Urban Forestry & Urban Greening 76 (2022) 127727

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Review

# The management of plants and their impact on monuments in historic gardens: Current threats and solutions

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A R T I C L E I N F O

Handling Editor: Matilda van den Bosch

*Keywords:*
Heritage gardens
Biodeterioration
Climate change
Veteran tree management
Phytosanitary control
Alien species

A B S T R A C T

The conservation of historic gardens is crucial for safeguarding monumental, aesthetic, historical, ecological and economic values in many countries of the World, as well as associated services, such as carbon stock, microclimate and water regulation, biodiversity conservation, pollution removal, and recreation. In historic gardens, architectural and sculpture elements coexist with an abundant plant component, which is currently often precarious due to senescence processes occurring nowadays. Unhealthy plants and reduced structural stability of trees represent a threat for both garden artistic structures and buildings, as well for the visitors' safety. Awareness in garden managers about the most relevant and current threats is necessary for garden conservation. This review, through a global survey of the literature since 1990, addresses two main questions (1) which are the most relevant threats on historic gardens vegetation as affected by environmental, biological and anthropogenic causes, and how do they impact on monuments? (2) Which are related strategies to counteract these threats? Regarding the whole analysed period, the impact of the biotic component on monuments was the most discussed threat; in recent years a growing concern on the effects of climate change and pathogens and pests on historic garden plants also emerged. Strategies to address current and future challenges of historic gardens are hereby identified from experiences reported in worldwide literature and discussed. Best practices are collected in tables to provide managers of historic gardens with a valuable tool and guide to conserve and enhance their value. Due to the heterogeneity of the threats to be addressed, a multidisciplinary approach to ensure the conservation of historic gardens is recommended.

## 1. Introduction

According to the Florence Charter on Historic Gardens (1981), a historic garden is 'an architectural and horticultural composition of public interest from historical or artistic point of view', i.e. a combined system of a living plant component and architectural or sculpture elements (here after defined artistic structures). Historic gardens provide citizens by regulating services (carbon storage, heat island mitigation, air pollution removal, and runoff regulation); supporting services (providing habitat for a range of plant and animals species) (Liu et al., 2018; Fineschi and Loreto, 2020) and offering strong cultural services (artistic, aesthetic, recreational and spiritual) (Sá Carneiro et al., 2012; Rostami et al., 2015). In addition, they also have economic interest because of their touristic attractiveness and their capability to create employment (Athanasiadou, 2019; Funsten et al., 2020).

Historic gardens conservation is currently regulated by the Florence Charter on Historic Gardens, which was adopted by the International Council of Monuments and Sites (ICOMOS) in December 1982, as modification of the Venice Charter of 1964 (Athanasiadou, 2019). Historic garden conservation is a widely discussed issue since it deals with

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https://doi.org/10.1016/j.ufug.2022.127727
Received 10 February 2022; Received in revised form 5 August 2022; Accepted 5 September 2022
Available online 7 September 2022
1618-8667/

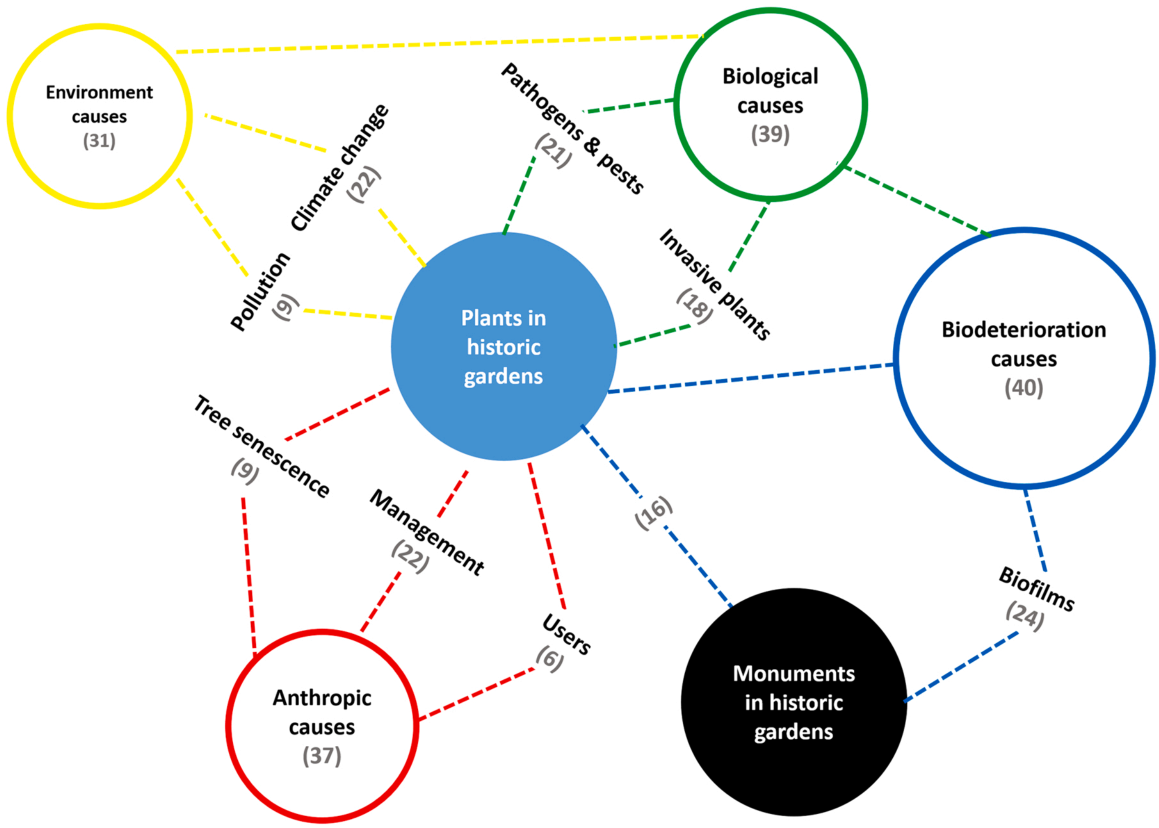


**Fig. 1.** Overview of the causes (circled) affecting historic gardens with specific agents of threats, and interactions among them. Numbers in brackets indicate the number of references found in the reviewed literature.

