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Invasive pathogens impacting forest and urban trees in Türkiye

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Abstract: Alien invasive pests and pathogens pose major threats to forest, ornamental and urban trees throughout the world. The history of invasions is reviewed in the context of human migrations in the past, and the importance of modern globalization of trade – in the absence of highly stringent detection and control measures - emphasised as undoubtedly the most important cause of the recent upsurge in incursions of problematic pests and pathogens. Examples of invasive pathogens, including the causes of sweet chestnut canker, Dutch elm disease, dieback of *Cupressus*, *Phytophthora* root rots, boxwood blight, canker stain (wilt) of *Platanus* and Dothistroma needle blight of pines are detailed. Measures taken by states and trading blocks to reduce the probabilities of invasions occurring and manage those that have already occurred are discussed, along with approaches that could be utilized to improve the protocols used to address these problems in Türkiye.
Keywords: Alien invasive pathogens, *Cryphonectria parasitica*, *Ophiostoma novo-ulmi*, *Seiridium cardinale, Phytophthora, Calonectria*, *Ceratocystis platani*, *Dothistroma*

Türkiye'de orman ve kent ağaçlarını etkileyen yabancı istilacı patojenler

Öz: Yabancı istilacı zararlılar ve patojenler, ormanlar, süs bitkileri ve kent ağaçları üzerinde dünya çapında ciddi tehditler oluşturmaktadır. Geçmişte insanların göçleri ile ilişkilendirilen yabancı istilacı türlerin hareketliliği, günümüzde artan ticaret ve küreselleşmenin ve yetersiz tespit ve karantina yöntemlerinin de etkisiyle kontrol edilemez boyutlara ulaşmıştır. Kestane dal kanseri, karaağaç ölümü hastalığı, servi kanseri, *Phytophthora* kök çürüklüğü, şimşir yanıklığı, çınar kanseri ve çamlarda *Dothistroma* ibre yanıklığına neden olan patojenler ve istilalardaki önemi bu derlemede ayrıntılı olarak verilmektedir. Bu tür zararlı ve patojen istilaları azaltmak veya hali hazırda bulaşmış olanları daha iyi yönetebilmek adına, ülkeler bazında ve ticaret sektöründe alınan önlemlerin yanı sıra, Türkiye'de bu sorunların üstesinden gelmek için uygulamadaki mevcut protokolleri geliştirmek yolunda mümkün olan yaklaşımlar da tartışılmıştır.
Anahtar kelimeler: Yabancı istilacı türler, *Cryphonectria parasitica*, *Ophiostoma novo-ulmi*, *Seiridium cardinale, Phytophthora, Calonectria*, *Ceratocystis platani*, *Dothistroma*

Introduction

It is likely that, since humans first began migrating over long distances, pests and pathogens were inadvertently carried with them on their journeys (Kauserud et al., 2007; Fisher et al., 2012; Santini et al., 2013; Santini et al., 2018; Doggett and Lee, 2023). Plant pests and pathogens probably accompanied humans on these migrations in any plant-based materials carried, including seed, fruit and tubers. With the advent of agriculture, approximately 10,000 years ago (Verhoeven, 2011), both wild-collected and cultivated grains would have been transported as food during journeys and for planting in locations some distance from their origins in Mesopotamia. Pests and pathogens which co-evolved with their natural hosts in regions of origin were, therefore, taken to other regions (Dark and Gent, 2001; Stukenbrock et al., 2008), some thousands of kilometres distant from the centres of evolution, with different climatic conditions and, probably, different potential host plants. These migrations certainly account for much of the widespread distribution of many cereal pests and pathogens we know in the world today (Dark and Gent, 2001). Many other organisms have also been dispersed outside their native ranges by human activities; being released from biotic and abiotic factors keeping these species in check in their native habitats has led to some species becoming problematic at various different levels, including impacting negatively on natural environments (e.g., Chinchio et al., 2020; Gioria et al., 2023).

During natural evolutionary processes, geographical barriers have restricted most organisms, including pests and pathogens, to particular regions over long periods, with further spread occurring only very slowly, if at all. In the past 500 years, however, human activities, particularly related to migrations between continents, have increased enormously, with a consequence that the geographical barriers to movement of pests and pathogens have been broken down (Richardson et al., 2000; Santini et al., 2013; 2018), resulting in indigenous plants becoming exposed to organisms with which they have had no recent exposure; sometimes, this exposure leads to major disease outbreaks, with potential near extinctions of susceptible host species. The rate of novel invasions has increased exponentially, particularly following the adoption of shipping containerisation, because of accelerations and improvements in modes of transport for plants.

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Despite the known invasions, recognition of the issue by regulatory authorities was slow to develop. An early example that was acted upon was when

European viticulture was seriously impacted by the accidental introduction, in 1862, of grape phylloxera, *Daktulosphaira vitifoliae* (syn. *Phylloxera vastatrix*), on vines imported from North America to a vineyard in France for breeding with European grape varieties (Stevenson, 1970; MacLeod et al., 2010). Representatives from seven European countries met in Berne, Switzerland, in 1878, to develop what is considered the first international phytosanitary agreement, the "International Convention on Measures to be taken against *Phylloxera vastatrix*" which specified actions to avoid further imports and spread of the highly destructive pest.

At about the same time, legislation entitled 'The Destructive Insects Act 1877' passed through parliament in the United Kingdom, to enable inspection of imports to reduce and prevent the accidental introduction of plant pests (MacLeod et al., 2010).

Countries globally instigated their own plant quarantine regulations, in attempts to reduce invasions. In Türkiye, plant quarantine is regulated under Law No. 6968 'agricultural control and agricultural quarantine and the Plant Quarantine Regulation'. The law was established in 1957, but is regularly updated to take account of newly discovered threats to Turkish agriculture and the wider environment. Current regulation was updated in 2016 and determines procedures to which plants, plant products and other substances are subject in terms of phytosanitary inspections on entry into or exit from Türkiye, with prescribed controls for imported and exported plants and plant products at customs, the species prohibited from entry and exit, those which require specific phytosanitary certificates, and the pests and pathogens subject to quarantine.

This review focuses on current issues of increased damage in Turkish forest ecosystems caused by invasive alien species (IAS), some of which have led to, or are threatening, near extinction events for several tree genera and species. In addition, known invasive pathogens which are, as yet not present in Türkiye are highlighted.

