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Review

Invasive Insect Pests of Forests and Urban Trees in Russia: Origin, Pathways, Damage, and Management

Dmitry L. Musolin [1,†], Natalia I. Kirichenko [1,2,3,†], Natalia N. Karpun [1,4], Evgeniy V. Aksenenko [5], Viktor B. Golub [5], Ivan A. Kerchev [6,7], Michail Y. Mandelshtam [1], Rimvys Vasaitis [8,*], Mark G. Volkovitsh [9], Elena N. Zhuravleva [4] and Andrey V. Selikhovkin [1]

1 Department of Forest Protection, Wood Science and Game Management, Saint Petersburg State Forest Technical University, Institutskiy Per. 5, 194021 Saint Petersburg, Russia; musolin@gmail.com (D.L.M.); nkirichenko@yahoo.com (N.I.K.); nkolem@mail.ru (N.N.K.); amitinus@mail.ru (M.Y.M.); a.selikhovkin@mail.ru (A.V.S.)
2 Department of Forest Zoology, Sukachev Institute of Forest, Siberian Branch of the Russian Academy of Sciences, Federal Research Center "Krasnoyarsk Science Center SB RAS", Akademgorodok 50/28, 660036 Krasnoyarsk, Russia
3 Institute of Ecology and Geography, Siberian Federal University, Svobodny Pr. 79, 660041 Krasnoyarsk, Russia
4 Federal Research Centre the Subtropical Scientific Centre of the Russian Academy of Sciences, Yana, Fabritsiusa Str., 2/28, 354002 Sochi, Russia; zhuravleva.cvet@mail.ru
5 Department of Zoology and Parasitology, Voronezh State University, Universitetskaya Pl. 1, 394018 Voronezh, Russia; entoma@mail.ru (E.V.A.); v.golub@inbox.ru (V.B.G.)
6 Institute of Monitoring of Climatic and Ecological Systems, Siberian Branch of the Russian Academy of Sciences, Akademicheskiy Pr. 10, 634055 Tomsk, Russia; ivankerchev@gmail.com
7 Department of Forestry and Landscape Construction, Biological Institute, National Research Tomsk State University, Lenina Pr. 36, 634050 Tomsk, Russia
8 Department of Forest Mycology and Plant Pathology, Swedish University of Agricultural Sciences, P.O. Box 7026, SE-75007 Uppsala, Sweden
9 Zoological Institute, Russian Academy of Sciences, Universitetskaya Emb., 1, 199034 Saint Petersburg, Russia; polycest@zin.ru
* Correspondence: rimvys.vasaitis@slu.se
† These authors contributed equally to this work.

Citation: Musolin, D.L.; Kirichenko, N.I.; Karpun, N.N.; Aksenenko, E.V.; Golub, V.B.; Kerchev, I.A.; Mandelshtam, M.Y.; Vasaitis, R.; Volkovitsh, M.G.; Zhuravleva, E.N.; et al. Invasive Insect Pests of Forests and Urban Trees in Russia: Origin, Pathways, Damage, and Management. *Forests* **2022**, *13*, 521. https://doi.org/10.3390/f13040521

Academic Editors: Young-Seuk Park and Won Il Choi

Received: 17 February 2022
Accepted: 25 March 2022
Published: 28 March 2022

Abstract: Invasive alien insects cause serious ecological and economical losses around the world. Here, we review the bionomics, modern ranges (and their dynamics), distribution pathways, monitoring, and control measures of 14 insect species known to be important invasive and emerging tree pests in forest and urban ecosystems of Russia: *Leptoglossus occidentalis* (Hemiptera: Heteroptera: Coreidae), *Halyomorpha halys* (Hemiptera: Heteroptera: Pentatomidae), *Corythucha arcuata* (Hemiptera: Heteroptera: Tingidae), *Agrilus fleischeri*, *A. mali*, *A. planipennis*, *Lamprodila* (*Palmar*) *festiva* (Coleoptera: Buprestidae), *Ips amitinus*, *Polygraphus proximus* (Coleoptera: Curculionidae: Scolytinae), *Cydalima perspectalis* (Lepidoptera: Crambidae), *Acrocercops brongniardella*, *Cameraria ohridella*, *Phyllonorycter issikii*, and *P. populifoliella* (Lepidoptera: Gracillariidae). We identified three major scenarios of tree pest invasions in the country and beyond: (1) a naturally conditioned range expansion, which results in the arrival of a pest to a new territory and its further naturalization in a recipient region; (2) a human-mediated, long-distance transfer of a pest to a new territory and its further naturalization; and (3) a widening of the pest's trophic niche and shift to new host plant(s) (commonly human-introduced) within the native pest's range frequently followed by invasion to new regions.

Keywords: forest entomology; forest health; biological invasions; outbreaks; insect pests; range expansion; urban trees; detection; controlling measures

1. Introduction

Insect invasions are a widely recognized problem. Indeed, many invasive insect species pose a serious threat to biodiversity and ecosystem functioning worldwide, affecting the well-being of modern human society [1–4]. With increasing intercontinental trade (including the trade of living plants and plant origin products) and global changes happening in the environment (e.g., climate change, deforestation, ecosystem degradations, etc.), the impact of invasive species will continue to grow [5–7].

Invasive insect species are often not pests in their natural range, where they are well-controlled by biotic and abiotic factors [8]. Furthermore, some of these species become known to science only after their invasions [9,10]. On one hand, alien pests that are often released from their native enemies can switch on non-coevolved hosts, resulting in successful invasion, with notable damage to the invaded ecosystem [11]. On the other hand, alien plants introduced into a new region can be a target to native pests that can benefit from the susceptibility of the novel hosts [12]. The ability of invaders to form novel trophic associations may present a threat to plants in their native range in cases of a pest accidental introduction. Our knowledge of the biology of novel pests, their invasive potential and impacts, as well as possible methods of monitoring and control is usually limited [13]. Often, such information is unavailable or scarcely published on a national language of a country from where a pest is originally known and is thus not accessible to an international audience.

Russia occupies a huge territory in Europe and Asia with different climatic zones, and the country is actively involved in international trade. Thus, it is not surprising that harmful organisms, arriving to the country via international trade (e.g., airfreight or shipping containers carrying crops, ornamental plants, wood, etc.) or through the movement of people (e.g., global tourism), are regularly detected here [14], and those that succeed in becoming established cause significant economic losses to Russia [15]. The opposite is also true. Pests are regularly found on plants and plant material in vehicles driving from or through the territory of Russia and, as a result, are recorded in new regions of the country or beyond, in foreign countries [8]. Information about the biology, monitoring, and control of alien invasive species that actively expand their ranges and have recently arrived in Russia or, in contrast, native species that are able to spread from Russia to other countries, is of a high importance for international specialists dealing with pest quarantine and forest protection in their homelands.

In this review, we analyzed the biology, distribution, pathways, monitoring, and control approaches of 14 tree insect species, which are considered highly important invasive or emerging insect pests of forests and urban woody plants in Russia [8,15]. It should be understood that they are not the only actual or potential invasive or emerging insect pests in Russia deserving attention. However, in our opinion, they can be considered as representative models of insect pest invasions at a national level.

2. Materials and Methods

In order to provide up-to-date knowledge on insect pests of forests and urban woody plants in Russia, we reviewed numerous studies, mostly published in a national language, and the references are given in each species' essay below. We have included the latest papers delivered at the All-Russia biennial conference "Dendrobiotic Invertebrates and Fungi and their Role in Forest Ecosystems (The Kataev Memorial Readings)", which serves as the main platform for discussing the most important issues on forest entomology, pathology, plant protection, and quarantine in the country [15]. We also examined "grey" and not easily accessible national literature (e.g., proceedings, conference notes, papers in regional editions, etc.). As a result, we compiled 14 brief essays on important invaders in Russia (mainly within its European part). Most of these pests (both alien invasive species which penetrated Russia and native national pests) can potentially further expand their ranges and pose a threat to woody plants in other countries.

The essays are arranged in taxonomic order. They briefly overview history of invasion, biology, basic monitoring and control measures, and are accompanied with photographs of pests and damage symptoms. A schematic map of the natural range (colored in yellow) and invasive range (colored in red) in Russia is also provided. In most cases, we outlined the entire administrative region/unit for published records, except for the cases when the area of the record is relatively small, whereas the region is large. The current ranges were mapped using ArcGIS 9.3 [16].

As there are discrepancies in the English naming of Russian administrative units and settlements, we applied the most commonly used names. To designate administrative units, the following terms were used: "Oblast" for Province and "Krai" for Administrative Territory.

3. Results

3.1. The Western Coniferous Seed Bug, Leptoglossus occidentalis Heidemann, 1910 (Hemiptera: Heteroptera: Coreidae)

Leptoglossus occidentalis (Figure 1) is a North American species that invaded Eurasia, North Africa, and Central America. The native range of the species covers the west of North America, from the south of Canada to Mexico [17]. In Europe, it was first recorded in 1999 in northern Italy [18], where it was accidently introduced from North America, probably by plane [19]. Over the next 10 years, the bug spread from Italy across Europe northward (to Norway) and eastward (to Russia and Turkey) (Supplimentary Table S1). At present, the invasive range of *L. occidentalis* in Eurasia covers significant parts of the Palaearctic. In Asia, it is known from Turkey, Israel, Armenia, Kazakhstan, Northeast China, Japan, and South Korea [17,20–25]. In Africa, it is recorded in Tunisia [26], Morocco [27], and South Africa [28]. It is also recorded in Chile [29], Brazil [28], Argentina [30], and Uruguay [31]. The first records in European Russia refer to Rostov-on-Don (but also to the neighboring Crimean Peninsula) [17]. Up to now, it has been recorded also in the Smolensk Oblast [32], Voronezh City [33], Volgograd City [34], Stavropol Krai [27], Krasnodar Krai, and North Ossetia (central Causasus) (Figure 1c) [19,27,35]. The species has spread along the entire Black Sea coast of the Caucasus (Krasnodar Krai) to the border with neighboring region of Abkhazia [19,35], from which it is also known [27]. In addition, it is documented from Transcaucasia: the neighboring region of South Ossetia [27], Georgia [36], and Armenia [25].

The routes of introduction into Russia are not known. Adults of *L. occidentalis* have good flying abilities and, thus, they can fly for long distances over regions having suitable habitats and host plants [17]. The bugs could have also been accidently introduced with coniferous plants, either with plants for planting or Christmas trees (whole or cut branches) [17,37]. The rate of spreading of *L. occidentalis* from the place of its first detection in Europe is approximately the same in all directions of its expansion and is estimated to be about 200 km per year [19]. Most likely, in addition to active distribution, the invader is moved passively with various types of transport [19].

Based on the record of the species in Voronezh City (the forest-steppe zone; approx. 500 km from Rostov-on-Don) and in the Smolensk Oblast (the forest zone; approx. 1000 km northward from Rostov-on-Don), a significant expansion of the invaded range northward in the European part of Russia should be expected. Successful establishment of the species in the forest-steppe zone is now evident at least in urban conditions, keeping in mind that average temperatures are higher in cities than in the surrounding environment [33]. The probability of spreading and establishment further eastward remains unknown.

(**a**)

(**b**)

(**c**)

Figure 1. The Western coniferous seed bug, *Leptoglossus occidentalis*: (**a**) a nymph of IV instar; (**b**) an adult, Voronezh City, September 2020; (**c**) the current invasive range in Russia (colored in red). Photo by E.V. Aksenenko.

The species is trophically associated with a wide range of plants from Pinaceae (e.g., *Abies*, *Cedrus*, *Picea*, *Pinus*, *Pseudotsuga*, and *Tsuga*), Cupressaceae (e.g., *Calocedrus*, *Cupressus*, and *Juniperus*) [17,20,35,38], and exceptionally documented on Anacardiaceae (*Pistacia vera*) [39]. In Russia, feeding on spruce *Picea glauca*, *P. pungens*, and fir *Abies cocolor* has been recorded [19].

The bug overwinters as adults or nymphs of the last (V) instar. For overwintering, they aggregate in cracks in the bark and other similar microhabitats in forests and can also penetrate dwellings, cars, etc. They leave overwintering shelters in April to May and start feeding on young microstrobili and megastrobili, causing growth impairment, deformation, and reducing the production of microspores [17]. Then, the adults mate and the females lay eggs. Females lay about 30 eggs (up to 80 maximal) in clusters along the needles [40]. Hatched nymphs and adults feed on maturing and ripe seeds and also suck sap from the apical shoots throughout summer. Adults emerge close to the end of August.

Within its native range in northern California, *L. occidentalis* produces one generation per year [37,41]. In Italy, it has two or three generations on the plain, and only one generation in the highlands [42]. In the south of Krasnodar Krai, two generations per year were recorded [19]. In Dagestan (North Causasus), at least one generation per year is possible, and in the area between Anapa and Novorossiysk cities, two generations can occur [19]. Further northward, thermal conditions are not favorable for this species.

The damage caused by *L. occidentalis* has not yet been fully evaluated in Europe. In North America, it destroys up to 26% of the seeds of *Pinus monticola* and up to 41% of the seeds of different *Pseudotsuga* species [41]. In West Europe, the species has not caused any significant damage so far [43], probably because: (1) its abundance has not yet reached the critical level in the newly colonized territories, and (2) causing damage only to seeds, the bug practically does not harm the trees themselves. In Russia, a 3-year study of the influence of *L. occidentalis* on seed germination of the Crimean pine and Scots pine in the Rostov Oblast demonstrated the high harmfulness of the seed bug [19].

The bug carries spores of the pathogenic fungus *Sphaeropsis sapinea* (=*Diplodia pinea*), which causes diplodia tip blight: a necrosis of the needles and shoot bark, as well as the withering of seedlings and young plants [44,45]. Thus, the cumulative damage to pines can be highly significant. In its native range, *L. occidentalis* is parasitized by *Trichopoda pennipes* (Diptera: Tachinidae) [46] and hymenopteran egg parasitoids, *Gryon pennsylvanicum* (Scelionidae), *Anastatus pearsalli* (Eupelmidae), and *Ooencyrtus* spp. (Encyrtidae) [47]. In Italy, the hymenopterans, *Anastatus bifasciatus* (Eupelmidae), *Tetrastichus servadeii* (Eulophidae), and *Ooencyrtus pityocampae* (Encyrtidae) parasitize the eggs of *L. occidentalis*. In Russia, parasitoids that able to control the bug are not known, except *Ectophasia crassipennis* (Diptera: Tachinidae) [35].

Leptoglossus occidentalis can be effectively controlled using pyrethroid preparations in the years when the pine yield is low and the bug's population density is high; however, this and other chemical control measures against this pest, as well as biological control focusing on its natural enemies, should be developed in Russia [35].

3.2. The Brown Marmorated Stink Bug, Halyomorpha halys (Stål, 1855) (Hemiptera: Heteroptera: Pentatomidae)

The native range of *Halyomorpha halys* (Figure 2), covers Southeast Asia: China, the Korean Peninsula, Japan, Taiwan, and Vietnam [48,49]. The history of the pest invasion began in North America, where the species was first recorded in 1996, and since then, it has actively spread throughout the country. By 2015, the bug had been reported in 41 states [50–52]. In Canada, *H. halys* was documented in 2010 in Ontario and Quebec [53]. In Central and South America, *H. halys* has not yet been recorded, except for the only detection in the Chilean border zone in 2017 [54]. In Europe, *H. halys* was first detected in 2004 in Liechtenstein [55] and spread quickly to at least 30 countries (Supplimentary Table S2). The species expansion in Europe was recently analyzed based on the distribution of different haplotypes [56]. In 2010, live specimens of the bug were intercepted in England and New Zealand in the luggage of passengers traveling by air. In New Zealand, it was also found in used cars brought from Japan, but the species did not spread across the countries [57,58].

(**a**)

(**b**)

(**c**)

(**d**)

Figure 2. The brown marmorated stink bug, *Halyomorpha halys*: (**a**) a nymph of the final (V) instar, Sochi, August 2017; (**b**) an adult on grape, Sochi, September 2017; (**c**) an overwintering aggregation in warehouse, Sochi, January 2018; (**d**) the current invasive range in Russia (colored in red). Photo: (**a**) by V.Ye. Zakharchenko and (**b**) and (**c**) by N.N. Karpun.

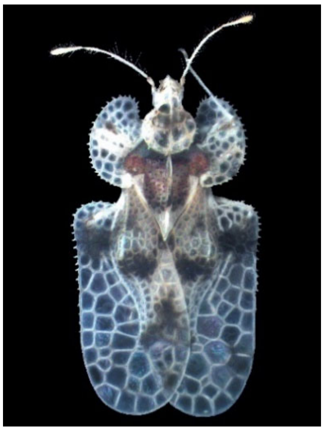
In Russia (Figure 2), *H. halys* was detected for the first time in 2014 [59] in two parks in Sochi, and already in 2015, an outbreak was observed in the humid subtropics of Russia and neighboring region of Abkhazia [60]. The species occurs on the Black Sea coast of the Caucasus at altitudes up to 800 m a.s.l. [61]. In the fall of 2016, the bug was noted in Krasnodar City, and during 2017, it invaded the territory of Krasnodar Krai and Adygea (West Causasus) [62–64]. In 2018, *H. halys* was detected in the Stavropol Krai and in neighboring Crimean Peninsula (in Simferopol, Sevastopol as well as in the nearby villages of Inkerman, Balaklava, on Cape Fiolent) [65,66]. Since 2019, the species adults were regularly caught in the City of Rostov-on-Don and in the Rostov Oblast [67,68]. In 2020, nymphs and adults were intercepted in the Stavropol City [69] and in Dagestan (North Caucasus, Samur Forest) [70]. It is likely that goods of non-plant origin transported during the winter are the major vector of *H. halys* distribution in Russia [63].

