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REVIEW ARTICLE

Climate Change and Invasive Insects in Forest Ecosystems - Recent Examples from Türkiye

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ABSTRACT

Recent climate changes -in contrast to changes in the past- are faster, and humans play a significant role in speeding up the process. Fauna usually responds strikingly to the changing climate; however, effects on animal species varies greatly. Indirect effects on insects through their host plants like the shifted shooting time, and the changed chemical composition and texture of the plant are significant. Direct effects like changes of the climatic elements (temperature, humidity) may cause a wide range of reactions, like change of the distribution area (e.g., northward shift) and/or change in the insects' biology (e.g., swarming time, generation cycle). The presence of invasive insects is usually not associated with changing climatic factors. Their arrival is mainly human activity driven and the changing climatic factors may promote their establishment only. Introductions are accidental in most cases, but there are also plenty of examples of intentionally introduced species. In this paper, we demonstrate the effect of invasive insect species on the forest ecosystems in Türkiye through the examples of the western conifer seed bug (*Leptoglossus occidentalis*), the box tree moth (*Cydalima perspectalis*), the Asian longhorn beetles (*Anoplophora glabripennis* & *A. chinensis*), the chestnut gall wasp (*Dryocosmus kuriphilus*), the oak lace bug (*Corythucha arcuata*) and the black stem borer (*Xylosandrus germanus*). The importance of invasive forest insect monitoring is also discussed.

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1. Introduction

Climate change is not a new phenomenon. Since the origin of life, the Earth underwent multiple events of strong climate change that have been shaping the Earth's ecosystems during millions of years (MacGabhann, 2005). Ice ages and warmer periods replaced each other causing changes and migration in flora, and fauna time-to-time (Hewitt, 2000). Not all plant and animal species could accommodate these changes, many of them perished. Climate changes even today. In contrast to changes in the past; however, this change is faster, and it has been already proved that humans play a significant role in speeding up the process. Even if several publications have already demonstrated the effect of climate change on plants and animals, it is very hard to predict the way and speed of response of them (Burke et al., 2018; König et al., 2022; Patacca et al., 2022).

The effects of climate change vary highly. It influences the flora significantly, their limited mobility; however, impedes

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spectacular reactions though there is no lack of response at all. The buffer capacity of certain plant species, especially trees with large genomes can significantly hide the effect until the change exceeds its threshold. Fauna usually responds strikingly to the change of climate (Both et al., 2006). Effects on animal species vary greatly as well. There are animal species with wide tolerance ranges that suffer less from the effects of climate change, but animals with narrow tolerance ranges may very soon be on the brink of extinction (Radchuk et al., 2019).

In the case of insects, their enormous species number has to be emphasized. Half of the animals known at present (around 1 M species) are classified into this group and, likely, the number of unidentified species is at least as high. In the case of herbivorous insects' indirect effects are also significant, i.e., effects induced by changes in the host plant. A good example of this is the shifted shooting time and the changed chemical composition and texture of the plant as a nutritive material (Jactel et al., 2019).

In this review study, the effects of invasive insects, increasing due to climate change, on forest ecosystems in general, and invasive insects that stand out for Türkiye in particular, were evaluated.

2. Effects of Climate Change on Insects

Climatic factors can have a significant influence on insects directly (e.g., via the various development stages) and indirectly (e.g., via their host plants) as well. Changes in each of the climatic elements (e.g., temperature, precipitation, air moisture, etc.) may result in a wide range of reactions (Grünig et al., 2020).

Two typical examples in the case of a forest insect community (Franić et al., 2023):

- Change of the distribution area: More preferable environmental conditions enable the extension of the distribution area of the species (mainly northward shift and/or expansion to higher elevations).

- Change in biology: Like the swarming time and generation cycle: Earlier or later swarming than usual; the development of more generations due to the warmer climate; more frequent and more prolonged outbreaks. Occurrence and damage from species that caused no economic damage before.

All these changes are generally accompanied by the reduction of the vitality of the host-tree species and they contribute significantly to the development of various damage chains as well.

