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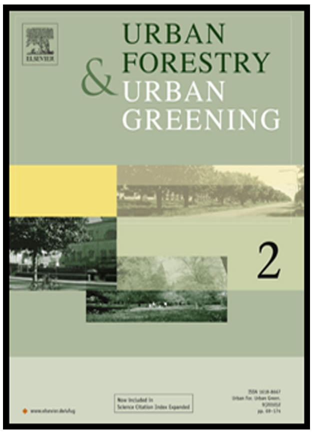

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PII: S1618-8667(25)00084-6

DOI: https://doi.org/10.1016/j.ufug.2025.128750

Reference: UFUG128750

To appear in: *Urban Forestry & Urban Greening*

Received date: 10 October 2024
Accepted date: 26 February 2025

Please cite this article as: Anna Maria Vettraino, Nikoleta Soulioti, Dinka Matosevic, H. Tuğba Doğmuş Lehtijarvi, Steve Woodward, Alberto Santini and Nicola Luchi, Management of fungal diseases of *Platanus* under changing climate conditions: case studies in urban areas, *Urban Forestry & Urban Greening,* (2025) doi:https://doi.org/10.1016/j.ufug.2025.128750

Management of fungal diseases of *Platanus* under changing climate conditions: case studies in urban areas

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ABSTRACT
Platanus species, especially *Platanus* × *hispanica* (London plane), play a key role in urban areas due to their ecological, social and aesthetic value. These trees are widely planted along roadsides, in parks and historical gardens, providing shade, reduce air pollution and enhance the aesthetic appeal of cities all over the world. *Platanus* species are well known for their resilience to abiotic factors and rapid growth. However, plane trees are vulnerable to pests and diseases, exacerbating urban plant health challenges. The EU Phytosanitary Regulation aims to control the spread of plant diseases, but many pathogens fall outside their scope. Although many of these pathogens are not devastating, they still require continuous management by authorities or private owners. This paper focuses on drawing up guidelines for managing diseases caused by *Ceratocystis platani*, the only EU regulated fungal disease on plane trees, and the other pathogens, *Apiognomonia platani*, *Macrodiplodiopsis desmazieri* and *Erysiphe platani*, which compromise the ecosystem services provided by *Platanus* trees and are a major issue that impact human health and safety.

Keywords:
Platanus, climate change, disease, management, urban areas

1. Introduction

The urban forest provides environmental, economic and social values amongst others, and is highly beneficial to the lives of the urban human population. In cities, healthy trees bring benefits to human health by mitigating temperature extremes (Esperon-Rodriguez et al., 2021), improving air quality (Nowak et al., 2014; Ren et al., 2023), and also reducing energy consumption (McDonald et al., 2020). As urban areas continue to expand, the importance of integrating green spaces, such as parks, gardens and tree-lined streets has been increasingly recognised for enhancing the quality life for residents, due to the ecosystem services provided by plants. However, with the rise of urban greenery comes a growing concern: plant disease. Urban environments, with their unique challenges and conditions, represent a fertile ground for the establishment, spread and exacerbation of plant diseases. The close proximity among urban plants allows pathogens to move rapidly from one host to another, leading to widespread infection. Moreover, urban plants are frequently subjected to different environmental stressors, including pollution, soil compaction, poor irrigation and heat island effects (Leal Filho et al., 2018; Percival, 2023; Piana et al., 2019). These stressors can weaken plants, making them more susceptible to diseases, especially if they are non-native plants. In addition, many clonal selections of trees are planted in urban areas, resulting in large numbers of individual plants being susceptible to damage from pests and diseases. In the last century, new planting programs in towns and cities globally led to the introduction of ornamental, often non-native tree species. Unfortunately, plant trade is well known as one of the main pathways for the introduction of invasive alien species (Antonelli et al., 2023; Marshall et al., 2021), due to the presence of asymptomatic plants which may harbor latent pathogens in their roots or epigeal tissues and in the growing substrate used (Antonelli et al., 2023; Laurence et al., 2024). Urban settings are junctions of international trade, and plantings of imported nursery stock which makes them centres for introduction of alien tree pests and diseases. The use of non-native plant species can affect their resilience to site conditions, leading to a higher susceptibility to abiotic and biotic stresses. The consequences of the presence of plant diseases in urban green spaces range from reductions in aesthetic appeal through psychological impacts, and to economic and environmental impacts (Antonelli et al., 2024; Tabassum et al., 2024; Tubby and Pérez-Sierra, 2015).

Extensive research has focused on creating and applying effective strategies to prevent and control introduced pests and pathogens that impact urban and forest trees. In some cases, the results have been integrated into decision-making and the implementation of management practices. The most recent phytosanitary regulation [(EU) 2016/2031)] for example is an attempt to present comprehensive defense systems to reduce the spread of specific plant diseases, by combining strict import regulations, post-entry quarantine, movement controls, and specific scientific data, pest risk analysis, impact assessment and survey results. However, plants can also harbor other plant pests and pathogens besides those considered in EU regulations, which although not devastating, require continuous management by local authorities or private owners, hereinafter referred to as "common not-devastating pest and pathogens (CDP)".

The aim of this paper is to identify common practices and challenges in prevention and effective management of fungal CDP, which, although not necessarily causing devastating infections, constitute major issues in urban environments, associated with plane trees (*Platanus* spp.). This tree genus has been chosen as a model plant, because it has become an integral part of international metropolises, particularly in roadsides and historical and botanical gardens. *Platanus orientalis*, the oriental plane tree, stands out for its significant contributions to urban areas, from the Caucasus to the Mediterranean regions. It has been particularly appreciated during Greek and Roman times and in the Renaissance (Tsopelas et al., 2017; Ciaffi et al., 2018; Rosati et al., 2015), for the generous shade provided by its large leaves. Over the past three centuries, *P.* x *hispanica* (formerly *P.* x *acerifolia*), a natural hybrid between *P. orientalis* and *P. occidentalis*, has been extensively planted as an ornamental tree for the multitude of ecological, social and practical benefits provided (Yang et al. 2015; Wang and Tu, 2023). *Platanus* × *hispanica* is one of the few tree genera present in 15 Italian cities chosen along a geographical and bioclimatic gradient (Bartoli et al., 2022), planted for its rapid growth and relative resistance to diseases.

2. Main diseases of *Platanus* in urban area

Plane trees are appreciated for their adaptability and resilience in urban environments including their ability to tolerate air and run-off pollution, poor soil conditions and drought. However, they are damaged by salt applications to roads and can be susceptible to a range of pathogens and pests that can significantly impact their health (Antonelli et al., 2024; Derviş et al., 2020). This study is focused on some of the most noteworthy pathogens affecting plane trees in Europe.

