Biotic factors – Pests and Diseases

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20. Biotic factors – Pests and Diseases

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Introduction

Arthropod pests including insects and mites and plant pathogens including viruses, bacteria, and especially fungi severely affect survival, growth and aesthetics of amenity trees in urban environments. Factors such as the loss of plant biodiversity and reductions in the diversity and abundance of natural enemies and antagonists predispose urban forests to pest and disease outbreaks and catastrophic tree loss. The introduction of nonnative plants can disrupt ecosystem processes with varying and sometimes contradictory results. Some nonnative plants are not consumed by native herbivores in the new range. The result is fewer consumers at higher trophic levels and simplification of predator communities in urban areas. When nonnative plants are introduced with their associated nonnative insects and mites, eruptive outbreaks of pests can occur in the absence of important natural enemies left behind in the aboriginal range. Moreover, nonnative pathogens that arrive on a plant from one region may spread to new hosts in the new geographic range. Nonnative plants lacking an evolutionary history with insects and pathogens in a new geographic location may lack defenses and succumb to indigenous pests and diseases. Similar and calamitous tree loss occurs when nonnative arthropod pests and pathogens are introduced to evolutionarily naïve plant hosts in a new geographic region. Classic examples of nonnative pests and pathogens devastating trees in a new location include emerald ash borer, hemlock woolly adelgid, chestnut blight and Dutch elm disease. Other features of the built environment including impervious surfaces and elevated temperatures stress plants lowering their defenses or increasing their nutritional value and predisposing them to attack by insects, mites and pathogens. Several anthropogenic inputs including ozone, nitrogen, and de-icing salts are associated with urban infrastructure. These too may increase the susceptibility of trees to attack by biotic agents. In this chapter we discuss several features of built environments that threaten the vitality and resilience of urban forests. We also deal with globally important pests and diseases in urban environments. Arthropod pests treated in the chapter include lethal borers, foliar pests, and sucking arthropods including scale insects, lace bugs, and spider mites. Specific arthropod case studies include oak processionary moth, *Thaumetopoea processionea*, emerald ash borer, *Agrilus planipennis*, and horse chestnut leafminer, *Cameraria ohridella*. Diseases encompass root rots and wood decays, canker diseases, including the canker stain of planetrees caused by *Ceratocystis platani* and ash dieback associated with *Hymenoscyphus fraxineus*, vascular diseases, including Dutch elm disease and oak wilt caused by *Ophiostoma novo-ulmi* and *Ceratocystis fagacearum*, respectively, as well as the most important anthracnose and foliar diseases of oaks, planes, maples and horse chestnuts. Pests and diseases are described in their significance, impact and diagnostic characters. Integrated management strategies and tactics are discussed.

BIOTIC FACTORS – 1: PESTS

Factors of urban forests affecting outbreaks of insects and mites

Herbivorous insects and mites often attain much greater densities and cause greater amounts of injury to trees and shrubs in urban environments compared to those found on woody plants in natural forests (Raupp et al., 2010, 2012). In recent reviews of arthropod outbreaks in built environments, (Raupp et al., 2010, 2012) discussed several key features contributing to insect and mite outbreaks. Here we present a summary of several of these factors and discuss mechanisms underlying outbreaks of insects and mites.

Low street tree diversity and catastrophic tree loss

Lack of plant diversity seriously compromises the sustainability of the urban forest when trees and shrubs confront new pests for which they lack coevolved defenses (Gandhi and Herms, 2010; Raupp et al., 2012). The catastrophic loss of elms to Dutch elm disease sounded a call for greater floristic diversity in urban forests; however, Raupp et al. (2006) found species and cultivars of *Acer* and *Fraxinus* had largely supplanted elms as the dominant the genera of street trees in North America thereby setting the stage for catastrophic tree losses with the arrival of Asian longhorned beetle, *Anoplophora glabripennis*, and the emerald ash borer, *Agrilus planipennis.* The domination of urban landscapes by a few species or genera of woody plants predisposes cities to catastrophic loss due to pests.

Loss of top-down regulation in simplified habitats

Regulation of arthropod populations has been broadly categorized as either top-down meaning population control by predators, parasites, or pathogens; bottom-up meaning limitations imposed by the plant on the pest; or a combination of both forces. Urban habitats sometimes have reduced floristic diversity and complexity (Raupp et al., 2010, 2012). This may be accompanied by reductions in the richness and abundance of natural enemies (Raupp et al. 2010, 2012; Martinson and Raupp, 2013). However, urban habitats with greater diversity of plant material and more layers (e.g. trees, shrubs, groundcovers) of vegetation are known to support greater numbers of species and greater densities of natural enemies, especially generalist predators that may aid in suppressing outbreaks of insect pests (Shrewsbury and Raupp, 2006). These generalist predators likely play an important role in limiting pest outbreaks not only in diverse natural landscapes, but also in diverse human-altered ones.

Nonnative plants and nonnative insects

Nonnative plants

Nonnative plants are widely used in urban landscapes (Berghardt et al., 2009). The addition of nonnative plants to urban landscapes can affect population dynamics of pests in several ways. Herbivorous insects with narrow host ranges and specialized feeding habits like Lepidoptera may not recognize nonnative plants as food (Berghardt et al., 2009). In turn this can reduce the abundance of caterpillars on nonnative plants. A paucity of prey in landscapes dominated by nonnative plants could result in fewer predators and loss of top-down regulation of pests in these alien dominated landscapes (Berghardt et al., 2009). This problem is exacerbated when nonnative pests accompany their host plant into the new realm where coevolved natural enemies may be absent (Raupp et al., 2010). In North America the nonnative azalea lace bug, *Stephanitis pyrioides* is a classic example of a nonnative pest that now outbreaks perennially on their nonnative hosts in the invaded range (Shrewsbury and Raupp, 2006).