Pathways of Invasion

Natural spread

The process of natural spread is slow, when compared with human-driven spread. Natural spread can also include pathogens vectored by animals. Insects are local vectors of many plant pathogens, either through 'accidental' adhesion of propagules to the exoskeleton or, in some cases, deliberate (biologically) carriage of the micro-organism in order to enhance the niche for egg laying (see: Santini and Battasti, 2019). Propagules of microorganisms, including pathogens, can also spread on feathers and feet of birds (Dadam et al., 2020), possibly enabling distant dispersal during migrations.

Trade Pathways

Imports

Currently, the most significant pathway for inadvertent distribution of invasive organisms is trade in live plants (Santini et al., 2013; Jung et al., 2016; Panzavolta et a., 2021). For example, in the last approximately 150 years, some 70% of invasive forest pests and pathogens establishing in the United States probably arrived on imported live plants (Liebhold et al., 2012).

International trade in plants and plant products has increased enormously in the last fifty to seventy years, with improvements in treatment of plants in transit and speed of travel. A significant factor in this increased efficiency of transport came with the adoption of containerised shipping, which began in the early 1950s. Given the massive numbers of plants traded globally each year, against the numbers of qualified phytosanitary inspectors working in biosecurity units, it is no surprise that many exotic pests and pathogens escape detection in imported materials. It is testament to the skills and dedication of the inspectors that many more damaging agents do not enter and establish in exotic locations.

With this human-caused expansion of the ranges of multiple problematic organisms have come massive disturbances to invaded ecosystems and severe socio-economic impacts (Aukema et al., 2010), as detailed below. In the past 25 to 30 years, there has been a further marked increase in the numbers of alien invasive pests and pathogens of plants recorded in populated continents of earth, damaging agriculture, horticulture and the wider environment, including both natural and plantation forest ecosystems. It must be emphasised: the reasons for this upsurge are clear - all involve interacting human-driven factors, with, arguably, global trade as the most important component in the complex (Santini et al., 2018). Climate change is also having an impact on the establishment and impact of invasive pests and pathogens (Jactel et al., 2020).

Examples of Invasive Pathogens Impacting Forest and Urban Trees in Türkiye

Sweet chestnut canker

A classical example of an alien invasive species (AIS), one commonly used in plant pathology textbooks, is the canker affecting *Castanea dentata* and *C. sativa*, caused by *Cryphonectria parasitica.* The disease was first noted in 1905 (Merkel, 1905) on dying *C. dentata* (American chestnut) trees growing in the New York Zoological Garden, USA. Within 40 years of this first discovery, the disease had spread throughout most of the natural range of the American chestnut, killing the above-ground parts of the trees and reducing this once mighty and common species to scattered shrubs (Anagnostakis, 1987). Along with the loss of the trees, industries associated with timber and bark use died out. In addition, the extensive ecological functions of the trees were lost, not least of which was the annual crop of edible nuts of value to many forest fauna as well as to humans.

Sadly, the disease soon spread out of North America. It was reported near Genoa and, further south, near Avellino in Italy, after which the pathogen spread throughout the Italian chestnut growing areas (Biraghi, 1950). The pathogen spread northwards, into France (1946) and Switzerland (1951) and more widely in southern Europe thereafter. By 1967, *Cryphonectria parasitica* was found killing *Castanea sativa* in the native range of the host, in Türkiye (Delen, 1975; Figure 1).

The spread of this damaging pathogen from the region of evolution, Far East Asia, into the USA was undoubtedly on either young chestnut plants, or in contaminated timber imported into New York, probably towards the end of the 19th century (Anagnostakis, 1987).

As with the Phylloxera issue affecting the grapevine in Europe, chestnut canker clearly illustrated the potential for alien invasive micro-organisms to cause disastrous, near extermination of populations of susceptible species that were not previously exposed to the problem.

Figure 1. Symptoms of sweet chestnut blight caused by *Cryphonectria parasitica* infections on *Castanea sativa*. A) Significant landscape-scale damage showing as dieback in North Macedonia; B) canker on a stem in Rise Region, Türkiye; C) fruiting bodies on a main stem in North Macedonia (Images a and c, courtesy of Prof. Kiril Sotirovski).

Dutch elm disease

Another striking example of the catastrophic impacts invasive alien pathogens potentially have on tree populations was the spread throughout the northern hemisphere in the 20th Century of two closely related Dutch elm disease (DED) pathogens, *Ophiostoma ulmi* and *O. novo-ulmi* (Figure 2). Serious dieback of elms was noted in France in 1918, late in the First World War and, ultimately, was shown to be caused by a wilt pathogen. This particular outbreak of Dutch elm disease, caused by *Ophiostoma ulmi*, resulted in the death of approximately 30% of elms. By the 1950s, the disease appeared to have attenuated and was causing very few problems (Peace, 1960). By the late 1960s, however, many elms in parts of England were dying, following symptoms reminiscent of the DED outbreak characterised earlier in the 20th Century (Gibbs and Brasier, 1973). Similar problems occurred in North America: the less aggressive outbreak was quickly followed by loss of elms on a huge scale.

Figure 2. Symptoms of Dutch elm disease on *Ulmus* species. A) Dying *U. glabra* in a field boundary, Scotland; B) killed elms may remain standing for several years after death; C) initial symptoms may appear on one side of the crown; D) severely wilted foliage of *U. glabra*; E) feeding groove (arrowed) caused by *Scolytus scolytus* on *U. minor*; F) typical dark brown staining in the xylem, indicative of vascular infection/dysfunction (D. Barrett).

The outbreak was investigated in great detail in the UK. Mapping demonstrated that deaths were focused on the hinterlands of major ports in England and Wales; a forensic investigation of imported logs of *U. thomasii* arriving from Canada into southern England showed that the DED pathogen was present and was being spread to local elms around the ports by the North America elm bark beetle, *Hylurgopinus rufipes* (Gibbs and Brasier, 1973). Bark beetles vector DED pathogens; in Europe, the vectors include several species of *Scolytus*, mainly *S. scolytus*, but replaced by *S. multistriatus* in more northerly latitudes (Santini and Faccioli, 2015). In further work, it became clear that this second epidemic of DED was caused by a species new to science, subsequently named *Ophiostoma novo-ulmi* (Brasier, 1991; 2000). Comparing isolates of the aggressive pathogen obtained in the UK with those from a newly noted outbreak of serious Dutch elm disease in the southeast of Europe indicated that the two populations were of the same species, but were distinguished by several morphological features. Isolates of the two populations, however, were sexually compatible and produced offspring which, hypothetically, could be more aggressive. A further aggressive species was subsequently found in northern Himachal Pradesh, western Himalayas, and named *O. himal-ulmi* (Brasier and Mehrota, 1995).