Among biotic stressors, the Ascomycota *Ceratocystis platani* (J.M. Walter) Engelbr. & T.C. Harr. stands out as a major pathogen, responsible for causing a lethal vascular wilt named "canker stain disease". The pathogen enters the tree host through wounds or via root anastomosis and spreads into the vascular system, leading to canopy decline and mortality, and the formation of characteristic canker stains on stems and in sapwood (Tsopelas et al., 2017). As an example of the destructive capacity of the pathogen, it is worth noting that in just over twenty years, the pathogen led to the death of 90% of plane trees in the Italian town of Forte dei Marmi (Panconesi, 1977; Panconesi, 1972). *Ceratocystis platani* remains of critical concern, and is regulated as a harmful organism in the

EU by the Commission Implementing Regulation (EU 2019/2072) and 2022/1629 (https://eur-lex.europa.eu/eli/reg_impl/2022/1629/oj), which establish measures for its containment within certain demarcated areas (Brunetti et al., 2022; Luchi et al., 2013b; Pilotti et al., 2012). The pathogen is also in the EPPO A2 list of quarantine organisms (EU 2019/2072; OEPP/EPPO 1986, 2003, 2014). The health of *Platanus* is further compromised by other fungal pathogens (Antonelli et al 2024; Derviş et al., 2020; Scattolini Rimada et al., 2023; Tubby and Pérez-Sierra, 2015). This study is focused on *Apiognomonia platani* (Lév.) L. Lombard, agent of plane anthracnose; *Macrodiplodiopsis desmazieri* (Mont.) Petr. 1922, causal agent of Massaria disease, and *Erysiphe platani* (Howe) U. Braun & S. Takam (Pastirčáková et al., 2014), agent of powdery mildew. These three pathogens do not cause the sudden death of the tree, as in the case of canker stain disease, but they seriously alter the stability of the branches and compromise the photosynthetic activities of leaves (Tubby et al., 2015; Kliuchevych et a., 2021). These diseases undermine the ecosystem services provided by plane trees and put public health at risk due to the potential for falling branches. Figure 1 illustrates the main characteristics of the diseases described above.

3. Challenges for growing healthy *Platanus* trees

3.1 Risk-based choices for Platanus planting

Due to the role of trees in the urban landscape, species selection should consider aesthetic, historical, physical, biological and functional factors (Wang and Tu, 2023).

The frequency and intensity of heat stress events globally have increased over the past 20 years (Percival, 2023). Increases in air temperature due to climate change are exacerbated in urban, compared to rural, areas by the heat island effect. Usually, in a temperate climate, this effect will have some benefits in cooler seasons, while in summer it will increase heat stress and energy used for cooling (Zhao et al., 2023; Watkins et al., 2007). However, several studies showed how urban design changes can improve thermal comfort (Zhao et al., 2023). The climate in cities where trees were grown had a significant impact on the cooling potential (Rahman et al., 2020). In particular, the density of tree canopies was clearly identified as the most influential factor amongst the different cooling mechanisms (Yin et al., 2024). On the other hand, trees are seriously threatened by climate change. Tree growth and ecosystem service provision strongly depend on temperature and adequate precipitation (Poschenrieder et al., 2022).

Platanus is rather resilient to drought periods, due to the ability to mitigate heat stress through morphological and physiological responses, such as transpiration-induced cooling (Bowden and Bauerle, 2008; Poschenrieder et al., 2022). The tree response to drought includes further physiological changes, such as bark exfoliation and variation in the timing of flowering (Cedro and Nowak, 2006; Milks et al., 2017; Mimet et al., 2009). The healthy status of *Platanus* is correlated with growth period as well as the temperature during winter time and the total precipitation in preceding years (Gregorová et al., 2010). Phenological traits of *Platanus* are affected not only by environmental factors but are also under strong genetic control. Velikova et al. (2018) reported that after drought periods Italian *P. orientalis* ecotypes were less damaged and showed a higher stability in chloroplast membrane parameters compared to the Bulgarian ecotypes.

Urban trees are under additional threat from limited water availability and low soil volume (Dowtin et al., 2023; Jim, 2019). Abiotic stresses are compounded by anthropogenic effects. For example, in urban architectural planning, trees are often planted in confined spaces alongside sidewalks, closely surrounded by asphalt and other structures, sometimes up to the very base of the tree stem. In these conditions the soil becomes impermeable, and consequently, water interception and root-level oxygen exchange are reduced. Moreover, the presence of asphalt increases the temperature at the tree collar, which can lead to cracking, splitting, or other forms of deterioration. Once the plant is established, irrigation and climatic conditions are key to ensuring plant growth. In urban environments, stress on the plant can increase as a result of water shortages. Frequently, in new plantings areas, inadequate or improper irrigation can lead to decay, and sometimes plant death. *Platanus* can grow quite large

and tall, thus it is important to ensure sufficient space for growth, both at the level of root systems and crown. In addition, ensuring sufficient space for epigeal growth allows the canopy of the plant to develop properly, thus reducing pruning interventions that are often the entry points for pathogens.
Future urban green management should consider selecting *Platanus* trees when this choice can ensure the provision of ecosystem services by this tree genus in the context of ongoing climate change.

3.2 Platanus diseases and climatic changes

Climate change also appears to greatly influence the establishment and spread of plant pathogens and may result in new host-pathogen interactions. The magnitude and direction of this interaction under climate change varies among microorganisms (Jactel et al., 2012; Raza and Bebber, 2022). Increased temperature and the absence of frost events in many cases allow the invasion and establishment of thermophilic or frost-sensitive pathogens (Franić et al., 2023). There might also be shifts in the interrelations in species communities that are difficult to predict. Some fungal species, that had previously been considered inconsequential, caused notable damage in drought periods during the last two decades; native fungi that were previously harmless and therefore received little attention may suddenly appear as agents of tree diseases (Cech et al. 2007; Engesser et al., 2008). Nevertheless, several authors hypothesized that the predicted increase in temperature, dry summers and extreme meteorological events will affect many harmful pathogens both by directly accelerating their propagation rates as well as by weakening host plants (Santini and Ghelardini, 2015; Singh et al, 2023). For powdery mildew disease of *Platanus,* Adamska et al. (2019) claimed a connection between the reduction in *E. platani* infections and climate conditions observed in Poland in 2016-2017, as an example. Consequently, to preserve tree health, it is essential to focus on the biology of specific pathogens, including in relation to climate change and other stressors.
The effect of temperature on *C. platani* growth and viability within infected woody tissue or soil is also evident. The pathogen grows at an optimal temperature of 25°C, while grows stops below 10°C or above 35°C; at temperatures above 37°C the pathogen loses viability (Jeger et al., 2016). In infections, *C. platani* produces more rapid disease progression in spring and summer, compared with late autumn (Pilotti et al. 2016; Tsopelas et al. 2017).
Over the last twenty years, heat, water stress and canopy humidity are regarded as major components in the increasing frequency and impact of other fungal diseases of *Platanus*. For instance, periods of cool, humid weather in early spring before bud flushing increase the severity of bud and twig blight, associated with infections by *A. platani*. Temperatures below 15°C during bud break and early leaf development favour new infections and the disease also develops from already infected tissues. Rainfall and/or high relative humidity support both sexual and asexual sporulation, increasing sporulation and, therefore, encouraging new infections (Cellerino and Anselmi, 1978). The most affected leaves fall early and, in severe infections, complete defoliation of the plant may occur (Cellerino and Anselmi, 1978).
After the above-average hot and dry summer of 2003 in Switzerland, Austria and Germany, several outbreaks of *Massaria* disease were recorded (Engesser et al., 2008; Kehr and Krauthausen, 2004; Tomiczek et al., 2009). *Macrodiplodiopsis desmazieri* cultures showed the highest mycelial growth in a temperature range between 20°C and 35°C (Börker, 2019). Higher numbers of pycnidia with incipient sporulation were observed at temperature ranges between 30°C and 35°C. The pathogen can colonize primarily cortical tissues and secondarily xylem tissues, even in low moisture conditions (Börker, 2019).
Similarly, to the pathogens described above, increases in temperature and humidity have led to a rapid spread of *E. platani* infection through spores, despite the application of fungicide treatments (Tello et al., 2000). As climate conditions shift, disease patterns and tree susceptibility also change, necessitating a risk-based approach to disease management including regular monitoring in disease surveys, focusing on pathogens not included in quarantine lists.