An additional problem arises when nonnative plants enter a new biotic realm. Pests enjoy what has been termed “defense free space” due to lack of a shared coevolutionary history with plants in the invaded range (Gandhi and Herms, 2010). Without a long standing association with a pest, plants may lack evolved defenses and be more susceptible to attack by novel pests. A notable example of this is seen in the high degree of susceptibility of North American ash trees to the emerald ash borer, *Agrilus planipennis*, a native of Asia, and the relative resistance of Asian ash trees to this pest (Herms and McCullough, 2014). Another prominent example is hemlock woolly adelgid, *Adelges tsugae*, which attacks and kills eastern North American hemlocks while Asian hemlocks are much more resistant (Gandhi and Herms, 2010). A mirror image of this relationship is seen in the high degree of susceptibility of Eurasian birches to the bronze birch borer, *Agrilus anxius,* a native of North America, and the strong resistance of North American birches to this pest (Nielsen et al., 2011).

Nonnative insects

Invasions by nonnative insects and mites result in direct and indirect disruption to ecological processes and economic losses in urban landscapes amounting to billions of dollars annually in the United States due to costs associated detecting and eradicating pests, protecting and removing trees, and lost property values (Gandhi and Herms, 2010; Aukema et al., 2011). The following three vignettes describe the significance and impact, diagnosis, life cycle, and management of three major invasive insect pests of urban forests. More encyclopedic guides to the biology and management of insect and mite pests on woody landscape plants include works by Johnson and Lyon (1991), and Alford (2012).

Thaumetopoea processionea, Oak Processionary Moth

Significance and impact - A major defoliator of several species of *Quercus*, caterpillars of this moth also attack *Fagus, Carpinus, Corylus, Betula,* and *Castanea* from Sweden to Southern Europe. In 2005 it was discovered in the United Kingdom. In addition to its pest status as a defoliator, it poses a major health risk to people exposed to urticating hairs found on larger caterpillars. These toxin-laced hairs cause dermatitis, severe rashes, eye irritations, and respiratory problems (Alford, 2012; Forestry Commission of the United Kingdom, 2015) (Fig.1). In southern Europe where the moth is native top-down pressure from indigenous natural enemies likely works in concert with environmental factors to prevent outbreaks (Forestry Commission of the United Kingdom, 2015).

Diagnosis – Eggs are deposited on small branches in symmetrical rows called plaques. Plaques are gray in color and about 20 mm in length. Larvae are brownish with darker brown heads and hairy. Older larvae have a grayish caste and are cloaked in long silvery hairs and may attain a length of 40 mm. They are gregarious throughout their larval stages and larvae move from place to place in a long head-to-tail procession. In summer they build nests of white silk on the trunks and branches of trees. Within these tents caterpillars, frass, and pupae can be found in summer months. Defoliation by early instars results in loss of leaf margins but late instar larvae skeletonize leaving behind only veins. Adults have a wingspan about 30 mm and are and gray moths with dark gray bands running across the wings (Alford 2012; Forestry Commission of the United Kingdom, 2015).

Life Cycle - The life cycle of processionary moth consists of one generation each year. Eggs are the overwintering stage. In the United Kingdom egg masses hatch and young caterpillars begin feeding in March and April. Caterpillars consume foliage from April into June and pass through six larval instars after which time they pupate in silken nests. Adults emerge in July and can be found into September. Adults fly and mate at night and females may lay 100 – 200 eggs. Eggs are deposited in masses on the bark of the tree where they remain dormant until hatching the following spring (Alford, 2012; Forestry Commission of the United Kingdom, 2015).

Management – The Forestry Commission of the United Kingdom (2015) recommends that individual homeowners contact professional arborists to treat and remove caterpillars due to health risks. Monitoring trees for egg masses and old nests in the autumn, winter, and early spring may help guide interventions before larvae hatch and begin feeding. Removal of overwintering egg masses may help reduce local populations. Pheromone traps are available and can assist in locating new infestations by trapping males in late summer. Nests containing caterpillars and pupa can be removed by professionals to reduce health risks and local populations. Many biologically based, organic, and reduced risk insecticides are available for controlling caterpillars.

Agrilus planipennis - Emerald Ash Borer

Significance and impact – The native range of emerald ash borer includes northeastern China, the Korean peninsula, and eastern Russia (Herms and McCullough, 2014). The spread of emerald ash borer from eastern to western Russia threatens forests in Europe. Tens of millions of ash trees in North America have been killed by emerald ash borer (Herms and McCullough, 2014) (Fig. 2). In the United States Aukema et al. (2011) estimated the annual losses and costs measured in terms of federal government expenditures, local government expenditures, household expenditures, residential property value losses and timber value losses to forest landowners to be $1.6 billion annually. Due to the rapid loss of forest canopy emerald ash borer is a major disruptor of ecological processes and services including nutrient cycling and plant succession in natural forests and cooling, carbon sequestration, water infiltration, and pollution mitigation in cities where ash trees comprise much of the urban forest (Herms and McCullough, 2014). In North America *Fraxinus* has a rich biota of more than 280 associated arthropods 43 of which are monophagous which are imperiled by emerald ash borer (Herms and McCullough, 2014). In North America a lack of bottom-up factors such as evolved resistance in ashes and top-down mortality related to fewer specialist parasitoids likely contribute to outbreaks that are less common in the native range in Asia.

Diagnosis – Symptoms of emerald ash borer infestation include dieback and thinning of the canopy, vertical bark cracks on the bole, and epicormic shoots at the base of infested trees. Woodpeckers are adept at finding emerald ash borer larva and elevated wood pecker activity on ash trees is indicative of an infestation. Adults exiting trees create diagnostic D-shaped holes 2 – 3 mm in diameter. Adults are slender, elongate beetles, iridescent green about 13 mm long. Larvae create serpentine galleries beneath bark as they bore through cambium and phloem. Larvae lack legs and are creamy white with indistinct heads. They can be 25 – 30 mm when fully grown.