The brown marmorated stink bug is a polyphagous pest damaging 300+ species of plants [50,71,72]. In southern Russia, nymphs and adults feed on 107 species of cultivated and wild plants, and during the year, the species migrates from one crop to another. It locally migrates to forest and forest plantations at the end of August or in September, concentrating in the crowns of beech, linden, hazel, and ash [73]. In 2016–2017, *H. halys* caused severe losses in the yield of fruit, subtropical, and vegetable crops [60,63,74]. In woody species, the pest destructs fruits. Thus, in hazel, kernels fail to properly form, while in Rosaceae, fruits are deformed and do not ripen [73]. On the Black Sea coast of Russia, two generations develop per year, and only one is likely to develop further north [74,75]. The monitoring of *H. halys* is possible by regular visual inspections of plantations during the summer and overwintering sites in the autumn and winter, as well as by pheromone trapping [62]. The traps are placed in crowns of woody plants or on poles in fields or other open areas. The composition of the aggregation pheromone of *H. halys* was identified as a mixture of two stereoisomers: (3S, 6S, 7R, 10S)-10,11-epoxy-1-bisabolene-3-ol and (3R, 6S, 7R, 10S)-10,11-epoxy-1-bisabolene-3-ol, in a ratio of 3.5: 1, respectively [76]. Among the pheromones produced in Russia, the most effective is a mixture consisting of an aggregation pheromone obtained from citronelal racemate and methyl (E, E, Z)-2,4,6-decatrienoate [77].

In the south of Russia, no effective predators and parasitoids of *H. halys* have been found so far. As biological control measures, the use of preparations based on entomopathogenic fungi (strains) of the following species is considered promising: *Beauveria bassiana*, *Metarhizium anisopliae*, *Isaria fumosorosea*, and *Ophiocordyceps nutans* [74,78–82]. Pheromone traps catch more than 100 individuals per week and can be effectively used in autumn [77,83]. To control nymphs and adults, neonicotinoids (based on imidacloprid, acetamiprid, thiacloprid, and thiamethoxam) and pyrethroids (based on bifenthrine, cypermethrin, lambda-cyhalothrin, alphacypermethrin, etc.) are effective [48,74,84–90].

3.3. The Oak Lace Bug, Corythucha arcuata (Say, 1832) (Hemiptera: Heteroptera: Tingidae)

Corythucha arcuata (Figure 3) is a North American species that is naturally distributed in the USA and the southern regions of Canada [91,92]. In Europe, the oak lace bug was first recorded in 2000 in Italy [93], and by now, it has quickly spread in almost 20 countries (Supplimentary Table S3). In Asia, it was found in 2002 (2003) in Northwest Turkey, and by 2008, it had spread about 600 km eastward [94,95]. In 2005, a specimen of the bug was caught in the north of Iran at the latitude of 1370 m a.s.l. in the vicinity of Urmia (Urmiech) [96]; however, no data on further acclimatization of the species in Iran are available.



(**a**)

(**b**)

(**c**)

(**d**)

Figure 3. The oak lace bug, *Corythucha arcuata*: (**a**) an adult, Krasnodar Krai, June 2016; (**b**) eggs, nymphs, and adults on a leaf of *Quercus hartwissiana*, Sochi, September 2017; (**c**) heavy discoloration of *Q. variabilis*, Sochi, September 2017; (**d**) the current invasive range in Russia (colored in red). Photo: (**a**) by V.A. Soboleva, with permission, (**b**) and (**c**) by V.Ye. Zakharchenko.

In Russia (Figure 3d), the first local outbreak of this pest was recorded in the summer of 2015 in Krasnodar City. By the autumn 2016, the species had spread across the Krasnodar Krai and was found in Adygea [90,97,98]. In September 2017, *C. arcuata* was found in the subtropical zone of the Black Sea coast of the Caucasus [99] and in the neighboring Crimean Peninsula [100], where it was later repeatedly documented [101,102]. In 2018, the bug was recorded in the Rostov Oblast and many regions of the North Caucasus (Stavropol Krai, Karachay-Cherkessia, Kabardino-Balkaria, North Ossetia, Chechnya, and Dagestan) [103]. Further pest expansion outside Russia to natural forests of Central Asia and the countries of the Caucasus is likely.

Corythucha arcuata spreads over long distances mainly due to human-mediated transportation (land, air, and water vehicles); the distribution on air currents and transportation with seedlings of plants and other plant material are not ruled out [104]. Within its natural range, it damages many oaks (*Quercus* spp.; Fagaceae) by sucking juice from leaves. Additionally, it has been noted feeding on toothed chestnut *Castanea dentata* (Fagaceae), willows (*Salix* spp.; Salicaceae), and *Cercis canadensis* (Fabaceae) [92,105]. In southern Russia, it damages various species of oak, as well as a number of other woody plants (e.g., *Castanea sativa*, *Corylus avellana*, *Acer platanoides*, *Alnus glutinosa*, *A. incana*, etc.) [106,107].

In North America, the oak lace bug produces two or three generations per year [108]. Under favorable conditions of the North Caucasus, Transcaucasia, and the Crimean Peninsula, up to three generations can develop in April to November (sometimes a part of its population can produce the fourth generation) [109].

Nymphs and adults suck juices from leaves, resulting in a pronounced discoloration, which is first seen as a marbled diffuse yellowing of foliage, and by the middle of summer, as complete discoloration due to chlorophyll loss [106,108]. Despite growing population densities, the bug impact on oak forests in Russia has not been estimated yet. Significant destruction of foliage in tree crowns during several years can greatly weaken the oaks, causing their gradual decline [103,109]. In addition, the decorative quality of trees massively infested by the oak lace bugs is significantly reduced, which may be critically important in urbanized environments [63].

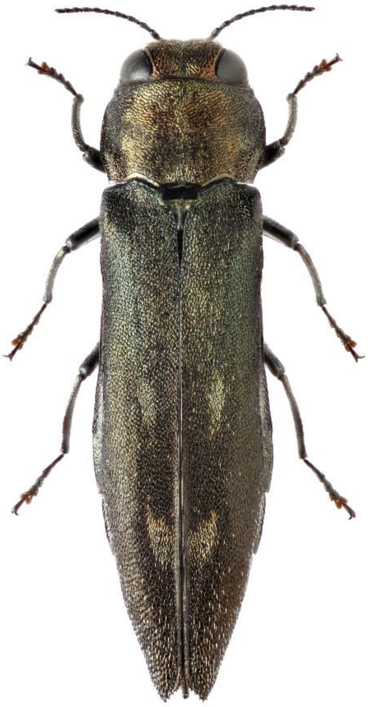
The oak lace bug should be monitored through regular visual ground surveys in forest and urban plantations [103,106], and remote sensing should be developed [110], since the damage caused to trees is clearly visible. Sweeping with classical entomological net in tree crowns and shrubs can also be used for surveys [102].

In Russia, predators and parasitoids of the oak lace bug have not yet been studied [111]. Nevertheless, it is believed that entomopathogenic fungi (e.g., *Beauveria* spp., *Metarhizium* spp., and *Cordyceps* spp.) can be potentially used for the biological control of *C. arcuata* [112,113]. Of the chemical preparations, avermectins, pyrethroids, and neonicotinoids are considered effective against this pest [114–116].

3.4. The Spotted Poplar Borer, Agrilus fleischeri Obenberger, 1925 (Coleoptera: Buprestidae)

Agrilus fleischeri (Figure 4), is a North Asian pest of poplars (*Populus* spp.) and, to a lesser extent, willows (*Salix* spp.), which produced outbreaks and caused tree mortality in poplar plantations in China (see below in this essay). Because of these circumstances, it is considered a potentially invasive pest of poplars in Europe and North America [117–119] and included in the European and Mediterranean Plant Protection Organization (EPPO) A2 List of pests recommended for regulation as quarantine pests [120].

The species was described from East Siberia (Transbaikalia: Berezovka settlement) [121]. In Russia, it is distributed across its Asian part: in West Siberia (Tyumen Oblast, Krasnoyarsk and Altai Krais, the Altai Republic), East Siberia (Tyva and Buryatia), and Far East (Primorskii and Khabarovsk Krais, Sakhalin, and Amur region) (Figure 4c).



(**a**)

(**b**)

(**c**)

Figure 4. The spotted poplar borer, *Agrilus fleischeri*: (**a**) a female; (**b**) a fragment of a larval gallery and an exit hole on a piece of firewood (*Populus* sp.), Jilin Province, China; (**c**) the native range in Russia (colored in yellow). Photo: (**a**) by A.V. Kovalev, after [119]; (**b**) by E. Jendek, both with permission.

In Asia, it is also known from Kazakhstan (eastern and, probably, northern parts; report from Karaganda Oblast on the east needs confirmation), Mongolia (Töv Aimag), China (Northeast and Central China: Heilongjiang, Liaoning, Beijing, Sichuan, and Shaanxi Provinces), North Korea, South Korea, and Japan (Hokkaido, Honshu) [119,122]. In the westernmost part, the range of *A. fleischeri* reaches, but does not overlap with, the range of closely related European *Agrilus ater* [119].

The spotted poplar borer is considered a potentially invasive species. Although it has never been reported beyond its native range, it is known to outbreak on planted exotic poplars [117–119]. Outbreaks of *A. fleischeri* on introduced *Populus nigra* var. *italica* resulting in tree mortality were first observed in China (Liaoning Province) in 2013 to 2015 [123].

The species may potentially spread to Europe and North America, where poplars are native and where cultivated poplar species from China, Asian Russia, or East Kazakhstan are planted. In Canada, adults of *A. fleischeri* have been intercepted on two occasions being transported with wood packaging material and wood dunnage [120]. The pest can be accidently introduced with poplar plants for planting, round and sawn wood, wood residues, and wood packaging material. Natural spread (e.g., from Asian Russia via European Russia to EU) or hitchhiking with transport are considered unlikely but possible pathways [120].

In China (Liaoning Province), in addition to feeding on the indigenous species of poplars and willows, *A. fleischeri* can also severely damage introduced *Populus nigra* var. *italica* [123]. The current situation with *A. fleischeri* is reminiscent of the early stages of the invasion of the emerald ash borer, *A. planipennis*, which switched from the indigenous ash species to the cultivated American ash species, triggering its outbreaks in Eastern China. Then, the pest was accidentally imported to North America and European Russia [119] (see also Section 3.6 below).

Currently, no special control measures have been developed in Russia. In China, sanitary felling of infested, dead, and dying trees is performed [120]. The dimethoate is considered an effective insecticide against adults during the flight period of different *Agrilus* species in China [120,124]. Some hymenopteran parasitoids (i.e., *Oobius saimaensis*, *O. fleischeri* [Encyrtidae]; *Polystenus rugosus*, *Spathius* sp. [Braconidae]; *Paramblynotus* sp. [Liopteridae]; and *Euderus fleischeri* [Eulophidae]) and entomopathogenic fungi *Beauveria bassiana* (Ascomycota: Cordycipitaceae), which were found infesting *A. fleischeri* eggs and larvae in China, can be considered potential agents for the biological control of the pest [120].

3.5. The Apple Buprestid, Agrilus mali Matsumura, 1924 (Coleoptera: Buprestidae)

Agrilus mali (Figure 5), originally described as a destructive pest of apple plantations in Korea, is currently regarded a dangerous quarantine pest of cultivated and wild apple trees in Russian East Siberia and the Far East, East China, and both Koreas (see below in detail). Shortly before 1993, *A. mali* was unintentionally introduced in the Ili River valley (Xinjiang Province, China) from Shandong and later caused extensive tree mortality in the wild apple, *Malus sieversii,* forests in the Tien Shan Mountains [125–130]. Thereby, *A. mali* is considered a potentially invasive pest threatening cultivated apple trees outside its native range, wild apple trees and, in particular, *M. sieversii*, which is an important tree of mountain deciduous forests in Northwestern China, Kazakhstan, and adjacent countries of the Middle Asia [118,119] and a key ancestor of the domestic apple tree [127–130]. *Agrilus mali* is a quarantine species in the Russian Federation, the Eurasian Economic Union [131], and the EPPO region [132].

Currently, *A. mali* is distributed in Asian Russia—East Siberia (Chita Oblast, Zabaikalskii Krai) and the Far East (Amur Oblast, Khabarovsk and Primorskii Krais) (Figure 5c)—Mongolia (Dornod and Tuv Aimags), China (Gansu, Guangxi, Hebei, Heilongjiang, Henan, Hubei, Nei Mongol, Qinghai, Sichuan, Shandong, Xinjiang, and Xizang Provinces), North Korea (Pyongyang), and South Korea (Gyeonggi-do, Inchon, Seoul, Taegu) [119,122,133], but some authors consider the Koreas and the Xinjiang Province of China as invasive range [126–130,134].

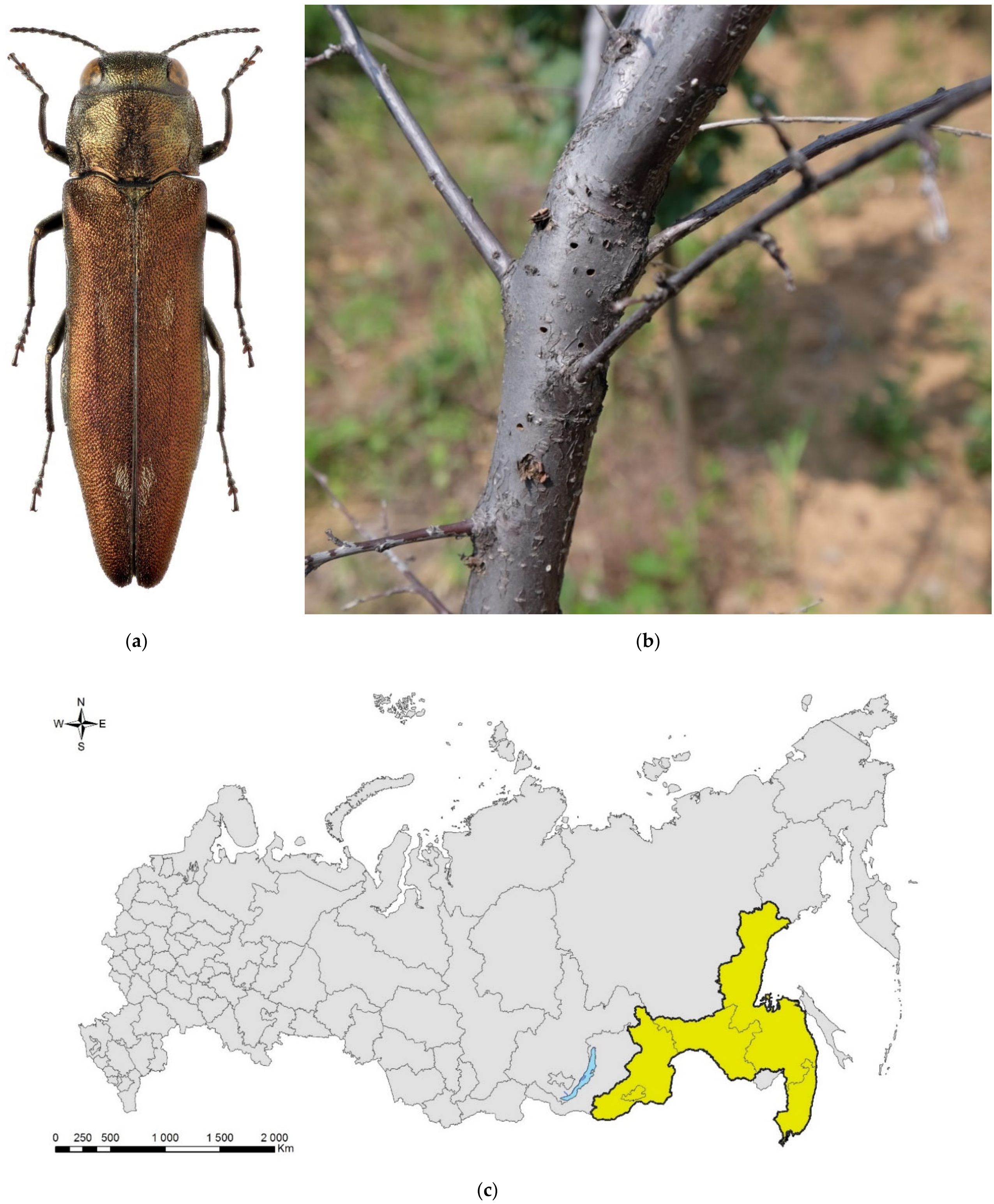


Figure 5. The apple buprestid, *Agrilus mali*: (**a**) a male; (**b**) exit holes of *A. mali* on a dead *Malus* sp. tree, Beijing District, China; (**c**) the native range in Russia (colored in yellow). Photo (**a**) by A.V. Kovalev, after [119]; (**b**) by E. Jendek, both with permission.

