipennis* (Coleoptera: Buprestidae), to selected regions of the electromagnetic spectrum. J Econ Entomol. 2009;102:2160–9. https://doi.org/10.1603/029.102.0620.
113. Francese JA, Crook DJ, Fraser I, Lance DA, Sawyer AJ, Mastro VC. Optimization of trap color for the emerald ash borer, *Agrilus planipennis* (Coleoptera: Buprestidae). J Econ Entomol. 2010;103:1235–41. https://doi.org/10.1603/ec10088.
114. Petrice TR, Haack RA. Comparison of different trap colors and types for capturing adult *Agrilus* (Coleoptera: Buprestidae) and other buprestids. Great Lakes Entomol. 2015;48(1):45–66.
115. Santoiemma G, Williams D, Booth EG, Cavaletto G, Connell J, Curletti G, Groot DD, Devine SM, Enston A, Francese JA, Franzen EKL, Giasson M, Groznik E, Gutowski JM, Hauptman T, Hinterstoisser W, Hoch G, Hoppe B, Hughes C, Kostaniwicz C, Peterson DL, Plewa R, Ray AM, Sallé A, Sućko K, Sweeney J, Rooyen KV, Rassati D. Efficacy of trapping protocols for *Agrilus* jewel beetles: a multi-country assessment. J Pest Sci. 2024. in press. https://doi.org/10.1007/s10340-023-01728-z.
116. Evans HF, Moraal LG, Pajares JA. Biology, ecology and economic importance of Buprestidae and Cerambycidae. In: Lieutier F, Day KR, Battisti A, Gregoire JC, Evans HF, editors. Bark and Wood Boring Insects in Living Trees in Europe, a Synthesis. Dordrecht: Kluwer; 2004. pp. 447–474.
117. Sakalian V, Langourov M. Colour traps a method for distributional and ecological investigations of Buprestidae (Coleoptera). Acta Societatis Zoologicae Bohemicae. 2004;68:53–9.
118. Campbell JW, Hanula JL. Efficiency of malaise traps and colored pan traps for collecting flower visiting insects from three forested ecosystems. J Insect Conserv. 2007;11:399–408. https://doi.org/10.1007/s10841-006-9055-4.
119. Pureswaran DS, Poland TM. Effects of visual silhouette, leaf size and host species on feeding preference by adult emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae). Great Lakes Entomol. 2009;42(1&2):62–71.
120. Pureswaran DS, Poland TM. Host selection and feeding preference of *Agrilus planipennis* (Coleoptera: Buprestidae) on ash (*Fraxinus* spp.). Environ Entomol. 2009;38(3):757–65. https://doi.org/10.1603/022.038.0328.
121. Chen Y, Poland TM. Interactive influence of leaf age, light intensity, and girdling on green ash foliar chemistry and emerald ash borer development. J Chem Ecol. 2009;35(7):806–15. https://doi.org/10.1007/s10886-009-9661-1.
122. Chen Y, Poland TM. Biotic and abiotic factors affect green ash volatile production and emerald ash borer adult feeding preference. Environ Entomol. 2009;38(6):1756–64. https://doi.org/10.1603/022.038.0629.
123. Chen Y, Whitehill JG, Bonello P, Poland TM. Differential response in foliar chemistry of three ash species to emerald ash borer adult feeding. J Chem Ecol. 2011;37(1):29–39. https://doi.org/10.1007/s10886-010-9892-1.
124. Saint-Germain M, Buddle CM, Drapeau P. Substrate selection by saprophagous wood-borer larvae within highly variable hosts. Entomol Exp Appl. 2010;134(3):227–33. https://doi.org/10.1111/j.1570-7458.2009.00960.x.
125. Paine TD. Application of chemical cues in arthropod management for forest trees. In: Wajnberg E, Colazza S, editors. Chemical Ecology of Insect Parasitoids. Hoboken: Wiley; 2013. p. 282–95.
126. Joyce AL, Millar JG, Gill JS, Singh M, Tanner D, Paine TD. Do acoustic cues mediate host finding by *Syngaster lepidus* (Hymenoptera: Braconidae)? Biocontrol. 2011;56:145–53. https://doi.org/10.1007/s10526-010-9321-y.
127. Jiang W, Chen Z, Zhang H. A time-frequency domain mixed attention-based approach for classifying wood-boring insect feeding vibration signals using a deep learning model. Insects. 2024;15(4):282. https://doi.org/10.3390/insects15040282.
128. Cerkvenik U. Biomechanics of a parasitic wasp ovipositor. Dissertation: Wageningen University; 2019. pp. 225.
129. Hespenheide HA. Larval feeding site of species of *Agrilus* (Coleoptera) using a common host plant. Oikos. 1969;20:558–61. https://doi.org/10.2307/3543220.
130. Hespenheide HA. Patterns in the use of single plant hosts by wood-boring beetles. Oikos. 1976;27:161–4. https://doi.org/10.2307/3543446.
131. Nielsen DG, Muilenburg VL, Herms DA. Interspecific variation in resistance of Asian, European, and North American Birches

(*Betula* spp.) to bronze birch borer (Coleoptera: Buprestidae). Environ Entomol. 2011;40(3):648–53. https://doi.org/10.1603/EN10227.
132. Dang Y, Wei K, Wang X, Duan JJ, Jennings DE, Poland TM. Introduced plants induce outbreaks of a native pest and facilitate invasion in the plants' native range: Evidence from the emerald ash borer. J Ecol. 2022;110(3):593–604. https://doi.org/10.1111/1365-2745.13822.
133. Herms DA. Host range and host resistance. In: Van Driesche RG, Reardon R, editors. Biology and control of emerald ash borer; Technical Bulletin FHTET 2014–09. Morgantown, WV: USDA Forest Service Forest Health Technology Enterprise; 2015. p. 65–73.