European, Eurasian and North American species of *Ulmus* are all highly susceptible to infection by *O. novo-ulmi* (Brasier, 2000), although certain Far-east Asian elms are far more tolerant, suggesting that the pathogen evolved in that region.

Cupressus canker

Cupressus sempervirens is an iconic tree species in the Mediterranean region, considered as a significant component in the typical landscape. This ornamental value, along with medicinal properties, was recognised thousands of years ago and humans spread the tree from the native range in Persia (now Iran) and the eastern Mediterranean, including Türkiye, throughout the Mediterranean basin. The tree had rather few highly damaging pests or pathogens over much of history, until the emergence of a canker, caused by *Seiridium cardinale*, which was first noted causing problems on the Monterey Peninsula, California (Wagener, 1928), but appeared to spread rapidly in subsequent years to Australia and New Zealand, Europe and South America, via movement of infected plant material (Grasso, 1951; Graniti, 1998). The pathogen infects species of *Cupressus, Chamaecyparis, Cryptomeria, Juniperus, Thuja,* and ×*Cupressocyparis* (Graniti, 1998), causing symptoms of varying severity.

The first outbreak in Europe was recorded in Italy in the 1930s (Graniti, 1998). *Cupressus sempervirens* proved to be highly susceptible to infection by the pathogen, resulting in notable damage to trees and reduced aesthetic appeal of the landscape (Figure 3). A *Cupressus* species showing low susceptibility, *C. arizonica*, is often used as a replacement tree with similar environmental tolerance, but this exotic tree does not replace the aesthetic landscape form of the fastigiate *C. sempervirens*, so important in the Mediterranean region. Infection occurs through wounds in the bark tissues, which may girdle branches or the main stem, leading to dieback (Graniti, 1998).

***Phytophthora* species**

There are many damaging plant and animal pathogens in the Kingdom Stramenopila, particularly in the Oomycota. Species of *Phytophthora, Pythium, Phytopythium*, *Saprolegnia Leptolegnia, Aphanomyces* and *Achlya*, are notorious for causing serious problems, resulting in massive losses globally in agriculture, horticulture, aquaculture and natural ecosystems (Benavent-Celma et al., 2021). Species of *Phytophthora* are causing epidemics on trees in different regions of the world, with the most well-known species overall arguably being *P. cinnamomi*, *P.* x *cambivora* and *P. ramorum* (Hansen, 2015). Currently, there are 192 formally described species (Abad et al., 2023; Coomber et al., 2023), but there could be 400–600 species in total (Brasier, 2009; O'Brien and Hardy, 2014), meaning many unknown species may be present in relatively unexplored ecosystems globally.

In terms of biosecurity issues, *Phytophthora* and other plant pathogenic oomycetes are commonly transported in the 'plants for planting pathway'; hardy woody ornamental plants traded in garden centres and online in Northern Europe, for example, almost all include pathogenic oomycetes on the plant root tissues or in the accompanying substrate/compost (Puertolas et al., 2021).

Phytophthora cinnamomi, one of the most damaging plant pathogens known, has a host list including over 5,000 plants (Hardham and Blackman, 2018). If suitable environmental conditions are present, serious problems can arise anywhere the pathogen is known, but hot spots of activity are known in certain regions of high biodiversity, such as in South Western Australia (Cahill et al., 2008; Figure 4A) and in the Fynbos, South Africa; the woody flora may die across landscapes, usually following human-caused disturbance (Engelbrecht and Van den Berg, 2013; Reeksting et al., 2014).

Figure 3. Symptoms of *Seiridium cardinale* infection on *Cupressus sempervirens*. A) Branches in the crown show early signs of dieback; B) Top dieback of a mature tree; C) initial symptoms of infection on a branch in the lower crown; D) resin bleeding seen on the main stem.