Forest ecosystems, at least in the case of natural or close-to-natural forests, are based on very complicated relationships. Each element in the food-chain is associated with climate elements by a thousand threads. What elements significantly influence the changes of insect communities in a forest? Apparently the most significant is the effect of temperature. Change in the absolute value determines the speed of development. The possible number of generations can be calculated from the annual heat-sum. The absence of winter colds can be classified into this group as well resulting in an increasing number of certain damaging species. Warmer wintertime periods; however, may cause a break in the overwintering stage. They may die due to the lack of available food, or pupas overwintering in the soil can be drowned in the occurring groundwater (Seppälä, 2009; Pureswaran et al., 2018).

Changes in the development and generation cycle of insects due to rising mean temperature were proved in several cases (Csóka et al., 2007). Caterpillars of geometrid moths' hatch from the eggs and reach the pupa and adult state much earlier than before. Jewel beetles (Coleoptera, Buprestidae) developed for two years earlier can reach adult state within one year as a result of increased temperature and deteriorated hostplants. They might even turn to harmful from a former neutral status. As an example, the jewel beetle [*Phaenops cyanea* (Fabricius, 1775)] occurring on pine trees or the beech splendour beetle [*Agrilus viridis* (Linnaeus, 1758)] causing mortality to beech trees could be mentioned (Lakatos & Molnár, 2009). Number of generations developing within one year also changes. The number of generations of the spruce bark beetle [*Ips typographus* (Linnaeus, 1758)] depends on altitude and latitude. Based on the latest model calculations, the number of generations may even double in Europe (Hlásny et al., 2019). The occurrence of extremities can have significant effects as well. Early or late frost weakens hostplants on which insects can become abundant. Even the behavior of the insects can change. Larvae of puss moth [*Cerura vinula* (Linnaeus, 1758)] used to eat the upper levels of the tree crown but now they move to the lower parts (Probert, 2021).

Changing climatic conditions often change the distribution areas of insects as well. In general, the distribution area of several insects is shifting towards the north parallel to the hostplants (Jump et al., 2009). This may mean that new species occur in a new area comes from the south and also force other species to leave the area to the north. Changes can appear in a wide range of forms. Species moving towards the north from the Mediterranean include for example oleander scale [*Aspidiotus nerii* Bouché, 1833)] and cypress and thuja bark beetles [*Phloeosinus* (Chapuis, 1869) species]. *Ithomiola* butterfly species that do not die during winter because of the warmer climate are also significant as they lay eggs now in spring and the next generation occurs now in spring. Such species are the cotton bollworm [*Helicoverpa armigera* (Hübner, 1808)] and the silver Y moth [*Autographa gamma* (Linnaeus, 1758)] (Srinivasa Rao et al., 2023).

Increase in the damage area was reported in the case of the following insects in Hungary: Brown-tail moth [*Euproctis* *chrysorrhoea* (Linnaeus, 1758)]; tortrix moths [*Tortrix viridana* (Linnaeus, 1758), *Archips xylosteana* (Linnaeus, 1758), …], acorn weevils and other weevils (*Curculio* spp.) and various bark beetles [*Ips typographus, I. sexdentatus* (Boerner & I.C.H., 1776)] (Hirka, 2009). Damage also occurred in the case of species that lived in woodlands but caused no economic damage earlier: Beech splendour beetle (*Agrilus viridis*), oak phylloxera [*Phylloxera quercina* (Ferrari, 1872)], and oak processionary moth [*Thaumetopoea processionea* (Linnaeus, 1758)] (Franić et al., 2023).

3. Invasive Insects in Forest Ecosystems

The presence of invasive insects is usually not associated with changing climatic factors. Their arrival is mainly human activity driven and the changing climatic factors may promote their establishment. Authors emphasizing the ecological nature of invasion consider invasive species to be any organism that expands rapidly, can settle in areas foreign to it, and has a significant impact on the given ecosystem for a shorter or longer period of time, regardless of whether it causes a natural, economic or public health problem (Venette & Hutchinson, 2021). In most cases, the introduction is accidental, but there are also plenty of examples of a deliberately introduced species becoming an invasive species over time. It is not easy to decide what effect a particular organism has on its environment, because both this effect and the properties of the organism can change continuously. However, the following definitions are generally accepted (Nentwig, 2007):

Non-native (‘alien’) species: A species appearing in a given area that was not native there before.