4. Regular Monitoring

Regular monitoring of tree health is critical to the maintenance of urban and suburban landscapes, where environmental stress can affect plant longevity and vitality. The use of diverse monitoring techniques allows for a full understanding of the health status of trees and rapid action to mitigate diseases and other problems. Effective monitoring and knowledge of pathogen biology form the basis for effective plant disease management. Different pathogens, such as those included here, have varied pathways of dispersal that are related to both anthropogenic and natural factors (**Figure 2**). Anthropogenic activities include transporting and trade in symptom-free infected or contaminated plants and using contaminated cutting tools, which can help spread inoculum during felling and pruning operations (**Figure 2**). The spread of pathogens also occurs by natural routes, e.g. wind and insects.

Apiognomonia platani and *E. platani* can spread over short distances through perithecia and conidia that mature on infected fallen leaves, from infected buds or within the one-year-old twigs on the tree, in the case of *A. platani*, and can be transported by wind and rain splash over the infected host (Simmt et al., 2023).

In contrast, infected *C. platani* can be disseminated to a distance within 200 m of the contaminated plant through sawdust produced during pruning cuts (Luchi et al., 2013), but canspread even greater distances when carried by stream and river water as has happened along the Canal du Midi, France (Willsher, 2011). In addition, *C. platani* produces resilient, long-lived chlamydospores that can persist in infected wood or soil. In this scenario there is the potential for the pathogen to be transmitted long distances on contaminated soil and arboricultural equipment.

Conducting a tree disease survey is a complex process that requires careful planning, systematic data collection and thorough analysis. A deep understanding of the risk factors, those elements responsible for the increased probability of the introduction and spread of a pathogen, and estimates of relative risk are essential for performing a risk-based survey. **Figure 3** outlines the main general steps of a survey guide for tree diseases. It is evident that each phase must be uniquely designed for the specific pathogen, host and environment studied, tailoring the choices accordingly. A brief description of the main actions that should be considered in monitoring *Platanus* diseases is given below.

A - PLANNING THE SURVEY

The aim and timeframe of a disease survey (e.g., assessing the presence of a specific disease, understanding disease distribution) should be well defined, in addition to the locations and plant species under consideration. As for any urban trees, it is crucial that surveyors prioritize places of high risk of development of plane tree diseases, such as for example old trees growing close to each other, in avenues, in close proximity to street and pedestrian traffic for enhancing the overall success of the survey (Mazurek and Nowik, 2018). In the case of *Platanus* health assesment in urban areas, tree inventory databases are currently used as the main background information. The evaluation of plant health status should be conducted annually if possible, by well trained personnel. In fact, a solid knowledge of specific plant diseases is crucial for enabling professionals to accurately recognize plant disease, to differentiate between various symptoms and to identify existing disease hotspots in a tree and in tree populations. The frequency of monitoring should be decided based on characteristics, climate events and incidence and severity of diseases that occurred in previous years or in the area surrounding the survey zone. In addition, in years with increased frequency and intensity of threats from plant pathogens, city-wide and nursery monitoring is required (Kessler and Cech, 2008).

The key aspects for planning and executing a plant disease survey outlined above should be integrated into a unique model. Recent studies have used mathematical modelling for identifying high-risk locations in the landscape (Parnell et al., 2014).

B-DATA COLLECTION FROM SYMPTOMATIC TREES

Routinely, monitoring of urban diseases is focused on a visual tree assessment using ground-based observation focused at the base of the tree, tree stem, main branches, crown shape (including branch network and the outer canopy) and leaf growth. However, this approach may not be the most suitable for evaluation of all tree diseases, especially if early detection is required. Moreover, accurate identification of plant diseases through visual assessment requires a deep understanding of the symptoms that plants exhibit when infected by various pathogens.

Canker stain disease. Symptoms associated with *Ceratocystis platani* generally comprise yellowing and wilting of the leaves, and sometimes elongated or lens-shaped cankers in the bark. Beyond the lesion, staining can be visible in the cambium. Removing the bark reveals infected wood; the staining in colonized tissues is of a striking darker color than uninfected tissues and of an irregular shape. A progressive deterioration is observed in the crown with yellowing and brown leaves, reductions in vegetative growth and generally stunted development. The acute symptomatology includes the sudden desiccation of some branches or of the whole crown. The infected tree can die in a few months to 2.5 – 3 years, depending on size and vigour (Griffin, 1968; Panconesi, 1999, 1977; Tsopelas et al., 2017; Vigouroux, 1979; Walter, 1946). Earlier in infection development, small cankers may be visible as dark patches underneath cracks in the bark surface; sap exudes from the cracks, becoming dark brown with oxidation. These small cankers are more conspicuous on the smooth bark of *P. occidentalis* and *P. x hispanica* than on the rough, thicker bark of *P. orientalis* (Panconesi, 1981; Walter et al., 1952). Lesions on the trunk are visible throughout the year, while deterioration in the crown is observed exclusively during the growing season (Panconesi, 1981; Walter et al., 1952). Infection by *C. platani* is difficult to detect before clear symptoms appear. The pathogen enters the host through wounds, which can be caused by human activities during arboricultural operations, and via root contacts. The latent period for *C. platani* can depend on environmental conditions and tree health.

Anthracnose disease. Symptoms progress in different tissues through four different stages: twig, bud, shoot and leaf blight (Himelick and Neely, 1961). In the twigs a brown area appears around the bud, as the fungus girdles the vascular tissue leading to the bud wilting before the bud opens. The brownish discoloration in the wood may extend proximally to varying distances from the bud. The pathogen may girdle individual buds or entire twigs, leading to death in the distal part. On the discolored bark of dead twigs and branches, small, black fruiting bodies erupt producing asexual spores that will infect leaves, slowing expansion and causing necrotic lesion along the veins (Simmt et al., 2023). The disease develops during the growing season in spring and early summer. The fungus attacks the buds and then grows into the twigs soon after the leaves appear. When the pathogen fully colonizes a twig, the formation of cankers is observed on both small twigs and larger branches. Once the twig tissue is completely girdled by the fungus death of all the distal tissues occurs. In leaves, the pathogen causes necrosis around the veins and in the surrounding tissue, thus leading to the formation of typical symptoms of the disease. In late spring a shoot blight stage occurs characterized by the sudden death of expanding shoots and young, immature leaves. On larger branches, cankers may develop, girdling and eventually kill them. The fungus can persist in the host tissues where it frequently becomes latent (Seifers and Ammon, 1980).

Massaria disease. First indications of *M. desmazieri* attacks are pinkish-purple to orange-reddish discoloration of the bark, primarily on the top of the branches in the form of stripes (Mazurek and Nowik, 2018; Mösch et al., 2014; Schmitt et al., 2014; Tubby and Pérez-Sierra, 2015). The infection spreads from the base or the middle of branches towards the tip. The infected zone is sharply demarcated from the healthy wood and, in cross-sections of branches, runs in a V-shape from the outer tissues to the pith. Infected bark becomes cracked, brittle and eventually peels off (Mösch et al., 2014; Tubby and Pérez-Sierra, 2015; Mazurek and Nowik, 2018). In some cases, affected branches can still have sparse apparently healthy leaves (Mösch et al., 2014). Branches that still appear healthy can break in a few months after the infection (Mösch et al., 2014). Symptoms on the upper part of the branches can be difficult to see from the ground, although the symptoms of infection observed in summertime are characterized by specific patterns (Mazurek and Nowik, 2018). Research conducted in Poland demonstrated that 95% of symptom incidence was observed on branches with diameters of <20 cm, and 63% of symptoms on branches with diameters of <10 cm (Mazurek and Nowik, 2018). In contrast, in the case of *Platanus* in streets of Vienna, infestation of branches over 10 cm in diameter was rare (Kessler and Cech, 2008). Massive occurrence of *Massaria* disease symptoms and thus the necessity for increased management and care to prevent branch breakage usually take place within several months of drought periods (Kehr, 2011; Mösch et al., 2014).