134. Orlova-Bienkowskaja MJ, Drogvalenko AN, Zabaluev IA, Sazhnev AS, Peregudova EY, Mazurov SG, Komarov EV, Struchaev VV, Martynov VV, Nikulina TV, Bieńkowski AO. Current range of *Agrilus planipennis* Fairmaire, an alien pest of ash trees, in European Russia and Ukraine. Ann For Sci. 2020;77:29. https://doi.org/10.1007/s13595-020-0930-z.
135. Nichols JO. Oak mortality in Pennsylvania: a ten-year study. J For. 1968;66:681–94. https://doi.org/10.1093/jof/66.9.681.
136. Jones EA, Reed DD, Mroz GD, Liechty HO, Cattelino PJ. Climate stress as a precursor to forest decline: paper birch in northern Michigan, 1985–1990. Can J For Res. 1993;23:229–33. https://doi.org/10.1139/x93-030.
137. Vansteenkiste D, Tirry L, van Acker J, Stevens M. Predispositions and symptoms of *Agrilus* borer attack in declining oak trees. Ann For Sci. 2004;61:815–23. https://doi.org/10.1051/forest:2004076.
138. Parrott PJ. Some insects attacking the pear, and their control. New York Agric Expt Stn.: Geneva; 1916. Circular No. 51, pp. 18.
139. Sever A, Cranshaw W, Brudenell R. *Agrilus quercicola* (Fisher) (Coleoptera: Buprestidae), the Gambel oak borer, as a pest of *Quercus* spp. Southwest Entomol. 2012;37(2):147–50. https://doi.org/10.3958/059.037.0207.
140. Coleman TW, Grulke NE, Daly M, Godinez C, Schilling SL, Riggan PJ, et al. Coast live oak, *Quercus agrifolia*, susceptibility and response to goldspotted oak borer, *Agrilus auroguttatus*, injury in southern California. For Ecol Manag. 2011;261:1852–65. https://doi.org/10.1016/j.foreco.2011.02.008.
141. Lu Z, Liu X, Wang T, Zhang P, Wang Z, Zhang Y, Kriticos DJ, Zalucki MP. Malice at the Gates of Eden: current and future distribution of *Agrilus mali* threatening wild and domestic apples. Bull Entomol Res. 2022;112(6):745–57. https://doi.org/10.1017/S000748532200013X.
142. Liu H, Bauer LS, Miller DL, Zhao T, Gao R, Song L, Luan Q, Jin R, Gao C. Seasonal abundance of *Agrilus planipennis* (Coleoptera: Buprestidae) and its natural enemies *Oobius agrili* (Hymenoptera: Encyrtidae) and *Tetrastichus planipennisi* (Hymenoptera: Eulophidae) in China. Biol Control. 2007;42:61–71. https://doi.org/10.1016/j.biocontrol.2007.03.011.
143. Rebek EJ, Herms DA, Smitley DR. Interspecific variation in resistance to emerald ash borer (Coleoptera: Buprestidae) among North American and Asian ash (*Fraxinus* spp.). Environ Entomol. 2008;37(1):242–6. https://doi.org/10.1603/0046-225X.
144. Koch JL, Carey DW, Mason ME, Poland TM, Knight KS. Intraspecific variation in *Fraxinus pennsylvanica* responses to emerald ash borer (*Agrilus planipennis*). New For. 2015;46(5–6):995–1011. https://doi.org/10.1007/s11056-015-9494-4.
145. Stanley RK, Carey DW, Mason ME, Doran A, Wolf J, Otoo KO, Poland TM, Koch JL, Jones AD, Romero-Severson J. Emerald ash borer (*Agrilus planipennis*) infestation bioassays and metabolic profiles of green ash (*Fraxinus pennsylvanica*) provide evidence for an induced host defensive response to larval infestation. Front For Glob Change. 2023;6:1166421. https://doi.org/10.3389/ffgc.2023.1166421.
146. Cipollini D, Wang Q, Whitehill JGA, Powell J, Bonello P, Herms D. Distinguishing defensive characteristics in the phloem of ash species resistant and susceptible to emerald ash borer. J Chem Ecol. 2011;37(5):450–9. https://doi.org/10.1007/s10886-011-9954-z.
147. Whitehill JGA, Opiyo SO, Koch JL, Herms DA, Cipollini DF, Bonello P. Interspecific comparison of constitutive ash phloem phenolic chemistry reveals compounds unique to Manchurian ash, a species resistant to emerald ash borer. J Chem Ecol. 2012;38:499–511. https://doi.org/10.1007/s10886-012-0125-7.
148. Whitehill JGA, Rigsby CM, Cipollini D, Herms D, Bonello P. Decreased emergence of emerald ash borer from ash (*Fraxinus* spp.) treated with methyl jasmonate is associated with induction of general defense traits and the toxic phenolic compound verbascoside. Oecologia. 2014;176(4):1047–59. https://doi.org/10.1007/s00442-014-3082-8.
149. Villari C, Herms DA, Whitehill JGA, Cipollini D, Bonello P. Progress and gaps in understanding mechanisms of ash tree resistance to emerald ash borer, a model for wood-boring insects that kill angiosperms. New Phytol. 2016;209(1):63–79. https://doi.org/10.1111/nph.13604.
150. Cappaert D, McCullough DG. Occurrence and seasonal abundance of *Atanycolus cappaerti* (Hymenoptera: Buprestidae), a native parasitoid of emerald ash borer, *Agrilus planipennis* (Coleoptera: Buprestidae). Great Lakes Entomol. 2009;42:16–29.
151. Duan JJ, Bauer LS, Abell KJ, Ulyshen MD, Van Driesche RG. Population dynamics of an invasive forest insect and associated natural enemies in the aftermath of invasion: implications for biological control. J Appl Ecol. 2015;52(5):1246–54. https://doi.org/10.1111/1365-2664.12485.
152. Duan JJ, Yurchenko G, Fuester RW. Occurrence of emerald ash borer (Coleoptera: Buprestidae) and biotic factors affecting its immature stages in the Russian Far East. Environ Entomol. 2012;41:245–54. https://doi.org/10.1603/EN11318.