Life cycle – Emerald ash borer in North America has one annual generation throughout much of its range but in some locations and under varying conditions of tree health, development may take two years. Adults emerge in late spring coincident with the blooming of *Robinia pseudoacacia*. They live for 3 – 6 weeks and after emerging from the tree and feed on ash foliage prior to laying eggs in bark crevices or under bark flaps. On average each female lays 40 – 70 eggs. Eggs hatch after about two weeks and tiny larvae bore though the bark and feed on meristematic and vascular tissue beneath. Larvae have four instars and feed throughout the summer and early autumn overwinter beneath the bark of infested trees. Pupation occurs the spring following deposition of eggs (Herms and McCullough, 2014)(Fig. 3).

Management - Herms and McCullough (2014) stress the importance of early detection in managing emerald ash borer. Due to the propensity of beetles to colonize upper canopies of trees new infestations are difficult to detect. A variety of traps baited with host volatiles and related have been developed to help delineate infestations. Attempts to eradicate isolated infestations of emerald ash borer by government agencies failed in Maryland, U.S.A. largely due to the high dispersal capability of adult beetles and the inability to limit human transit of infested wood and wooden products (Herms and McCullough, 2014). Raupp et al. (2006) noted the importance of diversifying urban forests that are now overstocked with *Fraxinus* as a way to mitigate catastrophic canopy loss. Ashes differ dramatically in resistance to emerald ash borer. Those of Asian provenance including Manchurian ash (*F. mandshurica*) are much more resistant than North American ashes including *F. americana, F. pennsylvanica,* and *F. nigra.* Blue ash, *F. quadrangulata,* appears to be the most resistant species of North American ash and could be a source of resistance in breeding programs (Herms and McCullough, 2014). The recent discovery of white fringe tree, *Chionanthus virginicus*, as a host for emerald ash borer in North America is disturbing. Several parasitic wasps imported from Asia have been released and established in many states but their impact on population dynamics of emerald ash borer is equivocal (Herms and McCullough, 2014). While intervention in native forests remains problematic, protection of individual trees with insecticides is feasible. Systemic insecticides such as the neonicotinoids imidacloprid and dinotefuron can be applied through the soil, through the bark as a spray, or injected into the vascular system. Biologically based systemics including emamectin benzoate and azadirachtin have also proven effective in controlling emerald ash borer as preventatives and curatives (Herms and McCullough, 2014). Many cities and municipalities are taking an integrated approach to managing emerald ash borer. The first step is to create a tree inventory to establish the location, size, and value of the ash resource. Interventions include removing low value and unthrifty trees, girdling trees to attract beetles and removing trees before beetles emerge, and progressively treating trees with insecticides over several years to distribute costs though time. Simulations demonstrate that integrated approaches can preserve the many benefits of valuable urban forest canopies while limiting costs of intervention (Herms and McCullough, 2014).

Cameraria ohridella – Horse Chestnut Leafminer

Significance and impact - The origins of horse chestnut leafminer are unclear but it now occupies several countries across Europe (Tilbury and Evans, 2003). The widespread use of horse chestnut trees (*Aesculus hippocastanum*) and the rapid spread of the leafminer have elevated this pest to major status (Tilbury and Evans, 2003; Percival et al., 2011). In addition to attacking *Aesculus hippocastanum*, Tilbury and Evans (2003) list other important landscape trees including *Aesculus pavia. Acer platanoides* and *A. pseudoplatanus* are occasional hosts of this pest. Percival et al.(2011) demonstrated that horse chestnut trees infested by leaf miners had lower photosynthesis and suffered reductions in stem extension, root carbohydrate concentration and twig starch content compared to trees protected from leafminers with insecticides. Percival et al. (2011) warn that long term repeated defoliations related to horse chestnut leafminer infestations threaten reproductive capacity of and long term persistence of horse chestnut in the invaded range.

Diagnosis – Horse chestnut leafminer feed on parenchyma cells between the upper and lower epidermal surfaces creating serpentine mines that may coalesce. Fresh galleries are light in color but as tissues die, mines turn brown giving the foliage a scorched appearance. In heavy infestations leaves are shed leaves prematurely in summer. Larvae are legless caterpillars, yellowish in color with distinct head and mouthparts at the anterior end. Adults are small moths less with a body length of 5 mm. Wing color is orange – brown with bands of white and black running across the wings. Eggs laid on the upper leaf surface are tiny (< 1mm), oval, and yellow. Pupae are found in silken cocoons within the mine (Tilbury and Evans, 2003; Alford, 2012).

Life Cycle – Conditions of weather and climate affect the number of generations each year. The average number of generations in Western Europe is three but in hot, dry locations up to five generations develop (Tilbury and Evans, 2003). Horse chestnut leafminers overwinter as pupae and in England. Adults appear in April and can be found throughout the growing season. Eggs are deposited along leaf veins on the upper leaf surface from May to August and individual leaves may house several hundred eggs. Eggs hatch in 2 – 3 weeks and larvae enter leaves and begin mining. Larvae complete five instars in about a month and pupate in a silken cocoon within the mine. During summer pupation lasts about two weeks but overwintering pupae live in fallen leaves on the ground for 6 – 7 months (Tilbury and Evans, 2003).