It is supposed that *A. mali*, was introduced to Korea from East China (Liaoning Province) [134], while the population in Xinjiang Province presumably originated from Shandong [127,128]. Imported apple tree seedlings are univocally indicated as a vector in both regions. It is believed that the potential invasive range of *A. mali* can cover the entire apple orchards' cultivation area [135]. Based on the first findings in Korea in 1915 [134], the invasion of *A. mali* to that country could have happen in the early 1900s and the invasion to Xinjiang Province probably happened at the end of the 1980s to the early 1990s because the first outbreak took place there in 1993 [125–130]. Thus, the massive foci of *A. mali* on *M. sieversii* in Xinjiang Province may represent a newly forming invasive range. The proximity of these sites to the wild apple stands and cultivated apple plantations in the Kazakhstan's part of Tien-Shan Mountains is a direct threat to Kazakhstan and other Central Asian countries [118,119].

Agrilus mali was reported to damage apple trees (i.e., *Malus* spp., *M. asiatica* var. *rinki*, *M. baccata*, *M. domestica*, *M. prunifolia*, *M. pumila*, *M. sieversii*, and *M. spectabilis*; Figure 5b), and it was also recorded to feed on other Rosaceae (i.e., *Cydonia oblonga*, *Prunus* spp., and *Pyrus* spp.) [127,128,133,136–138]. The record on *Emmenopterys henryi* (Rubiaceae) needs verification, and references to *Juglans* (Juglandaceae) and *Salix* (Salicaceae) are erroneous [133], while a report on *Sorbus* (Rosaceae) can refer to *A. mendax* [119].

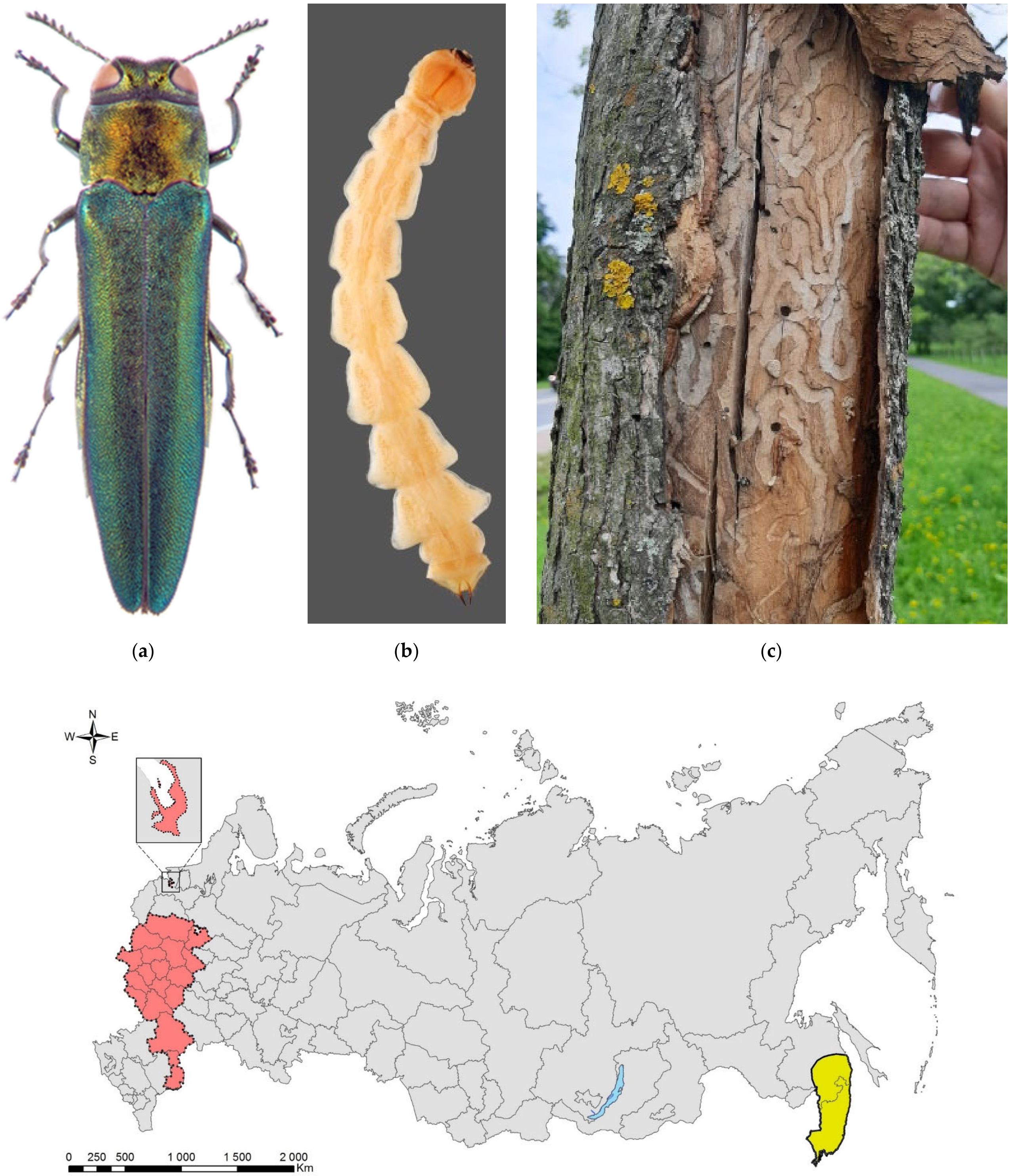
An instance of large-scale damage by *A. mali* to cultivated apple trees was documented in Korea [134]. In Russia, it was also reported as a dangerous pest of apple trees in East Siberia and the Far East [135,139,140]. In the latter, the infested area covered about 320 ha [135]. Since the establishment in Xinjiang Province in 1993, *A. mali* has killed millions of wild apple trees and has infested about 95% of the total area of wild apple forests in the Ili valley [130].

Russia has a ban on import of apple seedlings from the areas infested by *A. mali* [135]. Agro-technical measures, mainly pruning and the destruction of infested branches and trees, as well as chemical treatments, are suggested as the control measures [139,140]. A parasitoid of emerald ash borer, *Sclerodermus pupariae* (Hymenoptera: Bethylidae), has been experimentally released in Xinjiang (China) and showed some positive results against *A. mali* [130]. This parasitoid, together with braconids (i.e., *Atanycolus ivanowi*, *Doryctes undulatus*, *Pareucorystes varinervis*, *Polystenus rugosus*, *Spathius sinicus*, and *S. brevicaudis*; Hymenoptera: Braconidae) parasitizing on *A. mali* were suggested as potential agents of biological control [141]. Aerial insecticide sprays during the beetle flight period can also be effective [128,130]. The combination of biocontrol and spraying/pruning turned out to be the most effective management approaches [130].

3.6. The Emerald Ash Borer, Agrilus planipennis Fairmaire, 1888 (Coleoptera: Buprestidae)

Agrilus planipennis (Figure 6) is described from China (Beijing) [142]. Since the beginning of the XXI century, the emerald ash borer has turned from a little-known East Asian species into one of the most devastating pests of ash trees in the world [143]. It has killed millions of trees in the forests and urban plantings in North America, European Russia, and East Ukraine [144–148].

The species native range is confined to East Asia: Russian Far East (Khabarovsk and Primorskii Krais), China (Beijing, Hebei, Heilongjang, Jilin, Liaoning, Nei Mongol, Shandong, Sichuan, Taiwan (syn. *A. feretrius*), Tianjin, Xinjiang Provinces), Mongolia (syn. *A. marcopoli*), North Korea, South Korea, and Japan (Hokkaido, Honshu, Kyushu, Shikoku) (syn. *A. marcopoli ulmi*) [146]. There are some uncertainties regarding the native range and synonymy. As such, the records for Nei Mongol and Sichuan need confirmation, whereas the records for North Korea are still lacking, though *A. planipennis* occurs in all adjacent countries. In addition, the taxonomic state of *A. feretrius* and *A. marcopoli ulmi* needs verification, and the type locality of *A. marcopoli* (Mongolia or China) is still unclear.



(**d**)

Figure 6. The emerald ash borer, *Agrilus planipennis*: (**a**) an adult; (**b**) a mature larva; (**c**) larval galleries and exit holes in young tree, Saint Petersburg, September 2020; (**d**) the current distribution in Russia: the native range (colored in yellow) and invasive range (colored in red). Photo: (**a**) by K.V. Makarov, (**b**) by A.V. Kovalev, after [149], both with permission, (**c**) by M.G. Volkovitsh.

Outside its native range, *A. planipennis* was first recorded in the USA (Michigan) in 2002 [150] and in the European part of Russia—in Moscow City in 2003 [144,145,151,152].

By early 2022, the emerald ash borer was recorded in 5 provinces of Canada and 35 states of the USA [153]; 18 provinces of European Russia, Moscow City, St. Petersburg City (Figure 6d); and two provinces of Ukraine (Luhansk and Kharkiv) [147,148,154–157].

The pest could be introduced to European Russia unintentionally in the late 1980s to early 1990s with wooden crafts, ash seedlings, or packaging material [158]. Taking into account that its outbreaks in North America and Moscow began almost simultaneously, an introduction from a common source (most probably from China) seems the most likely.

Under natural conditions, the emerald ash borer feeds on the East Asian ash tree species without causing significant damage to them due to the resistance of local ash species to the pest. However, in the areas of invasion, it completely destroys mature ash trees within a few years, depending largely on tree size and local *A. planipennis* population density [143]. Not all ash species are equally susceptible to *A. planipennis*. The examination of the ash collection in the N.V. Tsitsin Main Botanical Garden of the Russian Academy of Sciences (Moscow) revealed that only two Asian species (i.e., Chinese ash, *F. chinensis*, and Manchurian ash, *F. mandshurica*) were resistant to the emerald ash borer, whereas the pest killed the trees of both North American (i.e., *F. pennsylvanica* and *F. americana*) and European origins (i.e., *F. excelsior*, *F. angustifolia*, and *F. ornus*) [159].

The emerald ash borer can spread due to active flight, the human-mediated movement of infested wood (in North America, particularly, firewood), or the occasional transportation by vehicles and ships. Presumably, the beetles can also be transported over long distances by wind [143,158].

Since the first detection in Moscow in 2003, *A. planipennis* significantly expanded its invasive range in European Russia. In 2006, it was found in the Moscow Oblast, whereas by 2013, it was detected already in 11 oblasts of European Russia [160] and by early 2021, in 18 oblasts and in Saint Petersburg City [148,154,161]. The most recent detected localities are Saint Petersburg City and the Astrakhan Oblast [148,156,157].

The emerald ash borer has killed over tens of millions of healthy ash trees at a cost of billions of US dollars since its occurrence in North America [143]. In Europe, the potential losses can reach USD 1.81 billion. By this indicator, the species ranks fourth among the most "costly" invasive pests [162]. The actual losses (observed costs) from *A. planipennis* invasion in European Russia are estimated at as much as USD 258.9 million during 2011–2016 [163,164]. The impact might be even higher in the regions where the invasive range of *A. planipennis* overlaps with the invasive range of the devastating ash dieback fungus, *Hymenoscyphus fraxineus* (Ascomycota) [145].

Infestation usually begins in the canopy, with subsequent attacks lower along the trunk, while in small-diameter trees, infestation often starts along the main trunk. Canopy drying, epicormic branching along the lower trunk, bark crevices, and D-shaped exit holes on the bark are the most common symptoms of infestation [143,158,160].

Since its initial detections in Moscow City and the Moscow Oblast, monitoring in European Russia has been performed and, at the beginning, mostly by volunteers and enthusiasts. Initially, the monitoring was limited to the search for new foci and heavily infested ash trees in the urban environments. By now, seven quarantine phytosanitary zones in five oblasts of European Russia are declared by the National Plant Protection Organization (Rosselkhoznadzor) [148]. The pest is included in A Unified List of Quarantine Pests of the Eurasian Economic Union [131], and it is also included in the priority pest lists of the EPPO [120] and the European Food Safety Authority (EFSA) [165].

A recent analysis suggests that *A. planipennis* can potentially invade most European countries; however, it would probably not be able to establish in some regions of Norway, Sweden, Finland, Ireland, and Great Britain because of low annual heat accumulation in these regions [166].

Control measures include the cutting of infested trees (mostly detected by dry branches and typical D-shaped exit holes on the bark), with a clear-cut zone, replacement of North American and European ash trees with more resistant Asian ash species (first of all, *F. chinensis* and *F. mandshurica*) or possibly hybrids, and chemical and biological control [145,167]. Currently, the biological control agents are intensively looked for within the native and invasive ranges [145,168–170].

3.7. The Cypress Jewel Beetle, Lamprodila (Palmar) festiva (Linnaeus, 1767) (Coleoptera: Buprestidae)

Lamprodila festiva (Figure 7) is originally a relatively rare Mediterranean species, which, about 20 years ago, suddenly became a devastating pest of ornamental cypress trees (Cupressaceae) in urban plantings and nurseries all over central and East Europe, including south of European Russia and Eastern Ukraine [160,171] (Supplementary Table S4). In addition to the Mediterranean, the native range of *L. festiva* covers North Africa, South Europe, the southern part of central Europe (*L. f. festiva*, and *L. f. cretica*) and Southwest Asia (*L. f. holzschuhi*) [160,171,172].

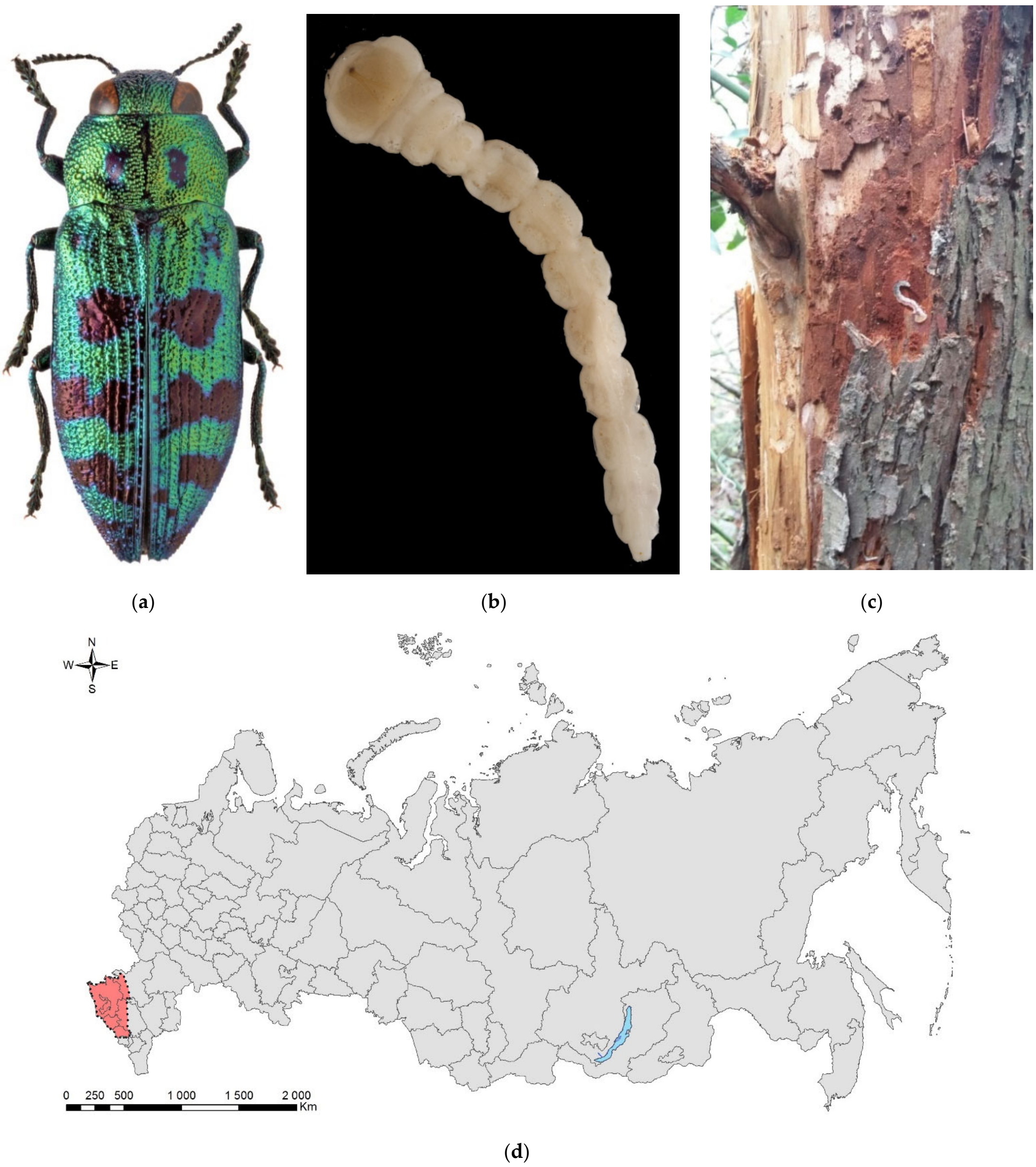


Figure 7. The cypress jewel beetle, *Lamprodila* (*Palmar*) *festiva*: (**a**) an adult; (**b**) a larva; (**c**) larval tunnels with larvae on the trunk of *Thuja plicata*, Sochi City, 2016; (**d**) the invasive range in Russia (colored in red). Photos: (**a**) and (**b**) by A.V. Kovalev, after [171], with permission; (**c**) by N.N. Karpun, after [172].