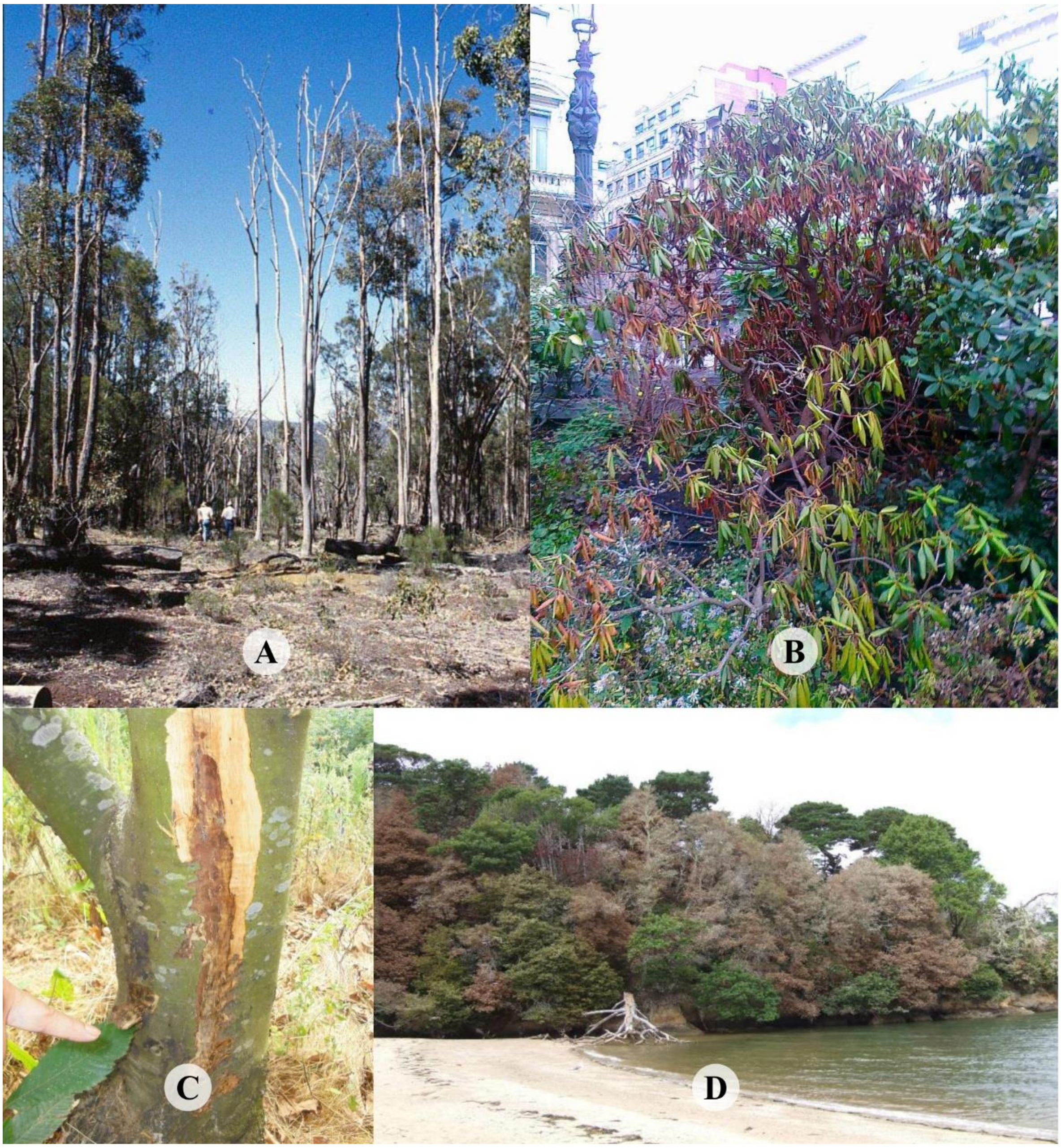

Figure 4. Dieback caused by *Phytophthora* spp. A) *Eucalyptus marginata* stand badly damaged by *P. cinnamomi* in Western Australia; B) *Rhododendron* variety in a small park in Brussels dying following infection, probably caused by *P. plurivora*; C) Typical sub-cortical lesion on *Castanea sativa* infected with *P.* x *cambivora* (contrast enhanced) in Türkiye; D) Extensive death of coastal forest trees infected with *P. ramorum* in California.

The pathogen was first described in the 1920s when cinnamon trees, native to Sri Lanka, were planted in Papua New Guinea and soon began to die (Rands 1922; Arentz and Simpson, 1986). It is likely that the pathogen was spread by human activity from its centre of origin, probably in the Celebes, before it was first isolated and described, as diebacks characteristic of this organism were already noted in several regions globally (e.g. Santini et al., 2013).

Phytophthora dieback, caused by both *P. cinnamomi* and *P.* x *cambivora*, is a well-known problem on *Castanea sativa* in Europe, but *P. cinnamomi* also causes dieback and mortality on *Quercus* species, amongst many other hosts (Fig. 2a). The pathogen causes epidemics on *C. sativa* and *Quercus* spp., especially *Q. suber*, throughout the Mediterranean region, with particularly serious attacks noted in Italy (Vannini and Vettraino, 2001; Scanu et al., 2013), Spain (Rodríguez-Molina et al., 2005), Portugal (Brasier et al., 1993; Moreira and Martins, 2005) and Türkiye (Balcı and Halmschlager, 2003a; Akıllı et al., 2012a). The Mediterranean climate favours these pathogens, particularly when associated with intermittent rainfall and droughts.

In Türkiye, both *P. cinnamomi* and *P*. x *cambivora* cause serious root disease on *C. sativa* (Akıllı Şimşek et al., 2019), although *P. x cambivora* appears to be more common and aggressive on this host. Other *Phytophthora* spp. may also be involved in root diseases on *C. sativa*, but the relative importance of these additional species in the problem is unclear. Work carried out in oak-dominated forests in Türkiye suggested that many species of *Phytophthora* were present in these ecosystems (Balcı and Halmschlager, 2003b), where *P.*

quercina was the most common cause of dieback, especially when the stands occurred on slopes subject to intermittent drought.

Box blight

Dieback of *Buxus sempervirens* clones used in ornamental plantings in England provided the first report of boxwood blight in 1994 (Henricot, 2006; Henricot and Culham, 2017). Subsequently, the disease was recognised globally in all regions where *B. sempervirens* is common in amenity plantings (see Leblanc et al., 2018). Unfortunately, the pathogen is killing *B. sempervirens* (and the putative species, *B. colchica*) in natural settings too, threatening these ecosystems. In Türkiye, *B. sempervirens* is a dominant understory species in the northern east Black Sea region, and 90% of some box populations were totally defoliated within 12 months of the first report of boxwood blight in the region (Figure 5; Akıllı et al., 2012b; Lehtijärvi et al., 2014; 2017a; Mirabolfathy et al., 2013). The environment in the Black Sea region of Türkiye and neighbouring Georgia is characterised by high humidity for much of the year, providing perfect conditions for the disease and spread of the spores.

Two similar species of *Calonectria*, *Calonectria pseudonaviculata* and *C. henricotiae*, initially classified as *Cylindrocladium*, cause the disease. As with many invasive plant pathogens, the origins of these species are unknown. It is certain, however, that they are spread by human activities, particularly through the transport of live plant materials (LeBlanc et al., 2018). A further highly damaging problem affecting box, the box moth, *Cydalima spectabilis*, was also recently introduced into Europe and Eurasia from Asia, threatening the future of *B. sempervirens* in natural forests and as ornamental plantings.

Figure 5. Impacts of box blight on *Buxus sempervirens* in the Black Sea region of north-east Türkiye. Early symptoms of infection causing lesions on the A) upper and B) lower foliage; C) *B. sempervirens* understorey in forest of the Black Sea Region showing severe defoliation. Foliage in the upper crowns remains green due to lower humidity; D) severe dieback of ornamental *B. sempervirens* variety. (Images courtesy of Prof. A. Lehtijärvi).

Canker stain of *Platanus*

This disease of *Platanus* species was causing notable dieback and mortality on occidental (*P. orientalis*) and hybrid (*P.* x *hispanica*; syn. *P.* x *acerifolia*) plane (American sycamore) planted in eastern North American cities in the 1930s (Crandal, 1935; Panconesi, 1999); it soon became clear, however, that although the commonly planted hybrid and oriental planes always died after infection, the occidental (*P. occidentalis*) plane suffered some dieback but usually survived (Panconesi, 1999). The pathogen responsible, *Ceratocystis platani*, maybe native to the southeast of North America (Engelbrecht et al., 2004), but was accidentally introduced into Europe, probably during World War II (Panconesi, 1999). The common clones of *P.* x *hispanica* planted in cities of Western and Southern Europe proved highly susceptible to mortality, dying quickly after infection (Ferrari and Pichenot, 1976; Panconesi, 1999). The plane species native in Türkiye, *P. orientalis*, is also highly susceptible and dies rapidly. As *P. orientalis* is an important city tree and major component of riparian ecosystems in the eastern Mediterranean region, continuing spread of the canker stain pathogen poses an enormous existential threat to these ecosystems. In Europe, problems caused by *C. platani* are reported in Italy, Switzerland, France, Greece, Albania and the European part of Türkiye.