Management – Several species of parasitic wasps in the families Eulophidae, Pteromalidae, Eupelmidae, Brachonidae, and Ichnuemonidae are known to attack immature stages of horse chestnut leafminer but associated mortality is generally low. Part of the explanation for this loss of top-down regulation is poor seasonal synchronization between the phenology of some parasites with that of their hosts (Grabenweger, 2004). Cultural control involving the removal of fallen leaves beneath infested trees, composting leaves, or burying them with soil or other plant material in autumn and winter may help eliminate overwintering pupae and reduce adults colonizing trees populations the following spring (Tilbury and Evans, 2003). Trunk injections of systemic insecticides including imidacloprid have proven highly efficacious in reducing populations of horse chestnut leaf miner on individual trees (Percival et al., 2011).

Impervious surfaces, heat islands, and water stress

Impervious surfaces fragment green spaces, reduce plant density, elevate temperatures, and reduce water infiltration affecting the growth and development of plants and the ecological relationships of insects and mites attacking them (Raupp et al. 2012; Dale et al. 2016). Spider mites are one of the most common taxa of eruptive herbivores in cities where elevated temperatures dramatically reduce generation times and elevate their fecundity (Raupp et al., 2012 and references therein). Scale insects also respond to warmer temperatures in cities with greater abundance and elevated fecundity (Dale et al., 2016 and references therein).

By reducing water infiltration impervious surfaces create water - stress on trees and shrubs in cities (Raupp et al., 2012, Dale et al. 2016 and references therein). Speight et al. (1998) found densities of horse chestnut scale, *Pulvinaria regalis,* elevated on trees surrounded by impervious surfaces and concluded that reduced water and nutrient availability resulted in stress that favored the scale. Despite conflicting results of the relationship between water- stress and chewing and sucking insects, there is general agreement that elevated levels of plant stress favor egregious and often lethal boring insects particular bark beetles and others species of cambium feeders (Raupp et al. 2012). Of trees commonly planted in urban settings water stress has been shown to reduce resistance of ash to clearwing borers, bark beetles, and roundheaded borers (Martinson et al., 2014) and eucalypts to the roundheaded borers (Hanks et al., 1999).

Anthropogenic inputs – pollutants, nutrients, and pesticides

Several anthropogenic inputs including ozone, nitrogen, and de-icing salts are associated with cities and urban infrastructure and may occur at higher levels in built areas than in nearby rural ones (Raupp et al. 2010, 2012). Atmospheric ozone is thought to generally reduce the resistance of plants to insect attack. Herms et al. (1996) found that increased levels of ozone increased the palatability of poplar leaves for several species on Lepidoptera. Elevated nitrogen deposition and higher ozone levels from the combustion of fossil fuels in southern California, U.S.A. in combination with drought stress were linked to outbreaks of bark beetles (Jones et al., 2004). In Munich viburnums exposed to atmospheric pollutants expressed higher levels of foliar nitrogen which supported elevated populations of aphids (Bolsinger and Flückinger, 1987). Elevated concentrations of minerals in soil from the use of deicing salts in several European cities have been linked to reduced resistance of plants with corresponding increases in populations of aphids along motorways (Braun and Flückiger, 1984).

A commonly held belief that fertilization can enhance plant resistance to attack by insects and mites helps explain the widespread application of fertilizers in arboriculture. However, Herms (2002) overwhelming demonstrated that fertilization generally increases the susceptibility of woody plants to defoliators including caterpillars, sawflies, and leaf beetles; sap – sucking arthropods including aphids, adelgids, lace bugs, psyllids, plant bugs, scales, and spider mites; and wood boring insects.

Insecticides are important tools for arborists to mitigate attack by pests. However, applications of insecticides have been shown to disrupt ecosystem processes at several spatial scales ranging from residential communities to individual trees (Raupp et al. 2010, 2012). Often these disruptions result in secondary pest outbreaks due to the elimination of natural enemies or attenuation of their top-down suppressive activities. Some classes of insecticides such as neonicotinoids have been shown to suppress plant defenses and thereby increase plant quality. This is turn can elevate fecundity of spider mites and cause outbreaks on several species of woody plants (Raupp et al. 2010, 2012 and references therein).

BIOTIC FACTORS - 2: DISEASES

A vast majority of tree diseases are caused by biotic agents, including viruses, phytoplasmas, bacteria, fungi, fungal-like organisms (e.g. oomycetes), parasitic plants and nematodes. Biotic disease agents are infectious, whether on their own or by means of vectors, and are thus transmissible from diseased to healthy trees. While relevant tree diseases may be caused by pathogens belonging to all groups listed above (e.g. elm yellows caused by the *Ca. Phytoplasma ulmi*, bacterial leaf scorch causes by *Xylella fastidiosa*, sudden oak death caused by the oomycete *Phytopththora ramorum*), fungi rank first as agents of significant tree diseases (Tainter and Baker, 1996).

Outbreaks with destructive effects are associated either with the emergence of native pathogens due to environmental and cultural reasons, including tree management, or can occur when pathogen or host introductions lead to novel host-pathogen interactions. Although invasiveness of tree pathogens has been reported to occur in association with ecological traits and with factors other than high virulence of pathogens (Gonthier et al., 2014), the lack of co-evolution between hosts and pathogens and the high susceptibility of native hosts to introduced pathogens are regarded as the major forces driving the invasions (Parker and Gilbert, 2004). The climate change may also be responsible for an increase of epidemics, including in urban environment (Tubby and Webber, 2010).

In this chapter, the most important classes of diseases and pathogens affecting trees in urban settings are described in their significance, impact and diagnostic characters. The most effective management strategies and tactics, including integrated disease management programs, are reported based on the biology of pathogens.