Introduced species: An alien species that enters a new area with (intentional or mostly unintentional) human intervention.

Invasive species: An alien or introduced species that expands rapidly and has a significant impact on the given environment.

The majority of invasive species are introduced, but species that expand “on their own” can also become invasive if environmental factors change in a favorable direction. However, it is important to emphasize that not all new species become invasive (Franić et al., 2023).

The amount of environmental, economic, and public health damage caused by organisms that have become invasive after introduction or deliberate introduction is constantly increasing worldwide. It is a common experience that pests alien to the fauna create significantly larger populations in their new habitat, thus causing more damage than in their native land. Among the introduced terrestrial organisms, most species are arthropods, primarily insects. Their damage can be traced back to the lack of natural enemies (predators and parasitoids) that regulate their populations. In new areas, native parasitoid species need a longer or shorter time after establishment to be able to effectively control the population of the invading species (Franić et al., 2023).

3.1. Pathways and the Ways of Introduction

Invasive species can arrive to a new location in various ways. We can divide the way of introduction into three groups: (i) species introduced on purpose, (ii) unintentional introduction (hitchhikers), and (iii) species arriving in a new area due to expansion of their original distribution area (Tuba et al., 2012).

3.1.1. Intentional introduction

The intentional introduction is rather rare for insects, it is much more typical for plant species (e.g., black locust, tree of heaven, ...) or vertebrates (e.g., raccoon, nutria, …). However, there are several examples of intentionally introduced insects as well: Japanese oak silk moth (*Antheraea yamamai* Guérin-Méneville, 1861) is native to Eastern Asia. First individuals have been introduced for silk production to Slovenia, some of them escaped and 10 years later it was also found in Ljubljana. They tried to breed them in several European countries because of their valuable silk around the 1900s. Nowadays, the species is present in several European countries but does not cause significant forest health problems there. The harlequin ladybird [*Harmonia axyridis* (Pallas, 1773)] was first used in Europe against aphids in the Ukraine (1964) and in Belarus (1968). In these countries, their population got eliminated without intervention. Its flightless population was settled in the Czech Republic. It did not cause any problems here either, the population disappeared without intervention as well. It was used in France in 1982, as a biological control, and it went into trade release because of its effectiveness in 1995. Since then, it got into several countries in Europe and established large populations quickly. From the ecological point of view, it threatens other ladybird species because it has a good competition ability (Tuba et al., 2012).

3.1.2. Unintentional introduction

There are many forms and ways of unintentional introductions. Insects arrive in new territories in the most diverse ways and manners. From this point of view, we have to highlight the long-distance transport of living plants (with aphids on them), the trade of plants in pots (with pests and pathogens living in the soil), timber transport in bark (with various wood and bark living insects) and wood packaging materials (insects living in wood) as major pathways (Tuba et al., 2012).

The fall webworm [*Hyphantria cunea* (Drury, 1773)] is a North American species, which arrived in Europe (Hungary) at the beginning of the Second World War most likely on a shipload. The first two specimens were collected in August of 1940 around the Harbour of Csepel (part of Budapest). Its identification happened first in 1946 when the collection of the

Natural Science Museum was rearranged and taken back to Budapest after a rural exile because of the war. The species was spreading from Budapest following roads and railroads. Its occurrence was registered from almost all across the country by 1948. It spread to the neighboring countries from Hungary as well, although also another introduction happened independently from the Hungarian too (e.g., Bordeaux, France, 1978) (Tuba et al., 2012).

3.1.3. Expansion of the distribution area

In most cases, it is hard to explain what causes have led to area shift. Several species are certainly affected by climate change. For others, human activity is an indispensable requirement for an explosion-like propagation. For example, the horse-chestnut leaf miner (*Cameraria ohridella* Deschka & Dimic, 1986) was first found in Macedonia near Lake Ohrid in 1985 and was first described in 1986. The genus includes several native species in North America and Asia. The only one member of the genus in Europe is *C. ohridella*. Its native range overlaps with the native range of its host plant the horse chestnut (*Aesculus hippocastanum* L.), which are the deep canyons of the Balkan Peninsula (especially in Albania and Greece). It is hard to explain its explosion-like propagation and spreading in Europe. It spread to the north and to the west naturally and with human intercession. It is an interesting observation that in most countries where it was introduced to it was first found next to highway resting places and parking areas (Valade et al., 2009).