After entering Italy, probably on munitions packing used by the USA military forces in World War II (Tsopelas et al., 2017), the problem gained notoriety when urban *P.* x *hispanica* began dying, seriously detracting from the aesthetics of the numerous major avenues of this species in urban centres (Figure 6). Subsequently, the pathogen was discovered in south-east France, spreading from likely additional introductions into the port of Marseilles. With a few possible exceptions in Sicily (Tutin et al., 1964), all *Platanus* trees killed in Italy, France and Switzerland were planted.

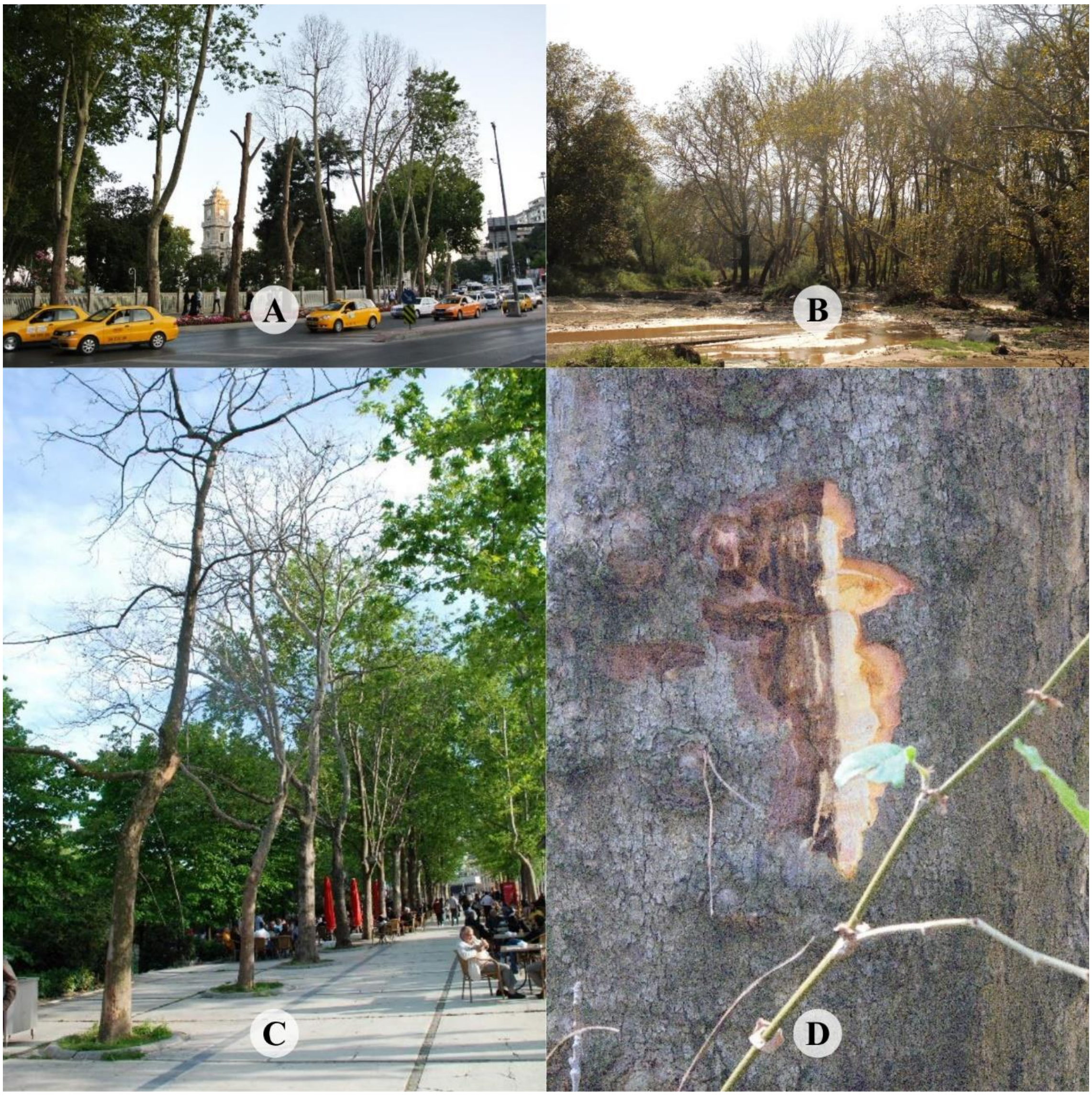

Figure 6. Damage caused by *Ceratocystis platani* to *Platanus* spp. A) Typical successional dieback of *P.* x *acerifolia* on an avenue along Dolmabahçe, Istanbul. The trees are probably clonal; B) Severe damage in a riparian stand of *P. orientalis* in Greece, with many dead and dying trees (contrast enhanced); C) Dying *P. orientalis* planted for ornamental purposes in an Gezi Park, Istanbul; D) Typical sub-cortical lesion-healthy tissue boundary on *P. orientalis* in Greece.