Factors affecting outbreak of infectious diseases in the urban environment

Tree diseases often attain higher incidences and severities in urban environment compared to natural ecosystems. In urban settings, trees are often planted in suboptimal conditions, with little area for root expansion (Tubby and Webber, 2010) (see chapters 18 and 20 of this book). This, along with the occurrence of soil compaction and the presence of impervious surfaces, may exacerbate the effects of drought, thereby weakening trees and predisposing them to the attack of secondary, opportunistic pathogens (Tubby and Webber, 2010). For the same reasons, heat island effects and air pollution, which are characteristic of urban areas, may favor pathogen outbreaks. Generally, the vegetative status of trees affects more significantly necrotrophic pathogens than biotrophic ones. It is not surprising that certain groups of pathogens, including canker/dieback pathogens, are more likely to be positively associated with host stress, particularly drought stress, than other groups, encompassing most foliar pathogens (Tubby and Webber, 2010). Incidentally, most necrotrophic pathogens may be strictly dependent to or may be favored by the presence of wounds for gaining entry into the trees, including pruning wounds and mechanical injuries.

In addition to the low floristic diversity, which may favor epidemics of specialized pathogens, the reduced spacing among trees in urban landscapes may also play a role in disease outbreaks. Short distance between trees may result in higher likelihoods of transmission of pathogens spreading through root grafts (e.g. viruses, phytoplasma, vascular pathogens) or contacts (e.g. root rots).

Root rots and wood decay

Significance and impact - Root rots and wood decay are caused by lignicolous basidiomycetes or, less frequently, ascomycetes fungi destroying the plant cell wall (Tainter and Baker, 1996). They may be classified either as white rot or brown rot agents, depending on the component of the plant cell wall they are able to decompose, i.e. lignin or cellulose, respectively. While only a few cases of intercontinental introduction of wood destroying fungi have been reported so far, some of them involve urban settings and parks (Coetzee et al., 2001; Gonthier et al., 2014). In general, however, root rots and wood decay are recognized as major forces of native ecosystems providing resources for a variety of living organisms, thus enhancing biodiversity (Lonsdale et al., 2008). Although the concept of dead wood ecology encompasses both forests and urban parks, the loss of wood mechanical properties caused by wood decay may predispose trees to the risk of failures, resulting in significant damages of property and/or tragic injuries, which is a pivotal aspect in urban environment.

In addition to hazardous situations, root rots and wood decay fungi may also determine aesthetic damages by causing stem or branch cankers, tree decline and death (Figs. 6 and 7). Such damages are more often associated with fungi colonizing the root system and the sapwood rather than with those affecting exclusively the heartwood (Gonthier, 2010; Vasaitis, 2013).

Diagnosis – The type of rot (e.g. white vs. brown) could aid in the diagnosis but generally it is not an exhaustive trait for the identification of wood decay fungi. Diagnosis is traditionally based on the inspection of trees for the presence of fungal fruiting bodies and on their identification by using mycological keys (Bernicchia, 2005; Gonthier and Nicolotti, 2007). However, a recent study conducted in both forest and urban sites clearly indicate that, on average, inspection of trees for the presence of fruiting bodies underestimates more than 90% of trees infected by wood decay fungi (Giordano et al., 2015), making visual inspection an inefficient diagnostic approach. Furthermore, fruiting bodies of some species (e.g. *Phaeolus schweinitzii*) are short-lived or may be found only in particular periods of the year (e.g. *Armillaria* spp.); thus, the timing of diagnosis is also important. Most of root rots and wood decay fungi can be easily cultured from decayed wood and therefore they could be identified through the use of appropriate keys, yet such approach is difficult and time consuming (Nicolotti et al., 2010).

A number of molecular tools are now available for the identification of the most important wood decay fungi (reviewed by Nicolotti et al., 2010). Polymerase Chain Reaction (PCR) assays with taxon-specific primers have been developed for the early detection of the most important and widespread root rot and wood decay fungi of both broadleaves and conifers (Guglielmo et al., 2007, 2008; Gonthier et al., 2015). Such assays provide reliable diagnostics starting from both fungal pure culture and wood samples (e.g. pieces of wood, cores, sawdust), especially when standardized sampling approaches are used (Guglielmo et al., 2010). Technology based on electronic nose is also promising, though not yet completely reliable for all host-pathogen combinations (Baietto et al., 2013).

Biology - The biology of wood decay fungi in living trees had been previously reviewed (Vasaitis, 2013). In general, primary infections occur by means of airborne spores through wounds, including pruning wound or injuries on roots, tree collar and stem. Some of these fungi may also operate a secondary, vegetative spread, allowing for the expansion of individuals established through primary infection. Depending on the pathogen, this expansion may occur through root grafts or contacts, leading to a tree-to-tree contagion, or by free growth of the fungus in the soil through rhizomorphs (e.g. *Armillaria* spp.) or mycelial cords (Gonthier, 2010; Vasaitis, 2013). Besides these general schemes, there is an increasing body of literature indicating that latent phases in symptomless tissues (i.e. endophytic phases) are possible (Vasaitis, 2013).

Management – Strategies and tactics to fight against the most important root rot and wood decay fungi have been previously reviewed (Tainter and Baker, 1996). The knowledge on the relative importance of primary vs. secondary infection is important for management purposes. Pathogens like *Armillaria* spp., *Heterobasidion* spp., etc. are able to spread secondarily. When this happens, a carry-over of the pathogen into new generations may occur, and therefore stump removal may be recommended.
To minimize primary infections, mechanical injuries should be avoided as much as possible. Shaping of irregular mechanical wounds by cutting loose pieces of knocked off bark has been suggested to enhance callus formation and wound closure (Vasaitis, 2013). Since large size pruning wounds may take years to occlude, pruning of large diameter branches should be avoided or performed only when strictly necessary. Based on literature review, wound dressing has been reported as generally ineffective in preventing infections by wood decay fungi (Clark and Matheny, 2010).