3.2. Processes in the Invaded Area

Authors who highlight the ecological aspects of invasion consider every organism an invasive species which spreads fast, is able to establish itself on foreign territory, and has a significant impact for a shorter or longer period on a given ecosystem, irrespective of causing natural, economical or public health issues (Roques et al., 2009).

Invasive species are able to transform the structure and patterns of the ecosystem by competing or suppressing certain species. On the one hand directly through competition, on the other hand indirectly through altering the food chain. One of the greatest problems of plant pest control is the control of invasive insects. It is well known that invasive insects have significantly larger populations in their new area than in their native territory thereby causing higher levels of damage (Roques et al., 2009). Their damage can mainly be traced back to the lack of their natural enemies (predators and parasitoids) controlling their populations.

Nowadays globalization tendencies, especially the rapid broadening of trade and travelling possibilities as well as climate change are all factors accelerating the introduction of alien species and their establishment. The process cannot be stopped. However, it seems to be a realistic goal to decelerate the rate of introductions and establishments by consequent control, and, if there is a possibility to eradicate as well. To achieve that we need to recognize the fact of early detection and rapid response.

3.3. Case Studies/Examples - Türkiye

In the last 50 years, the forests of Türkiye have been influenced by invasive species such as *Dendroctonus micans, Ips typographus, Ophelimus maskelli, Leptocybe invasa, Ips amitinus, Ips cembrae, Ips duplicatus, Leptoglossus occidentalis, Cydalima perspectalis, Ricania simulans, Corythucha arcuata* and *Rhynchophorus ferrugineus.* (Avcı & Oğuzoğlu, 2017). The main ones are tried to be introduced in this study.

3.3.1. Western conifer seed bug - Leptoglossus occidentalis Heidemann, 1910 (Heteroptera: Coreidae)

3.3.1.1. distribution

Its native distribution area is the western coast of North America. It started spreading even in the United States eastwards in the middle of the 20th century. In Europe, it was first recorded in Italy in 1999 (Tescari, 2001), followed by a rapid expansion and arrived in Türkiye in 2009 in İstanbul-Sarıyer (Arslangündoğdu & Hizal, 2010) and then in Edirne in October (Fent & Kment, 2011). Although the insect was detected in Türkiye in 2009, it is estimated that the entry of the insect into Türkiye was in the early 2000s, considering the crop losses in pinecones in the Bergama Kozak Basin (Fent & Kment, 2011).

3.3.1.2. morphology

Adults are 15-22 mm. Its special characteristic is the leaf-like expansion on the tibia of the hind legs. Its body is brown, adorned by several light or dark spots and stripes. The western conifer seed bug (both adults and larvae) sucks the sap of conifers. Its host range is rather broad (*Pinus* L., *Picea* Mill., *Pseudotsuga* Carrière, *Calocedrus* Kurz, *Abies* Mill., *Juniperus* L., *Cedrus* Trew spp.) (Kondorosy & Kóbor, 2023).

3.3.1.3. biology and damage

The bug has one generation a year in Central Europe, but two generations have been reported in Southern Europe (Spain and Türkiye) (İpekdal et al., 2019). Adults overwinter in bark crevices, leaf litter, or in buildings.

The bug's rapid dispersal suggests that it has the potential to become dominant in the colonized areas. As a result of its damage, the number of germinating seeds in the cone is significantly reduced, making the natural or artificial regeneration of forests more difficult, and in some cases even impossible (Connelly & Schowalter, 1991).