an intrinsic garden characteristic: the copious presence of plants concurrent with the artistic structure (Goulty, 2003). Plants differ from stone artefacts, since changes in their characteristics (size, shape, health conditions, environmental requirements) occur due to environmental pressures more rapidly, thus requiring the adoption of prompt management strategies (Sá Carneiro et al., 2012). Likely, physical elements, such as soil/subsoil and hydrography, gradually mutate because affected by plant growth (Bisgrove and Hadley, 2002). The conservation of the plant component is an outstanding concern in historic gardens, especially under global change (Martin, 2015). Rapid alterations of climatic variables and their associated effects can determine different impacts on vegetation, depending on the ecological and climatic region in which the historic garden is located. In addition, phytosanitary problems and biological invasions have significantly increased in the last decades (Paap et al., 2017), contributing to a further worsening of the conservation status of the garden. For these reasons, historic garden managers must face a complexity of problems often related to recent and less-known threats to plants. Moreover, an inadequate management of trees in historic gardens may represent a risk for artistic structures and, overall, visitor safety (Sales, 2009; Sá Carneiro et al., 2012; Fineschi and Loreto, 2020). This is often determined by the need to preserve the original design of the historic garden that can hinder the implementation of appropriate adaptation strategies to the current threats (Bisgrove and Hadley, 2002). Hence garden managers need to be informed and prepared about the most relevant and current threats. Taking advantage from experiences tackled for other historic gardens or urban forests may represent a good strategy. Experiences of good conservation practices adopted in historic gardens are widely reported worldwide (e.g. Goulty, 2003; Carneiro et al., 2005; Yoon and Kwon, 2010; Rostami et al., 2015; Gao and Dietze-Schirdewahn, 2018; Gullino et al., 2020a). However, a global evaluation of current risks specifically related to historic gardens well the identification of effective strategies is still missing.

With this review we analysed the scientific literature from 1990 to 2021 to identify the relative importance of threats associated with plants in historic gardens and related management solutions. Specifically, we: i) identified all threats addressed in the literature for the plant component, also in relation to artistic structures ii) revealed their relative importance with a temporal analysis and ii) extracted the most promising and effective sustainable management strategies regarding the discussed threats.

## 2. Methodology

In this review, we followed Pullin and Stewart (2006), hence we started planning the review (question formulation and definition of a review protocol). The starting questions were: i) Which are the main threats related to plant management in historic gardens? ii) Are there published sources giving appropriate solutions?

Then, we developed a review protocol: we used two main categories of relevant keywords, e.g. 'historic garden' and 'agent of threat' searched in combination using the AND operator. We specify that 'botanic* garden' was also included in the historic garden category since first botanical gardens were planned in the Renaissance according to the 'Italian' or 'formal' style of the historic garden (Tongiorgi Tomasi, 2005). 'Agent of threat keywords' were grouped into four categories (here below referred to as causes): environmental, biological, anthropic and biodeterioration. Hence, we had the following paths:

a) environmental causes: ("historic* garden" OR "heritage garden" OR "historic* park" OR "heritage park" OR "botanic* garden") AND ("climate change" OR pollut*)
b) biological causes: ("historic* garden" OR "heritage garden" OR "historic* park" OR "heritage park" OR "botanic* garden") AND

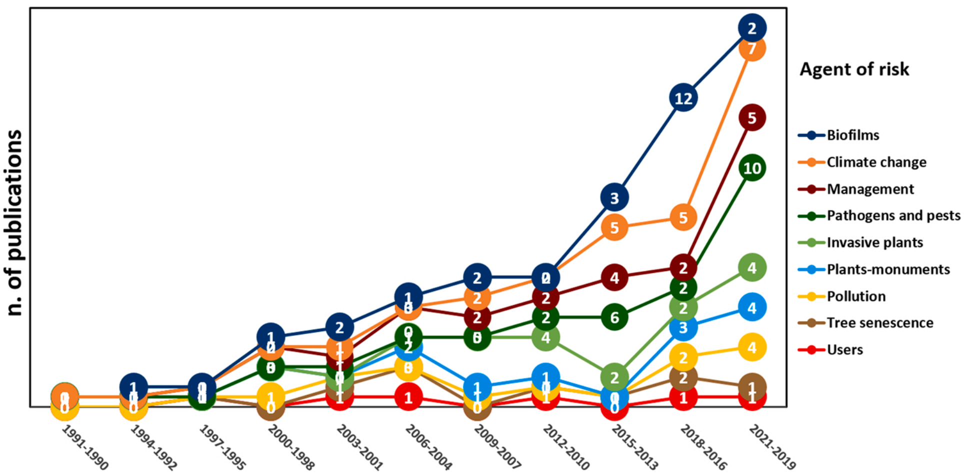


**Fig. 2.** Temporal distribution of threat agents for historic gardens based on the number of publications in which they were addressed from 1990 to 2021.