153. Yang Z-Q, Wang X-Y, Yao Y-X, Gould JR, Cao ML. A new species of *Sclerodermus* (Hymenoptera: Bethylidae) parasitizing *Agrilus planipennis* (Coleoptera: Buprestidae) from China, with a key to Chinese species in the genus. Ann Entomol Soc Am. 2012;105(5):619–27. https://doi.org/10.1603/AN12017.
154. Duan JJ, Schmude JM, Petrice T, Bauer LS, Poland T, Chandler J, Crandall R, Elkinton JS, Driesche RV. Successful establishment, spread, and impact of the introduced parasitoid *Spathius galinae* (Hymenoptera: Braconidae) on emerald ash borer (Coleoptera: Buprestidae) populations in post-invasion forests in Michigan. J Econ Entomol. 2023;116(5):1518–28. https://doi.org/10.1093/jee/toad149.
155. Orlova-Bienkowskaja MJ, Belokobylskij SA. Discovery of the first European parasitoid of the emerald ash borer *Agrilus planipennis* (Coleoptera: Buprestidae). Eur J Entomol. 2014;111:594–6. https://doi.org/10.14411/eje.2014.061.
156. Taylor PB, Duan JJ, Fuester RW, Hoddle M, Van Driesche RG. Parasitoid guilds of *Agrilus* woodborers (Coleoptera: Buprestidae): their diversity and potential for use in biological control. Psyche. 2012;Article 819329:1–10. https://doi.org/10.1155/2012/813929.
157. Vétek G, Thuróczy C, Pénzes B. Notes on the parasitoids of the raspberry cane midge, *Resseliella theobaldi* (Barnes, 1927) (Diptera: Cecidomyiidae) and the rose stem girdler, *Agrilus cuprescens* (Ménétriés 1832) (Coleoptera: Buprestidae). IOBC Bulletin. 2008;39:51–64.
158. Tsolova E, Koleva L. Management and control of *Agrilus aurichalceus* Redt. (Coleoptera: Buprestidae) in biological raspberry production. 3rd International Symposium for Agriculture and Food-ISAF 2017. 2018; pp. 26–31. https://doi.org/10.55302/JAFES18723026t.

159. Gould JR, Hickin M, Fierke MK. Mortality of emerald ash borer larvae in small regenerating ash in New York forests. J Econ Entomol. 2022;115(5):1442–54.
160. O'Dea JK, Milnes JM, Triapitsyn SV, Rugman-Jones PV. *Baryscapus rugglesi* (Rohwer, 1919) (Hymenoptera: Eulophidae) discovered in western North America: Redescription, notes on biology, and implications as a parasitoid of its host, *Agrilus cuprescens* (Ménétries, 1832) (Coleoptera: Buprestidae). Pan-Pac Entomol. 2023;99(4):246–65. https://doi.org/10.3956/2023-99.4.246.
161. Braza RD. Parasitoids of immature stages of *Agrilus sexsignatus* (Fisher) (Coleoptera: Buprestidae) attacking *Eucalyptus deglupta* Blume in Surigao del Sur. Philippine Entomol. 1989;7(5):479–83.
162. Morin RS, Liebhold AM, Pugh SA, Crocker SJ. Regional assessment of emerald ash borer, *Agrilus planipennis*, impacts in forests of the eastern United States. Biol Invasions. 2017;19:703–11. https://doi.org/10.1007/s10530-016-1296-x.
163. Zhang YZ, Huang DW, Zhao TH, Liu HP, Bauer LS. Two new species of egg parasitoids (Hymenoptera: Encyrtidae) of woodboring beetle pests from China. Phytoparasitica. 2005;53:253–60.
164. Triapitsyn SV, Petrice TR, Gates MW, Bauer LS. Two new species of Oobius Trjapitzin (Hymenoptera, Encyrtidae) egg parasitoids of *Agrilus* spp. (Coleoptera, Buprestidae) from the USA, including a key and taxonomic notes on other congeneric Nearctic taxa. Zookeys. 2015;498:29–50. https://doi.org/10.3897/zookeys.498.9357.
165. Yao XY, Duan JJ, Hopper KP, Mottern JL, Gates MW. A new species of *Oobius* Trjapitzin (Hymenoptera: Encyrtidae) from the Russian Far East that parasitizes eggs of emerald ash borer (Coleoptera: Buprestidae). Ann Entomol Soc Am. 2016;109:629–38. https://doi.org/10.1093/aesa/saw022.
166. Duan JJ, Schmude JM, Larson KM, Fuester RW, Gould JR, Ulyshen MD. Field parasitism and host specificity of *Oobius primorskyensis* (Hymenoptera: Encyrtidae), an egg parasitoid of the emerald ash borer (Coleoptera: Buprestidae) in the Russian Far East. Biol Control. 2019;130:44–50. https://doi.org/10.1016/j.biocontrol.2018.12.005.
167. Yao YX, Duan JJ, Mottern JL, Wang XY, Yang ZQ, Bauer LS, Gates NW. Two new species of *Oobius* (Hymenoptera: Encyrtidae) and their phylogenetic relationship with other congeners from northeastern Asia. Can Entomol. 2018;150:303–16. https://doi.org/10.4039/tce.2018.17.
168. Noyes JS. A new genus and species of encyrtid (Hymenoptera, Chalcidoidea) parasitoid of the eggs of the varicose borer, *Agrilus sexsignatus* (Fisher) (Coleoptera, Buprestidae), a pest of bagras (*Eucalyptus deglupta* Blume) in the Philippines. J Nat Hist. 1990;24(1):21–5.
169. Nash RW, Duda EJ. Gray NH. Studies on extensive dying, regeneration, and management of birch. Maine Forest Service Bulletin 1951; No.15.
170. Marsh PM. Family Braconidae. Washington, DC, USA: Smithsonian Institution Press; 1979.
171. Bauer LS, Liu HP, Haack RA, Miller DL, Petrice TR. Natural enemies of emerald ash borer in southeastern Michigan. Proceedings of the Emerald Ash Borer Research and Technology Meeting. Michigan, USA: USDA FS FTET, Port Huron; 2004.