Vascular diseases: Dutch elm disease and oak wilt

Significance and impact – Dutch elm disease (DED) and oak wilt (OW) are major and destructive fungal diseases of elms (*Ulmus* spp.) and oaks (*Quercus* spp.), respectively. *Ophiostoma ulmi* and *O. novo-ulmi* were responsible for two different epidemics of DED. The former species appeared around 1910 in northwestern Europe and subsequently spread throughout Europe and in North America. The latter species, displaying higher virulence than the former one, was first reported in UK in the early 1970s , and is now separated into two subspecies distributed in Eurasia and North America: *Ophiostoma novo-ulmi* subsp. *novo-ulmi* and *O. novo-ulmi* subsp. *americana*. The origin and the patterns of introduction and invasion of DED pathogens were previously reviewed (Kirisits, 2013). *Ophiostoma ulmi* caused considerable losses in elm populations: in about 50 years, 10-20% of the elm population was estimated to have died. In Europe and parts of Asia *O. novo-ulmi* killed the majority of mature elm trees (Kirisits, 2013).

OW is caused by *Ceratocystis fagacearum* and is a major cause of oak mortality in many locations of the eastern and southern USA (Harrington, 2013). While loss of oak timber can be economically detrimental, losses of amenity trees are even of greater economic importance (Harrington, 2013). Members of the red oak group, such as northern red oak (*Q. rubra*) and northern pin oak (*Q. ellipsoidalis*), are highly susceptible, but some members of the white oak group can also be affected (Harrington, 2013). Whereas the disease is present only in North America, the susceptibility of European and Asian oaks and chestnuts (*Castanea* spp.) has been demonstrated, suggesting that *C. fagacearum* could be a threat if accidentally introduced in Eurasia. It should be noted that the fungus is a quarantine-regulated pathogen in Europe.

Diagnosis – Being true vascular diseases, DED and OW result in a black to brown discoloration of one or several growth rings (i.e. functional sapwood), which is visible in cross sections of wilted twigs and branches (Harrington, 2013; Kirisits, 2013). DED affected leaves wilt, turn to yellow brown and finally drop. If the development of symptoms is acute, leaves may remain attached to the twigs for a long time. Dead tips bend downwards in a hook-like manner (reviewed by Kirisits, 2013). The distribution of symptoms on the crown also depends upon the way of disease transmission (see below). OW may also be diagnosed by mat production under the bark of recently dead trees, which are generally clustered-distributed forming infection centers (Harrington, 2013).

Biology – DED and OW pathogens are able to infect healthy trees by spreading from diseased trees through the vascular systems of grafted roots (Tainter and Baker, 1996). Functional root grafts could play a prominent role in disease transmission when trees of sufficient age and size are involved, and especially in the case of OW (Harrington, 2013). In addition of spreading locally through root grafts, DED and OW pathogens are also disseminated, though in a different way and with a different efficiency, by insect vectors.

All vectors of DED are bark beetles mostly belonging to the genus *Scolytus* which breed in stressed or recently dead trees and disseminate the pathogen propagules exozoically and endozoically (Kirisits, 2013). Disease transmission to healthy trees occurs during maturation feeding of beetles, taking place in crotches of thin twigs or at the base of leaves on newly formed shoots in the tree crown (Kirisits, 2013). When disease transmission is mediated by the feeding activity of bark beetles, external symptoms are initially restricted to one or a few branches in the upper or outer parts of the crown, rather than being generalized to large portions or to the whole crown, as it generally occurs following infections through root grafts. Although the efficiency to act as pathogen vectors has been reported to vary depending on the size of beetles, elm bark beetles are generally regarded as efficient vectors of DED (Kirisits, 2013).

In the case of OW, pathogen association with sap beetles of the Family Nitidulidae is strong, but clearly less efficient for disease transmission than *Scolytus* for DED (Harrington, 2013). *Ceratocystis fagacearum* produces mats under the bark of recently killed oaks, especially red oaks. Once the bark cracks, mats become attractive for nitidulids, some species of which (e.g. *Colopterus truncatus*, *Carpophilus* spp.) can carry spores of the pathogen to fresh wounds (Harrington, 2013). Pruning of amenity trees and other fresh injuries may lead to new infections especially in the springtime, when sporulating mats and nitidulids carrying the fungus are most abundant (Harrington, 2013).

Management – management strategies and tactics to control DED and OW have been previously reviewed (Harrington, 2013; Kirisits, 2013). These include the adoption of planting distances large enough to avoid root graft transmission, should the diseases occur in the future, and sanitation campaigns aimed at destroying dead and dying trees, branches, stumps etc. and any infected material which bark beetles utilize for breeding or which may be attractive for sap beetles. In the case of DED, if trees are already colonized by bark beetles, sanitation measures have to be completed before juvenile insects emerge (Tainter and Baker, 1996). Debarking can prevent insect breeding and can kill ‘white stages’ (larvae and pupae) of bark beetles if present. Sanitation campaigns can be incorporated into general shade tree maintenance programs.

Soil applications or injections/infusions of systemic fungicides into the functional xylem of trees have been proved effective to prevent rather than to cure infections (Tainter and Baker, 1996). Thiabenzole has been used against DED and propiconazole against both DED and OW. In the case of DED, treatments may be more effective if combined with therapeutic pruning of diseased branches. It is recommended to treat pruning and surgery wounds to decrease their attractivity to the insects and to prevent infections by *C. fagacearum* (Tainter and Baker, 1996). Any type of paint (latex, oil-based, spray-on, brush-on, or wound dressing) will suffice. Disinfecting felling and pruning equipment used for preventive, sanitation and curative treatments with 70% alcohol or sodium hypochlorite is also recommended (Tainter and Baker, 1996).