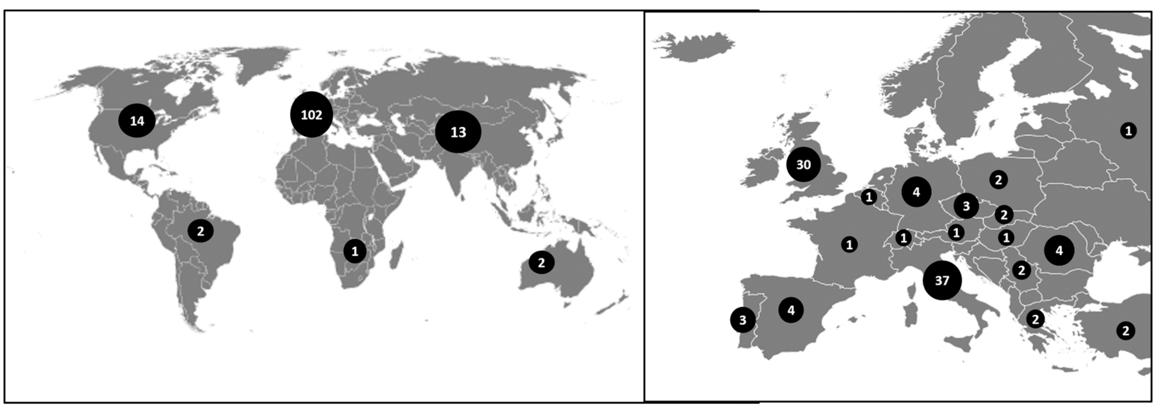


**Fig. 3.** Geographic distribution of the reviewed literature at world level on the left and at European level on the right. Numbers in circles refer to the number of publications.

(pathogen OR pest OR "invasive plant" OR "alien plant" OR "non-native plant")

c) anthropic causes: ("historic* garden" OR "heritage garden" OR "historic* park" OR "heritage park" OR "botanic* garden") AND ("monumental tree" OR "veteran tree" OR "tree senescence" OR management OR visitor OR user)

d) biodeterioration (e.g. biotic impact of plants and microorganisms on monuments): ("historic* garden" OR "heritage garden" OR "historic* park" OR "heritage park" OR "botanic* garden") AND (biodeterioration OR root OR moss OR lichen OR alg* OR fung* OR bacter*)

Next the search was conducted on Scopus, Web of Science and Google Scholar platforms. The main search was performed in December 2020 and updated in August 2021 when the draft was completed.

By reading title and abstract, we selected articles when meeting the following criteria:

1. Available in English language (at least title and abstract).

2. Including a relevant subject, thus reporting threats for historic gardens attributable to the following causes: environmental, biological, anthropic and biodeterioration.

3. Publication time from 1990 up to 2021, independently from the geographical location. Year 1990 was established in compliance with the first IPCC report (Houghton et al., 1990), this date conventionally represents the setting of climate change awareness for the first time.

Next, through a geographical and temporal analysis of the selected publications, we checked for i) the importance of the agent of threat based on the number of publications where it was reported in the reference period (1990–2021); ii) the current relevance of the agent of threat based on its presence in the last 3 years' literature (2019–2021). Finally, we reported solutions for each threat discussing them with scientific literature.

Nomenclature of taxa and syntaxa was based on the International Plant Names Index (IPNI, 2022).

## 3. Threats for historic gardens: overview

The initial search provided a total of 1526 results. From this list we checked the consistency according to criteria 1–3. Only 133 out of the total resulted to be relevant. The causes of threats treated by the literature were quite diverse (Fig. 1), and often the same paper may deal with more than one of them. Moreover, we found that all threat causes were addressed in an increasingly higher number of publications and reported in the last three years at least in one study (Fig. 2). The most represented threat was the biotic component impact on the artistic structures, the less was the environmental cause; biological and anthropic causes were similarly represented. Regarding the specific agents of threat, despite the number of papers on "biofilms" was generally high during the 32 years of observation, in 2019–2021 such threat agent was less discussed, while "pest and pathogens" and "climate change" were the most represented in the same period (Fig. 2).

Finally, the geographical distribution of studies (Fig. 3) revealed that the subject of this review was addressed in all continents but, in

**Table 1**
Strategies for agents of threat related to environmental causes; direct subjects of impact and references are also indicated.

| Threat | | Impact on | Solutions | References |
|---|---|---|---|---|
| *Climate change* | Extreme temperatures | Plants & Monuments | Planning the species turnover; relocating specimens among gardens according to temperature requirements; botanic gardens and veteran trees as experimental sites and indicators to define species vulnerability; planning for extreme weather events; keeping adequate climatic refuges for visitors. | Bisgrove and Hadley, 2002;Ghelardini et al., 2019;Lupton et al., 2010;Seiler, 2020;White, 2014;Williams et al., 2012; Martin, 2015;Symes, 2017;Entwisle et al., 2017;Dobrescu et al. 2021 |
| | Drought | Plants | Planning the species turnover; xeriscape approach (selecting drought resistance species); grouping species according to water requirements; regulating irrigation; applying measures to store rainfall; soil mulching. | Bisgrove and Hadley, 2002;Hüttl et al., 2019;Cinar and Guzel, 2020;Morar et al., 2020 |
| | Waterlogging | Plants | Matting and aeration techniques; installing drains and soakaways for water collection. | White, 2008;Martin, 2015 |
| | Windthrow | Plants & Monuments | Applying measures to favour wind-firm root system: pit instead of slit planting; improving drainage; tree monitoring and maintaining; installation of alarmed anemometers; closing garden entrance when wind speeds might be dangerous for visitors; arranging wind resistant glasses for greenhouses. | Bisgrove and Hadley, 2002;White, 2014;Martin, 2015 |
| | Low organic content in soil | Plants | Mulching and leaving the litter on the ground; periodic nutritional analyses. | Bisgrove and Hadley, 2002;Hüttl et al., 2019;Cinar and Guzel, 2020 |
| *Pollution* | Atmospheric pollutants | Plants & monuments | Monitoring trees (tree crown defoliation assessment and visible leaf injury). | De Marco et al., 2017;Sicard et al., 2020 |

particular, across Europe. Such imbalance is probably due to the interest in garden protection and conservation increased in Europe since the 19th century (Hodor et al. 2021). The most represented countries were Italy and the UK. This was not surprising given the tradition of gardens in the two countries (Connel, 2005; Funsten et al., 2021).

In the next chapters, we first describe the effects of threat agents grouped for causes (environmental, biological, anthropic and biodeterioration) and then we report and discuss related solutions extracted from published experiences.