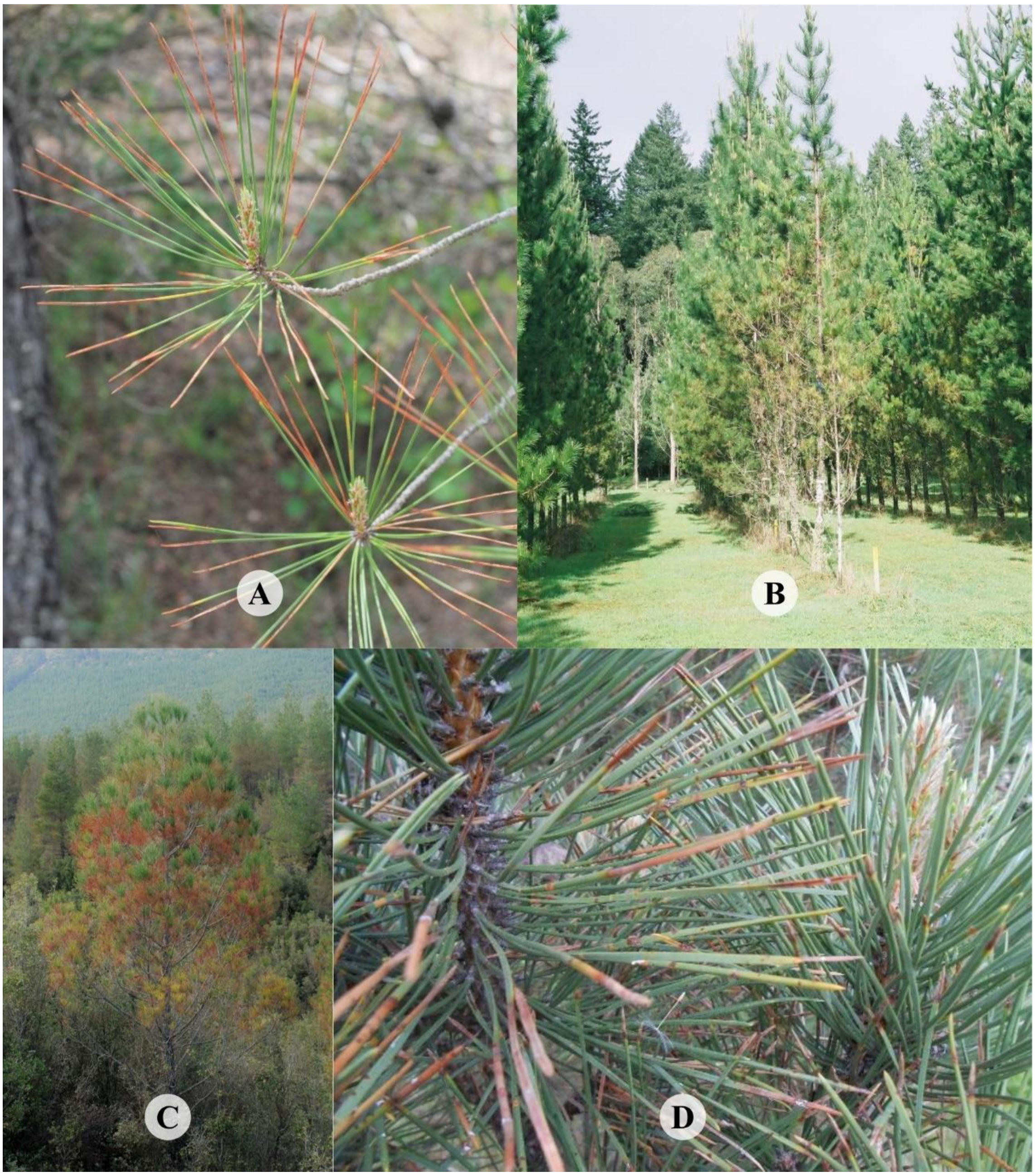

Figure 7. Dothistroma needle blight on A) *P. brutia* showing typical low needle density and death of needle tissues, mostly at the tips; B) *Pinus radiata* tolerance trial, Rotorua, New Zealand; C) Severe symptoms of *D. septosporum* infection on *P. brutia* in Türkiye; D) Close-up of lesions caused by *D. septosporum* on needles of *P. mugo*. [Images a and c courtesy of Prof. Asko Lehtijärvi.]

Figure 8. Brown spot needle disease. A. B) severe needle infections have killed this dwarf variety of *P. nigra* ssp. *pallasiana* in Ataturk Arboretum, Istanbul; C, D) clear infection issues on needles of *P. mugo*, Tartu, Estonia.

The disease was confirmed on *P. orientalis* trees in natural stands in Greece in the early 2000s (Tsopelas and Angelopoulos, 2004; Tsopelas and Soulioti, 2011), probably following import into Greece on plane trees from nurseries in Italy. Since that time, canker stain has spread into Albania, initially near to the Greek border (Tsopelas et al., 2015), but recent observations suggest that it has now spread further in Albania: *P. orientalis* trees are dying along river valleys in the eastern Albanian Alps, towards the border with North Macedonia (personal observations, September 2021). More recently, canker stain was discovered killing important amenity *Platanus* trees in Istanbul: in the city, both the hybrid and *P. orientalis* are highly significant iconic trees, comprising a major proportion of the urban tree population (Lehtijärvi et al., 2017b). Further spread into both city and natural stands of *P. orientalis* in Türkiye are considered highly likely.

Ceratocystis platani gains access to host trees via wounds exposing inner bark tissues, often created by pruning activities in urban areas. Subsequently, the pathogen grows rapidly in the secondary phloem and into sapwood, where toxins are released causing a catastrophic disruption to water balance in hosts: stomatal regulation is disrupted, with subsequent wilting, dieback and, ultimately, death (Panconesi, 1981). Pruning, traditionally carried out on urban *Platanus* trees to maintain the crown size and increase leaf growth, improving shading in urban areas, increases the probability of spread of *C. platani*, accelerating the serious impacts caused to the aesthetics of street and park plantings.

Dothistroma needle blight (DNB)

Although recognised as a pathogen in the early 20th century (Doroguine, 1911; Drenkhan et al., 2016), until approximately 30 years ago DNB (previously known as red band needle blight) (Figure 7D) was considered a serious problem only in pine plantations in the southern Hemisphere (Gibson, 1974). The highlands of countries in East Africa were considered to have conditions ideal for growth of sub-tropical pines, but in the 1950s-60s, plantations established there were devastated by attacks of *Dothistroma*. A similar problem occurred in radiata pine plantations in New Zealand at about the same time; methods for reducing the damage in New Zealand, however, received considerable attention and the implementation of management methods to maintain the health of *P. radiata* which, diseases notwithstanding, grows exceptionally well in the region (Will, 1964). (Figure 7B).

In the early 1990s, however, serious outbreaks of DNB occurred extensively in European and North American natural pine forests and plantations, causing significant yield losses and mortality in several *Pinus* spp. (see Drenkhan et al., 2016).

Until the early 2000s, it was thought that a single pathogenic species, named *Dothistroma pini* was the causal agent of DNB. Molecular analyses at FABI in South Africa, however, proved that two cryptic species, now named *D. pini* and *D. septosporum* (Barnes et al., 2004), were present. *Dothistroma septosporum* appears to be the more common species responsible for serious DNB outbreaks in pine forests of much of the Northern Hemisphere. Most species of pine may be badly damaged in their natural habitats and plantations by DNB, although occurrence of significant infection and disease development is dependent on prolonged periods of very high humidity (Bulman et al., 2013). Fluctuating climatic conditions lead to sporadic epidemics. With relevance to Türkiye, most sub-species of *P. nigra* and some provenances of *P. brutia* (Figure 7A,C) can be severely infected (Aday Kaya et al., 2019; Oskay et al., 2020a). Globally, however, *Dothistroma* species have been recorded infecting 109 Pinaceae hosts, the majority of which are *Pinus* spp., although *D. septosporum* is also known to infect species of *Abies, Cedrus, Larix, Picea* and *Pseudostuga*, with serious infections leading to some needle loss (Drenkhan et al., 2016).