Powdery mildew. The most visible symptoms by *E. platani* include a typical white powdery leaf blade coating, slight leaf chlorosis and distortions of leaves, followed by defoliation (Pastirčáková et al., 2014). The pathogen infects young leaves more severely than older ones. Leaf buds can also die back (Adamska et al., 2019). On leaves, a whitish felt develops on the surface, particularly on young leaves and at the apex of fresh shoots. In severe attacks, leaf growth is halted,the lamina tears, darkens and then dries out by crumpling upward. Irregular leaf development also occurs due to attacks on twigs, which are also covered with white mold. The fungus is an epiphytic pathogen that develops on the external surface of the host; it then actively penetrates the plant tissues through the cuticle and feeds on epidermal cells of the formation of specialised structures called haustoria. From the hyaline mycelium developing on tissue surfaces, conidiophores differentiate carrying short chains of conidia that, once released, are the means for spreading the disease. Attacks occur in spring and recur in autumn, requiring mild and humid weather conditions.
Generally, visual tree inspection for disease is difficult to perform from the ground, especially with the naked eye. In order to gather accurate data for disease diagnosis and decision-making it is crucial to involve trained personnels and use appropriate survey instruments and approaches, e.g. binoculars, remote sensing or tree climbers, for the assessment of specific diseases (Mösch, et al. 2014; Cech et al.,2007).
In a disease survey, a report should include detailed descriptions and photographs of symptoms and information about the area surveyed. Samples of affected tissues (leaves, bark, roots) should be collected for laboratory analysis.

C - LABORATORY ANALYSIS

Accurate and rapid diagnosis is crucial for successful disease management. Thus, laboratory tests must be performed to establish the causal agent of a disease, as several different pathogens may cause similar symptoms. For instance, the presence of chlorotic and wilting foliage can be correlated with both *M. desmazieri* and *C. platani* attacks during the initial stages of infection. However, *C. platani* is lethal to plane trees, whereas *M. desmazieri* does not cause death of trees not observed (Mösch et al., 2014). Traditionally, *C. platani, A. platani* and *M. desmazieri* detection has relied on a number of isolation methods and morphological observations, which can be time consuming and lead to false negative responses (OEPP/EPPO, 2014; Pilotti et al 2012; Lumia et al 2018). Conversely, leaves infected by *E. platani* are evaluated by light microscopy (Admaska, 2019).
Among the pathogens considered in this study, specific and sensitive molecular analysis has been developed only for *C. platani*, mainly using Real-Time PCR based methods (Brunetti et al., 2022; Luchi et al., 2013; Lumia et al., 2018; Pilotti et al., 2012). In contrast, *A. platani, M. desmazieri* and *E. platani*, being considered of lesser importance, have not, to date been the focus of studies on sensitive, state-of-the-art diagnostic techniques. In addition, it is important to highlight that a detailed understanding of the population structure of a pathogen is also critical for accurate diagnosis and effective disease management. Different pathogen lineages could have different levels of virulence and host preference (Armitage et al., 2021; Jung et al., 2021). For example, *Phytophthora ramorum* lineages exhibit differences in morphological traits, temperature-growth rate responses and pathogenicity (Grünwald et al., 2008; Jung et al., 2021; Mascheretti et al., 2009). Transcriptomic analysis of genomes of *P. cactorum* isolates, collected from strawberries and apples samples, demonstrated gain and loss of effector compliments, which could be determinants of host specialization (Armitage et al., 2021; Nellist et al., 2021). Similarly, haplotypes within the population

of *Gnomoniopsis castanea* exhibit significant genetic diversity and variations in virulence (Seddaiu et al., 2023). Thus, the lack of understanding of the population structure of a pathogen could lead to inefficacy of detection and management strategies.

Focusing on the pathogens of the present study, the genetic homogeneity of *C. platani* in Europe, suggests that this population had a genetic bottleneck, probably due to the introduction of a single genotype into Europe, on infected material transported during World War II from the United States (Engelbrecht et al., 2004). Conversely, although genetic diversity was found within the *A. veneta* population, there is no hypothesis on the centre of origin (Sogonov et al., 2007).

Population structure of *E. platani* and *M. desmazieri*: difference between geographical origins

The structure of *E. platani* populations was studied using the Neighbor-Joining method and the ITS1-5.8S-ITS2 sequences deposited in the NCBI database (Table SF1). A phylogenetic analysis of *M. desmazier*i, based on the 18S rRNA (SSU) and 28S rRNA (LSU) genes, was performed using the Neighbor-Joining method. Sequences were retrieved from the NCBI database (Table 1). Evolutionary distances were computed using the Kimura 2-parameter method. Evolutionary analyses were conducted using MEGA 11 (Kumar et al, 2018).

The homogeneity of *E. platani* global populations was confirmed, consistent with findings previously reported by Scholler et al. (2012) (Figure SF1).

The population analysis of *M. desmazieri* showed two distinct groups: North American and European clusters (**Figure 4**). It was interesting that the 18S region analysis in isolates from Switzerland showed that the strains UASWS2027 and UASWS2028 clustered with isolates from the USA, while strains CBS 123811 and CBS 123812 grouped together with other European isolates. We can assume, therefore, that the pathogen spread from the USA to Switzerland and subsequently to other European countries. In agreement with Crous et al (2015), strain MFLUCC 12-0088 a specimen collected by Erio Camporesi at Forlì-Cesena Province (Ibola Valley), from branches of *Platanus x hispanica* was excluded from the phylogenetic analysis due to an erroneous identification. The diversity within plant pathogen populations may reflect adaptations to different ecological niches, such as varying soil types, climatic conditions, hosts and different virulence. Accordingly, the introduction of new genotypes could have serious implications in the implementation of control measures to mitigate the impact of a pathogen. Knowledge of the population structure of a pathogen, therefore, can guide management strategies, which must integrate an awareness of continuous new factors affecting plant disease associated with climate change and intensification of the plant trade.

D-DATA ANALYSIS

Modern approaches to the epidemiology of pests and diseases include the use of mathematical models to analyze and predict the dynamics of spread. Modeling work is important because once all available data (e.g., pathogen growth and virulence, environmental factors, distribution of hosts) have been acquired, analyses can be performed to predict the effectiveness of disease management intervention efforts. Following this approach, in recent years, the use of risk maps has become increasingly widespread, providing a valuable tool for enhancing the ability to predict, prevent and manage disease outbreaks (Baxter et al., 2017; Firester et al., 2018; Manici et al., 2014). These tools commonly integrate climatic data with host and pathogen data, sometimes also with historical data to identify trends in disease incidence, prevalence and spread. For example, some National Plant Health Inspection Services currently incorporate epidemiological information into surveying strategies using risk-based methods, to develop sampling programs, as this approach is designed to be more comprehensive (Parnell et al., 2014).