## 4. Environmental causes

### 4.1. Climate change

The agent of threat "climate change" was the second in importance in the reviewed literature (Fig. 1) becoming one of the main issues treated in the last three years (Fig. 2) in Europe (7 Countries), Asia (2 Countries), USA and Australia. Climate change is recognised as a main abiotic stressor affecting the ecosystems, including human beings, currently and in the future (Hoegh-Guldberg et al., 2019). Since 'most of historic gardens and parks were created during a climate that itself is becoming historic' (Bisgrove and Hadley, 2002), some garden features may likely become more vulnerable in the near future (Lupton et al., 2010; Martin, 2015; Hüttl et al., 2019; Seiler, 2020). The question was largely debated between 2016 and 2019 by the members of the interdisciplinary research group 'Historic Gardens and Climate Change' of the Berlin-Brandenburg Academy of Sciences and Humanities. This research group concluded that the current efforts to maintain the initial structure of the garden may be no longer feasible for many historic gardens due to the changes of climate (Hüttl et al., 2019). On this regard, the recent paper of Jagiełło (2021) underlined the need of a new Florence Chart, more consistent and based on sustainable management principles addressing climate change impacts.

The reviewed literature identified the following climatic variables affecting historic gardens:

1) Mean temperature: climate warming, winter chilling and photoperiod, modulates spring phenology (Menzel et al., 2006). Moreover, early budburst - related with phenological shifts - makes trees more exposed to late frost (Sgubin et al., 2018), determining necrosis and frequent pathogen attacks. Evidence of phenological shifts was reported for heritage gardens after observations of flowering in Iran (Fitchett et al., 2014) and UK (Martin, 2015).
2) Drought and flooding: several authors addressed the problem of drought for historic gardens (e.g. Bisgrove and Hadley, 2002; Reháčková, 2015; Hüttl et al., 2019; Morar et al., 2019; Cinar and Guzel, 2020). Alteration in precipitation regimes is a result of climate change leading to prolonged drought periods and higher frequency of violent and sudden rain (Rummukainen, 2012). Because of drought, plants suffer from multiple stress conditions resulting in alterations in their physiological processes (Martinez-Vilalta et al., 2019). Regarding the consequences of drought in gardens, many selected papers dealt with the problem of the water use efficiency (Reháčková, 2015; Cinar and Guzel, 2020; Morar et al., 2020) as well with the accelerating loss of organic soil material, soil structure and water permeability (Piccolo et al., 1998; Bisgrove and Hadley, 2002). Moreover, water surplus in gardens due to violent rains, associated with climate change, could damage plants for waterlogging (Bisgrove and Hadley, 2002) and cause soil erosion and run off especially after summer drought (Lupton et al., 2010).
3) Windstorms: the increased frequency of windstorms is considered a major disturbance process at global scale (Mitchell, 2013). Cyclones on plant stands have immediate consequences and long term legacies (Lugo, 2008). Such risk for historic gardens was accounted by several authors by underling different consequences: i) direct damages to trees, shrubs, artistic structures, buildings and greenhouses (Martin, 2015; Nath et al., 2018); ii) additional damages caused by falling trees to garden elements, staff and visitors, as well opening of gaps in the tree cover that may expose previously shaded understorey components to light stress (Bisgrove and Hadley, 2002).

#### 4.1.1. Strategies to face effects of climate change in historic gardens

The most promising strategy to cope with higher temperatures and droughts was "planning of species turnover" (Bisgrove and Hadley, 2002; Williams et al., 2012; Lupton et al., 2010; White, 2014; Ghelardini et al., 2019; Seiler, 2020) (Table 1). Evidence to support this solution is that some species may no longer be adapted to particular environments, especially when they are settled close to their ecological and physiological borders (Menzel et al., 2006; Bussotti et al., 2014). Shifting tree species range through migration represents a strategy that plants develop for facing changing environmental conditions both in natural (Shuman et al., 2011; Shojae and Zarei, 2017; Thurm et al., 2018) and semi-natural ecosystems (Yang, 2009; Ordóñez Barona, 2015).

Even though some authors suggested to maintain the original garden composition and authenticity (e.g. Reháčková, 2015), the adoption of a pure conservative strategy could be expensive. Moreover, it could also be unsustainable, since it might lead to loss of original species prior to their replacement and cause the disappearance of iconic elements of the historic garden (Bisgrove and Hadley, 2002; Lupton et al., 2010). In addition, conservation and adaptation, i.e. actions to make the garden more suitable to the new environment, should not be considered as opposite strategies. To increase the resilience of the garden, several authors suggested to apply a proactive conservation approach able to maintain the original structure of the garden, while replacing species that are no more adapted to the new environment (Lupton et al., 2010; Williams et al., 2012; White, 2014; Seiler, 2020). Plant choice in historic gardens should carefully consider species ecophysiological requirements in relation to the present and future climate conditions (Ghelardini et al., 2019).

In anthropic ecosystems the species turnover should be planned in the long term by managers (Martin, 2015). The 'Landscape Succession Strategy' applied at the Melbourne Botanic Gardens is a good example, as reported by Symes (2017). The plan foresees that by 2036 the 75 % of taxa in the gardens will be suitable for the projected climate of 2090 (Entwisle et al., 2017). In some European historic parks, a species turnover has already successfully occurred supporting such management choice. For instance, in Peleș Castle Gardens of Sinaia (Romania) non-native species originating from warmer climates were introduced in the period 1900–1980 and are in good conditions, unlike native species adapted to colder climates (Dobrescu et al., 2021).

The modification of species composition must be preceded by an "evaluation of the current garden composition" in order to define which species will be more sensitive to climate modifications, as done in six historic gardens and parks in Bratislava by Reháčková (2015). She found that nearly half of the recorded species could potentially shift their ecological optimum at least 100 km northward and part of them over 250 km northward. Regarding the selection of species to be used, important data can be provided by studies conducted in botanic gardens on timing of flowering and leaf-out of living collection (Primack and Miller-Rushing, 2009; Smith, 2019; Primack et al., 2021) or by dendrochronological analysis on veteran trees to be used as bio-indicators of species vulnerability to climate change (Ghelardini et al., 2019).