A very noticeable impact of DNB on pines is thinning of crowns resulting from a significant reduction in the number of years foliage retained (Drenkhan et al., 2016).

The origins of the *Dothistroma* pathogens are unknown. There is considerable diversity in the *D. septosporum* population in Türkiye (Oskay et al., 2020a), suggesting that this particular species may have evolved in the region. It is thought likely that the upsurge in DNB intensity in the late 20th into the 21st century, however, was due to the spread of different genotypes of the pathogen showing variations in virulence, as clearly demonstrated in Northern Britain (Piotrowska et al., 2017; Ennos et al., 2020).

Brown spot needle blight of pines

Lecanosticta acicola (syn. *Scirrhia acicola*; *Mycosphaerella dearnesii*) causes brown spot needle disease of *Pinus* spp., and is a particular problem in plantings of highly susceptible pines and in Christmas tree plantations in North America. Disease symptoms include brown lesions on infected needles (Figure 8A), causing premature abscission of foliage; if the disease is severe and re-occurs affected trees may die (Figure 8B). The pathogen has spread from the presumed centre of evolution in North America, into Central and South America, Asia, Europe and Türkiye (https://gd.eppo.int/taxon/SCIRAC/distribution). Over forty *Pinus* species are known hosts of the pathogen (van der Nest et al. 2019); in Türkiye, *Cedrus libani* is also known be susceptible, suffering defoliation (Oskay et al., 2020b).

In the past 15 – 20 years, *L. acicola* has spread rapidly in parts of Europe, with reports from different countries in the region (Van der Nest et al., 2019). The pathogen adds another threat to growth and production of pine, arguably one the most important forest trees in the northern Hemisphere.

Other pathogens spreading globally

Other invasive pathogens could be introduced into Türkiye in the near future, particularly *Hymenoscyphus fraxineus*, the cause of ash dieback (Figure 9A,B; e.g., Davydenko et al., 2022). To date, the disease has not been recorded in the country, although vigilance is required to prevent invasion which could damage the extensive native ash forests and the trees planted trees urban environments.

There are many other examples of pathogens spreading outside their natural ranges and causing serious problems in hitherto naïve populations of forest and urban trees. In addition, there are many pathogens known in other parts of the world which may be inadvertently transported to Türkiye and establish within the state. Examples of serious invasive pathogens threatening Turkish forests and forest industries include the pine wilt nematode, *Bursaphelenchus xylophilus*, pine pitch canker, *Fusarium circinatum* (Figure 8C,D) and many *Phytophthora* species as yet undetected in the country. Pine wilt nematode is particularly problematic on species of *Pinus* that are not native to its native range in North America (Rodrigues et al., 2015). It is vectored from affected to unaffected trees via longhorn beetles in the genus *Monochamus*, of which several are present in Europe (Wallin, 2013). Infection with the nematode causes mortality of pines. The nematode is present in Portugal and Spain in Europe and highly stringent biosecurity protocols are in place in an attempt to prevent further spread. Pine pitch canker is also a highly damaging pathogen affecting most pines to a greater or lesser extent, and certain other Pinaceae, particularly *Pseudotsuga menziesii* (Wingfield et al., 2008; Drenkhan et al., 2020). The pathogen causes disease in two distinguishable forms, one affecting young plants in the nursery resulting in damping-off, the second causing cankers and excessive resin bleeding on older trees in the field (Figure 8B). *Pinus brutia* is known to be susceptible to the pathogen (Doğmuş, unpublished).

In addition to the *Phytophthora* spp. mentioned above, there are many other species in the genus which infect and damage trees. These species spread readily in the plants for planting pathway (Jung et al., 2016; Puertolas et al., 2021), which is an extensive global trade and very difficult to monitor with accuracy.

The xylem-limited bacterium, *Xylella fastidiosa*, is a great concern globally (EPPO, 2024). It was known for many years in North America, particularly causing Pierce's Disease on grapevine, although the causal agent was not characterised until the 1980s (Wells et al., 1987). It is now clear, however, that pathovars of *X. fastidiosa* are well established in parts of Europe and, alarmingly, particularly damaging to olive trees (Morelli et al., 2021). Spread of these organisms into Türkiye would be of huge concern for the olive industry, but also because of damage caused to other crops and trees.

What can be done to mitigate problems caused by invasive pathogens?

Arguably, the most important and probably beneficial approach to take to reduce the import and export of damaging pathogens is the application of very stringent biosecurity protocols in producing nurseries, at exporting ports, and on arrival of the plants/plant materials at ports in the receiving states. Beyond that approach, the question is how to deal with these invasions as they occur. In the USA and Australasia, biosecurity protocols are far more stringent than in many other countries, although many invasions still occur in both countries.

Figure 9. Other highly damaging invasive pathogens. A) severe crown dieback of *Fraxinus excelsior* caused by the ash dieback pathogen, *Hymenoscyphus fraxinea*; B) Typical elongated bark lesion on young stem of F. excelsior infected with *H. fraxinea*; C) extensive dieback of *Pinus greggii* following infection by *Fusarium circinatum* in South Africa; D) *Fusarium circinatum* infection of radiata pine accompanied by excessive resin flow from tissues around lesions (northwestern Spain).

Prevention of introduction is, by far, the most effective method for minimizing biological invasions, a simple conclusion that is supported by economic analyses (Crystal-Ornelas et al., 2021). As there are many potentially invasive pathogens known, it can be useful to conduct specific risk assessments, a very time-consuming process at this level. An alternative approach that has received considerable attention and scientific support recently is the pathways approach, focusing on the mode of dispersal rather than individual taxa. Both approaches enable targeting of biosecurity protocols at weak points in the system, to reduce the risks of introduction. It is very important, however, that any policies and protocols adopted utilize a strict evidence-based approach to avoid national protectionism and excessive competition (Potter, 2013), which contravenes World Trade Organization regulations, designed through cooperation between member states (Ormsby and Brenton-Rule, 2017). Rules within International Standards for Phytosanitary Measures (ISPM) No. 11 (Pest Analysis for Quarantine Pests) require countries to prepare pest risk analyses to justify precisely why any pathogen should be considered a significant quarantine problem and subject to biosecurity protocols on import (International Plant Protection Convention, 2017). Relevant to Türkiye are the European and Mediterranean Plant Protection Organization (www.eppo.int) A1 and A2 lists of threatening organisms (viruses, fungi, bacteria, insects, nematodes, parasitic plants). The A1 list is a compilation of pest organisms unknown in the EPPO region, whereas the A2 list covers pests with restricted distribution within the same region. These lists are updated regularly, based on recommendations by member countries who provide the required scientific evidence for inclusion, including pest risk analyses.