Until recently, *L. festiva* has never been recorded in Russia or the former USSR. The first symptoms of infestation were detected in the Black Sea coast (Greater Sochi) in 2013, and the first larvae and adults were collected in 2016 [172,173]. Most probably, the pest was unintentionally introduced together with cypress planting stock from the European nurseries (likely from Italy, Spain, or Montenegro) in 2011 to 2013, during intense landscaping in Sochi before the XXII Winter Olympic Games in 2014 [172,174]. Presently in Russia, the cypress jewel beetle is distributed along the Black Sea coast from Sochi to Anapa, in North Caucasus (Dombai, Krasnodar, Nalchik, Rostov, Stavropol, Nevinnomyssk, and Cherkessk Cities), and the south coast of the neighbouring Crimean Peninsula, from Sevastopol to Gurzuf (Figure 7d) [107,160,171,172,175–178].

During 2013–2021, *L. festiva* expanded its invasive range as much as approx. 500 km north (Donetsk, Ukraine), about 240 km northeast (Stavropol), and 310 km east (Nalchik). It is distributed along the Black Sea coast for about 360 km from Vityazevo settlement at the north to Sukhum City in the south, with the maximal distance from the initial record locality (Sochi) of 250 km (Vityazevo). Actually, the first reported findings outside Sochi were from Gelendzhik (170 km northwest from Sochi) in 2017 [177]. These records indicated a high rate of distribution of the pest, most likely associated with the spread of infested planting stock.

Until recently, the cypress jewel beetle was regarded as a secondary pest of wild and some introduced Cupressaceae (*Thuja* spp.), without significant damage [172]. Currently, the beetle is recorded on a wide range of cultivated cypress species from *Callitris*, *Chamaecyparis*, *Cupressus*, *Juniperus*, *Platycladus*, *Tetraclinis*, and *Thuja*, including their hybrids and cultivars [171]. Recently, *L. festiva* was reported to attack *Sequoia sempervirens*, weakened by fungal decease in the Nikitsky Botanical Garden (Crimean Peninsula) [176]. Thus, now, *L. festiva* is considered a dangerous pest of ornamental cypress trees in many European countries [160,172,179–184]. There are still no quantitative data available on the economic losses caused by this pest to urban plantings; however, the estimated damage to ornamental plants is considered to be significant [160,174,181,183].

The early symptoms of tree infestation with Cypress jewel beetle are brown drying needles, the death of damaged branches, and, in case of heavy infestation, drying and death of a whole plant. The secondary symptoms are fissures, resin leakage, swellings, bark detachment, presence of frass on the trunks and on the soil under the plants, exit holes, and larval galleries under the bark (Figure 7c) [172].

Monitoring of *L. festiva* in Russia is performed locally since the first discovery of damaged cypress trees in the Black Sea coast [172–174,176,177,185,186]. The monitoring is mainly restricted to the search for new foci. The pest control has not been elaborated so far.

The parasitoids of the cypress jewel beetle, such as *Pyemotes* sp. (Acarina: Pyemotidae) and *Metacolus unifasciatus* (Hymenoptera: Pteromalidae), are reported from Bulgaria [184]. On the Black Sea coast, chemical control is carried out during the *L. festiva* adult flight period (preventive treatments of cypress trees with insecticides from the pyrethroid and organophosphorus compounds to prevent colonization of new plants) [107].

3.8. The Small Spruce Bark Beetle, Ips amitinus (Eichhoff, 1872) (Coleoptera: Curculionidae: Scolytinae)

Ips amitinus (Figure 8) is a European species which has been considered a secondary pest associated with dying conifers, including different spruce species (e.g., *Picea abies* and *P. omorica*) and several species of pines (e.g., *Pinus cembra*, *P. mugo*, *P. peuce*, and *P. sylvestris*) [187]. Its native range spreads from The Netherlands to Turkey [188]. In the XX and early XXI centuries, the range of *I. amitinus* rapidly expanded into Northern Europe [189–192]. The first recorded specimens of *I. amitinus* from Estonia are dated by 1900 [193–195]. In the following decades, the species spread northward, and it had occupied the whole of Estonia by the end of the 1930s [194,196,197] and was recorded from southern Finland (Tuusula Administrative Region) in 1951 [198,199]. The species spread rapidly northward in Finland [200], so that in 1968, it was already recorded in Northeast Finland at the boundary with the modern Paanajärvi National Park [201], where it was most probably absent in 1960 [202]. The small spruce bark beetle invaded northern Sweden, apparently from Finland, in 2012 and continues to move southward [203].

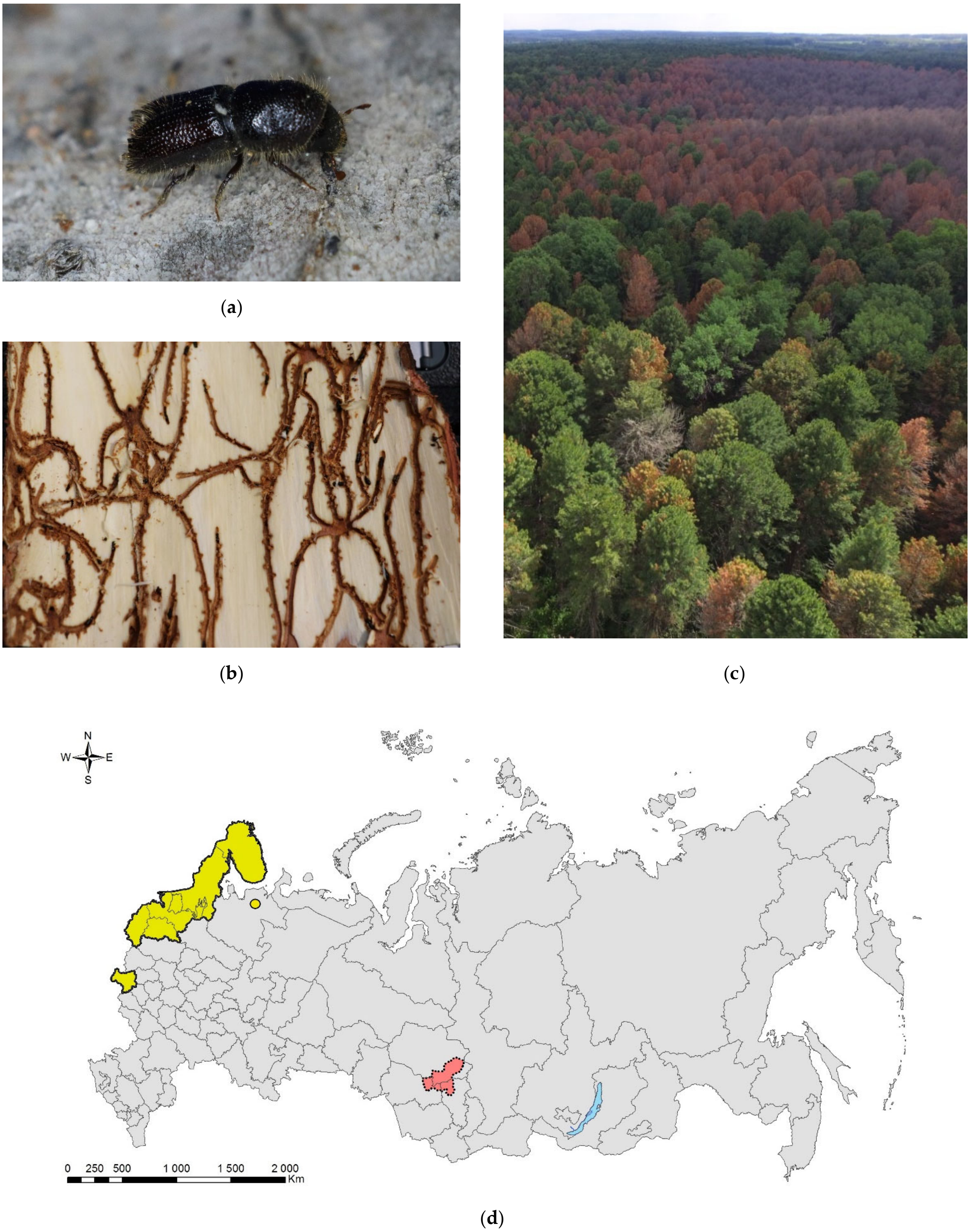


Figure 8. The small spruce bark beetle, *Ips amitinus*: (**a**) an adult on a branch of *Pinus sibirica*, Tomsk Oblast, 2021; (**b**) galleries on *P. sibirica*, Tomsk Oblast, 2021; (**c**) *I. amitinus* foci in the Siberian pine forest near settlement Luchanovo, Tomsk Oblast, June 2020; (**d**) the current distribution in Russia: the native range (colored in yellow) and invasive range (colored in red). Photo by I.A. Kerchev.

The first record in Russia refers to the Briansk Oblast and is dated back to 1920 [204,205]. The "newly" inhabited territories of *I. amitinus* in Russia includes the Leningrad Oblast (Zelenogorsk in the Karelian Isthmus, 1976), though its appereance here was expected much earlier [205,206]. In the 1980s, the species was already widely distributed in Russian Karelia. Investigation of Titova [207] did not reveal *I. amitinus* in Karelia, but Yakovlev and coauthors [208] reported the species in southern Olonets and Loimola, as well as the central part of Karelia (Voloma). In 1989, it spread up to the Murmansk Oblast, Kandalaksha Nature Reserve [206,209]. In 2011, *I. amitinus* was recorded on pines nearby the northern range of a conifer forest in Pasvik Nature Reserve (Melkefoss; on the border between Russia and Norway) [210].

The easternmost record of *I. amitinus* in Europe known to date is the Pinega settlement in the Arkhangelsk Oblast, where the species was collected in 2013 on pine logs, but no infestations on spruces were recorded [189,211]. In 2000, the beetle was found in Pudozh, east to Onega Lake [206]. Thus, *I. amitinus*' range spreading continues not only northward but also eastward. Natural barriers (such as Ladoga Lake) provide limitations to the species spreading and only in 2007 was *I. amitinus* trapped on Valamo Island and only in a wood harbor on the logs imported from the mainland [205,212].

The species invaded Western Siberia relatively recently (presumably, in 2005–2010), attacking a new host tree, the Siberian pine (*Pinus sibirica*), and, at least in the Tomsk Oblast, it was absent until 2012 [213]. The first symptoms of tree damage caused by the small spruce bark beetle were noted in 2014 in the Kemerovo Oblast on the borderline with the Tomsk Oblast [213–215]. A rapid growth of the *I. amitinus* population in 2016–2017 was provoked by the outbreak of the Siberian moth, *Dendrolimus sibiricus,* and favorable weather conditions, which altogether resulted in a considerable number of heavily defoliated and snow-broken trees [213,216]. By the time the invasion was registered in 2019, *I. amitinus* had already switched to healthy trees and started to breed on the tree stands nearby undamaged by the Siberian moth [217]. By 2019, the area of the outbreak foci had reached 237 ha in the Tomsk Oblast and 1033 ha in the Kemerovo Oblast. By the end of 2020, it was already 1207.5 and 1232.4 ha, respectively. The invasive range currently covers Tomsk, Kemerovo, and the Novosibirsk Oblasts, having a total area of 31.2 mln ha [218].

The most probable pathway of *I. amitinus* invasion is natural range expansion in the European part of Russia and Fennoscandia, and transportation with wood by railroads from European part of Russia to Western Siberia. This is confirmed by a number of proofs, such as a long distance between its native and invasive ranges, the proximity of the first recorded outbreak foci in Siberia to the Trans-Siberian Railway, and the rates of invasive range expansion observed at the moment [217]. In Western Siberia, the median density of *I. amitinus'* nuptial chambers on *P. sibirica* was 2.7 (up to 20.0) per dm^2 [216], i.e., 10 times higher than on trap spruce trees in the Czech Republic [219].

The strategy to control this new pest has not been developed in Russia yet. The application of a complex of classical forest protection measures are hampered by a ban on sanitary felling in specially protected natural areas. The first attempts to control *I. amitinus* carried out in the Tomsk and Kemerovo Oblasts were inherently flawed because a species-specific attractant of *I. typographus* was used for the mass pheromone trapping. Moreover, this approach had a negative effect, as it attracted to traps a natural enemy, a checkered beetle *Thanasimus femoralis* (Coleoptera: Cleridae) [215].

The outbreak of *I. amitinus* can be slowed down by sanitary cutting of infested trees and by using trap trees, as well as by timely removal of wind-broken and snow-fallen trees; however, these measures have not been undertaken so far [215]. In the Tomsk Oblast, the death of trees has reached a catastrophic rate [220]. As the attacks mostly begin on the tree tops, drones carrying digital cameras can help to accurately assess the damage [220].

In 2020, *I. amitinus* caused the death of introduced mountain pine (*Pinus mugo*), Korean pine (*P. koraiensis*), and some individuals of native conifers (e.g., *P. sibirica*, *P. sylvestris*, and *Picea obovata*) in the Arboretum "Kedr" of the Institute of Monitoring of Climatic and Ecological Systems, Siberian Branch of the Russian Academy of Sciences (Tomsk Oblast).

The noted trophic preferences of the bark beetle indicate that it strongly prefers the five-needle pines, a trait that has likely developed in the course of coevolution with *P. cembrae* and *P. peuce* in its native range [217].

We believe that further expansion of *I. amitinus* range will continue eastward rather than northward, and the pest will be able to attack eastern pines, for instance, *P. koraiensis* in the Russian Far East [217]. In Western Russia, the species' arrival is also expected up to the Ural Mountains.

Keeping in mind that the species is highly aggressive to Siberian pine and has a potential to outbreak in spruce stands in Europe, its populations should be monitored both in European and Asian parts of Russia. Dramatic rates of Siberian pine stands decline caused by the small spruce bark beetle in West Siberia has shown that the species invasion potential had been underestimated.

3.9. The Four-Eyed Fir Bark Beetle, Polygraphus proximus Blandford, 1894 (Coleoptera: Curculionidae: Scolytinae)

Polygraphus proximus is a conifer pest species of East Asian origin, which, in the last few decades spread in Russia westwards [221,222]. It naturally occurs in Japan, North and South Koreas, Northwest China (Heilongjiang and Jilin Provinces) [188], and in the south of the Russian Far East (Khabarovsk and Primorskii Krais, Sakhalin Island, and Southern Kurils) (Figure 9). In its native range, it develops on firs (i.e., *Abies nephrolepis*, *A. sachalinensis*, *A. holophylla*, and *A. mayriana*; Pinaceae) [223,224]. According to the list of the fir bark beetle's host plants from the native range [225] and analysis of the trees colonized by the beetle in artificial plantations [226,227], it was concluded that firs from the sections Balsamea and Grandis are most preferred, while those from the section Abies are least preferred by this bark beetle [225]. Less common *P. proximus* can be found on other genera of Pinaceae: *Picea* (*P. jezoensis*), *Pinus* (including Korean pine, *P. koraiensis*), *Larix*, and *Tsuga* [224,225].

The first record outside of the species' native range is dated back to 1999, to the Leningrad Oblast [228]. As the species was never documented in this region again, we consider this record to be doubtful [190]. The species was unintentionally introduced to Moscow City [226], where it was recorded in 2006 on artificial stands of *Abies sibirica* and *A. balsamea* along Kurkino highway in the Khimki District. It was also discovered in 2006–2007 on Norway spruce (*P. abies*) and *A. sibirica* in Pushkin, Odintsovo, and Podolsk Districts of the Moscow Oblast [226]. In the East European Plain, fir bark beetle's outbreaks have been registered in the Agryz region of Tatarstan, in the Sarapulsky, Kiyasovsky, Zavyalovsky, and Malopurginsky regions of the Udmurt Republic [229,230].

The species invaded Siberia, from where it was recorded for the first time in 2008, and the beetles were found in pheromone traps for *Ips sexdentatus* in *P. sibrica* stands nearby Tomsk City [231]. In 2009, the presence of *P. proximus* was confirmed in Krasnoyarsk Krai, and it then became clear that this species (and not *Xylechinus pilosus* as it had been though before) was the real cause of Siberian fir stands decline [221–234]. The most probable pathway of *P. proximus* invasion is the transportation of unbarked timber or packaging materials from the Far East. Presently in Siberia, the four-eyed fir bark beetle is found in Tomsk (except the north part), the Kemerovo, Novosibirsk, and Irkutsk Oblasts, Altai, and Khakassia (Figure 9d) [221–236]. It was recorded at an altitude of 100–200 m a.s.l., and in mountainous areas, it inhabits the belt of 300 to 1490 m a.s.l. [225].

The dendrochronological analysis revealed that the beetle killed the first trees in Krasnoyarsk Krai in about 1976 [237] and in the Tomsk Oblast before 2020 [238]. It was suggested that the pest could have been introduced to the Siberian fir range much earlier, e.g., in the 1960s when fir lumber from the Russian Far East was brought to the Kemerovo Oblast for construction of mines [229,237].