3.3.1.4. management

The species often aggregates in and around buildings for overwintering, with the help of the aggregation pheromones emitted by the male (Blatt & Borden, 1996). This may allow the application of monitoring and control methods in the future. In Türkiye, a pheromone trap developed for another bug species [*Leptoglossus zonatus* (Dallas, 1852)] has also been tested, but without success (İpekdal et al., 2019). Currently, mechanical control can be applied, by way of destroying overwintering individuals. Although chemical control is possible in gardens and parks, it is not recommended. The application of chemical control methods in pine forests or pine plantations is highly inadvisable (Kondorosy & Kóbor, 2023).

3.3.2. Box tree moth - Cydalima perspectalis Walker 1859 (Lepidoptera: Crambidae)

3.3.2.1. distribution

The box tree moth originates from the Far-East (India, China, Japan) (Mally & Nuss, 2010). It most likely came to Europe with containerized host plants. It was first found in Southern Germany (2006) but it spread very rapidly to other countries of Europe as well. The first detection of *C. perspectalis* in Türkiye was in 2011 on the leaves of *Buxus sempervirens* and *B. sempervirens* cv *'aureavariegata'* in parks and gardens in the Sarıyer district of Istanbul (Bahçeköy, Emirgan, Hacıosman, Zekeriyaköy) (Hızal et al., 2012). The primary host plant is European boxwood (*Buxus sempervirens* L.), but larvae can also develop on other members of the *Buxus* genus too (Tuba et al., 2012).

3.3.2.2. morphology

It is a medium sized moth with a wingspan of 40-45 mm. Both pairs of its wings are silky white with a wide brown edge, and it has a typical white crescent on a further brown patch on the middle section of the forewings. The larva is about 4 cm long before pupation. It has a yellowish-greenish base color with a black and light-yellow striping and black dots having white plumes in them (Tuba et al., 2012).

3.3.2.3. biology and damage

In its native range it can even have five generations annually. In Europe it has three generations per year. The female lays its eggs in packs on the backside of the leaves. In the beginning, the larvae only peel the leaves and later they consume them totally. They often make webbings from the leaves where they can feed protected. They pupate between the leaves in a loose web. The last generation also overwinters this way (Kenis et al., 2013).

It consumes the leaves of the box tree common in urban and natural environments. Besides the host plant, the loose web made by the larvae can be a marker by the identification of the species or its appearance in the given area (Tuba et al., 2012; Nagy et al., 2017).

3.3.2.4. management

Insecticides used in horticultural/agriculture against defoliating caterpillars (e.g., pyrethroids and chitin synthesis inhibitors) can be effective against the species too. It is an active flyer, but no exact data on its spreading ability have been reported. Transportation of its host plants can be a major contributor to its spread (Lopez-Vaamonde et al., 2010). There have been trials to control the box tree moth with solar-powered pheromone traps in Kastamonu (Cide, Pınarbaşı), Bartın, and Istanbul (Şile) in Türkiye (Ok et al., 2023).

Biological control methods together with integrated pest management are possible tools as well. One of the entomopathogens, *Bacillus thuringiensis* var. *kurstaki* was widely used against Lepidoptera larvae including *C. perspectalis.* A wide range of fungal pathogens, including *Metarhizium* sp., *Beauveria* sp., *Verticillium* sp., *Alternaria* sp., *Mucor* sp., *Isaria* sp., and *Beauveria bassiana* have also been reported to reduce *C. perspectalis* infestation (Yaman, 2023).

3.3.3. Asian longhorn beetle & Asian citrus longhorn beetle - Anoplophora glabripennis (Motschulsky 1853) & A. chinensis (Forster 1771) (Coleoptera: Cerambycidae)

3.3.3.1. distribution

All *Anoplophora* species are native to Asia. *A. glabripennis* has been introduced to North America (United States, Canada), and several countries in Europe. In Europe it was first found in Austria (Braunau) (Tomiczek, 2001; Lingafelter & Hoebeke, 2002). Later, it was detected in several other European countries. Some of them (e.g., Belgium, United Kingdom) succeeded in eradicating it, but the species has already several well-established populations across Europe. It may have entered the continent in wood packaging materials of stones and large machines. Its first appearance is usually in or close to inhabited areas, near the premises of companies trading internationally (Favaro et al., 2015).