Other factors, e.g. traffic and co-presence of other pathogens (or pests) that can threaten the plant, are generally not included in disease risk-maps, although they could impact the severity and incidence of plant diseases. Adamska et al. (2019) showed that in high traffic areas and when there was a co-presence of *A. platani*, the infection rate of *E. platani* increased.

The European Food Safety Agency (EFSA) conducts pest risk analysis to evaluate the risk of the introduction and spread of newly detected pests, their impact in the EU, and the appropriate phytosanitary measures required to protect plant resources (Jeger et al., 2017, 2016). In 2014, the EFSA Panel on Plant Health performed a pest categorisation for *C. fimbriata f.* sp. *platani* Walter, now known as *C. platani* (EFSA-Q-2014-00261), and in 2021 The full pest survey card on *Ceratocystis platani* was published and available online in the EFSA Plant Pest Survey Cards Gallery (https://arcg.is/15CyXW). *Apiognomonia veneta*, *M. desmazieri* and *E. platani* have historically been underrepresented in such studies, possibly due to their perceived lower economic impact compared to *C. platani*.

E-REPORTING AND MANAGEMENT RECOMMENDATIONS

The final step which can translate the results of a survey into strategies for effectively containing the spread of a disease and mitigating its impact comprises an accurate report that includes findings, risks of spread and management recommendations.

Proper Pruning and Wound Management

Although it is well known that pruning activities improve air circulation in the tree crown and result in microclimatic conditions that are less favorable to fungal infections, such as those caused by *A. veneta* and *E. platani*, one of the main reasons for plant pruning in cities is citizen safety. Tree branches can interfere with power lines, traffic signals. In broadleaved species cladoptosis, which is considered a physiological response of a tree to senescence and stress conditions, can be very difficult to manage in an urban setting, as it dramatically increases the risk of an accident. Moreover, this phenomenon can be exacerbated by diseases, such as *Massaria* disease. Branches affected by *M. desmazieri* die and break quickly (Kehr and Krauthausen, 2004; Stobbe and Dujesiefken, 2011; Mösch et al., 2014).

It is important to note that even when regulations establish specific practices for managing the spread of a pathogen during wood removal and pruning activities, they do not always specify the exact timing and procedures. EU Regulation (2022/1629 of 21 September 2022, Article 4), for containment of *C. platani*, mandates that in infected areas, specified plants and wood must be removed before the next growing season. In addition, stumps, sawdust, wood parts and soil debris must be appropriately treated to prevent the spread of the pathogen. However, the regulation does not clearly define the exact period for wood removal or specify the type of treatment required. According to findings by Pilotti et al. (2016), only the coldest and driest periods of the year should be considered as less conducive to facilitating new infections, and are also the most suitable times of the year for removing infected trees and pruning activities. In contrast, severe pruning activities are often carried out during late spring, and often on large branches, causing big lesions that are more vulnerable to pathogen infections.

Sanitation Practices

Pathogens can spread through infected seeds, transplants, irrigation water, contamination equipment or human activity. For these reasons, sanitation is one of the most important methods helping to prevent the spread of pathogens to healthy trees. Reduction of the inoculum load can be facilitated through pruning and destruction of all infected material to eliminate potential overwintering sites. Pruning tools and machinery should be cleaned and disinfected between uses to avoid transferring diseases from one tree to another, as described for the management of canker stain disease management (OEPP/EPPO 2024).

Chemical and biological treatments

In urban areas, the use of chemical treatments is limited as much as possible for human health reasons. However, should the need arise, the choice of products to be used becomes crucial to minimize undesirable effects related to species and surfaces not targeted by the intervention, including antagonists of the harmful species, pollinators and the complex micro/macro fauna of the soil. The chosen option should be directed toward products that are as selective as possible toward pathogens and have minimal effects on human health and the wider environment.

In the case of the pathogens examined in this paper, *M. desmazieri* cannot be controlled chemically or biologically (Mösch, et al. 2014), while some studies found a suitable control of *Platanus occidentalis* anthracnose through the injection of systemic fungicides in the fall before leaf abscission occurs (Himelick and Duncan, 1982; Himelick and Neely, 1988). However, it has been reported that a continual application of the fungicide to control *A. veneta* is unaffordable in practice especially for urban trees (Tello et al., 2000). Treatments with products with specific action against powdery mildew (e.g., sulfur powder), carried out during the first fungal attacks, can be effective in controlling this disease. However, these interventions are rarely sustainable in urban areas.

External chemical treatments against *C. platani* are not particularly effective (Panconesi, 1999). Conversely, pressure injection of fungicides has been successful in temporarily arresting the infection, but not in eliminating the pathogen from the plant (Panconesi, 1999; Causin et al. 1995). These chemicals were not approved for this type of use, however, and therefore are not used in urban areas. Biocontrol measures also seem to also fail to provide good levels of control against *C. platani* (Accordi, 1989; Turchetti e Panconesi, 1982).

Cultural Practices

In order to minimize the spread of plane diseases in the future, long-term site improvement measures should be considered, but these measures in particular reach their natural limits in older tree specimens and in site and climatic conditions stressful for the trees and favorable for pathogen reproduction and spread (Mösch, et al. 2014). As a general consideration, it is evident that healthy soil supports the development of root systems and enhances the resilience of plants. For these reasons, practices such as fertilization and application of organic amendments with plant growth promoting bacteria can improve plant health. In urban areas, it is also necessary to implement correct procedures to standardize maintenance work and develop suitable arboricultural practices. These actions must take into consideration how regular inspections are carried out, as well as risk assessment and prioritization regarding the need to remove infected branches or plants. All of these requirements can make it possible to reduce the pathogen inoculum load, but also help to safeguard public safety in urban environments.

Resistant plane varieties

Different species of *Platanus* exhibit varying degrees of resistance to pests and diseases, as well as to environmental stresses. Understanding resistance is important for selecting appropriate plane species, hybrids and varieties for urban green purposes. For instance, *P. occidentalis*, is more susceptible to anthracnose compared to *P. orientalis* (Santamour, 1976; Simmt et al., 2023). Conversely, *P. x acerifolia*, being a hybrid between *P. occidentalis* and *P. orientalis*, mainly seed propagated, shows an extremely high degree of variability in susceptibility (Santamour, 1976). However, since 1984, plane trees are mainly propagated by cloning, which showed a lower genetic diversity vs seed propagated trees (Morton et al., 2008).

Different susceptibility against anthracnose and to powdery mildew are also evident among cultivars (Santamour, 1984; Svihra and McCain, 1992).

There is only one patented and registered variety of plane tree resistant to diseases available on the market: PLATANOR® "Vallis Clausa". It is resistant to canker stain and anthracnose, and it offers greater resistance to lace bugs and powdery mildew compared to the hybrid plane tree *P.* x *acerifolia* (Vigouroux, 2006). However, this variety ends up dying if planted on contaminated *C. platani* soils (Anses, 2019). To our knowledge, there are no indications of varieties resistant to Massaria disease.

F - FOLLOW-UP AND MONITORING

Disease monitoring should be carried out routinely in order to track disease spread and incidence and the effectiveness of management strategies. Data collected regularly should be included in the risk maps. It is now universally recognized that to prevent the establishment and spread of a pathogen, it is crucial to identify the causal agent(s) early. However, it is also evident that most national plant protection authorities have limited capacity, in terms of professionals involved in greenspace management, and financial resources. Thus, the use of public participation has been explored recently, with success, in a range of citizen science projects for its ability to supplement official surveillance. Although this approach offers valuable opportunities, certain limitations need to be acknowledged and addressed for effective disease management strategies. Together with adequate training of citizen volunteers and their adherence to protocols of reporting, the validation and verification of the reports is still necessary in order to avoid the risk of misidentification or failure to detect symptoms.
In the new technology era, community engagement has been facilitated through many mobile apps designed for plant disease detection, diagnosis and treatments. For instance, Siddiqua et al. (2022), evaluated 606 mobile apps, reporting that most of them tended to lack many basic and important functions to detect plant disease and some provide incorrect diagnoses.