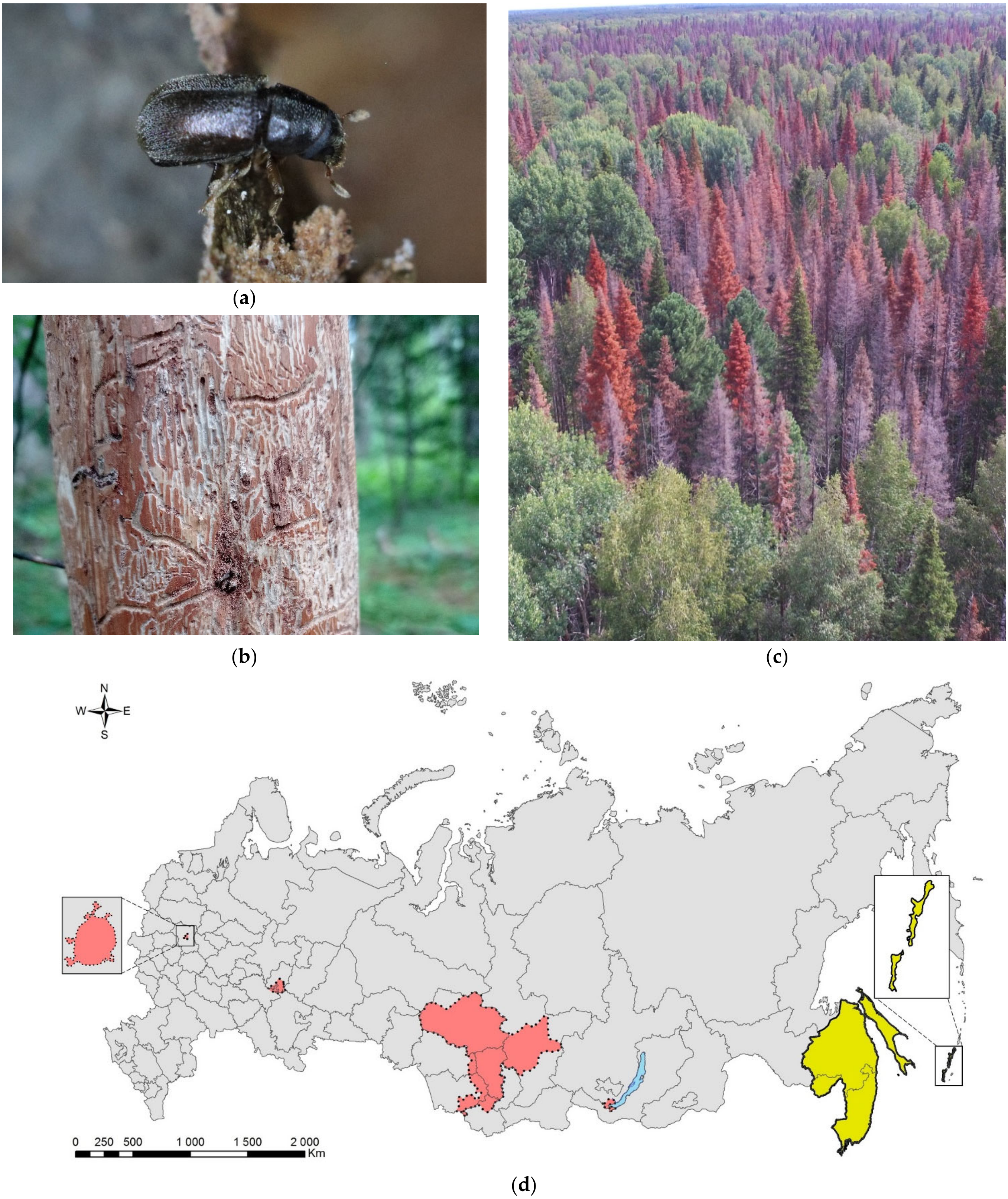


Figure 9. The four-eyed fir bark beetle, *Polygraphus proximus*: (**a**) an adult on *Abies sibirica*, Tomsk Oblast, 2021; (**b**) maternal and larval galleries with pupal chambers on a stem of *A. sibirica*, Tomsk Oblast, 2021; (**c**) *P. proximus* foci in the dark coniferous forest near settlement Barbig, Tomsk Oblast, July 2017; (**d**) the current distribution in Russia: the native range (colored in yellow) and invasive range (colored in red). Photo by I.A. Kerchev.

The four-eyed fir bark beetle was introduced into the Tomsk Oblast and the Udmurtia at approximately the same time, in the mid-1990s, since the beetles taken from both localities belong to the same haplogroup, as suggested by the cytochrome oxidase subunit 1 (COI) mitDNA analysis [239], whereas the specimens from the Krasnoyarsk Krai and Khakassia belong to a divergent group [239,240].

Since the first record in Siberia, mass infestations of *P. proximus* were recorded only on the Siberian fir, but not on other tree species, whereas laboratory tests demonstrated the pest's ability to develop on other Pinaceae species (e.g., *Pinus sibirica*, *Picea obovata*, and *Larix sibirica*) [241]. Later, in the outbreak foci, infestation of wind-broken spruces, Scots pine (*Pinus sylvestris*) and Siberian pine (*P. sibirica*), by *P. proximus* was documented [225].

The beetle can vector an obligate symbitic fungus *Grosmannia aoshimae* (Ascomycota: Ophiostomataceae), and development of the fungus leads to rapid weakening of the host trees [242]. This fungus arrived at Siberia together with *P. proximus* [242,243]. Laboratory tests demonstrated that the fungus could colonize and develop on the same unusual host tree species as *P. proximus* [244]. This work revealed the possibility of a hidden existence of invasive complexes even on the hosts that are not favorable for reproduction of the pest.

Polygraphus proximus kills fir stands in Siberia causing significant changes in the structure of the ecosystem [245]. In declining forests, the microclimate changes, creating preconditions for future replacement of taiga with deciduous trees. Falling down of dead trees leads to a significant imbalance between the intensity of production and destruction processes in the ecosystems [246]. Significant changes are also observed in the vegetation cover and structure of the local insect fauna [233,247,248]. Natural enemies of *P. proximus* [225,249,250] and entomopathogens [251] are not able to control the pest in its invasive range [225]. One of the control methods that has shown high efficiency against the fir bark beetle is the traditional practice of keeping cut trees submerged in water [252]. An integrated approach including treatment with systemic insecticides, timely sanitary cutting and removal of colonized trees used in the N.V. Tsitsin Main Botanical Garden of the Russian Academy of Sciences (Moscow), showed high efficiency in suppression of an outbreak on a relatively small territory [253].

As mentioned above, firs from the sections Balsamea and Grandis are most preferred by the beetle [225]. Thus, possible accidental introduction of *P. proximus* to North America, where firs from these sections are widely distributed, would result in enormous damage. In Europe, firs are represented by *Abies alba* and *A. nordmanniana* from the section Abies [254], which is less preferred as a host by the beetle than representatives of sections Balsamea and Grandis [225]. Nevertheless, phytosanitary and monitoring measures aimed at preventing the invasion of this species and early detection should be prioritized. In the regions where *P. proximus* spreads widely, efforts should be put to minimize damage by conducting timely forest sanitary measures.

3.10. The Box Tree Moth, Cydalima perspectalis (Walker, 1859) (Lepidoptera: Crambidae)

Cydalima perspectalis (Figure 10) is an East Asian species naturally distributed in China, Japan, the Korean Peninsula, the Russian Far East, and India [255,256]. Outside of its native range, the pest was detected in Germany in 2006, where it was presumably imported with boxwood planting material from China [257]. Further invasion of the species in Europe proceeded rapidly (Supplimentary Table S5). In 2007, it was included in the EPPO Alert List, but already in 2011, it was excluded as a species widespread in the region [120]. In 2021, the boxwood moth was found in North America (USA: Connecticut, Michigan, and South Carolina) [258].

(**a**)

(**b**)

(**c**)

(**d**)

Figure 10. Box tree moth, *Cydalima perspectalis*: (**a**) a larva of VI instar, Sochi, August 2013; (**b**) an adult moth, Sochi, September 2014; (**c**) severely damaged box tree, *Buxus sempervirens*, Sukhum District, Abkhazia, July 2015; (**d**) the current distribution in Russia: the native range (colored in yellow) and invasive range (colored in red). Photo: (**a**) and (**c**) by N.N. Karpun, (**b**) by E.N. Zhuravleva.

In Russia (Figure 10d), the larvae of *C. perspectalis* were first recorded on the planting stock of *Buxus sempervirens* in 2012, in the nursery with planting material imported for landscaping the territory of the Main Olympic Village in Sochi [259]. In 2013, the species gave an outbreak in the ornamental plantations in the city of Sochi [260] and was recorded in the plantations in the city of Grozny (Chechnya) [261], and by 2014, it had spread across the Krasnodar Krai and the neighboring region of Abkhazia [262]. In 2015, the species was recorded in the Crimean Peninsula, in Adygea (West Caucasus), in the Mineralnye Vody region (Stavropol Krai), and North Ossetia (North Caucasus) [97,263–265], while in 2016 and in 2017, it was recorded in Rostov-on-Don [266] and in the neighboring region of South Ossetia [267], respectively. In 2019, the boxwood moth was found in Dagestan (North Caucasus) [268] and in 2020 in the Kaliningrad Oblast (southeast of the Baltic Sea) [269]. The main pathway of *C. perspectalis* invasion was the introduction of infested boxwood planting material [63,257,259,270].

The pest causes dramatic defoliation of boxwood in both natural and ornamental plantations (Figure 10c). In 2015–2017, it had almost completely destroyed the natural plantations of boxwood in the North Caucasus and the Black Sea coast of Russia and further eastwards situated region of Abkhazia [63]. Caterpillars of the early (I–III) instars gnaw the lower part of the leaf without touching the upper epidermis, and matured caterpillars consume the whole leaf. At high population densities, they also eat the bark of branches and trunks.

Within the native range, *C. perspectalis* damages *Buxus* spp. (Buxaceae), *Euonymus japonicus* (Celastraceae), and *Ilex purpurea* (Aquifoliaceae). In Europe, it feeds on all native and cultivated species of boxwood, while in Russia, it feeds on 9 boxwood species and 13 cultivars [271].

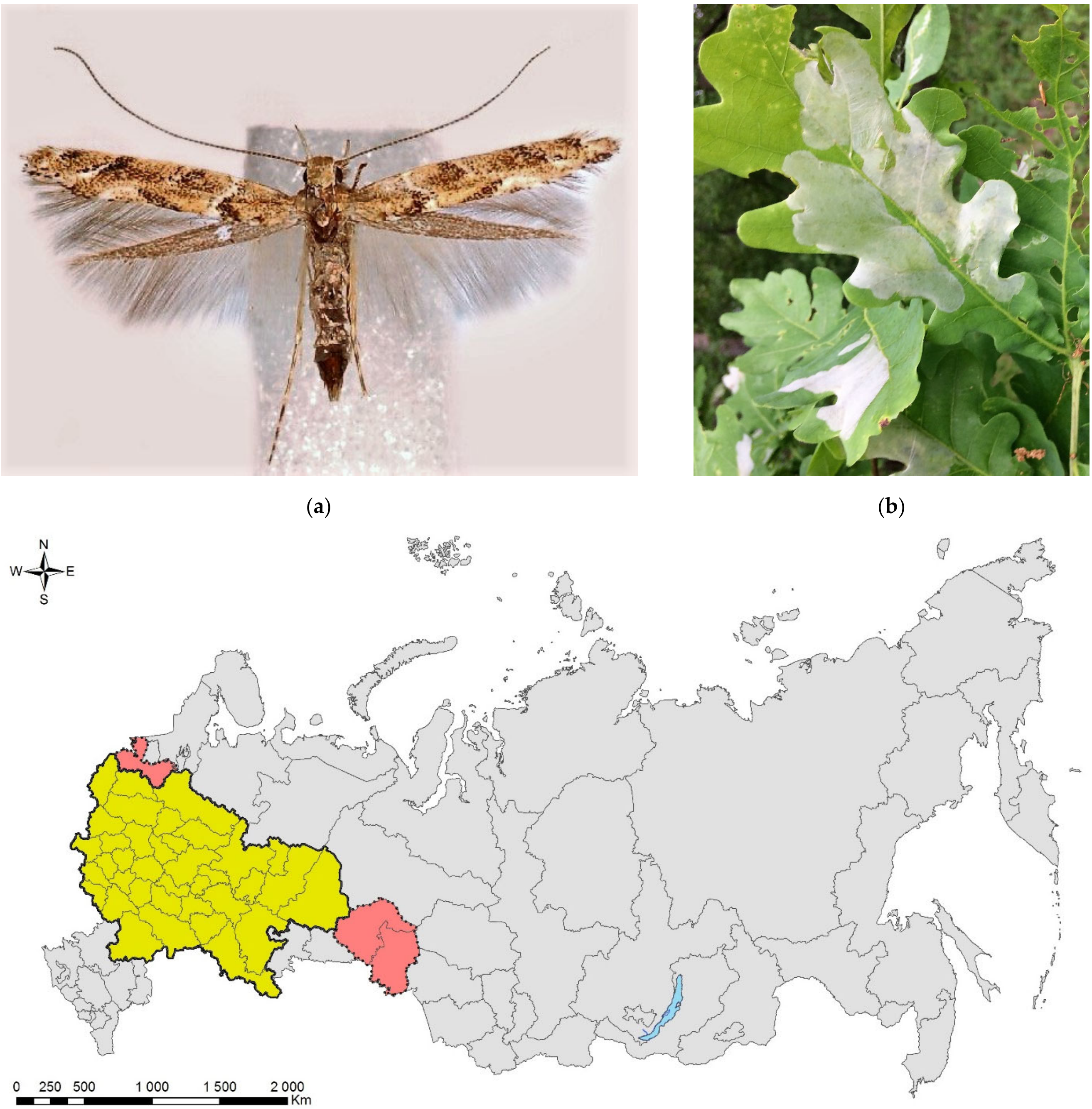
In the humid subtropics of the Black Sea coast of Russia, the pest produces three generations per year and, under favourable conditions, four generations per year can develop. The species overwinter at different stages: egg, caterpillar, and pupa. As a result, different generations overlap [63].

The boxwood moth is monitored by regular visual inspections of plantations and by pheromone trapping. Standard glue deltoid traps are used and they are placed on the branches of boxwood or nearby. The pheromone combines unsaturated aldehydes: (Z)-11-hexadecenal (Z11-16:Ald), (E)-11-hexadecenal (E11-16:Ald), and (Z)-11-hexadecenol (Z11-16:OH) [272–274].

Within the invasive range in Southern Russia, only a few birds and parasitoid wasps (Hymenoptera) attack the alien pest. Despite the fact that in Europe, parasitoids, entomopathogenic fungi, and nematodes are considered ineffective in the control of this pest under natural conditions [275,276], in the humid subtropics of Russia, the early results of the application of entomopathogenic fungi are encouraging [277]. *Bacillus thuringiensis*-based preparations are effective against early-instar caterpillars [276,278,279], whereas avermectins, organophosphorus compounds, pyrethroids, and neonicotinoids are considered effective against older-instar caterpillars [279–282]. Further range expansion of *C. perspectalis* from Russia is likely into natural forests across the Caucasus (Transcaucasia) and to countries located further south.

3.11. The Leaf Blotch Miner Moth, Acrocercops brongniardella (Fabricius, 1798) (Lepidoptera: Gracillariidae)

Acrocercops brongniardella (Figure 11) is a micromoth species widely distributed in Europe and European Russia (except northern and southern regions) [283,284]. The presence of *A. brongniardella* in the Russian Far East is questionable. A single record of the species in Khabarovsk Krai, in fact, refers to *Caloptilia infuscatus* [285], a taxon which might represent a senior synonymy of the East Asian sister species, *Acrocercops amurensis* [286].



(c)

Figure 11. The leaf blotch miner moth, *Acrocercops brongniardella*: (**a**) an adult moth; (**b**) leaves of *Quercus robur* with mines; (**c**) the current distribution in Russia: the native range (colored in yellow) and invasive range (colored in red). Photo: (**a**) by D. Lees; (**b**) by I.A. Utkina, both with permission.

In European Russia, *A. brongniardella* has been found to expand its native range to northern territories, in particular to the Leningrad Oblast and Saint Petersburg City, where it was detected for the first time in 2018 [287,288]. In the following years, the species was recorded south and north of Saint Petersburg, in Gatchina and Sestroretsk, respectively [289,290]. In addition, *A. brongniardella* was also documented in a few localities in Western Siberia, Omsk, and Tyumen Oblasts (Figure 11c) [291–293], where it is considered an alien species. In the city plantations of Omsk, it produces noticeable outbreaks [291].

The pest mines the leaves of oaks (*Quercus* spp.), including evergreen species (e.g., *Q. ilex*), whereas the most common host is the deciduous oak, *Q. robur* [284]; occasionally, the mines can be found on leaves of *Castanea sativa* (Fagaceae) [294]. The mines are big blotches on the upper sides of leaves, often covering a significant area of the leaf lamina (Figure 11b). Fully developed mines are easy to spot by the whitish color. Occasionally, up to 16 young mines can be found on a leaf, later on merging into a big blotch [291,295]. Leaf mining starts in May, then the larvae vacate the mines in July and pupate externally. Adult emergence is prolonged. Moths overwinter in bark crevices and dwellings [291,295]. In Ukraine, the species produces two generations per year [295,296], whereas in Russia, one generation per year was documented [291,297–299].