Regarding the problem of water use efficiency, we grouped the following solutions: "water regulation according to soil-site characteristics" (Morar et al., 2020), "storing water from rainfall events" (Reháčková, 2015), using "plant groups with similar water requirements and adapted to the planting area" (type of soil and lighting characteristics) (Cinar and Guzel, 2020) (Table 1). Indeed, it is known that plant adaptability to water stress varies greatly among species with different traits. Species adapted to cool, shady environment or with extensive, superficial, fibrous root systems tend to wilt in a short time in full sun even if the roots are sufficiently supplied by water; while sclerophyllous and succulent species, which have fleshy or reduced leaves and very thick, waxy or hairy light-reflecting leaf surfaces, can tolerate severe drought for months or even years (Bisgrove and Hadley, 2002).

Moreover, practices such as "mulching or organic content supplement" and "leaving litter to the soil" were also supported (Hüttl et al., 2019; Cinar and Guzel, 2020). It is known that such practices enhance the humus content in the soil and may contribute to i) increase the nutrient retention capacity ii) reduce the thermal amplitude in the soil and iii) reduce the evaporation from the soil (Hüttl et al., 2019; Cinar and Guzel, 2020). However, overmuch litter may also diminish water availability when it retains a large proportion of rainfall (Facelli and Pickett, 1991). In addition, soil improvement measures can be supplemented by targeted "periodic nutritional analyses" (Hüttl et al., 2019).

To contrast lawn compaction and waterlogging, useful strategies were reported by Martin (2015): "regular drain and soakaways management" and "replacing concrete or tarmac paths with porous paving" (Table 1).

Regarding the problem of windstorms, appropriate cultural practices may reduce the impact of windthrow and let trees develop a wind-firm root system. As best practices, authors suggested "water drainage and pit planting" instead of slit planting, such practice seems effective to reduce waterlogging and provide higher tree stability (Bisgrove and Hadley, 2002). Moreover, "monitoring" and "continuous management" were practices shared by several authors to reduce the risk of falling branches and stems and avoid risks to visitor and monument safety (Bisgrove and Hadley, 2002; White, 2008). "Closing gardens to visitors" in case of severe windstorms was a frequently followed practice. Hence, "the setting up of meteorological stations network", (provided for instance with alarmed anemometers) may help in signalling the occurrence of wind risks for people and suggesting promptly garden closure (Martin, 2015) (Table 1).

In a specific study performed at the Royal Botanic Garden of Edinburgh, Martin (2015) suggested some practices to prevent damages due to such events to infrastructures (i.e. the use of wind-resistant and energy-efficient glasses in greenhouses).

### 4.2. Pollution

Pollution is mentioned as threat in historic garden 9 times in the selected literature mainly in Europe (Fig. 1; e.g. Ionescu et al., 2010; Caneva et al. 2020; Uğuryol, 2020; Dobrescu et al., 2021), and particularly in the last three years (Fig. 3). Plants suffer from pollutant effects ($SO_2$, $H_2S$, $NO_x$ and mainly $O_3$) activating general protection mechanisms (e.g. Papazian and Blande, 2020) and showing stress symptoms that can be recognized in field. However, no papers reported details on the quantification of the pollutant effects on historic gardens (e.g. assessment of the damage on plants).

#### 4.2.1. Strategies to control atmospheric pollutant effects on plants in historic gardens

Despite the mention of the agent of threat in the revised publications, our review showed that applied solutions regarding the problem of pollution in historic gardens are still lacking. In order to control the effect of pollutants on plants in historic gardens, we suggest monitoring systems such as "tree crown defoliation" (De Marco et al., 2017) and - specific for $O_3$ - "visible leaf injuries" (Sicard et al., 2020) assessments, which are utilised in forest and in urban green specifically for pollutant effects on plants (Eichhorn et al., 2016; Schaub et al., 2016; Paoletti et al. 2019) (Table 1).

## 5. Biological causes

### 5.1. Pathogens and pests

Pathogens and pests are reported as the third agent of threat per number of publications in the whole period (Fig. 1) and the most present in the literature in the last three years (Fig. 2). The global concern about such issue is justified by the increasing frequency of harmful attacks by pests and pathogens affecting plants of wide ornamental use (Paap et al., 2017). Two main interconnected factors are responsible for such situation: the increase of international travels often coupled with the application of ineffective control measures on trade routes, and climate change (Bisgrove and Hadley, 2002; White, 2014). As hubs of human-mediated movement, urban green areas, botanical and historic gardens often represent the places where exotic plant species are introduced together with their pests and pathogens. For this reason, they play an important role as 'sentinel', thus intercepting accidentally introduced pests and pathogens, which may become resident (Paap et al., 2017).

In the history of the host/parasite system some of the most virulent outbreaks caused by alien pathogens refer to historic gardens. *Seiridium cardinale* (W.W. Wagener) Sutton & Gibson was the main factor responsible for *Cupressus sempervirens* L. decline in Boboli gardens (Florence, Italy). *Ceratocystis platani* (Walter) Engelbrecht & Harrington, causing the plane canker stain disease and affecting European *Platanus* species, was first recorded in the 1940's and is largely distributed in historical gardens (Ciaffi et al., 2018). More recently, other woody species are threatened by alien pathogens and pests. *Buxus* L spp. in historic gardens all over the World suffer blight symptoms caused by the fungus *Calonectria pseudonaviculata* (Crous, Groenew. & Hill) Lombard, Wingf. & Crous, (Bartíková et al., 2020; Bordas et al., 2014; Mitchell et al. 2018), and damages caused by the moth *Cydalima perspectalis* Walker (Plant et al., 2019). *Sirococcus tsugae* Rossman, Castlebury, D.F. Farr & Stanosz causes shoot blight in *Cedrus* Trew. (Woudstra, 2019), and the red palm weevil (*Rhynchophorus ferrugineus* Olivier) is the main threat for palms since 2000 s (Funsten et al., 2020; Gullino et al., 2020a; Manachini et al., 2013; Raciti et al., 2013). The recent scientific literature warns against a series of alien pathogens and pests characterised by rapid spread and high virulence which could represent a main threat for their host plant species in historic gardens, nowadays and in the near future (Table 2).