3.3.3.2. morphology

Adults are 25-35 mm long, with several irregular white spots on the shiny, black elytra. The female beetle lays the eggs into tiny pits chewed in the bark of the host on thick branches and on the trunk. Larvae are approx. 500 mm before pupation and typical round headed borer in shape. Pupation occurs at the end of the larval gallery. Complete larval development takes up to three years depending on environmental conditions and host quality. Exit holes are round shapes, approx. 10 mm in diameter (Csóka & Hirka, 2023).

3.3.3.3. biology and damage

A. glabripennis is highly polyphagous. Major host plants are poplars, willows, maples but almost any other broadleaved tree species can be considered as host.

The Asian citrus longhorn beetle (*Anoplophora chinensis*) has almost the same native range and life history, looks very similar to the Asian Longhorn Beetle. Host tree species are also similar, with some preference to citruses and tree species of the rose family. Its possible introduction may have happened with live plants. It is more common in nurseries, especially if they trade imported plants. Damage symptoms are similar to the Asian longhorn beetle too (Csóka & Hirka, 2023).

3.3.3.4. management

Both of the above-mentioned species are very hard to eradicate as when the first symptoms became visible the species has already well-established population in the area. Rapid removal of infested trees seems to be the only effective method. Various methods have been used for early detection of the beetles, where the use of trained dogs proved to be successful (Hoyer-Tomiczek & Sauseng, 2013; Csóka & Hirka, 2023).

3.3.4. Chestnut gall wasp - Dryocosmus kuriphilus Yasumatsu 1951 (Hymenoptera: Cynipidae)

3.3.4.1. distribution

The chestnut gall wasp originates from China. It was taken to Japan (1941), to the United States (1974) and to Northern-Italy (2002). From there it spread to the north (Slovenia, Croatia). The insect was detected for the first time in Türkiye in 2014 in the village of Gacık in the Çiftlikköy District of Yalova (Çetin et al., 2014). It is monophagous, it makes galls on the Japanese (*Castanea crenata*), Chinese (*C. mollissima*), American (*C. dentata*), European chestnut (*C. sativa*), and their hybrids (Avtzis et al., 2019).

3.3.4.2. morphology

Females are 2.5-3 mm in size. Developed larvae are 2.5 mm long, milk-white, they have no eyes and legs. Pupae are dark brown and averagely 2.5 mm long. According to the observations made so far it is a univoltine species reproducing with parthenogenesis. Only the asexual form is known. A single female lays more than 100 eggs. They sink their eggs in groups of three to five inside the buds of young shoots between June and August. Larvae hatch in 30-40 days. The small larvae overwinter, and they only start their development lasting for 20-30 days in the spring of the following year. They make their galls at the same time. Their pupa stage is short: about 10 days. Hatching can stretch from the end of May even to the end of July. Adults have a short lifespan of 10 days (Avtzis et al., 2019).

3.3.4.3. biology and damage

It makes its galls on young shoots, leaf stalks and main veins. Galls have a diameter of 8-20 mm, they are green or reddish. A gall usually contains 1-7 or sometimes 8 cells where the young larvae evolve. Empty galls are arborescent, and they indicate the place of infection for years. By attacking and blocking vegetative buds they strongly decrease shoot production and indirectly the yield as well. Heavy infections that return annually can lead to branch die-off or even death of younger trees (Tuba et al., 2012).

3.3.4.4. management

Late cropping variants of the Japanese chestnut are less susceptible to the infection. According to the literature *C. crenata* x *C. sativa* hybrids are less susceptible to the infection. To be more exact the larvae hatch but they are not able to make galls, so they die soon. In its native range its natural enemies are mostly Hymenoptera parasitoids. Even in Italy, they managed to raise several native gall wasp parasitoids in its galls. They settled its specialist Hymenoptera parasitoid species native to China called *Torymus sinensis* Kamijo, 1982. Where it is possible, the removal of infected shoots and branches can also decrease the rate of infection (Tuba et al., 2012).