G - CHALLENGES AND FUTURE PERSPECTIVES

Plane disease management faces significant challenges, as described above. By combining knowledge with technologies and sustainable practices, the management of tree diseases can overcome these challenges. Recently, many studies have reported the development of machine learning (ML) based systems for early detection of diseases. These approaches, mainly applied in the field of agriculture, provide quite reliable results, and are neither time consuming nor costly compared to traditional detection methods. Machine learning offers powerful tools for enhancing plant disease surveillance including in urban areas. Plant disease surveillance in urban areas should be based on an integrated model (IM) including: a) ML for image recognition to identify disease symptoms based on visual patterns, b) Internet of Things (IoT) devices which can collect data on environmental conditions (e.g., temperature, humidity, soil moisture) that strongly influence plant health and pathogen fitness, c) models which can predict the likelihood of disease outbreaks based on current and forecasted conditions, and d) GIS integration for spatial analysis of disease patterns. The IM strategy will allow urban foresters to achieve more accurate, efficient and dynamic disease management, leading to urban ecosystems more resilient to pest and disease outbreaks and to climate change. Moreover, IM will help prioritize areas for intervention on disease risk, optimizing resource allocation. Collaborative efforts with local authorities, scientific communities and local citizens are also needed for more successful disease control in urban areas. In particular, public awareness and community engagement can lead to increases in the areas monitored, raise the chance for an early detection, and lower the cost of surveys and treatments, including removal of dead trees.

6. Conclusions

As global temperatures continue to rise, understanding and adapting to these changes is crucial for maintaining the health and ecological functions of urban trees. By acknowledging the impacts of climate change and implementing informed urban forestry practices, we can ensure that plane trees and other urban greenery continue to thrive in our cities.
In the future, the risks posed by *A. platani*, *M. desmazieri* and *E. platani* could become more significant under changing climatic conditions. Despite their lower profile, it is crucial to consider the potential effects of climate variability on these pathogens. Changes in temperature, humidity and precipitation patterns could enhance the virulence or expand their geographic range, leading to unforeseen impacts on plant health. Therefore, including pathogens like *A. platani*, *M. desmazieri* and *E. platani* in future assessments could provide a more comprehensive understanding of how climate change may influence plant disease dynamics.
Urban green planners and managers play a pivotal role in ensuring that trees can thrive in city environments. They must take a proactive approach, considering the long-term implications of the

greenspace designs and making informed decisions based on ecological principles. Collaborations between arborists, landscape architects and environmental scientists can enhance the effectiveness of urban forestry projects. Additionally, public education and community engagement are essential for fostering a culture of care and appreciation for urban green spaces.

CRediT authorship contribution statement

Anna Maria Vettraino: Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nikoleta Soulioti:** Writing – review & editing. **Dinka Matosevic:** Writing – review & editing. **H. Tuğba Doğmuş Lehtijarvi;** Writing – review & editing. **Steve Woodward:** Writing – review & editing, Data curation, Conceptualization. **Alberto Santini:** Writing – review & editing. **Nicola Luchi**: Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Acknowledgements

The authors gratefully acknowledge the support provided by CA20132 ``Urban Tree Guard - Safeguarding European urban trees and forests through improved biosecurity (UB3Guard)” project aimed to collect, share and harmonise scientific and stakeholder knowledge and to increase European competitiveness in the field of biosecurity. Authors express their gratitude to Giovanna Vettraino who contributed to the creation of the hand-drawn graphical abstract.

Declaration of Competing Interest

The authors declare that they have no known competing financial or non-financial interests that could have appeared to influence the work reported in this paper.

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Table 1. *Macrodiplodiopsis desmazieri* 18 S and 28 S sequences used for phylogenetic analysis

Genes	Specie	GenBank Accession Number	Strain code	Geographic Origin	Host
18S	*Darksidea alpha*	JN859360	REF140	Hungary	*Stipa borysthenica*
	Macrodiplodiopsis desmazieri	NR 132924	CPC 24971	Switzerland	*Platanus sp.*
	Macrodiplodiopsis desmazieri	KR873233	CBS 123811	Austria	*Platanus x acerifolia*
	Macrodiplodiopsis desmazieri	KR873234	CBS 123812	Austria	*Platanus x acerifolia*
	Macrodiplodiopsis desmazieri	KR873235	CBS 125026	London, UK	*Platanus x acerifolia*
	Macrodiplodiopsis desmazieri	KR873236	CBS 221.37	USA	*Platanus occidentalis*
	Macrodiplodiopsis desmazieri	Kr873237	CPC 22645	Germany	*Platanus orientalis*
	Macrodiplodiopsis desmazieri	KR873239	CPC 24648	Germany	*Platanus orientalis*
	Macrodiplodiopsis desmazieri	KR873240	CPC 24971	Switzerland	*Platanus sp.*
	Macrodiplodiopsis desmazieri	KR873241	CPC 24972	Switzerland	*Platanus sp.*
	Macrodiplodiopsis desmazieri	KR873242	CPC 24973	Switzerland	*Platanus sp.*
	Macrodiplodiopsis desmazieri	KR873243	L138	Spain	*Platanus orientalis*
	Splanchnonema platani	MN833926	UASWS2027	Switzerland	*Platanus sp.*
	Splanchnonema platani	MN833927	UASWS2028	Switzerland	*Platanus sp.*
28S	*Darksidea alpha*	JN859482	REF132	Hungary	*Ailanthus altissima*
	Macrodiplodiopsis desmazieri	NG 058182	CPC 24971	Switzerland	*Platanus sp.*
	Macrodiplodiopsis desmazieri	KR873268	CBS 123811	Austria	*Platanus x acerifolia*
	Macrodiplodiopsis desmazieri	KR873269	CBS 123812	Austria	*Platanus x acerifolia*

Macrodiplodiopsis desmazieri	KR873270	CBS 125026	UK	*Platanus x acerifolia*
Macrodiplodiopsis desmazieri	KR873271	CPC 24648	Germany	*Platanus orientalis*
Macrodiplodiopsis desmazieri	KR873272	CPC 24971	Switzerland	*Platanus sp.*
Macrodiplodiopsis desmazieri	KR873273	CPC 24972	Switzerland	*Platanus sp.*
Macrodiplodiopsis desmazieri	KR873274	L138	Spain	*Platanus orientalis*
Splanchnonema platani	JX681100	CBS 221.37	USA	*Platanus occidentalis*
Splanchnonema platani	KR909316	CBS 222.37	USA	*Platanus occidentalis*

Figure captions:

	BLUE STAIN CANKER DISEASE	MASSARIA DISEASE	ANTHRACNOSE DISEASE	POWDERY MILDEW
Causal agent (as reported in Index Fungorum- https://www.indexfungorum.org/)	*Ceratocystis platani* (J.M. Walter) Engelbr. & T.C. Harr. 2005 (syn. *Ceratocystis fimbriata* f.s. *platani* C. May & J.G. Palmer 1959; *Endoconidiophora fimbriata* f. *platani* J.M. Walter). Photo: this study	*Macrodiplodiopsis desmazieri* (Mont) Petr. 1922 (syn. *Hendersonia desmazieri* Mont. 1849; *Macrodiplis desmazieri (Mont.) Clem. & Shear* *Stegonsporium platani* Preuss 1853; *Sphaeria platani* Ces., in Rabenhorst 1854; *Massaria platani* Cesati, 1861; Hendersonia platani Peck 1872; *Splanchnonema platani* (Cesadola) Barr, 1982.. Photo: https://www.forestresearch.gov.uk/tools-and-resources/fthr/pest-and-disease-resources/massaria-disease-splanchnonema-platani/	*Apiognomonia platani* (Lév.) L. Lombard 2021 (syn. *Apiognomonia veneta* (Sacc. & Speg.) Höhn., 1920) Photo: https://it.wikipedia.org/wiki/Apiognomonia_veneta]	*Erysiphe platani* (Howe) U. Braun & S. Takam. (syn. *Microsphaera platani* Howe, in Bessey 1874) Photo: this study
Host	*Platanus occidentalis*, *P. orientalis* (Main host), *P. racemosa* and *Platanus x hispanica* (Panconesi, 1981; Walter et al., 1952.)	*Platanus occidentalis*, *P. orientalis* and their hybrid *P. x acerifolia*, *P. hispanica* and *P. racemosa* (Otth, 1865; Saccardo, 1914; Straus, 1959; Nalli, 1981; Groselaude and Romiti, 1991; Kehr and Krauthausen, 2004; Cech et al., 2007; Jurc, 2013; Anonymous 1960; French, A.M. 1989; Woodward and Boa, 2013; Mösch et al., 2014).	*Platanus occidentalis*, *P. orientalis*, *Platanus x acerifolia* (Neely, 1976; Santamour, 1976; Farinas Simmt et al., 2023; Santamour, 1976..	*Platanus occidentalis*, *P. orientalis*, *P.x acerifolia* and *P. hispanica* (Helute et al., 2013; Ligoxigakis et al., 2015; Pastirčáková and Pastirčák, 2006; Pastirčáková et al., 2014; CABI/EPPO 2013). The fungus was also found on *Punica granatum* (pomegranate) (Nemes et al., 2019) and on *Ailanthus altissima* (Beenken, 2001; Marchica et al., 2020).
Origin	*Ceratocystis platani* is thought to have arrived from the USA via infected wood packaging material to several Southern European ports at the end of World War II	The fungus is of unknown geographic origin. It has appeared causing problems in urban plantations of *Platanus* in North America and Europe.		*Erysiphe platani* is a fungus native to North America and has been introduced in South America, South Africa, Australia, Asia, New Zealand, and also in many European countries (CABI/EPPO, 2013; Pastirčáková & Pastirčák 2006; Pastirčáková et al., 2014; Helute et al., 2013; Ligoxigakis et al. (2015). In Europe the first report of the pathogen was in Italy on *P. occidentalis* (Ciferri and Camera, 1962) and *P. hybrida* (Gullino and Rapetti, 1978), then the pathogen was spread throughout the warm regions of the Mediterranean area (Anselmi et al., 1994).
Distribution	*Ceratocystis platani* has been reported in several European countries, including Albania, Armenia, France, Greece, Italy, Switzerland and Turkey. In Spain, although the disease has been reported several times, it has been confirmed only in 2010 in Girona, Catalonia (EPPO, 2014). The outbreak in Girona is now considered eradicated. Reports from Armenia and Iran have not been verified (Simonian and Mamikonyan, 1982; Salari et al., 2006)	The pathogen is common in warmer Mediterranean climates and Northern United States. The pathogen seems to have been in Europe for almost 160 years (Otth, 1865) however, not found further north than the Netherlands (Crous et al., 2015)	*Apiognomonia veneta* is an ascomycete probably native to Europe, now present (and widespread in 13 EU States - CABI, 2023) both in areas where plane trees are planted as amenity trees as well as in North America where *P. occidentalis* is native. In the US the pathogen is present in 10 different States (CABI, 2023) , while in the past years the pathogen has been reported even in South America (Chile), causing damage on Platanus (Luisi et al., 1987). The pathogen has been also present in South Africa (Swart et al., 1990), Pakistan (Lodhi et al., 2007), South Korea (Kim KyungHee et al., 1997), New Zealand (Hitchock and Cole, 1978) and Australia (Seebens et al., 2017)	

FIGURE 1: *Platanus* diseases in urban areas, reported as case studies in this work.

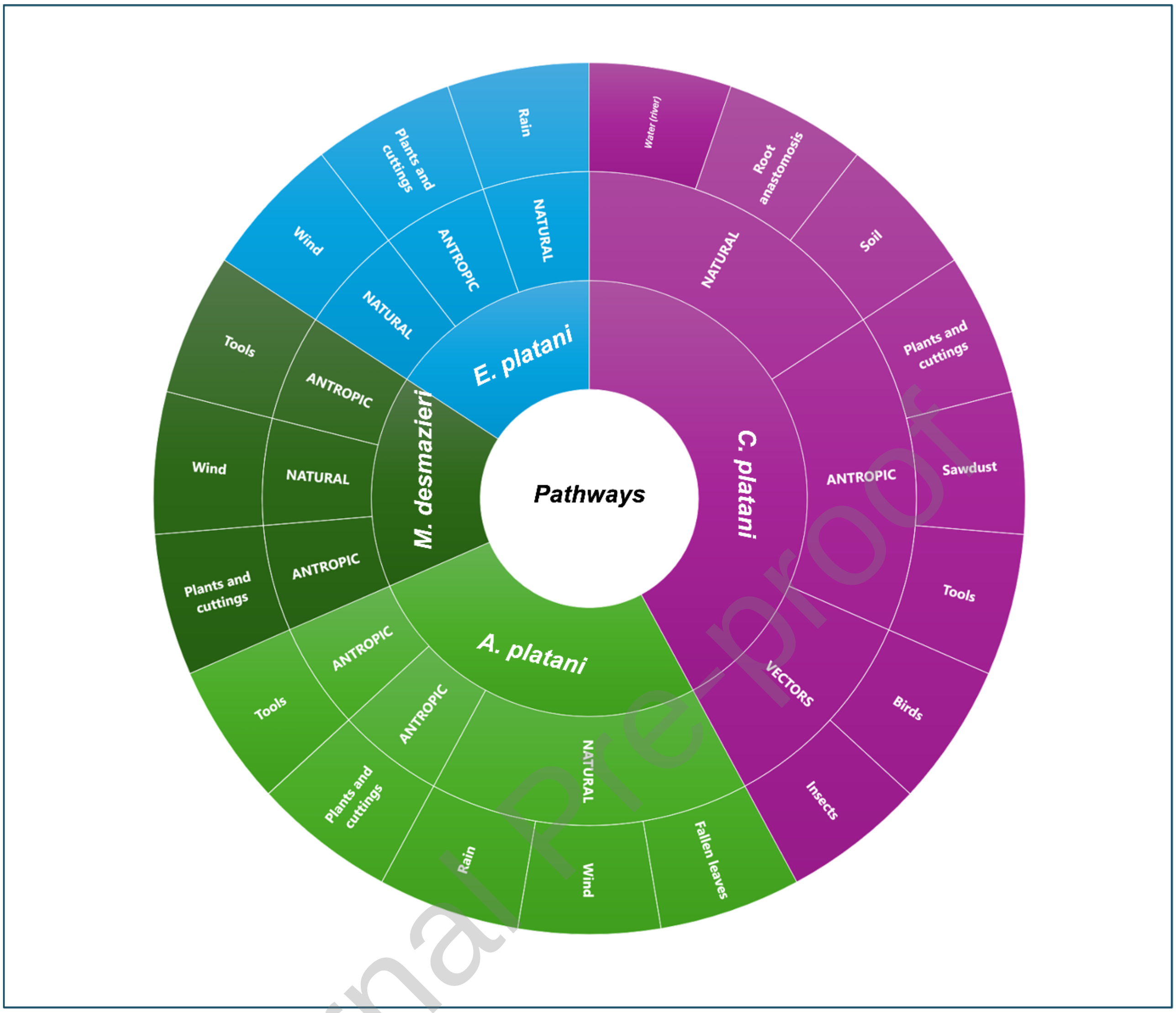

FIGURE 2: Main pathways of introduction of *C. platani*, *A. platani*, *M. desmazieri* and *E. platani*.