Regarding the effects of climate change on the development of particular phytosanitary problems, the trend of temperature increase, both in summer an in winter, combined with wetter winters and drier summers, is likely to enhance the severity of pest and pathogen attacks on plants by i) extending parasite reproductive stages (Bisgrove and Hadley, 2002; Lupton et al., 2010; Garrett et al., 2014) ii) favouring the spread of phytosanitary problems related to agents coming from warmer climates (Lupton et al., 2010) iii) predisposing plants to infection due to the stresses associated with global change-induced disturbances. This is the case of the generalist pathogen *Phytophthora* sp., especially of its invasive species *Phytophthora ramorum* Werres, De Cock & Man in 't Vel, *P. lateralis* Tucker & Milbrath, and *P. kernoviae* Brasier, Beales & S.A. Kirk, associated with warmer and wetter winters, and recognised as major threats for historic gardens (Walters et al., 2010; Martin, 2015; Drake and Jones, 2017).

### 5.2. Strategies to control pests and pathogens in historic gardens

Literature showed that the implementation of "biosecurity protocols" was a winning strategy to control plant disease in historic gardens (Table 3). Since 2008, in the UK the National Trust has successfully developed a suite of biosecurity protocols specific for *Phytophthora ramorum* and *P. kernoviae*. The implementation of these protocols in 220 heritage gardens turned out to have positive effects against most pests and pathogens threatening gardens, not only against *Phytophthora* (Wright and Slawson, 2010). Martin (2015) suggested specific practices such as: installation of disinfection mats at the garden entrance, placement of information panels in different locations for advising visitors about pests and diseases, and regular monitoring and signalling. Furthermore, the availability of the "complete list of plant species present in the garden" may help managers to be prepared for phytosanitary issues that the plants can encounter (Morar et al., 2019).

Other solutions are related to species choice and garden design: "choosing mixed stands" (i.e. composed by different species) instead of monoculture and supporting the use of "rare trees and shrubs" were good practices to reduce the incidence of pests and pathogens (Graves, 2017; Marim Toledo et al., 2021). Ciaffi et al. (2018) suggested "in vitro propagation" for producing pest and pathogens free plants, such as planes resistant to *C. platani* and to the species of Ambrosia beetles, which often occur in nursery stocks. Alternatively, the origin of new plant material should be accurately checked, both for material collected in the wild and/or purchased from the nurseries (Sales, 2014) or implementing the quarantine procedure for newly purchased plants as it is done in Kew Botanic Gardens (Brasier, 2008).

"Pruning" can be recommended only in particular cases, for example the routine pruning may help maintaining the vitality of younger trees against *Hymenoscyphus fraxineus* (T. Kowalski) Baral, Queloz & Hosoya (Marciulyniene et al., 2017); however, garden managers must consider the risk to create entry zones for pathogens and therefore to establish disinfection procedures for pruning tools (Tubby and Pérez-Sierra, 2015). Regarding *Phytophthora* spp., some practices may limit its expansion in gardens, e.g. "replacing grass and bark paths with gravel surfaces", which prevent water collection, or "removing over large areas of its preferential host". The latter was the successful case of *Rhododendron ponticum* L. at the Benmore Garden (Scotland) (Knott, 2021).

### 5.3. Invasive plant species

The high presence of alien species in historic gardens and heritage sites is largely reported in Europe, USA and China (Bravo et al., 2012; Schmidt and Sütöri-Diószegi, 2013; Cicinelli et al., 2018; Atha et al., 2020; Celesti-Grapow and Ricotta, 2021; Gullino et al., 2020b;). There is an overwhelming body of global evidence that invasive alien species represent one of the major threats for biodiversity conservation of our time (Russell and Blackburn, 2017). Selected papers dealing with the alien plants as threat belong to two types. Most of them addressed the problem for managers to control non-native species in their gardens, especially when particularly invasive with recommendation to managers to counteract the risk for plant biodiversity of surrounding natural ecosystems. Historic and botanic gardens can be a source of plant invasion around the globe (Hulme, 2011; 2015; Cindi and Jaca, 2016) even higher than agriculture at least in the Mediterranean area (Sanz-Elorza et al., 2009). Most ornamental species in living collections around the globe are alien species (Hulme, 2011; van Kleunen et al., 2018).

The link between alien species and historic gardens dates back to the Renaissance with the searching activity of plant hunters (Siniscalco, 2015). According to Křivánek and Pyšek (2008), there is a close relationship between the invasion success of a woody plant and its residence time. Early introduced and cultivated plants are listed by IUCN among the most invasive species worldwide. Indeed, those species are more adapted than recently introduced ones, because of the longer residence time (Pyšek and Jarošík, 2005), and for their frequent use in gardens (Lambdon and Hulme, 2006; Bucharova and Van Kleunen, 2009). Examples of historic invasions caused by the use in gardens are *Oxalis pes-caprae* L. (Papini et al., 2017) and *Tulipa sylvestris* L. (Kowarik and Wohlgemuth, 2006) in Europe, *Opuntia pubescens* H.L. Wendl. ex Pfeiff. in South Africa (Cindi and Jaca, 2016), *Lantana* L. species in India (Kannan et al., 2013), and *Wisteria* Nutt. in the Southeastern United States (Trusty et al., 2007).

The second type of publications focused on the impact of alien species on monuments. Such issue is addressed in chapter 7.1.