172. Duan JJ, Bauer LS, Abell KJ, Driesche RV. Population responses of hymenopteran parasitoids to the emerald ash borer (Coleoptera: Buprestidae) in recently invaded areas in north central United States. Biocontrol. 2012;57:199–209. https://doi.org/10.1007/s10526-011-9408-0.
173. Duan JJ, Taylor PB, Fuester RW, Kula RR, Marsh PM. Hymenopteran parasitoids attacking the invasive emerald ash borer (Coleoptera: Buprestidae) in western and central Pennsylvania. Fla Entomol. 2013;96:166–72. https://doi.org/10.1653/024.096.0122.
174. Cao LM, Zhang YL, Achterberg CA, Wang ZY, Wang XY, Zhao WX, Yang ZQ. Notes on braconid wasps (Hymenoptera, Braconidae) parasitizing on *Agrilus mali* Matsumura (Coleoptera, Buprestidae) in China. ZooKeys 2019;867:97–121. https://zookeys.pensoft.net/issue/1831.
175. Hopkins AD. The raspberry gouty-gall beetle. Bulletin 15. Morgantown, W Va Agr Exp St Bull. 1891;2(3):81–4.
176. Kailidis DS. Beobachtungen ¨uber zwei Pappelsch¨adlinge in Griechenland. [Observations on two poplar pests in Greece.]. Anz Schadl. 168:41:38–41.
177. Muesebeck CFW, Walkley LM. Family Braconidae, in Hymenoptera of America North of Mexico—Synoptic catalog. In: Muesebeck CFW, Krombein KV, Townes HK, editors. U.S. Department of Agriculture Monograph. 1951. pp. 90–184.
178. Kula RR, Cappaert DL, Gandhi JK, Knight KS, Bauer LS, Rebbeck J. *Leluthia astigma* (Ashmead) (Hymenoptera: Braconidae: Doryctinae) as a parasitoid of *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae: Agrilinae), with an assessment of host associations for nearctic species of *Leluthia* Cameron. P Entomol Soc Wash. 2010;112(2):246–57. https://doi.org/10.4289/0013-8797-112.2.246.
179. Amrine JW Jr. Multiflora rose. In: Van Driesche R, Blossey B, Hoddle M, Lyon S, Reardon R. (eds). US Department of Agriculture Forest Service Publication FHTET-2002–04: Biological Control of Invasive Plants in the Eastern United States. Washington D.C.: United States Department of Agriculture; 2002. pp. 265–292 iv + 413.
180. Yang ZQ, Wang XY, Gould JR, Wu H. Host specificity of *Spathius agrili* Yang (Hymenoptera: Braconidae), an important parasitoid of the emerald ash borer. Biol Control. 2008;47(2):216–21. https://doi.org/10.1016/j.biocontrol.2008.08.001.
181. Yang ZQ, Wang XY, Gould JR, et al. Biology and behavior of *Spathius agrili*, a parasitoid of the emerald ash borer, *Agrilus planipennis*, in China. J Insect Sci. 2010;10(1):30. https://doi.org/10.1673/031.010.3001.
182. Belokobylskij SA, Yurchenko GI, Strazanac JS, Zaldívar-Riverón A, Mastro V. A new emerald ash borer (Coleoptera: Buprestidae) parasitoid species of *Spathius* Nees (Hymenoptera: Braconidae: Doryctinae) from the Russian Far East and South Korea. Ann Entomol Soc Am. 2012;105:165–78. https://doi.org/10.1603/AN11140.
183. Moraal LG, van Achterberg C. *Spathius curvicaudis* (Hymenoptera: Braconidae) new for The Netherlands; a parasitoid of the oak buprestid beetle, *Agrilus biguttatus* (Coleoptera: Buprestidae). Entomologische Berichten. 2001;6(11):165–8.
184. Haack RA, Benjamin DM, Schuh BA. Observations of the biology of *Phasgonophora sulcata* (Hymenoptera: Chalcididae), a larval parasitoid of the twolined chestnut borer, *Agrilus bilineatus* (Coleoptera: Buprestidae), in Wisconsin. Great Lakes Entomol. 1981;14:113–6. https://doi.org/10.22543/0090-0222.1386.
185. Wang XY, Cao LM, Yang ZQ, Duan JJ, Gould JR, Bauer LS. Natural enemies and their impacts on emerald ash borer populations in its native range, with new records of parasitism by two species of beetles. Can Entomol. 2016;148:329–42. https://doi.org/10.4039/tce.2015.57.
186. Duan JJ, Fuester RW, Wildonger J, Taylor PB, Barth S, Spichiger SE. Parasitoids attacking the emerald ash borer (Coleoptera: Buprestidae) in Western Pennsylvania. Fla Entomol. 2009;92(4):588–92. https://doi.org/10.1653/024.092.0409.
187. Pfeiffer DG. Rednecked cane borer, *Agrilus ruficollis* (F.) Virginia Cooperative Extension Publication (ENTO-210NP). Blacksburg, VA, USA: Virginia Tech State University; 2016.
188. Liu H, Bauer LS. Microbial control of emerald ash borer, *Agrilus planipennisi* (Coleoptera: Buprestidae) with *Beauveria bassiana* strain GHA: Greenhouse and field trials. Biol Control.

2008;45(1):124–32. https://doi.org/10.1016/j.biocontrol.2007.12.008.
189. Kyei-Poku G, Gauthier D, Schwarz R, Frankenhuyzen KV. Morphology, molecular characteristics and prevalence of a *Cystosporogenes* species (Microsporidia) isolated from *Agrilus anxius* (Coleoptera: Buprestidae). J Invertebr Pathol. 2011;107:1–10. https://doi.org/10.1016/j.jip.2010.12.010.