3.3.5. Oak lace bug - Corythucha arcuata (Say, 1832) (Heteroptera: Tingitidae)

3.3.5.1. distribution

It is native to North America, in the Eastern United States, up to the south of Canada (Barber, 2010). It was first detected in Europe in 2000, in Italy (Bernardinelli, 2000). It is supposed that the species arrived in Europe by live plants. It was also detected in Türkiye, approximately 200 km east of Istanbul in 2002 (Mutun, 2003). It was recorded in Iran (West Azerbaijan Province) in 2005 (Samin et al., 2011). As of the summer of 2008, its distribution in Türkiye covered 28,000 km^2 (Mutun et al., 2009).

It probably spread on towards the Balkan Peninsula and Central Europe from Türkiye. However, the exact dispersal routes are not known. As a typical hitch-hiker species, new infestation appeared far away from earlier known locations (Csóka & Paulin, 2023).

3.3.5.2. morphology

The adult bug is approx. 3 mm. Three brown markings are typical on the lace-like wings (in comparison to the also introduced sycamore lace bug, where these tree dark spots are missing). The brown spotted nymphs are flattened, oval, and spiny (Tuba et al., 2012).

3.3.5.3. biology and damage

The oak lace bug has two-three overlapping generations a year, so every developmental stage is present simultaneously from May to October. Overwintering bugs hide themselves in bark crevices, under peeling bark, or in tree forks covered in leaf litter, in aggregated groups. Females lay their eggs in clusters on the undersides of leaves in late spring. In Europe, the main hosts are the native oaks but bugs are often found on other tree and shrub species as well (Csóka et al., 2019). Severe infestation causes discoloration, drying, and early abscission of foliage. Repeated damage year after year may have negative effects on the health condition of oaks in the long run. Interactions between humans and (both oak and sycamore) lace bugs become increasingly common, bugs are able to suck blood (Tuba et al., 2012).

3.3.5.4. management

Oak lace bug become a significant factor in the oak forests of Europe. Heavily affected trees have reduced acorn production (both size and amount) which hinders the natural regeneration of oak forests, and also makes the production of seedlings for artificial regeneration difficult. Native natural enemies and entomopathogens are not able to regulate the populations of oak lace bug, which may be linked to the very low number of native lace bug species in Europe. A successful classic biocontrol programme seems to be the only possible solution in the future where natural enemies form the native range of the bug will be identified, tested, introduced and applied (Csóka & Paulin, 2023).

3.3.6. Black stem borer - Xylosandrus germanus (Blandford, 1894) (Coleoptera: Curculionidae)

3.3.6.1. distribution

The Black Stem Borer is of Asian origin, it is native to China, Japan, the Korean Peninsula, Taiwan, Thailand, and Vietnam. It was introduced to North America (1932), where it first fed on grape vines cultivated in greenhouses. It later escaped and damaged several host plants (Alonso-Zarazaga et al., 2017). It probably entered Europe at the beginning of the 20th century, in oak timber imported from Japan, but it was only detected in Germany in the late 1940s. After this, it was probably repeatedly introduced to various parts of Europe with infested timber. Today it occurs in a large part of Europe (Fiala et al., 2020). The species was first found in Türkiye in 2011 in a kiwi orchard, later also in hazelnut (Tuncer et al., 2017).

3.3.6.2. morphology

The Black Stem Borer is an ambrosia beetle (Curculionidae, Scolytinae) developing in the xylem. The beetle has a tiny (1.0-1.5 mm), rotund, shiny black body. It looks similar to the native *Xyleborus dispar*, but it is much smaller (Lakatos & Tuba, 2023).

3.3.6.3. biology and damage

Its galleries mostly consist of straight tunnels boring into the wood, with small chambers at their ends. The larvae develop in these. It cultivates various fungi in its galleries, on which both larvae and adults feed. The most common of these is *Ambrosiella hartigii,* but the Black Stem Borer is also known as the vector of other *Ambrosiella, Fusarium* and *Ophiostoma* species (Ito & Kajimura, 2017). These fungi are usually pathogenic to the host plant. A healthy tree attacked by the Black Stem Borer is likely to die. It usually has one generation per year, but a second generation has been observed in several European countries (Germany, Italy, Hungary) (Tuba et al., 2012).