#### 5.3.1. Strategies for invasive plant management in historic gardens

"Listing non-native species", "classifying them according to their invasiveness" and "monitoring non-native species with invasive traits" represent essential first steps to counteract the spread of alien species in historic gardens (Bravo et al., 2012) (Table 3). Those strategies were applied in different geographical contexts and reported by different authors: four alien species identified in the Royal Park of Moncalieri Castle in northern Italy, were monitored and included in the blacklist of its region (Gullino et al., 2020b). Alien species were also recorded in the New York Central Park (Atha et al., 2020), the Roosevelt-Vanderbilt National Historic Sites in Hyde Park, NY (Bravo et al., 2012), and in the Buda Arboretum of Corvinus University, Budapest (Schmidt and Sütöri-Diószegi, 2013). We underline the evaluation of species invasiveness should also consider climatic scenarios, as diverse

**Table 2**
List of alien pathogens and pests included in main lists of invasive species: EPPO alert list (EPPO), U.S. Regulated Plant Pest List by USDA (USDA), the Global Register of Introduced and Invasive Species of China (GRISC), and the Global invasive species database (GIS), which encountered (or may encounter) new hosts in woody species occurring in historic gardens, thus becoming particularly aggressive and dangerous. Species lists indicated in this table represent observations reported in literature, as well as species that might become particularly dangerous in historic gardens according to their main hosts and distribution.

| Species | Major host species (or genus) | Reported symptoms | Distribution | Reference list |
|---|---|---|---|---|
| **Pathogens** | | | | |
| *Calonectria pseudonaviculata* | *Buxus spp.* | Shoot blight | Canada, USA, Europe, New Zealand, | EPPO |
| *Fusarium circinatum* | *Pinus spp., Abies alba, Pseudotsuga menziesii* | Formation of conspicuous resin exudates ('pitch') in response to fungal infection | USA, Mexico, Japan, South Africa, Brazil, Chile, and Europe (only Portugal and Spain) | EPPO |
| *Geosmithia morbida* fungus and the walnut twig beetle (WTB, *Pityophthorus juglandis*) | *Juglans nigra* | Branch mortality, numerous small cankers on branches and the bole, and evidence of tiny bark beetles, yellowing foliage | USA, Italy | USDA/ EPPO |
| *Heterobasidion irregulare* | *Abies spp., Arbutus menziesii, Calocedrus spp., Erica arborea, Juniperus spp., Larix spp., Pinus spp., Picea spp., Pseudotsuga spp., Quercus spp., Thuja plicata, Tsuga spp.* | Formation of resinous heartwood, trees become sensitive to white root rot and fungus may cause death of the tree | Canada, Cuba, Dominican Republic, Mexico, USA, Europe (only Italy) | EPPO |
| *Hymenoscyphus fraxineus* | *Fraxinus spp.* | Necroses on leaves, rachides and shoots/ branches; infected leaves are wilt, turn black, become dry and often remain attached to the stem; bark necrosis | China, Japan, Korea Republic, Europe | EPPO |
| *Phytophthora ramorum* | *Abies* sp., *Acer* spp., *Arbutus* spp., *Camellia* spp., *Fraxinus* spp., *Laurus nobilis*, *Magnolia* spp., *Osmanthus* spp., *Quercus* spp., *Rhododendron* spp., *Rosa* spp., *Syringa vulgaris*, *Taxus baccata*, *Viburnum* spp. | Bark cankers; leaf spots; twig dieback | USA | EPPO/ USDA |
| *Raffaelea lauricola* | *Cinnamomum camphora, Laurus nobilis, Persea spp.* | Vascular black discoloration, rapid wilting, necrosis of foliage and defoliation | USA, Japan, Myanmar, Taiwan | EPPO/GIS |
| **Pests** | | | | |
| *Anoplophora glabripennis* | *Populus* spp., *Salix* spp., *Ulmus* spp., *Robinia* spp., *Betula* spp., *Acer* spp., Fagus spp., | Unseasonable yellowing leaves; branches dropping or dying | USA, China, Japan, Korea Republic, France, Italy | USDA/ GRISC/ GIS |
| *Agrilus planipennis* | *Fraxinus sp.* | Yellow, thin or wilted foliage; shoots growing from roots or a tree's trunk, often with larger-than-normal leaves | Canada, Usa, China, Japan, Russia, Ukraina | USDA/ GIS |
| *Apriona germari* | *Citrus spp., Cinnamomum camphora, Diospyros kaki Eriobotrya japonica, Ficus. Spp Juglans, Mauls, Morus Populus, spp. Punica granatum, Robinia pseudoacacia, Salix spp. Ulmus spp.* | Serious damage to twigs; resin bleeds can be observed from oviposition holes and larval tunnels in the bark | China, India, Bangladesh | GRISC |
| *Cydalima perspectalis* | *Buxus spp.* | Larvae feeding on leaves and shoots and severe infestations that can lead to almost complete defoliation | Canada, USA, China, Japan, Korea Republic Europe, | USDA/ EPPO |
| *Dryocosmus kuriphilus* | *Castanea spp.* | Localisation of galls on shoots, leaf midribs or leaf stipules | Canada, USA, China, Korea Republic, Nepal, Europe | EPPO |
| *Euwallacea sp.* and its symbiotic fungus *Fusarium euwallaceae* | *Acer spp., Liquidambar styraciflua, Platanus spp., Prunus dulcis, Persea, Quercus spp., Salix spp, Wisteria floribunda* | Entry holes; small tubes of compacted sawdust; discoloration of the outer bark surrounding holes; white powdery exudate covering; brownish staining of the xylem under the infested spot; gumming, wilting of branches; leaf yellowing; branches broken at the site of beetle galleries | South Africa, Mexico, USA, Israel | EPPO |
| *Hyphantria cunea* | *forest deciduous trees* | Woven silk nests enclosing a number of leaves are conspicuous; rapid defoliation of forest | North America. Europe. China Japan, Korea. Kazakistan | GRISC/ GIS |
| *Lycorma delicatula* | *Acer spp, Alnus spp., Betula spp., Carya spp., Dyospirus spp., Eleagnus spp., Juglans spp, magnoilia ssp, Platanu spp., Populus spp., Ulmus spp.* | Plants that ooze or weep with a a fermented odor; buildup of sticky fluid (honeydew) on plants and on the ground underneath infested plants; sooty mold on infested plants | USA, China Japan, Korea | USDA |
| *Lymantria dispar* & *Lymantria dispar asiatica* | *Alnus spp., Betula spp., Malus spp., Corylus spp., Larix spp., Populus spp., Salix spp., Quercus spp.* | Defoliated trees | Europe, Asia, North America | USDA/ GIS |
| *Popillia japonica* | *Acer spp, Aesculus hippocastanum, Castanea app, Corylus spp., Lagerstroemia indica, Malus spp., Prunus spp., Wisteria spp.* | Skeletonized foliage; severely damaged leaves soon turn brown and drop | Nort America Italy Korea, Portugal, Switzerland, Russia | USDA |
| *Rhynchophorus ferrugineus* | *Phoenix dactylifera, Phoenix canariensis and most species of Arecaceae* | Wilting and yellowing | USA, Bangladesh, Cambodia, China, India, Iran, Iraq, Israel, Japan, Pakistan, Philippines, Thailand, Taiwan, United Arab Emirates, Vietnam, Europe | EPPO |
| *Xyleborus glabratus* | *Laurus spp., Persea spp.* | Vascular black discoloration; rapid wilting, necrosis of foliage and defoliation | USA, China, India, Japan, Korea Republic, Myanmar, Taiwan, Thailand, Vietnam | EPPO/ GIS |