190. Johny S, Kyei-Poku G. A molecular tool for detection and tracking of a potential indigenous *Beauveria bassiana* strain for managing emerald ash borer populations in Canada. J Invertebr Pathol. 2014;122:16–21. https://doi.org/10.1016/j.jip.2014.07.005.
191. Duan JJ, Schmude JM, Larson K. Effects of low temperature exposure on diapause, development, and reproductive fitness of the emerald ash borer (Coleoptera: Buprestidae): implications for voltinism and laboratory rearing. J Econ Entomol. 2021;114:201–8. https://doi.org/10.1093/jee/toaa252.
192. Reed K, Denman S, Leather SR, Forster J, Inward DJG. The lifecycle of *Agrilus biguttatus*: the role of temperature in its development and distribution, and implications for acute oak decline. Agric For Entomol. 2018;20:334–46. https://doi.org/10.1111/afe.12266.
193. Gould JR, Warden ML, Slager BH, Murphy TC. Host overwintering phenology and climate change influence the establishment of *Tetrastichus planipennisi* Yang (Hymenoptera: Eulophidae), a larval parasitoid introduced for biocontrol of the emerald ash borer. J Econ Entomol. 2020;6:2641–9. https://doi.org/10.1093/jee/toaa217.
194. Raghuvir NN. Biology and control of the rose stem girdler, *Agrilus rubicola communis*, Obenb., on raspberry. Dissertation. Logan: UT, Utah State University; 1962.
195. Jones BA. Invasive species impacts on human well-being using the life satisfaction index. Ecol Econ. 2017;134:250–7. https://doi.org/10.1016/j.ecolecon.2017.01.002.
196. Duan JJ, Watt T, Larson K, Taylor P, Lelito JP. Effects of ambient temperature on egg and larval development of the invasive emerald ash borer (Coleoptera: Buprestidae): implications for laboratory Rearing. J Econ Entomol. 2013;2013(106):2101–8. https://doi.org/10.1603/EC13131.
197. Ayres MP, Lombardero MJ. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. Sci Total Environ. 2000;262:263–86. https://doi.org/10.1016/S0048-9697(00)00528-3.
198. Holopainen JK, Virjamo V, Ghimire RP, Blande JD, Julkunen-Tiitto R, Kivimäenpää M. Climate change effects on secondary compounds of forest trees in the Northern Hemisphere. Fron Plant Sci. 2018;9:1–10. https://doi.org/10.3389/fpls.2018.01445.
199. Hamann E, Blevins C, Franks SJ, Jameel JI, Anderson JT. Climate change alters plant–herbivore interactions. New Phytol. 2021;2021(229):1894–910. https://doi.org/10.1111/nph.17036.
200. Haack RA. Will global warming alter paper birch susceptibility to bronze birch borer attack? In: Mattson WJ, Niemela P, Rousi M, editors. Dynamics of forest herbivory: quest for pattern and principle. St. Paul, MN: USDA Forest Service General Technical Report, North Central Forest Experiment Station; 1996. pp. 234–47.
201. Haavik LJ, Billings SA, Guldin JM, Stephen FM. Emergent insects, pathogens and drought shape changing patterns in oak decline in North America and Europe. For Ecol Manage. 2015;354:190–205. https://doi.org/10.1016/j.foreco.2015.06.019.
202. Haack RA, Petrice TR. Historical population increases and related inciting factors of *Agrilus anxius*, *Agrilus bilineatus*, and *Agrilus granulatus liragus* (Coleoptera: Buprestidae) in the Lake States (Michigan, Minnesota, and Wisconsin). Great Lakes Entomol. 2019;52:21–33. https://doi.org/10.22543/0090-0222.2337.
203. Bauer LS, Duan JJ, Gould JR, Van Driesche RG. Progress in the classical biological control of *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae) in North America. Can Entomol. 2015;147:300–17. https://doi.org/10.4039/tce.2015.18.
204. Duan JJ, Jennings ED, Williams D, Larson KM. Patterns of parasitoid host utilization and development across a range of temperatures: implications for biological control of an invasive forest pest. Biocontrol. 2014;59:659–69. https://doi.org/10.1007/s10526-014-9604-9.
205. Kovacs FK, Haight RG, McCullough DG, Mercader RJ, Siegert NW, Leibhold AM. Cost of potential emerald ash borer damage in U.S. communities, 2009–2019. Ecol Econ. 2010;69:569–78. https://doi.org/10.1016/j.ecolecon.2009.09.004.
206. Aukema JE, Leung B, Kovacs K, Chivers C, Britton KO, Englin J, et al. Economic Impacts of non-native forest insects in the continental United States. PLoS ONE. 2011;6(9):e24587. https://doi.org/10.1371/journal.pone.0024587.
207. Jennings ED, Duan JJ, Bean D, Kimberly AR, Williams GL, Bells SK, Shurtleff AS, Shrewsbury PM. Effects of the emerald ash borer invasion on the community composition of arthropods associated with ash tree boles in Maryland, U.S.A. Agri Forest Entomol. 2017;19:122–9. https://doi.org/10.1111/afe.12186.
208. Klooster WS, Gandhi KJ, Long LC, Perry KI, Rice KB, Herms DA. Ecological impacts of emerald ash borer in forests at the epicenter of the invasion in North America. Forests. 2018;9(5):250. https://doi.org/10.3390/f9050250.
209. Engelken P, Benbow ME, McCullough DG. Legacy effects of emerald ash borer on riparian forest vegetation and structure. For Ecol Manag. 2020;457:117684. https://doi.org/10.1016/j.foreco.2019.117684.
210. Engelken P, McCullough DG. Riparian forest conditions along three northern Michigan rivers following emerald ash borer invasion. Can J For Res. 2020;50:800–10. https://doi.org/10.1139/cjfr-2019-0387.
211. Jacobsen A. Emerald ash borer in the ash (*Fraxinus* spp.)-dominated tidal swamps of the lower Patuxent River. Maryland Northeastern Nat. 2020;27:817–40. https://doi.org/10.1656/045.027.0419.