Early detection of invasive pathogens and infected plants is key to reducing invasions. Pest and pathogen detection and identification has progressed rapidly, mostly based on the deployment of rapid molecular techniques (see below). The numbers of reported interceptions by phytosanitary officers increases as the methods for detection improve, but the process does not prevent further invasions, as all applied methods have weaknesses. In the absence of any such protocols, however, it is likely that invasions would increase exponentially.

In the importing state, the first approach, once all the correct phytosanitary documentation has been checked, is to inspect the plant consignments, either whilst still in shipping or immediately after transfer to port facilities. Visual inspection is used extensively at this stage. As many billions of plants (and plant parts/products) are exported/imported each year, inspection must be focused. The stated aim of many biosecurity facilities is to inspect approximately 2% of imported plants visually (Eschen et al., 2015), a Figure calculated to maximise discovery of potential problems within the confines of the staffing levels present.

The advent of molecular biology techniques brough an ability to detect tiny quantities of pathogen DNA in plant tissue extracts (e.g., Hu et al., 2020). Currently, the main detection methods include quantitative polymerase chain reaction (qPCR), high throughput sequencing (HTS) and loop-mediated isothermal amplification (LAMP), each requiring varying levels of time inputs and technical expertise. Both qPCR and LAMP can be extremely useful when examining symptomatic plants where the identity of the causal agent is suspected. HTS is more useful in determining the possible presence of a potentially damaging pathogen in samples showing no immediate symptoms; downstream processing of the data arising from HTS requires a great deal of skill, making this system, arguably, expensive, although costs are reducing rapidly (Hale et al., 2020). It is extremely difficult to determine the presence of potentially invasive problems in the absence of symptoms, however, although research is underway on methods not relying on molecular methods, such as the use of 'sniffer dogs' or the electronic nose (Mota et al., 2021; Verma et al., 2022) and analyses of volatile organic compounds given off by the micro-organisms or infected plants (e.g., Nordström et al., 2022; Sherwood et al., 2024).

Once a pathogen is established in a territory, attempts at eradication may be made. Unfortunately, if the problem has been noticed in ecosystems that were previously considered free of the disease, it is almost always too late to destroy every infected tree and all colonised inoculum/substrate. Sanitation felling may be used to fell all infected trees; it is usual, in this procedure, to fell healthy-appearing trees in the immediate vicinity of known infections to reduce the possibility that these individuals are already infected but remain symptom-free.

Application of pesticides to affected trees is extremely unlikely to be effective in eliminating an infection. Moreover, pesticides do not have specific activity against any pests: use of fungicides, for example, will disrupt the total fungal population in an application area, potentially killing beneficial species that could act antagonistically to the problematic species and also reducing host vigour through damaging populations of mutualistic species.

An approach to managing chestnut canker, Dutch elm disease, *Phytophthora lateralis* and some of the highly destructive rust diseases affecting pines in North America is selection and breeding for resistance (Diskin et al., 2006; Martín et al., 2019; Conrad et al., 2024). In agriculture, selection of resistant germplasm is considered the most effective way to control plant diseases in the long-term, but has generally required continuous breeding of novel resistant lines, to combat the genetic changes that occur in pathogen populations as a result of the deployment of resistance. This point is of particular importance in breeding trees for resistance to pathogens, as their long-life spans can result, with time, in exposure to a wider range of pathogens and pathogen genotypes (e.g., Kinloch et al., 2004; Sniezko and Koch, 2017). It is essential, therefore, that breeding for resistance in trees and other woody plants aims to incorporate multi-gene resistance in the plants, avoiding the single-gene resistance traits that have been commonly used in agricultural crops (Stuthman et al., 2007).

Once an invasive pathogen has established within a territory, actions can be instigated to 'slow the spread' (containment), can be applied (Liebhold and Kean, 2019), applying active management methods. This approach was used to reduce the speed of spread of *P. ramorum* in Oregon, for example (LeBoldus et al., 2022). In some instances, local quarantines can be used, in attempt to prevent spread of the invasive species between regions by strictly managing the movement of particular commodities known to be involved in spread, such as transport of plants and soils, or movement of timber. An example of this approach is banning the movement of firewood over approximately 74 cm in length in New York State, in an attempt to minimize the risk of spread of the oak wilt pathogen, *Bretziella fagacearum* (syn. *Ceratocystis fagacearum*) (New York Department of Environmental Conservation, 2020).

Ultimately, however, it may be necessary to learn to live with the problem, as has occurred many times in the past, sometimes resulting in the effective loss of a tree species or genus for use in forestry or ornamental plantings (Liebhold et al., 2024).

Conclusions

As for other states globally, Turkish plant-based ecosystems, including forests and urban tree plantings, are being attacked by invasive pathogens in addition to the endemic species already present. Many invasive pest and pathogen problems are already present, but actions can be taken to minimize the risk of further invasions occurring and to reduce the spread of already established problems:

- Care must be taken to ensure that any imported trees and other plants, plus plant-based materials, are from sources that maintain scrupulous hygiene in their production facilities;
- For any new imports of plants and plant products, risk analyses are probably available from other countries for perusal by authorities who consider shipping plans and should be reviewed to make sure that all available

information on the particular commodity is taken into consideration prior to licensing the imports;

- In the USA and the UK, national databases are available of potentially threatening pests and pathogens of trees and other plants known globally (e.g., Gilligan et al., 2013; Krist et al., 2014). These online databases provide quantifications of hazards posed by invasive organisms, based on expert opinion. A similar database for Türkiye would greatly assist in surveillance and rapid responses to incoming alien invasive species; the database should be flexible enough to cover novel problems as they occur;
- Outreach events should be organised to inform stakeholders (foresters, urban greenspace managers, nursery owners and managers) and for the general public, to increase awareness of the threats posed to trees in Türkiye by alien invasive pests and pathogens.

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