It is one of the most important folivore insect pests of oaks in Russia. The intense and prolonged outbreaks have been recorded in central parts of European Russia [299,300]. In a foci, often more than 75% of leaves carry mines and increased population density can be observed for several successive years [297,298]. Long-lasting outbreaks can lead to decrease of radial growth, drying of crowns, and death of oaks [301]. However, the impact of this species remains insufficiently well studied [297–299].

In the Leningrad Oblast, where *Q. robur* is a native tree and where the northern limit of its range in Russia is known [302], so far, the moth has been found in low density [287,289,290]. In contrast, in Western Siberia (in particular the Omsk Oblast), the moth shows a tendency to outbreak and harm *Q. robur* [291], an introduced tree in Western Siberia. The first planting of *Q. robur* in the Omsk Oblast is dated to 1898, whereas, in the city of Omsk, it has been planted since 1948. The moth could have arrived to the region with plants for planting, with vehicles or by itself, naturally expanding its range.

In the northeast of European Russia (Udmurtia), no outbreaks have been recorded in the last 35 years [303,304]. We hypothesize that insufficiently warm summers in the north of Russia could limit the moth population density in Saint Petersburg area. The observed climate warming in Saint Petersburg [288] and availability of the main host plant, *Q. robur*, in the city plantations may favor the pest outbreaks in the following years.

In cities, the control of *A. brongniardella* populations is complicated. Removal of leaf litter in order to reduce the population density will unlikely lead to desirable results as with the pest, its native enemies (in particular parasitoids) are killed. The use of insecticides is often impossible in urban areas. Injections of systemic insecticides into trees in high-value plantings and protected areas might be a perspective to keep in mind, given their effectiveness against other pestiferous invasive gracillariids [305–307]. However, so far, this approach has not been tested against this pest in Russia.

3.12. The Horse-Chestnut Leaf Miner, Cameraria ohridella Deschka et Dimić, 1986 (Lepidoptera: Gracillariidae)

Cameraria ohridella (Figure 12) is a tiny moth that became widely known due to its fast distribution across Europe and scenic damage to the horse chestnut, *Aesculus hippocastanum* (Sapindaceae) [308]. It is the only species of the genus *Cameraria* occurring in Europe, while the majority of the genus representatives (83 species) are distributed in North America, with a few species found in Asia and Africa [284]. Curiously, *C. ohridella* was not even known to science before it started invading Europe (Supplimentary Table S6). In the 1980s, it was discovered in high densities in North Macedonia near the Ohrid Lake, from where it was formally described [9]. In the following years, the moth was recorded in many European countries and, in approx. three decades, it occupied most of Europe [308,309].

(**a**)

(**b**)

(**c**)

(**d**)

Figure 12. The horse-chestnut leaf miner, *Cameraria ohridella*: (**a**) an adult moth; (**b**) a mature larva; (**c**) damaged leaves of *Aesculus hippocastanum*, Anapa City, 2021; (**d**) the invasive range in Russia (colored in red). Photo by N.I. Kirichenko.

For more than 20 years, the origin of the species was unclear. Some authors hypothesized it to be a relict species that, together with its host, survived the glaciation of the Tertiary Period [9]. Hellrigl [310] suggested that the species originated from southeastern Europe, where it could have shifted from maple (*Acer* spp.) to *Ae. hippocastanum*. Finally, others suggested the species to be alien for Europe and probably originating from North America or Asia [311]. A phylogeographic study showed that the most probable motherland of the species is the Balkans [312,313]. Furthermore, a survey of historical herbaria confirmed the long-term presence of the species in the Balkans, since the mines were found in pressed leaves sampled more than a century ago, that is, long before the moth was recorded in other parts of Europe [313].

Progressively spreading on the European continent, the moth arrived in European Russia [314,315]. In Russia, its first record is dated to 2003, and refers to Kaliningrad City (southeastern coast of the Baltic Sea) [315]. In 2005, the moth was documented in Moscow [316], about 1000 km east from Kaliningrad and about 450 km from the border with Ukraine and Belarus, where the pest was already present by that time [315,317]. In the following years, the species was found in several regions of European Russia, where the horse chestnut, an exotic plant for the country, is grown in ornamental plantings. By 2015, *C. ohridella* was recorded in 13 central regions of European Russia [318]. Shortly after that, the species occupied the south of European Russia, in particular the Black Sea coast, where it gives spectacular outbreaks in resort areas [319,320]. It also invaded the neighboring Crimean Peninsula (including Sevastopol City), Ciscaucasia [321,322], including North Caucasus [323]. On the north, *C. ohridella* was documented in Saint Petersburg in 2013 [287,324]. The easternmost region where the pest has been found in European Russia is the Volga region [325,326].

In European Russia, *C. ohridella* develops from early May to early October and produces two or three generations per year [306,318,321]. In Moscow and Pskov, it develops in two generations and the third generation is usually incomplete [306,327]. In the south, in particular in Stavropol City, it is able to complete four generations per year [321].

The up-to-date distribution map, compiled based on the literature and modern records, indicates that the species has already occupied a significant part of European Russia (Figure 12d). By now, *C. ohridella* was confirmed in 40 out of 58 (i.e., 69%) administrative units of European Russia, mostly in its central and southern parts. Since the horse chestnut is used ornamentally in nearly all regions of European Russia, further distribution of *C. ohridella* eastward up to the Urals, in our opinion, can be expected. Further expansion east of the Urals will not be possible, as *Ae. hippocastanum* is hardly used in plantings in Western Siberia due to the harsh climate [328].

The female lays eggs individually on the upper sides of leaves [306], and the average fecundity is about 40 eggs per female [329]. Larvae develop in blotches of reddish-brown mines between secondary veins (Figure 12c). Up to 250 mines per leaf have been reported from outbreaking populations [329]. Larvae live solitary in mines, but in heavily infested trees, individual mines merge into big ones [321]. Pupation occurs in the mine. The species hibernates as pupae in the mines of the fallen leaves [321], whereas, in Moscow, overwintering at the adult stage was also documented [306]. Multivoltinism, high fecundity, and easy distribution (that is largely associated with human activities) in short-to-long distances can explain the successful invasion and high population densities of *C. ohridella* in European Russia [306,329].

The main host plant is the horse chestnut, *Ae. hippocastanum*, a native species to the Balkans that started being widely planted in Europe in the early XVII century [330]. In European Russia, this tree has been actively used as an ornamental since the XIX century [328]. Other horse chestnut species, such as Japanese *Ae. turbinate*, American *Ae. octandra* (=*flava*), and *Ae. Glabra*, are also suitable hosts for the moth [331,332]. According to the recent observations in Kaliningrad City, *Ae. carnea*, *Ae. glabra*, and *Ae. pavia* are resistant to the pest [318], while in Moscow, the two latter species are the least damaged [333]. In Europe, the moth can also occasionally attack maples, *Acer pseudoplatanus* and *A. platanoides* (Sapindaceae, the same family as of the horse chestnut), when neighboring horse chestnut trees are infested [310,334]. Mines of *C. ohridella* were also found on *A. platanoides* in the N.V. Tsitsin Main Botanical Garden of the Russian Academy of Sciences (Moscow) in 2006–2009; however, the larvae did not succeed to pupate [306]. In Moscow, it can also successfully develop on *Ae. glabra* [306].

The moth spreads fast through natural dispersion and anthropogenic transportation [306]. In European countries, local dispersal involves both adult flight and the dissemination of infested leaves by the wind [335]. Over long distance, the dispersal of *C. ohridella* is possible by wind (as a part of the aerial plankton), but mostly it happens via passive transportation of infested leaves and adult moths as stowaway in/on cars, trucks, and other vehicles, as well as via the movement of infested seedlings [335,336]. Within Russia, the transportation of live plants of *Ae. hippocastanum* (with leaves that may already contain mines of the pest) undoubtedly facilitates the insect distribution. Furthermore, adults from outbreaking populations can be easily moved over significant distances with any plants and vehicles [306].

Similar to the European countries where *C. ohridella* causes severe aesthetic damage to horse chestnut trees [337], it is a highly important pest of *Ae. hippocastanum* in European Russia [306,329]. This species is listed among the Top 100 most dangerous invasive species in Russia [338]. Heavily infested trees start losing foliage already in July, resulting in pronounced aesthetic (i.e., social) impact in urban areas [318,327]. In addition to *C. ohridella*, since 2012–2013, in the Krasnodar Krai and Adygea (West Caucasus), the horse chestnut trees were affected by an invasive bacterium, *Pseudomonas syringae* pv. *aesculi*, which causes bleeding canker disease [339]. No link between the damage caused by the moth and the infestation by the bacteria was found, rejecting the hypothesis that *C. ohridella* can facilitate the distribution of the disease or increase its impact [340,341].

In European countries, at least 60 parasitoid species are known to attack *C. ohridella* [284]. However, parasitism rates remain generally low, usually within 10–25% in southeast Europe and generally lower than 10% in recently invaded countries of Europe [342–345]. The parasitoid *Pediobius saulius* (Walker) (Hymenoptera: Eulophidae), the most abundant species in the Balkans, gradually followed the invasion of its host, *C. ohridella* [346,347]. Exceptionally, on the south of European Russia, in particular in Krasnodar City, where *C. ohridella* was for the first time recorded in 2010, the parasitism level reached 33.6% already by 2013 [348]. The parasitoid complex in Krasnodar includes 44 parasitoid wasps from Braconidae, Eupelmidae, Ichneumonidae, Pteromalidae, and Eulophidae (Hymenoptera), with most of them having diverse trophic relations with local insects [348]. This parasitoid complex seemed to be effective in controlling *C. ohridella* in Krasnodar, dropping the population density significantly by 2014 [348]. In contrast, in another southern region (Stavropol Krai), no entomophages were recorded in a rather dense pest population, despite the following predators being found: three ladybirds (*Adalia bipunctata*, *Adonia variegata*, *Coccinella septempunctata*), the common earwig (*Forficula auricularia*), common orb-weaving spider (*Araneus* sp.), and tit (*Parus* sp.) [321]. However, this predator complex did not appear to be efficient in controlling the pest and stopping its outbreak [321].

Bearing in mind that the aesthetic damage caused to *Ae. hippocastanum* by the invasive moth can be severe, the strategies to control *C. ohridella* have been extensively explored in European Russia. Since the larvae of *C. ohridella* are endophagous, the use of chemicals with contact-intestinal action cannot provide reliable protection against the pest [306]. A high mortality rate of larvae can be reached by the application of systemic insecticides (e.g., new BI-58, Danadim, etc.); however, their use in settlements is impossible because of their toxicity [306]. Chemical control by aerial spraying is efficient but expensive and not adapted to the urban area [349], while in some European countries, such a measure has raised public concern [350]. Other pesticides with fewer non-target effects can be feasible [351], and in particular, stem injections can provide satisfactory results [352]. The 2-year experiment carried on the horse chestnut in Moscow, demonstrated the high efficiency of the stem injection with Abasol, already the next year after application [352].

In European Russia, the use of pheromone trapping utilizing the synthetic pheromone of *C. ohridella* developed in the Czech Republic [353] was intensively explored. Unitrap pheromone traps and Delta adhesive traps showed high efficiency in *C. ohridella* monitoring and could be also effective in its control [329,354]. Biocontrol approaches, such as the release of specialist parasitoids attacking the leafminer in its native range, have been studied but are still far from practical applications in European Russia [306].

The complete removal of leaf litter in which pupae hibernate can be an effective control measure [321]. However, bearing in mind that damaged leaves start shading early, foliage should be removed repeatedly starting already in mid-summer onward [306]. The majority of adults can be prevented from emerging when leaves are properly composted (by mulching damaged leaves with soil) [321]. However, such approach will likely adversely impact parasitoids, which might stay in *C. ohridella* mines [355].

Replacing horse chestnut with other species is one of the discussed measures [321], but evidently it will be economically very expensive for big cities. Furthermore, the feasibility of tree species chosen for replacement should be carefully assessed.

3.13. The Lime Leaf Miner, Phyllonorycter issikii (Kumata, 1963) (Lepidoptera: Gracillariidae)

Phyllonorycter issikii (Figure 13) is a tiny moth of East Asian origin that in the mid-1980s invaded the western part of the Palearctic, becoming a notable pest of limes *Tilia* spp. (Supplimentary Table S7; [288,356–358]). The moth is known to naturally occur in Japan [356], the Russian Far East (Primorskii Krai) [357], and South Korea [358]. A recent study based on the survey of historical herbaria and sequencing of the larvae and pupae found in the mines revealed a wide distribution of *P. issikii* in China [359,360].

The earliest record of *P. issikii* outside its native range is dated to 1985 and refers to the ornamental plantations of Moscow [361]. Two years later, the species was documented in Voronezh City, i.e., 500 km southwest of Moscow, already at a high population density [362]. During the next 20 years, it spread over the territory of Europe [363,364]. In Russia, the pest occupied most of the European part, except the southernmost and northernmost regions (Figure 13). In 2021, our surveys did not reveal the pest on limes in Sochi City and in settlements of Krasnodar and the Stavropol Krais. Remarkably, the species invaded Western Siberia, with the first record dated to 2006 in Tyumen City [365]. Presently, *P. issikii* is found in Siberia up to the river Yenisei, despite the fact that limes are rare elements of Siberian flora and are mostly used as ornamental plants in cities and smaller settlements [309]. Further expansion to Eastern Siberia is limited due to the absence of its host plants on the territory from the Krasnoyarsk Krai to the Amur Oblast [360].

A phylogeographic study of its currently known range discovered a high genetic diversity of *P. issikii* in Europe vs. East Asia, suggesting multiple pest introductions and its further dispersal [366]. Extensive surveys of 250-year-old herbaria confirmed the East Asian origin and the invasive status of the species in the western Palearctic, as well as highlighted the contribution of China to the species' invasion westward [360]. Furthermore, the historical herbaria clarified the absence of the species from North America [360].

The pest larvae feed exclusively on limes, *Tilia* spp. (Malvaceae), and reference to *Betula* spp. as the host [356] should be regarded as an error. In its native range, the species develops on East Asian limes, among which *T. amurensis* and *T. mandshurica* are most regularly documented hosts [356,358,366]. In the invaded regions, *P. issikii* shifted to novel hosts, for example, *T. cordata* (a main host), *T. platyphyllos*, *T. sibirica*, and others [363,366,367]. Notably, *P. issikii* willingly attacks American lime (*T. americana*) planted in Russian botanical gardens, in particular in Moscow City [368]. It is a common plant in eastern USA [369], and in case of accidental *P. issikii* introduction, *T. americana* will likely fit as a favorable host plant for the pest.

In the invaded regions of Russia, the species develops in one or two generations per year, from May to September, depending on the region [364,368]. Larvae live in the lower side tentiform mines (Figure 13b,c), and occasionally, upper side mines occur in dense populations [360]. In exceptional cases, up to 29 mines per leaf were recorded in Novosibirsk on *T. cordata* [357]. The species hibernates at the adult stage.