212. Baron JN, Rubin BD. Secondary invasion? Emerald ash borer (*Agrilus planipennis*) induced ash (*Fraxinus* spp.) mortality interacts with ecological integrity to facilitate European buckthorn (Rhamnus cathartica). Can J For Res. 2021;51:455–64. https://doi.org/10.1139/cjfr-2020-0134.
213. Straw AN, Williams DT, Kulinich O, Gninenko YI. Distribution, impact, and rate of spread of emerald ash borer *Agrilus planipennis* (Coleoptera: Buprestidae) in the Moscow region of Russia. For: Int J For Res. 2013;86:515–22. https://doi.org/10.1093/forestry/cpt031.
214. Wei X, Reardon D, Wu Y, Sun JH. Emerald ash borer, *Agrilus planipennis*, in China: a review and distribution survey. Acta Entomol Sinica. 2004;47:679–85.
215. Aminaee MM, Zare R, Zohdi H. An investigation on *Lecanicillium muscarium* as a biocontrol agent of stem borer pests of *Rosa damascena* in Kerman Province of Iran. Arch Phytopathol Plant Prot. 2010;43(7):678–88.
216. Tanasković S, Sretenović D, Inđić D, Vuković S, Gvozdenac S. Economically important pests in raspberry and blackberry plantings. Biljni lekar. 2012;40(5):391–9.
217. Larson DJ. The rose stem girdler (*Agrilus aurichalceus* Redtenbacher) (Insecta: Coleoptera: Buprestidae), a new threat to prairie roses. Blue Jay. 2003;61(3):176–8.
218. Larson DJ. Notes and observations on the rose stem girdler (*Agrilus cuprescens* Ménétriés) (Insecta: Coleoptera: Buprestidae) in southern Alberta and Saskatchewan. Blue Jay. 2009;67(2):82–5.
219. Haldeman SS. The *Agrilus ruficollis*. Am Q J Agric Sci. 1846;4(7):300–1.
220. Hixson E. The red-necked cane borer. Oklahoma Agricultural Experiment Station. Circular. 1939;18:2.

221. Tanaka K. On *Agrilus auriventris*, Saund., a serious pest of citrus. Agric Hort. 1928;3(12):1437–44.
222. Zheng H-H, Wei S-J, Huangfu W-G, Shi Z-H, Chen X-X. Spatial distribution pattern of *Agrilus auriventris* Saunders (Coleoptera: Buprestidae). Acta Entomol Sinica. 2006;49(5):805–9.
223. Jendek E, Nakládal O. Revision of citrus trees pests of *Agrilus angulatus* species–group (Coleoptera, Buprestidae) from South and Southeast Asia with description of one new species. J Asia-Pac Entomol. 2019;22(1):316–32.
224. Matsumura S. Life history of *Agrilus mali* Mats (Buprestidae). In: Muramatsu S, editor. Bionomics on Apple Trees in China and Korea. 1924. p. 1–21.
225. Zhang X, Zhang YL, Zhang P, Cui ZJ, Han P, Gao GZ, Poland TM, Zalucki MP, Lu ZZ. *Agrilus mali* Matsumura (Coleoptera: Buprestidae) density and damage in wild apple *Malus sieversii* (Rosales: Rosaceae) forests in Central Eurasia under four different management strategies. Entomologia Generalis. 2021;41(3):257–66.
226. Moraglio ST, Corte M, Tavella L. Occurrence and impact of *Agrilus* spp. and associated egg parasitoids in hazel groves of Northwest Italy. J Appl Entomol. 2013;137(10):761–72. https://doi.org/10.1111/jen.12057.
227. Wapshere AJ. Recent work in Europe on biological control of *Hypericum perforatum* (Guttiferae) for Australia. Entomophaga. 1984;29:145–56.
228. Northcroft EF. The blackberry pest. N Z J Agric. 1928;36(4):261–75.
229. Picard F. Les insectes du groseillier et du framboisier. Le Progres Agricole Viticole. 1914;49(23):713–20.
230. Walton RR. Control of the red-necked cane borer on prostrate brambles by summer pruning. J Econ Entomol. 1951;44(6):950–4.
231. McCullough DG. Challenges, tactics and integrated management of emerald ash borer in North America. Forestry. 2020;93(2):197–211. https://doi.org/10.1093/forestry/cpz049.
232. Mercader RJ, McCullough DG, Storer AJ, Bedford JM, Heyd R, Poland TM, et al. Evaluation of the potential use of a systemic insecticide and girdled trees in area wide management of the emerald ash borer. For Ecol Manage. 2015;350:70–80.
233. Herms DA, McCullough DG, Clifford CS, Smitley DR, Miller FD, Cranshaw W. Insecticide options for protecting ash trees from emerald ash borer. North Central IPM Center Bulletin. 3rd Edition. 2019; pp. 16 x. https://www.emeraldashborer.info/documents/Multistate_EAB_Insecticide_Fact_Sheet.pdf
234. Sadof CS, Mockus L, Ginzel MD. Factors influencing efficacy of an area-wide pest management program in three urban forests. Urban For Urban Gree. 2021;58:126965. https://doi.org/10.1016/j.ufug.2020.126965.
235. Poland TM, McCullough DG. Emerald ash borer. Invasion of the urban forest and the threat to North America's ash resource. J For. 2006;104(3):118–24. https://doi.org/10.1093/jof/104.3.118.
236. Francese JA, Mastro VC, Oliver JB, Lance DR, Youseff N, Lavalee SG. Evaluation of colors for trapping *Agrilus planipennis* (Coleoptera: Buprestidae). J Entomol Sci. 2005;40:93–5.
237. Poland TM, Petrice TR, Ciaramitaro TM. Trap designs, colors, and lures for emerald ash borer detection. Front For Glob Change. 2019;2:80. https://doi.org/10.3389/ffgc.2019.00080.
238. Coleman TW, Chen Y, Graves AD, Hishinuma SM, Grulke NE, Flint ML, Seybold SJ. Developing monitoring techniques for the invasive goldspotted oak borer (Coleoptera: Buprestidae) in California. Environ Entomol. 2014;43(3):729–43. https://doi.org/10.1603/EN13162.