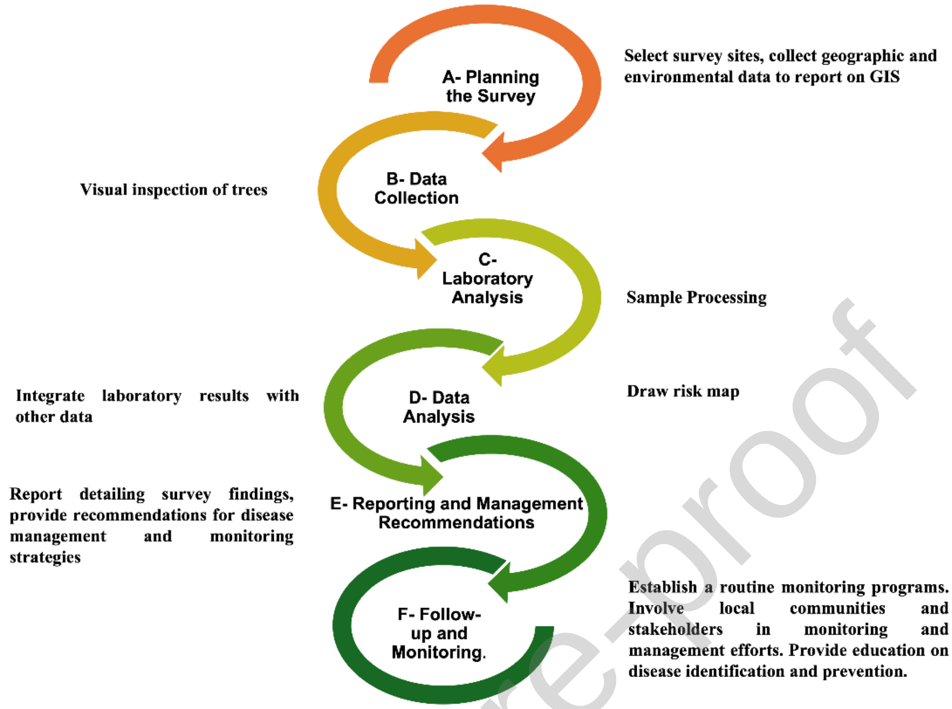

FIGURE 3: A general scheme for regular monitoring of tree diseases in surveys.

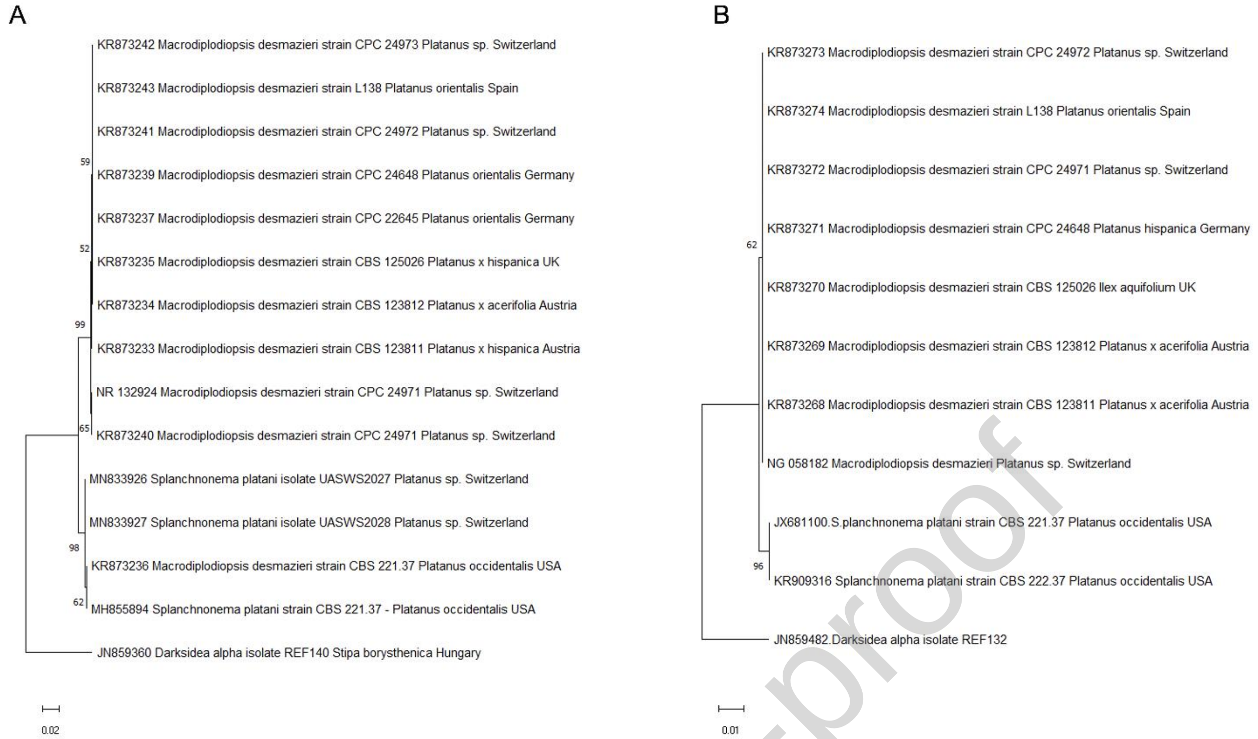

FIGURE 4: Neighbor joining (bootstrap repeat is 10,000) phylogenetic trees of *M. desmazieri* sequences, based on 18S rDNA (A) and 28SrDNA (B) regions. *Darksidea alpha* was used as an outgroup. Numbers above the branches represent bootstrap values based on 1,000 replicates. Highest possible support is 100. Values below 70 are considered weak, and values below 50 are not shown.

FIGURE SF1: Neighbor joining (bootstrap repeat is 10,000) phylogenetic trees of *E. platani* sequences, based on ITS1-5.8S-ITS2 regions. Numbers above the branches represent bootstrap values based on 1,000 replicates. Highest possible support is 100. Values below 70 are considered weak, and values below 50 are not shown. *Erysiphe akebiae* (KY660758) was used as an outgroup.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

HIGHLIGHTS

- *Platanus* spp. are widespread urban trees.
- Understanding plant diseases is a key issue for the management of urban greenspace.
- *Ceratocystis platani*: EU regulated fungal disease on *Platanus* trees.
- *Apiognomonia platani*, *Macrodiplodiopsis desmazieri* and *Erysiphe platani*: pathogens with significant impacts which require attention.

Graphical abstract