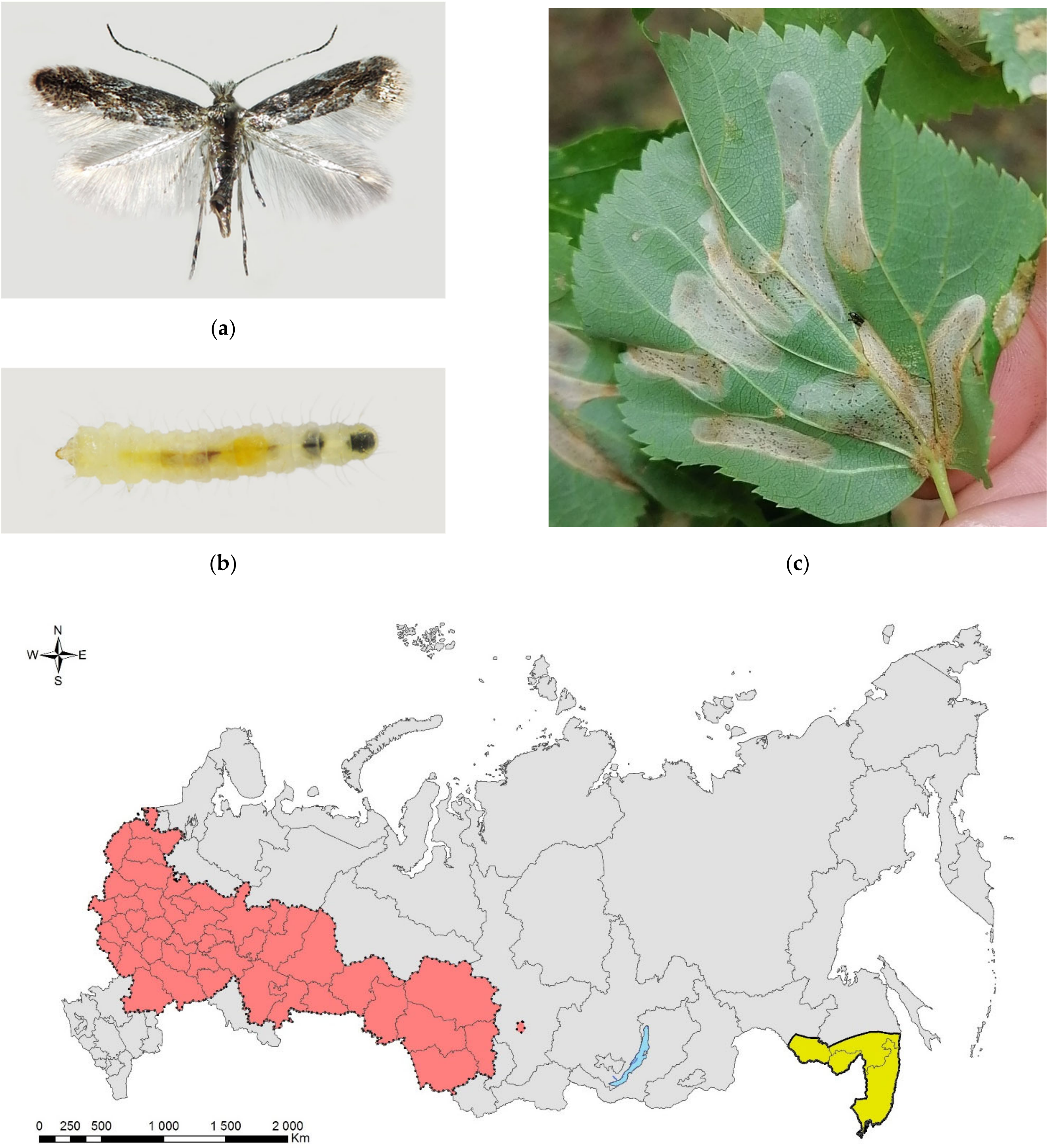


Figure 13. The lime leaf miner, *Phyllonorycter issikii*: (**a**) an adult moth; (**b**) a mature larva; (**c**) damaged *Tilia cordata* in Central Siberian Botanical Garden of the Siberian Branch of the Russian Academy of Science, Novosibirsk. (**d**) the current distribution in Russia: the native range (colored in yellow) and invasive range (colored in red). Photo by N.I. Kirichenko.

Adults of *P. issikii* fly only over short distances [363]. Long-distance dispersal on air currents is possible, as well as the distribution of *P. issikii* by hitchhiking with various land and air transports, bearing in mind that adult moths hide themselves in crevices and other shelters and thus can be passively moved to remote territories [308,363,370].

The species is generally known as an ornamental pest causing aesthetic damage to limes in parks and gardens [363]. In addition, *P. issikii* was also reported as affecting natural stands in European Russia [371] and Western Siberia (Kemerovo Oblast) [366]. In high densities, the lime leaf miner negatively impacts lime growth; furthermore, the pest may adversely affect the sugar content in nectar, subsequently decreasing honey production, as documented in the Udmurtia (east of Volga River) [371]. In Western Siberia, the pest threatens vulnerable Tertiary relic limes groves [366]. Notably, so far, the species has been known by its exceptionally outbreaking character in the invaded regions of Russia [364,366]. Exploration of the lime herbarium specimens provided evidence of a population density increase in *P. issikii* in Primorskii Krai (Far East) in some years in the period of 1914 to 1958 [372].

The control methods have not been effectively developed against this pest. No data on pheromone monitoring and sex disruption are available in Russia. In European Russia, the parasitoid complex of *P. issikii* accounts for at least 43 species (Braconidae, Eulophidae, and Pteromalidae; Hymenoptera) vs. 13 parasitoid species known from its native range (East Asia), with only 6 species in common [373,374]. In European Russia and Siberia, the parasitism level varies within 1.4–37.0% but still remains low [368,375]; the highest value (up to 37.0%) was documented in the Volga Basin [376]. In the invaded regions of Russia, the commonly recorded hymenopteran parasitoids are *Sympiesis gordius*, *Pnigalio soemius* (both Eulophidae), and *Minotetrastichus frontalis* (Chalcidoidea) [373]. The latter species is also present in East Asia [374]. These are generalist parasitoids, with a wide host range among Gracillariidae [374]. Thus, their potential application against the invasive lime leaf miner is questionable, keeping in mind that they may also attack other native gracillariids, including rare species. Nevertheless, *M. frontalis* has been proposed as a biocontrol of *P. issikii* in Russia [377]. In East Asia, little data are available about parasitism rate in *P. issikii* populations [374], whilst these data would be of a high importance for the biocontrol of the pest.

3.14. The Poplar Leafminer, Phyllonorycter populifoliella (Treitschke, 1833) (Lepidoptera: Gracillariidae)

Phyllonorycter populifoliella (Figure 14), is a micromoth species widely distributed across the Palearctic [284]. In Russia, this native species occupies large territory from Kaliningrad City (southeastern coast of the Baltic Sea) to the Far East, except northern regions in the Asian part of the country (Figure 14d) [283,378,379]. Recently, the pest was detected beyond its known range, in northern India, in high densities on introduced poplars fueling the hypothesis about its accidental introduction [380].

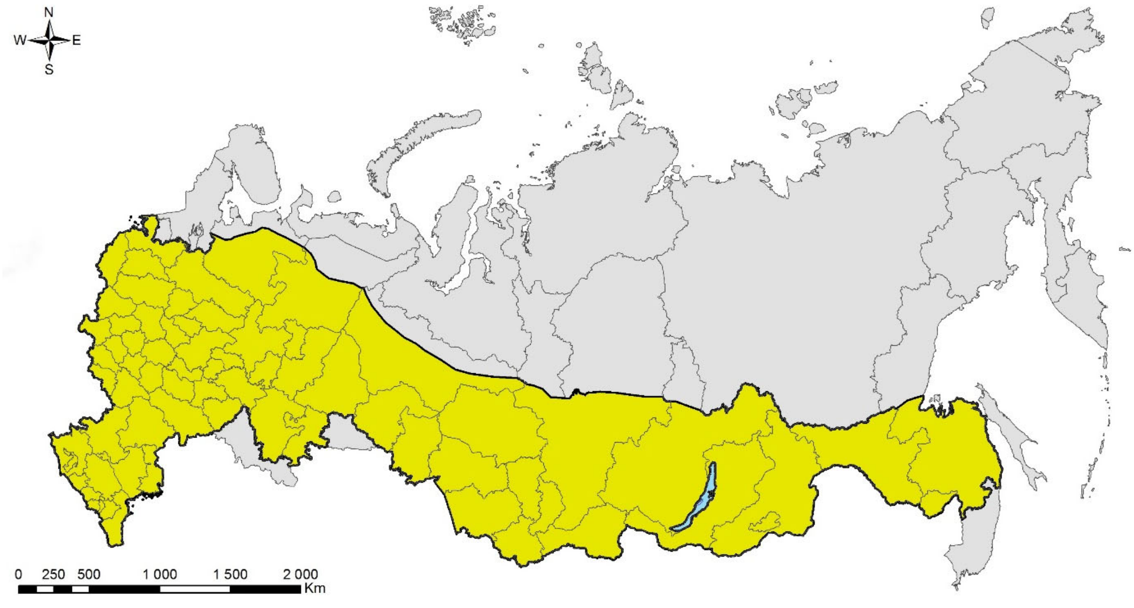
The moth develops on poplars, *Populus* spp., preferring black and balsam poplars (i.e., Aigeiros and Tacamahaca sections, respectively), to other poplars [379,381–383]. The larvae make distinctive blotch mines on the lower side of leaves, while in dense populations, upper side mines can also occur [384].

The poplar leafminer is known as a severe pest of balsam poplars and their hybrids with black poplars widely planted as ornamental in European Russia, in the Ural region and in Siberia [382–388]. In European Russia, the first outbreak of the pest was documented in the 1930s in Moscow [389]. Further east, in Siberia, the moth foci are known since the middle of the XX century in Irkutsk [385], and later, they were documented in other cities [382,386]. Interestingly, in some regions of European Russia where the poplar leaf miner was never known as an outbreaking pest, nowadays it provides noticeable damage to poplars. For instance, in Saint Petersburg, *P. populifoliella* was known as a rare species with the first record of the moth dating to 1936 [387,390], and the next finding was done only in 1974 [391]. In 1991, a sharp increase in population density was documented, with an outbreak in Saint Petersburg lasting from 1992 to 1999 [392,393]. For almost the next 20 years, the population density of this species was very low again, but since 2017, the new outbreak began in Saint Petersburg [387], where the pest showed the tendency to develop foci on new territories [289–390,394].

(**a**)

(**b**)

(**c**)



(**d**)

Figure 14. The poplar leafminer, *Phyllonorycter populifoliella*: (**a**) an adult moth; (**b**) a mature larva; (**c**) a down side of a leaf of *Populus* × *berolinensis* heavily damaged by *P. populifoliella*, Saint Petersburg, August 2020; (**d**) the native range in Russia (colored in yellow). Photo: (**a**) and (**b**) by N.I. Kirichenko and (**c**) by N.A. Mamaev, with permission.

Severely damage poplars start losing their leaves already in late July to early August, which significantly reduces the aesthetic and ecological functioning of poplars in settlements and big cities. The pest can affect tree growth [395]. The mass death of poplars in Saint Petersburg in the early 2000s might have a link to the preceding pest outbreak [387]. Presently in Saint Petersburg, the *P. populifoliella* gives only one generation per year, since the larvae of the second generation are not able to complete their development and die not reaching the pupal stage. Climate warming will favor the second generation, thus increasing the pest population density [289,290]. Currently, there is no regular monitoring of the poplar leaf miner in Russia. Injection of poplars with systemic insecticides is a possible way to reduce the pest population densities, but this approach is not used due to its high economic and labor cost. The removal of fallen leaves (carrying mines with larvae and pupae of the pest) is not an effective approach as it can also affect survival of native enemies (parasitoids) that can be helpful in pest control [396]. The complexes of parasitoids attacking *P. populfoliella* in European Russia, includes overall 68 species [383], which in some years, can kill up to 90% of the second generation of the moth as found in Moscow [383,396].

The gradual replacement of poplars with other tree species could help decrease the pest's impact. Black and balsam poplars commonly used as ornamental in Russian cities should be planted rather in small groups in order to avoid the formation of large foci of *P. populifoliella* [383,395].

Bearing in mind the *P. populifoliella* outbreaks on balsam poplars and their hybrids with black poplars in Russia, the accidental introduction of the moth to North America, where balsam and black poplars (e.g., *Populus balsamifera, P. trichocarpa, P. deltoides,* and *Populus* × *canadensis*) have a wide range, may potentially result in significant tree damage.

4. Discussion

4.1. Taxonomy

This review analyzes the most recent data on 14 species of insects from 3 orders: Hemiptera-Heteroptera (3 species from 3 families), Coleoptera (6 species from 2 families), and Lepidoptera (5 species from 2 families) that are known as highly invasive in Russia or native to the country but also pose a potential danger to woody plants elsewhere (Table 1). The very approximate estimations of the insect fauna of Russia suggest that it includes 80–100 thousand species [397], which is roughly close to the earlier assessments of the insect fauna of the former USSR (approximately the same, 81 and 119 thousand species, respectively [398]). Overall, 192 species of phytophagous alien insects from 48 families and 8 orders had been documented in the European part of Russia by 2011 [8]. Undoubtedly, their number has increased since that time, both because of the escalating invasions and the increased detection of alien species due to growing survey efforts. Looking at all these estimations, it is unjustified to conclude that the listed three orders and seven families of insects include all the most dangerous pests, and it is impossible to say that in other taxa there are no species which are already identified or potentially can be considered pestiferous for woody plants. Out of 14 species, 4 species belong to Gracillariidae, including *Cameraria ohridella*, which intensively invades urban environments providing scenic outbreaks. Four species, actual or potential invaders, represent the family Buprestidae. The question remains open whether or not there are specific family-level traits that drive the family representative to invade new territories. Taxonomic estimates are still very rough and cannot be used to estimate the invasive potential of any particular taxon. In the coming years, in our opinion, in addition Coleoptera and Lepidoptera, economically important invaders can also be well expected in Hemiptera-Homoptera, Hymenoptera, and Diptera.

Table 1. Invasive and emerging insect pests of forest and urban woody plants in Russia: possibility of further invasions, damage, monitoring, and control (Summary).

No.	Species	Native Range	Invasive Range	Availability of Host Plants Outside Russia	The Regions and/or Countries to Where the Invasion Is Possible from Russia	Damage Level (in Forests/ Urban Areas)	Monitoring Measures *	Control Measures *	
								General and in Forests	Specific in Urban Areas
1	Conifer seed bug, *Leptoglossus occidentalis* (Hemiptera: Heteroptera: Coreidae)	West of North America: from South of Canada to Mexico	Most of Europe: from South of Norway to Mediterranean Sea, from British Isles to European Russia; Asia: Kazakhstan, Northeast China, Japan, South Korea; Africa: North and South; South America: Chile, Argentina, Uruguay	All conifer, native and introduced Pinaceae	Mongolia, Kyrgyzstan, Asian Turkey	Moderate to high level of damage in forests, coniferous tree nurseries, and urban areas	Visual inspection; analysis of seed damage and germination of seeds from infested trees	Biological and chemical control	Biological control
2	Brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Heteroptera: Pentatomidae)	Southeast Asia: China, Taiwan, Korea, Japan, Vietnam	North America; Europe (including South of European Russia); Asia: Kazakhstan	300+ species of vascular plants	Transcaucasia, Middle Asia	Major damage in fruit, berry, and nut plantations	Inspections of overwintering quarters; visual inspection of host plants; pheromone traps	Quarantine measures; pheromone traps; biological and chemical control	Pheromone traps
3	Oak lace bug, *Corythucha arcuata* (Hemiptera: Heteroptera: Tingidae)	North America	Europe (including South of European Russia); Asia Minor	*Quercus* spp. and other Fagaceae, some species of Salicaceae, Rosaceae, Fabaceae	Middle Asia, Transcaucasia, Ukraine, Moldova, Belarus	Major in urban areas; moderate in forests	Inspections of overwintering quarters; visual inspection of host plants	Biological and chemical control	Biological control
4	Spotted poplar borer, *Agrilus fleischeri* (Coleoptera: Buprestidae)	North Asia: Russia (West and East Siberia, Far East), East Kazakhstan, Mongolia, Northeast and central China, North Korea, South Korea, Japan	unclear	Native and introduced *Populus* spp. and *Salix* spp.	West Kazakhstan, Europe (including east of European Russia), North America	In urban areas and forests (minor; during outbreaks—major)	Visual, color, and pheromone traps	Quarantine measures; sanitation felling; chemical control should be developed; biological control (egg and larval parasitoids) should be developed	Elimination of individual infested trees; chemical control should be developed (stem injections with insecticides); biological control (egg and larval parasitoids) should be developed

Table 1. *Cont.*

No.	Species	Native Range	Invasive Range	Availability of Host Plants Outside Russia	The Regions and/or Countries to Where the Invasion Is Possible from Russia	Damage Level (in Forests/ Urban Areas)	Monitoring Measures *	Control Measures *	
								General and in Forests	Specific in Urban Areas
5	Apple buprestid, *Agrilus mali* (Coleoptera: Buprestidae)	East Asia: Russia (East Siberia, Far East), Mongolia, Northeast and central China, North Korea (**), South Korea (**)	Asia: China (**): Xinjiang, North Korea (**), South Korea (**)	Cultivated and wild *Malus* spp., *Cydonia* spp., *Prunus* spp., *Pyrus* spp.	Kazakhstan and other Central Asian countries; entire apple orchard cultivation area	In agricultural areas and forests (major)	Visual, color, and pheromone traps	Quarantine measures; biological control (egg and larval parasitoids) and chemical control should be developed	Pruning; elimination of individual infested trees; chemical control (stem injections with insecticides) and biological control (egg and larval parasitoids) should be developed
6	Emerald ash borer, *Agrilus planipennis* (Coleoptera: Buprestidae)	East Asia: Russian Far East, Northeast China, Japan, Mongolia, North Korea, South Korea	Europe: Central, Northwest, South and Southeast of European Russia, Eastern Ukraine; North America	Native and introduced *Fraxinus* spp., *Chionanthus* ssp., potentially other Oleaceae	Ukraine, Belarus, Poland, Baltic countries, Finland, and other European countries	In urban areas and forests (major)	Visual, color and pheromone traps; checking nests of *Cerceris* spp. (Hymenoptera)	Quarantine measures; sanitation felling; chemical control should be developed; biological control (egg and larval parasitoids)	Elimination of individual infested trees; chemical control (stem injections with insecticides); biological control (egg and larval parasitoids)
7	Cypress jewel beetle, *Lamprodila* (*Palmar*) *festiva* (Coleoptera: Buprestidae)	Europe: Mediterranean countries, South Europe, South of central Europe; North Africa; Southwestern Asia	Europe: Central and East Europe, South of European Russia, Eastern Ukraine	Native and introduced Cupressaceae	Transcaucasia, entire Ukraine, Moldova, Belorussia, Poland, Baltic countries, North America	In urban areas (major) and forests	Visual, color, and pheromone traps	Quarantine measures; sanitation felling; chemical control (insecticides during adult flight period); biological control (egg and larval parasitoids) should be developed	Elimination of infested trees; chemical control (pyrethroid insecticides during adult flight period, if allowed and stem injections with insecticides); biological control (egg and larval parasitoids) should be developed