239. Imrei Z, Lohonyai Z, Muskovits J, Matula E, Vuts J, Fail J, Gould PJL, Birkett MA, Tóth M. Domingue MJ: Developing a non-sticky trap design for monitoring jewel beetles. J Appl Entomol. 2020;144:224–31. https://doi.org/10.1111/jen.12727.
240. Evans HF, Williams D, Hoch G, Loomans A, Marzano M. Developing a European Toolbox to manage potential invasion by emerald ash borer (*Agrilus planipennis*) and bronze birch borer (*Agrilus anxius*), important pests of ash and birch. For: Int J For Res. 2020;93(2):87–96. https://doi.org/10.1093/forestry/cpz074.
241. Kuhn A, San Martin G, Hasbroucq S, Beliën T, Bonte J, Bouget C, et al. Enhancing Buprestidae monitoring in Europe: Trap catches increase with a fluorescent yellow colour but not with the presence of decoys. PLoS ONE. 2024;19(7):e0307397. https://doi.org/10.1371/journal.pone.0307397.
242. Duan JJ, Van Driesche RG, Schmude JM, Crandall R, Rutledge C, Quinn NF, Slager BH, Gould JR, Elkinton JS. Significant suppression of invasive emerald ash borer by introduced parasitoids: potential for North American ash recovery. J Pest Sci. 2022;95:1081–90.
243. Mapbiocontrol. Agent release tracking and data management for federal, state, and researchers releasing biocontrol agents for management of the emerald ash borer. 2024; Available online: http://www.mapbiocontrol.org/. Accessed 15 Apr 2024.
244. Hanover JW. Physiology of tree resistance to insects. Annu Rev Entomol. 1975;20:75–95.
245. Nielsen DG. Exploiting natural resistance as a management tactic for landscape plants. Fla Entomol. 1989;72:413–81.
246. Herms DA. Understanding the biology and management of wood-borers. Part I: Fatheaded borers. Tree Care Ind. 2003;19:8–17.
247. Johnson DT, Mayes RL. Biology and control of the red necked cane borer *Agrilus ruficollis* (F) (Coleoptera Buprestidae) on blackberries in Arkansas. J Entomol Sci. 1989;24(2):204–8. https://doi.org/10.18474/0749-8004-24.2.204.
248. Ball J, Simmons G. The relationship between bronze birch borer and birch dieback. J Aboriculture. 1980;6(12):309–14. https://doi.org/10.48044/jauf.1980.075.
249. Nielsen DG. The hidden enemy. Weeds, trees, and turf. 1985;24:48–60.
250. Katovich S, Wawrzynski R, Haugen D, Spears B. How to grow and maintain a healthy birch tree. NA-FR-02–97. Radnor, PA: U.S. Dep. of Agriculture, Forest Service, Northern Area State & Private Forestry; 1997.
251. Herms DA. Effects of fertilization on insect resistance of woody ornamental plants: reassessing an entrenched paradigm. Environ Entomol. 2002;2002(31):923–33. https://doi.org/10.1603/0046-225X-31.6.923.
252. Katovich SA, Munson AS, Ball J, McCullough DG. Bronze birch borer. Washington DC: U. S. Forest Service Forest Insect Disease Leaflet No. 111; 2000.
253. Looney CE, D'Amato AW, Palik BJ, Slesak RA, Slater MA. The response of *Fraxinus nigra* forest ground-layer vegetation to emulated emerald ash borer mortality and management strategies in northern Minnesota, USA. For Ecol Manage. 2021;389:352–63. https://doi.org/10.1016/j.foreco.2016.12.028.
254. Palik BJ, D'Amato AW, Slesak RA, Kastendick D, Looney C, Kragthorpe J. Eighth-year survival and growth of planted replacement tree species in black ash (*Fraxinus nigra*) wetlands threatened by emerald ash borer in Minnesota, USA. For Ecol Manage. 2021;484:118958. https://doi.org/10.1016/j.foreco.2021.118958.
255. Windmuller-Campione MA, Russell MB, Slesak RA, Lochner M. Regeneration responses in black ash (*Fraxinus nigra*) wetlands: implications for forest diversification to address emerald ash borer (*Agrilus planipennis*). New For. 2021;52:537–58. https://doi.org/10.1007/s11056-020-09807-0.
256. D'Amato AW, Palik BJ, Slesak RA, Edge G, Matula C, Bronson DR. Evaluating adaptive management options for black ash forests in the face of emerald ash borer invasion. Forests. 2018;9(6):348. https://doi.org/10.3390/f9060348.

257. MacDonald B, Baydack R, Westwood AR, Walker D. Predicting emerald ash borer adult emergence and peak flight activity in Winnipeg, Manitoba Canada. Front Ecol Evol. 2022;10(846144):1–12. https://doi.org/10.3389/fevo.2022.846144.
258. Barker BS, Coop L, Duan JJ, Petrice TR. An integrative phenology and climatic suitability model for emerald ash borer. Front Insect Sci. 2023;3(1239173):1–20. https://doi.org/10.3389/finsc.2023.1239173.
259. O'Dea JK, Hill SE. Rose stem girdler emergence model. Prosser, WA: Washington State University AgWeatherNet. 2022; Available from: https://weather.wsu.edu/?p=12065
260. Chen Y, Flint ML, Coleman TW, Doccola JJ, Grosman DM, Wood DL, Seybold SJ. Impact of the goldspotted oak borer, *Agrilus auroguttatus*, on the health of coast live oak before and after treatment with two systemic insecticides. Pest Manag Sci. 2015;71(11):1540–52. https://doi.org/10.1002/ps.3959.
261. Coleman TW, Smith SL, Jones MI, Graves AD, Strom BL. Efficacy of systemic insecticides for control of the invasive goldspotted oak borer (Coleoptera: Buprestidae) in California. J Econ Entomol. 2017;110(5):2129–39. https://doi.org/10.1093/jee/tox199.