While a biological treatment (i.e. Dutch Trig®) based on the principle of cross protection is available for DED, the transmission of OW may be prevented by digging trenches to delimit infected from healthy trees. Equipment and methods to conduct efficient soil trenching have been previously described (Harrington, 2013). Integrated disease management against vector-transmitted vascular diseases also rely on a number interventions aimed at controlling directly or indirectly insect vector populations.

Canker/dieback diseases: canker stain of planetrees and ash dieback

Significance and impact – canker stain of planetrees (CSP) and ash dieback (AD) currently stand among the most destructive fungal diseases affecting woody ornamentals. CSP is a lethal disease on planetrees (*Platanus* spp.) caused by *Ceratocystis platani*, an ascomycete native to eastern US and accidentally introduced into southern Europe in the middle of the last century (Harrington, 2013). Once introduced, the fungus spread throughout Italy, Switzerland, southern France and Greece, with devastating effects on London planetree (*P. x hybrida*) and oriental planetree (*P. orientalis*). Hundred thousands of trees were killed in Europe by the pathogen, which is also very infectious, making CSP probably the most harmful and damaging tree disease in parks and urban settings.

AD is a lethal disease caused by the ascomycete *Hymenoscyphus fraxineus* on *Fraxinus excelsior* and *Fraxinus angustifolia* in Europe (Gross et al., 2014). The fungus, often known with the name of its asexual stage *Chalara fraxinea*, is probably native to East Asia but was introduced into central Europe, where AD first appeared. Subsequently, the pathogen spread epidemically throughout the entire distribution range of host trees (Gross et al., 2014). The impact of AD is tremendous, hence it has been hypothesized that the combined effects of AD and emerald ash borer could seriously threat the survival of ashes in Europe.

Diagnosis – CSP can be recognized by a rapid branch and crown dieback preceded by a shortening of the internodes, leaf wilting and chlorosis and leaf fall. It may take only a few months or years since infection for a tree to die. The fungus, which is commonly associated with sapwood becoming dark or brown stained, can attack the cambium resulting in the formation of cankers (Fig. 8). Two characteristic features of CSP cankers are that they lack or have very little callus growth at the canker margins and that the bark covering cankers dries, cracks and changes in its colour. Sprouts may develop below cankers. Detailed guidelines for laboratory diagnosis are available as well.

Early symptoms of AD include small necrotic spots on stem and branches, which then enlarge in necrotic lesions. Cankers on branches generally appear, as well as wilting, leaf fall and death of top of the crown. Isolation of *H. fraxineus* from necrotic lesions on the bark is pivotal for diagnosis, as previously reported (Gross et al., 2014). Molecular typing through PCR-based assays is also very useful to distinguish *H. fraxineus* from the native, yet non-pathogenic species *H. albidus* (Gross et al., 2014). The two fungal species can also be distinguished based on some characters of fruiting bodies, that appear as macroscopic whitish apothecia on infected tissues (Gross et al., 2014).

Biology – *C. platani* colonizes a tree by moving systemically and rapidly through the non-living vessels. Therefore, functional root grafts among adjacent trees represent important pathways of disease transmission. However, the most important infection courts are human-caused wounds, including pruning wounds or other wounds of even small size due to mechanical injuries (Harrington, 2013). Infectious inoculum is represented by spores or colonized sawdust. Mechanical transmission of *C. platani* through pruning saws, climbing ropes, earth moving machinery, etc. has been reported as pivotal for the epidemics of CSP (Harrington, 2013). Sporulating fruiting bodies of *H. fraxineus* develop during the summer on leaf debris of the previous year (Gross et al., 2014). Leaves become infected by means of windblown spores. Subsequently, the pathogen can spread along the leaf veins and can occasionally colonize across the junction between petiole and stem, thus initiating a necrotic lesion on the stem (Gross et al., 2014). The asexual stage of the fungus develop in autumn and winter on ash petioles in the litter, but asexual spores are not infectious (Gross et al., 2014).

Management – *C. platani* is a quarantine pathogen in Europe for which prescriptions for disease control are regulated at the country level. Control may be achieved with the adoption of planting distances large enough to avoid root graft transmission, as described above for vascular diseases. The prompt removal of dead or symptomatic trees along with the two neighboring planetrees on either side is recommended. Sawdust generated during cuttings should be collected in tarps and trees should not be sawn in windy days. The stump and the root system should be removed whenever possible. Pruning should be avoided or conducted in the coldest months while fungicide dressing for the protection of wounds should be used. For instance, Thiophanate-Methyl is recommended for that purpose. Pruning tools and other tools should be disinfected after operating on a tree and before operating on the next. Breeding efforts have led to the selection of a hybrid cultivar (i.e. 'Vallis Clausa') which is resistant to CSP (Vigouroux and Olivier, 2004), while displaying good levels of resistance to other pest and diseases, including the anthracnose of planetrees caused by *Apiognomonia veneta* (Harrington, 2013).

There are currently no effective strategies to control AD, although various physical and chemical approaches have been proposed to reduce the risk of infection, including the removal or treatment of plant debris with fungicides, the prevention of movement of infected plant material, the use of disinfectants to treat contaminated footwear, clothing and equipment. The application of endotherapic products through trunk injection has been shown promising to manage the disease (Dal Maso et al., 2014).

Foliar and shoot diseases

Significance and impact – foliar and shoot diseases encompass a broad range of infectious diseases potentially reducing the ornamental value of trees. Their significance depends on the size of the epidemic area, the severity of leaf and shoot infection, tree age, the time of infection in the growing season, and the longevity of disease, which may occur in one or a few successive seasons (Kowalski, 2013). Damage is greater if the disease occurs over two or more successive years (Kowalski, 2013). It has been reported that low severity of disease, appearing as a few spots on leaves or local infection of single leaves, leads to minor damage to a tree while higher disease severity resulting from advanced colonization of leaves and shoots causes reduction in photosynthesis and plant growth and, occasionally, premature defoliations or dieback of various parts of the tree (Kowalski, 2013). High disease severity associated with extreme environmental conditions may sporadically result in the death of trees, regardless of their age (Kowalski, 2013).