3.3.6.4. management

It is a highly polyphagous species and occurs both on broadleaf and coniferous species. As both developing larvae and adults feed on the mycelia of fungi cultivated inside the galleries, the host tree does not have any significant effect on the development of the Black Stem Borer. Its most important hosts are Beech (*Fagus sylvatica*) and oak species (*Quercus* spp.), but it is frequent on various conifers as well. Damage done to healthy trees has not yet been reported, but by developing in harvested trees, its populations can grow rapidly (Fiala et al., 2020). From Türkiye, it was reported as a significant pest of the hazelnut (*Corylus* sp.) (Tuncer et al., 2019). In Europe; however, it usually appears in forests, and mainly on felled trees (Lakatos & Tuba, 2023).

3.4. Monitoring of Invasive Insects

Monitoring of insects is widely used (1) to detect non-native species, (2) to assess biodiversity, and (3) to assist pest management. Information can be collected: (i) on the presence/absence of a species, (ii) on its biology (e.g., flight period, number of generations), and (iii) population development (e.g., damage and spread). All this information is crucial for forest management activities but also for the selection of the appropriate control method (Montgomery et al., 2021).

There is a great variety of methods which can be used for insect monitoring. Physical surveys in the field, setting up various traps, aerial surveys or remote sensing methods are available for the detection of harmful insects. Physical surveys concentrate on the detection of the various life stages of an insect (e.g., egg masses) or looking for typical damage symptoms (e.g., galleries). Traps attract insects either using different chemicals (e.g., pheromones) or even light (e.g., different colors), but a simple physical barrier can act as trap as well (e.g., window and interception traps). There is a great variety of traps. The size and construction of the trap may have a significant influence on the efficacy and clearly define the applicability of the trap, i.e., for which insect species and under which conditions it can be used. There is no single monitoring method that is suitable for all insect species. In each case, it is necessary to search for the best-fitting monitoring method for the given insect species and in the ideal case we will also find it. In recent years, modern technologies allow us to collect information on insect species and the damage caused by them more economically. Aerial surveys (e.g., drones) or remote sensing (e.g., satellite images) can supplement data acquired physical surveys in the field, especially in remote areas or on difficult terrains. Modern molecular methods allow us to identify a species by traces left behind too. Analyzing environmental DNA (eDNA) collected from a wide variety of surfaces allow us to detect the presence of a species in an area (Tuba et al., 2012).

It is quite difficult to control the populations of invasive species in the area where they settle. Due to the import of wood raw materials, wood packaging materials and a large number of live plants, it is of great importance to implement quarantine measures with great care in order to prevent the entry of these species. In addition, it is of great importance to increase the effectiveness of decontamination measures. Firstly, the survey studies that should be carried out for invasive species should determine how far the invasive species can spread and "Pest Risk Maps" should be created in relation to foreign invasive species. Today, globalization trends, especially the rapid expansion of trade and travel opportunities, and climate change are all factors that further accelerate the introduction and establishment of alien species. The increasing concentration of trade via the Internet allows seeds to move freely all over the world. In addition, the endophytic lifestyle of most insects associated with seeds makes it difficult to detect their presence during transportation and import operations. In most cases, examining only the outside of the seeds does not provide evidence of larvae of any insect that can be detected by X-ray of the seeds (Auger-Rozenberg & Roques, 2012; Yılmaz et al., 2022). Our goal is to at least slow down the rate of importation and establishments with consistent inspections, and if possible, prevent it. For all of this, it is necessary to recognize the fact of importation as soon as possible.

4. Conclusion

Recent changes in forest insect communities are influenced mainly by two factors, the climate change and the introduction of non-native (invasive) species. Responses vary greatly and influenced by indirect effects (via host plant) and direct effects like northward shift and/or change in the insects' behavior. The presence and/or absence of invasive forest insects is usually not associated with the changing climatic factors. Their arrival is mainly human activity driven and the changing climatic factors may promote their establishment only. Introductions are in the most cases accidental, but there are also plenty examples of intentionally introduced species. In this review study, the effects of invasive insects, increasing due to climate change, on forest ecosystems in general, and invasive insects that stand out for Türkiye in particular, were evaluated. The importance of invasive forest insect monitoring is also highlighted.

Conflict of Interest

The authors declare that they have no conflict of interest.

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