262. Appleby JE, Randell R, Rachesky S. Chemical control of bronze birch borer. J Econ Entomol. 1973;66:258–9. https://doi.org/10.1093/jee/66.1.258.
263. Alston D. *Rose Stem Girdler* (ENT-178–15). Logan, UT: Utah State University Extension and Utah Plant Pest Diagnostic Laboratory; 2015. Available at: https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1772&context=extension_curall
264. Naka K, Ohashi H. Occurrence and chemical of flathead citrus borer, Agrilus auriventris E. Saunders, in Wakayama Prefecture. Bull Wakayama Fruit Tree Exp Stat (Japan). 1996;10:61–8.
265. Petrice TR, Haack RA. Efficacy of three insecticides applied to bark to control *Agrilus planipennis* (Coleoptera: Buprestidae). Great Lakes Entomol. 2006;39:27–33.
266. McKenzie N, Helson B, Thompson D, Otis G, McFarlane J, Buscarini T, Meating J. Azadirachtin: An effective systemic insecticide for control of *Agrilus planipennis* (Coleoptera: Buprestidae). J Econ Entomol. 2010;103:708–17. https://doi.org/10.1603/ec09305.
267. Smitley DR, Rebek EJ, Royalty RN, Davis TW, Newhouse KF. Protection of individual ash trees from emerald ash borer (Coleoptera: Buprestidae) with basal soil applications of imidacloprid. J Econ Entomol. 2010;103:119–26. https://doi.org/10.1603/ec09137.
268. McCullough DG, Poland TM, Tluczek AR, Anulewicz A, Wieferich J, Siegert NW. Emerald Ash Borer (Coleoptera: Buprestidae) densities over a 6-yr period on untreated trees and trees treated with systemic insecticides at 1-, 2-, and 3-yr intervals in a Central Michigan forest. J Econ Entomol. 2019;112(1):201–12. https://doi.org/10.1093/jee/toy282.
269. Poland TM, Ciaramitaro TM, McCullough DG. Laboratory evaluation of the toxicity of systemic insecticides to emerald ash borer larvae. J Econ Entomol. 2016;109(2):705–16. https://doi.org/10.1093/jee/tov381.
270. De Andrade RB, Abell K, Duan JJ, Shrewsbury P, Grunera DS. Protective neighboring effect from ash trees treated with systemic insecticide against emerald ash borer. Pest Manag Sci. 2021;77:474–81. https://doi.org/10.1002/ps.6041.
271. Burkhard R, Binz H, Roux CA, Brunner M, Ruesch O, Wyss P. Environmental fate of emamectin benzoate after tree micro injection of horse chestnut trees. Environ Toxicol Chem. 2015;34(2):297–302. https://doi.org/10.1002/etc.2795.
272. Arborjet Inc. TREE-äge safety data sheet. 2016. https://arborjet.com/product/tree-age/. Accessed 25th Apr 2024.
273. Davidson D, Rieske LK. Establishment of classical biological control targeting emerald ash borer is facilitated by use of insecticides, with little effect on native arthropod communities. Biol Control. 2016;101:78–86. https://doi.org/10.1016/j.biocontrol.2016.06.010.
274. Duan JJ, Crandall RS, Grosman DM, Schmude JM, Quinn N, Chandler JL, Elkinton JS. Effects of emamectin benzoate trunk injections on protection of neighboring ash trees against emerald ash borer (Coleoptera: Buprestidae) and on established biological control agents. J Econ Entomol. 2023;116:848–84. https://doi.org/10.1093/jee/toad074.
275. Rodrigues TB, Rieske LK, Duan JJ, Mogilicherla K, Palli SR. Development of RNAi method for screening candidate genes to control emerald ash borer, *Agrilus planipennis*. Sci Rep. 2017;7(1):7379. https://doi.org/10.1038/s41598-017-07605-x.
276. Leelesh RS, Rieske LK. Oral ingestion of bacterially expressed dsRNA can silence genes and cause mortality in a highly invasive, tree-killing pest, the emerald ash borer. Insects. 2020;11(7):440. https://doi.org/10.3390/insects11070440.
277. Fan Z, Zhang Z, Zhang X, Kong X, Liu F, Zhang S. Five visual and olfactory target genes for RNAi in *Agrilus planipennis*. Front Genet. 2022;13:835324. https://doi.org/10.3389/fgene.2022.835324.
278. Pampolini F, Rieske LK. Foliar application of dsRNA to induce gene silencing in emerald ash borer: systemic distribution, persistence, and bioactivity. Forests. 2023;14(9):1853. https://doi.org/10.3390/f14091853.
279. Rodrigues TB, Duan JJ, Palli SR, Rieske LK. Identification of highly effective target genes for RNAi-mediated control of emerald ash borer, Agrilus planipennis. Scientific Rep. 2018;8(1):5020. https://doi.org/10.1038/s41598-018-23216-6.
280. Liu H. Under siege: ash management in the wake of the emerald ash borer. J Integr Pest Manag. 2017;9(1):5. https://doi.org/10.1093/jipm/pmx029.
281. Arbab N, Grabosky J, Leopold R. Economic assessment of urban ash tree management options in New Jersey. Sustainability. 2022;14(4):2172. https://doi.org/10.3390/su14042172.
282. Sadof CS, McCullough DG, Ginzel MD. Urban ash management and emerald ash borer (Coleoptera: Buprestidae): facts, myths, and an operational synthesis. J Integr Pest Manag. 2023;14(1):1–13. https://doi.org/10.1093/jipm/pmad012.
283. Haack RA. Exotic bark-and wood-boring Coleoptera in the United States: recent establishments and interceptions. Can J For Res. 2006;36(2):269–88. https://doi.org/10.1139/x05-249.
284. Mattson WJ, Haack RA. The role of drought in outbreaks of plant-eating insects. Bioscience. 1987;37(2):110–8. https://doi.org/10.2307/1310365.

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