Finally, foliar and shoot diseases can weaken host trees, thus favoring the attack of secondary pathogens and pests (Tainter and Baker, 1996).
Relevant damages in urban settings are caused by a number of fungal diseases, including the anthracnose of planetree (Fig. 9), the anthracnose of horse chesnut (*Aesculus hippocastanum*) caused by *Guignardia aesculi* (Fig. 10) and the tar spot of maples (*Acer* spp.) caused by *Rhytisma acerinum*. In addition, powdery mildews of planetrees and oaks (*Quercus* spp.) caused by *Erysiphe platani* and *E. alphitoides*, respectively, can be locally important, especially in nurseries or where associated with young trees. The widely grown boxwood (*Buxus* spp.) is susceptible to a damaging blight caused by *Cylindrocladium buxicola*.

Diagnosis – diagnosis is based on the observation of symptoms of the disease in the field, commonly followed by laboratories examinations. Keys for the diagnosis and description of symptoms of the main foliar and shoot diseases have been previously published (Sinclair and Lyon, 2005; Tainter and Baker, 1996). Occasionally, disease symptoms are so characteristics that they may allow the identification of the causal agent directly in the field (Kowalski, 2013). This may occur for pathogens characterized by high degrees of host specificity and causing a specific symptomatology, e.g. tar spot of maples, powdery mildew of planetrees, etc. Many pathogens of leaves and shoots develop sexual or asexual fruiting bodies having diagnostic relevance on the surface of infected tissues. If fruiting bodies are absent on leaves, induction of fructification by incubating samples in moist conditions (moist chambers) or isolation of fungi on artificial media is necessary (Kowalski, 2013). The most common symptoms of foliar diseases occurring on ornamental and shade trees are necrotic leaf spots, which vary in colour and size depending on the disease. For some anthracnose diseases, including the anthracnose of planetrees, symptoms develop not only on leaves, but also on shoots, which may display cankers or turn dark before dying. In the case of powdery mildews, infected leaves and young shoots display a whitish-gray powdery looking coating on their surface, which is formed of vegetative and sporulating hyphae.

Biology – The large majority of foliar pathogens infects new leaves in the springtime through spores produced on fallen leaves, after overwintering on the ground (Tainter and Baker, 1996; Kowalski, 2013). Pathogens attacking shoots (i.e. anthracnose agents) may overwinter in cankers and dead plant tissues. Spore discharge usually increases during intensive rainfall and decreases during droughts (Kowalski, 2013). Spores are mainly dispersed by wind or rain and splashing water. With some exceptions (e.g. powdery mildews), infections and disease severity increase with increasing leaf wetness duration.

Many pathogenic ascomycetes, after infecting plant tissues, produce asexual stages liberating asexual spores. These may infect other leaves and shoots. Thanks to the asexual stages and depending on the fungal species and environmental conditions, one to several cycles of infection may occur during the growing season.

Management – The removal of fallen leaves in the spring before the development of new leaves is pivotal to prevent infections (Kowalski, 2013). To reduce the source of inoculum of pathogens that overwinter in cankers and dead twigs, symptomatic parts should be pruned and completely removed by spring (Kowalski, 2013). Cultural practices (e.g. pruning) aimed at reducing the level of relative air humidity in the crown and free moisture on leaves play a significant role in preventing new infections. Application of preventative fungicides on the crown may reduce the level of infections or totally prevent infections. Systemic fungicides applied to the soil, foliage or through injection/infusion can have therapeutic effects against foliar diseases. It should be noted that chemicals can be applied on a given host against a certain pathogen only if it is approved for that use, as indicated in the label and technical sheet of the product. The label also reports a number of details on how to prepare and apply the fungicide. As a general rule, it is important to alternate fungicides with different modes of action to delay the development of pathogen strains resistant to fungicides (Kowalski, 2013).

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Figure legends:

Fig. 1: In addition to being an important defoliator of hardwoods, irritating hairs of oak processionary moth caterpillars, *Thaumetopoea processionea*, pose a major health risk. Photographic credit Glynn Percival.

Fig. 2: Emerald ash borer, *Agrilus planipennis*, has killed millions of ash trees in natural forests and built landscapes in North America. Photographic credit Paula Shrewsbury.

Fig. 3: Emerald ash borer larvae, *Agrilus planipennis,* consume phloem and cambium effectively girdling and killing trees. Adults (inset shown 1/3 actual size relative to larvae) feed on ash foliage causing little damage. Photographic credit Michael Raupp.

Fig. 4: In heavy infestations entire canopies will appear scorched with almost every leaf infested by horse chestnut leafminer *Cameraria ohridella.* Photographic credit Glynn Percival.

Fig. 5: Individual leaves will contain several mines caused by larvae of horse chestnut leafminer *Cameraria ohridella.* Photographic credit Glynn Percival.

Fig. 6: Oak infected by the wood decay agent *Inonotus dryadeus*. Fungal fruiting body and decayed wood at the base of the tree.

Fig. 7: Canker caused by the wood decay fungus *Inonotus obliquus* on birch. The conk of the fungus is present.

Fig. 8: Canker and internal symptoms caused by *Ceratocystis platani* on London planetree.

Fig. 9: Symptoms of the anthracnose of planetree caused by *Apiognomonia veneta*: foliar symptoms on the left (a) and canker on the right (b).

Fig. 10: Symptoms of the anthracnose caused by *Guignardia aesculi* on horse chestnut.