Table 1. *Cont.*

No.	Species	Native Range	Invasive Range	Availability of Host Plants Outside Russia	The Regions and/or Countries to Where the Invasion Is Possible from Russia	Damage Level (in Forests/ Urban Areas)	Monitoring Measures *	Control Measures *	
								General and in Forests	Specific in Urban Areas
8	Small spruce bark beetle, *Ips amitinus* (Coleoptera: Curculionidae: Scolytinae)	Europe: Central, South, and North Europe; Baltic countries; Northwest Russia	Asia: West Siberia	Different conifers, especially *Pinus* spp. and *Picea* spp.	China, North America	Major pest of all conifer forests; possible economic effect is unpredictable	Surveys; pheromone traps	Pheromone traps; sanitation felling	Pheromone traps; elimination of individual infested trees
9	Four-eyed fir bark beetle, *Polygraphus proximus* (Coleoptera: Curculionidae: Scolytinae)	Asia: Northeast China, Japan, Korea, Russian Far East	Europe: central Russia; Asia: West and East Siberia	Different conifers, especially *Abies* spp.	North and Central Europe, North America	Major pest of firs in forests and urban areas	Phytosanitary quarantine and surveys	Pheromone traps; sanitation felling	Pheromone traps; elimination of individual infested trees
10	Box tree moth, *Cydalima perspectalis* (Lepidoptera: Crambidae)	Asia: China, Japan, Korea, Russian Far East, India	Europe: South of European Russia, Georgia, Turkey	*Buxus* spp.	Natural forests across the Caucasus (Transcaucasia) and to countries located further south	Major in urban areas and forests	Visual, UV-light, or pheromone traps	Pheromone traps; biological and chemical control; sanitation felling	Pheromone traps; elimination of individual infested trees; biological and chemical control
11	Leaf blotch miner moth, *Acrocercops brongniardella* (Lepidoptera: Gracillariidae)	Europe	Europe: St. Petersburg and the Karelian Isthmus	*Quercus* spp.	Siberia, Far East, North America	Mainly in urban areas	Visual (mines); pheromone traps	Biological control (egg and larval parasitoids) should be developed	Stem injections with insecticides should be developed
12	Horse-chestnut leaf miner, *Cameraria ohridella* (Lepidoptera: Gracillariidae)	Europe: The Balkans	Europe: East and West Europe, European Russia (except some northern and eastern regions)	Native and introduced *Aesculus* spp., and possibly *Acer* spp.	East Asia, East and West of North America	Mainly in urban areas	Visual; pheromone traps (might be not efficient al low density)	Biological control (parasitoids, disease agents)	Stem injections with insecticides; removal of leaf litter (populations with overwintering of pupae)

Table 1. *Cont.*

No.	Species	Native Range	Invasive Range	Availability of Host Plants Outside Russia	The Regions and/or Countries to Where the Invasion Is Possible from Russia	Damage Level (in Forests/ Urban Areas)	Monitoring Measures *	Control Measures *	
								General and in Forests	Specific in Urban Areas
13	Lime leaf miner, *Phyllonorycter issikii* (Lepidoptera: Gracillariidae)	East Asia: Japan, South Korea, China, Russian Far East	Europe: East and West Europe, European Russia (except some northern and southern regions); Asia: Western Siberia	Native and introduced *Tilia* spp.	North America	Mainly in urban areas, occasionally in forests	Visual; pheromone traps (might be not efficient al low density)	Biological control (parasitoids, disease agents)	Protection of natural enemies
14	Poplar leafminer, *Phyllonorycter populifoliella* (Lepidoptera: Gracillariidae)	Eurasia	Europe: North of European Russia; Asia: Siberia	*Populus* spp.	Far East, and North America	In urban areas	Visual (mines); pheromone traps	Biological control (egg and larval parasitoids) should be developed	Stem injections with insecticides should be developed

* Already used in Russia or elsewhere. ** Not clear, native or invasive populations.

4.2. Directions of Invasions

In terms of the directions of invasions, the pests included in this review can be clustered into four groups:

(1) Invasions from Asia to West or central Europe and then (or directly) to European Russia: This is the most numerous group, which consists of five species—*Cydalima perspectalis*, *Phyllonorycter issikii*, *Halyomorpha halys* (likely first invaded North America and only then Europe and European Russia; see above), and two species, which actually skipped West or central Europe and arrived directly to European Russia, namely, *Agrilus planipennis* and *Polygraphus proximus*;
(2) Invasions from North America to West or central Europe and then to European Russia: *Leptoglossus occidentalis* and *Corythucha arcuata*;
(3) Invasions from Europe to Asia: the case of *Ips amitinus*;
(4) Range expansions within Europe and invasions to European Russia: *Lamprodila festiva* and *Cameraria ohridella*.

Additionally, there is a group of potential invaders currently changing their ranges within European and/or Asian parts of Russia: As described above, two beetle species (*Agrilus fleischeri* and *A. mali*) have not yet noticeably expanded their native ranges in Asian Russia but demonstrate a potential of range expansion and/or host plant shift; somewhat similar could be said about *Acrocercops brongniardella* and *Phyllonorycter populifoliella*.

Thus, there is no common geographic pattern of invasion, and different invaders spread in very different directions.

4.3. Causes and Pathways of Invasions

Invasions of almost all discussed species were associated with human activity, except *Ips amitinus* (in North Europe) and *Acrocercops brongniardella*, which are believed to expand their ranges due to natural causes. Some species (e.g., *Leptoglossus occidentalis*, *Halyomorpha halys*, and *Corythucha arcuata*) at the beginning of their invasions were most likely transported by airplanes (from one continent to another) with goods of plant or non-plant origin. *Agrilus planipennis* was likely moved with wood products or packaging materials; *Polygraphus proximus* and *Ips amitinus* (in Siberia) with timber by railway roads; and *Lamprodila festiva*, *Cydalima perspectalis*, *Cameraria ohridella*, and *Phyllonorycter issikii* with plant materials and/or plants for planting. Very small insects such as *Corythucha arcuata* and *Cameraria ohridella* could use air flow for mass spreading. In other cases, the invasive processes (actively developing (e.g., in *Agrilus planipennis* and *Lamprodila festiva*) or just beginning at the early stages (e.g., in *Agrilus fleischeri*, *A. mali*, *Acrocercops brongniardella*, and *Phyllonorycter populifoliella*)) are probably more complicated and involve host plant shifts as a result of planting or introduction of susceptible host plant species or hybrids (see corresponding essays above).

4.4. Probability of Further Invasions to Neighboring and Distant Countries

All species reviewed are expected to spread further to (in) Europe, including countries of the Caucasus region (i.e., nine species: *Leptoglossus occidentalis*, *Halyomorpha halys*, *Corythucha arcuata*, *Agrilus fleischeri*, *A. mali*, *A. planipennis*, *Lamprodila festiva*, *Polygraphus proximus*, and *Cydalima perspectalis*) or to (in) Asia (i.e., nine species: *Leptoglossus occidentalis*, *Halyomorpha halys*, *Corythucha arcuata*, *Agrilus fleischeri*, *A. mali*, *Ips amitinus*, *A. brongniardella*, *Cameraria ohridella*, and *Phyllonorycter populifoliella*). Moreover, it is expected that nine species can potentially invade North America and/or other continents (i.e., *Agrilus fleischeri*, *A. mali*, *Lamprodila festiva*, *Ips amitinus*, *Polygraphus proximus*, *Acrocercops brongniardella*, *Cameraria ohridella*, *Phyllonorycter issikii*, and *P. populifoliella*) (Table 1).

4.5. Role of the Trophic Factor in Insect Pest Range Expansion

Analysis of invasion histories performed in the framework of this review, suggests that in some cases, invasions start with the widening of the pest's trophic niche and shifts to new host plant(s) (commonly human-introduced) within the native pest's range, frequently followed by invasion to new regions (e.g., *Agrilus fleischeri*, *A. mali*, *Acrocercops planipennis*, *Lamprodila festiva*, and *Phyllonorycter populifoliella*). The data reviewed above suggest that a few steps can be usually recognized within those five scenarios:

(1) A shift in an insect species (often not even a pest) within its native range from its usual host plant(s) to introduced and cultivated host plant(s) (usually from the same or close genus of woody plants and often non-resistant because of lack of co-evolution) (e.g., a shift in *Agrilus planipennis* in Russian Far East and China, from local Asian ash species to introduced North American ash species; a shift in *Phyllonorycter populifoliella* in European Russia and Siberia, from local poplars to widely cultivated introduced North American balsam poplar and hybrids; a shift in *Lamprodila festiva* from wild Cupressaceae to introduced *Thuja* and other cultivated representatives of this family, including their hybrids and cultivars in the Mediterranean region; a shift in *Agrilus fleischeri* to introduced poplars in China);

(2) A local niche expansion due to exploration of cultivated, recently introduced host plants in anthropogenic (urban or agricultural) landscapes; local population build-up and outbreaks (e.g., recorded earlier in *Agrilus planipennis*, *A. mali*, *Phyllonorycter populifoliella*, and *Lamprodila festiva*, and currently seen in *A. fleischeri*);

(3) A range expansion outside the limits of the native range through anthropogenic (urban or agricultural) landscapes, i.e., beginning of invasion (e.g., *Agrilus mali* and *Lamprodila festiva*);

(4) A distant invasion (e.g., invasions of *Agrilus planipennis* to European Russia or North America or *Ips amitinus* to Siberia);

(5) A secondary host plant shift to the native (for the invaded region) food plant(s) (e.g., shift in *Agrilus planipennis* to *Chionanthus virginicus* in North America [399] and to *Fraxinus excelsior* in European Russia; shift in *A. mali* from cultivated apples to the wild apple, *Malus sieversii* in China).

Separately, we should mention *Acrocercops brongniardella*. This species does not shift to new host plants but simply follows range expansion of its usual host plant (*Quercus robur*) [360].

4.6. Monitoring and Control Measures

The monitoring methods recommend for the reviewed species are mainly limited by visual inspections and application of pheromone and color traps (Table 1). These methods might be quite effective when used appropriately and systematically. However, as this review demonstrates, in many cases, the monitoring system does not work properly, and many invasive pests rapidly increase their secondary ranges in Russia (e.g., *Leptoglossus occidentalis*, *Halyomorpha halys*, *Agrilus planipennis*, *Cydalima perspectalis*, *Lamprodila festiva*, and *Cameraria ohridella*). The lack of effective integration between organizations responsible for the monitoring and management of forests, urban, and suburban woody plantations in Russia (on both the national and local levels) creates serious difficulties for the practical and systematic use of these methods, especially keeping in mind the vast territory of the country. To increase the effectiveness of the monitoring, it is advisable to create a fast and flexible system of information exchange between the public and the organizations responsible for the monitoring and management of forests, urban, and suburban woody plantations, as well as to increase the level of effective involvement of scientists, university professionals, and citizens in monitoring of invasive insect pests of woody plants.

The control measures understandably differ between forests and urban woody plantations. To control the spread of the reviewed invasive pests in forests, we mostly suggest developing and use biological and chemical methods (Table 1). Special attention should be paid to a braconid *Spathius polonicus* Niezabitowski (Hymenoptera: Braconidae: Doryctinae), a parasitoid, which seems to have potential to effectively control *Agrilus planipennis* in European Russia, although it is likely that a few years are needed to build up a sufficient parasitoid population [145,169,400]. The effective use of sanitation fellings in the forests of the Russian Federation is currently much overcomplicated by the existing regulatory framework, which does not allow timely felling of trees infested by insect pests. The use of pheromone traps proposed as a measure to control some invaders (e.g., *Halyomorpha halys*, *Corythucha arcuata*, *Ips amitinus*, *Polygraphus proximus*, and *Cydalima perspectalis*; Table 1) is possible and potentially effective only when we deal with a limited, relatively small forest area.

The situation is different with the invasive pest control in urban and suburban woody tree plantations. The use of chemical control is significantly legally limited in such environments, whereas the application of stem injections is not always possible (taking into account its cost) but advisable, especially against insect pests that live inside the plant tissues (e.g., mining insects, gallers, wood-borers, etc.) in individual trees in urban areas. Within a relatively small woody tree plantation, it is possible to use biological control methods, pheromone traps, elimination of individual infested trees and other specific methods. It should be kept in mind that overall such control methods might be very expensive.

5. Conclusions

The majority of the reviewed insect pests have demonstrated their invasive behaviour in Russia during the last 10–30 years. In most cases, first reports of these invaders in Russia were unexpected for the stakeholders, who were supposed to provide forest and urban woody plants' monitoring and management. These invasions led to significant ecological and economic losses and caused negative social consequences [15,63,338,360].

We suggest that there are three major scenarios of invasions of woody plant's pests: (1) a naturally conditioned range expansion, which results in the arrival of a pest to a new territory and its further naturalization; (2) a human-mediated long-distance transfer of a pest to a new territory and its further naturalization; and (3) a widening of the pest's trophic niche and shift to new host plant(s) (commonly human-introduced) within the native pest's range, frequently followed by invasion to new regions.

Bearing in mind these and many other examples of devastating invasions of tree pests as well as unpredictable emergence of novel invaders, it is essential to stress the importance of insect pest monitoring (including the episodes of host plant shift) and more effective use of early detection programs (e.g., sentinel plantings) [7,401,402] and application of new and developing species identification techniques (e.g., DNA-barcoding) [403].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13040521/s1; Supplimentary Table S1: Timeline of the first records of the Western coniferous seed bug, *Leptoglossus occidentalis* in its invasive range in Europe; Supplimentary Table S2: Timeline of the first records of *Halyomorpha halys* in its invasive range in Europe; Supplimentary Table S3: Timeline of the first records of *Corythucha arcuata* in its invasive range in Europe; Supplimentary Table S4: Timeline of the first records of *Lamprodila* (*Palmar*) *festiva* in its invasive range in Europe; Supplimentary Table S5: Timeline of the first records of *Cydalima perspectalis* in its invasive range in Europe; Supplimentary Table S6: Timeline of the first records of *Cameraria ohridella* in its invasive range in Europe; Supplimentary Table S7: Timeline of the first records of *Phyllonorycter issikii* in its invasive range in Europe.

Author Contributions: Conceptualization, D.L.M., N.I.K., A.V.S. and R.V.; methodology, D.L.M., N.I.K. and A.V.S.; formal analysis, D.L.M., N.I.K., N.N.K., E.V.A., V.B.G., I.A.K., M.Y.M., R.V., M.G.V., E.N.Z. and A.V.S.; writing—original draft preparation, D.L.M., N.I.K., N.N.K., E.V.A., V.B.G., I.A.K., M.Y.M., M.G.V., E.N.Z. and A.V.S.; writing—review and editing, D.L.M., N.I.K., N.N.K., E.V.A., V.B.G., I.A.K., M.Y.M., R.V., M.G.V., E.N.Z. and A.V.S.; visualization, D.L.M., N.I.K., N.N.K., E.V.A., I.A.K., M.G.V. and E.N.Z.; supervision, D.L.M., R.V. and A.V.S.; project administration, D.L.M.; funding acquisition, R.V., A.V.S. and D.L.M. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by the Russian Science Foundation (data collection and analysis for Hemiptera-Heteroptera and Lepidoptera species in general, preparation of maps: project No. 21-16-00050, D.L.M.; data collection and analysis for *Ips amitinus* and Coleoptera species in general: project No. 21-16-00065, A.V.S.). N.I.K. was partially funded by the basic project of Sukachev Institute of Forest SB RAS, Russia (Project No. 0287-2021-0011) [review of *Phyllonorycter issikii*]. I.A.K. was partially supported by the Russian Foundation for Basic Research (project No. 20-04-00587) [review of *Polygraphus proximus*]. N.N.K. and E.N.Z. were partially supported by the State assignment of the Federal Research Centre of the Subtropical Scientific Centre RAS, project No. FGRW-2022-0006 [review of *Cydalima perspectalis*]. The study by M.G.V. [review of *Lamprodila* (*Palmar*) *festiva*, *Agrilus fleischeri*, *A. planipennis*, and *A. mali*] was performed in the frame of state research project No. 122031100272-3. The study by R.V. was funded by a grant from the Forest Damage Centre, Swedish University of Agricultural Sciences.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available upon email request to the authors.

Acknowledgments: We sincerely acknowledge V.A. Soboleva (Voronezh State University, Voronezh, Russia), E. Jendek (Czech University of Life Sciences, Prague, Czech Republic), K.V. Makarov (Moscow Pedagogical State University, Moscow, Russia), A.V. Kovalev (All-Russian Plant Protection Institute, Saint Petersburg, Russia), D. Lees (Museum of Natural History, London, UK), I.A. Utkina (Institute of Forest Science, Moscowskya Oblast, Russia), and N.A. Mamaev (Saint Petersburg State Forest Technical University, Saint Petersburg, Russia) for permissions to use their photographs of insects or damage symptoms and I.A. Mikhailova (Sukachev Institute of Forest SB RAS, Krasnoyarsk, Russia) for help with mapping. We thank Eddy Velez for language improvement and two annonimous reviwers for their useful comments and helpful criticism.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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