(*continued on next page*)

Table 2 (*continued*)

| Pests | | | | |
|---|---|---|---|---|
| *Xylosandrus compactus* | *Camellia sinensis, Coffea spp., Phillyrea spp., Pinus spp., Pistacia lentiscus, Quercus ilex, Viburnum tinus* | Leaf and stem necrosis extending from the entrance hole; lagging of branches 5–7 days after initial gallery formation; wilting of twigs and branches after weeks of infestation | Africa, Brazil, Cuba, Ecuador, Peru, Puerto Rico, USA, China, India, Indonesia, Japan, Malaysia, Taiwan, Sri Lanka, Thailand, Europe (only France, Greece, Spain, Italy), Oceania islands | EPPO/ GIS |

**Table 3**
Strategies for agentsng public awareness on historic garden benefits; taking advantage of exd references are also indicated.

| Threat | Impact on | Solutions | References |
|---|---|---|---|
| *Pest and pathogens* | Plants | Quarantine for plant material; biosecurity measures at the garden entrance (e.g. installation of disinfection mats, information panels, pathogens and pests monitoring); replacing grass and bark paths with gravel surfaces which prevent the collection of water (particularly for fungus diseases); avoiding monospecific cultures over large areas; updating list of plant species; planning cloning (when possible) of veteran trees; pruning only when effectiveness is verified. | Brasier, 2008;Wright and Slawson, 2010;Martin, 2015;Tubby and Pérez-Sierra, 2015;Graves, 2017;Marciulyniene et al., 2017;Ciaffi et al., 2018;Morar et al., 2020;Marim Toledo et al., 2021;Knott, 2021 |
| *Invasive plant species* | Plants & monuments | Surveying and controlling invasive species occurrence; considering plant invasiveness in planning; breeding of plant varieties without traits that enhance plants' invasiveness. | Abendroth et al., 2012;Bravo et al., 2012;Kümmerling and Müller, 2012; Kannan et al., 2013;Schmidt and Sütöri-Diószegi, 2013;van Kleunen et al., 2018;Atha et al., 2020;Gullino et al., 2020a;Monder, 2021; |

environmental conditions could indeed change the invasion potential of plant species (Bradley et al., 2010).

Many authors recommended the use of native species for new plantations in historic gardens (e.g. Abendroth et al., 2012; Kümmerling and Müller, 2012; Kannan et al., 2013) or even the elimination of invasive specimens (Schmidt and Sütöri-Diószegi, 2013). However, when non-native species have a historical role in the original design of gardens, e.g. *Cedrus* spp. and *Ginkgo biloba* L., managers must take into account their actual invasiveness and decide for the application of "control measures" to maintain them instead of eliminate or avoiding plantations (Bravo et al., 2012; Monder, 2021).

A general suggestion for the creation of new ornamental cultivars is to "avoid traits promoting invasiveness", such as the fast growth (van Kleunen et al., 2018).

## 6. Anthropic causes

Under this category we grouped all challenges related to the anthropic origin of the historic garden; three sub-categories were identified on the basis of the revised literature: management issues, tree senescence, and user behaviours.

### *6.1. Management*

Among anthropic issues, the major threat in historic gardens is their neglected or incorrect management (e.g. Goulty, 2003; Lambert and Lovie, 2006; Sales, 2009; Athanasiadou, 2019). The academic interest for this agent of threat was generally constant during the whole analysed period. Labour cost represents the most expensive item in garden maintenance (Sales, 2000). In earlier times this cost was usually managed by owners, which is mostly unfeasible now; consequently, most historic gardens are managed with limited resources (Thoday, 2014). To support appropriate maintenance, funding should be consistent enough to ensure continuous employment of skilled and properly equipped gardeners (Sales, 2000; Lambert and Lovie, 2006; Sales, 2009). As broadly explained in chapter 6.2, many plants require expert gardeners especially for the practice of pruning (Clark and Matheny, 2010). Economic problems are not only related to staff training but also to the general management of gardens (Thorne, 2014), e.g. management of paths (Bandaranayake, 1997) or operations and maintenance costs associated to garden irrigation (Pérez-Urrestarazu et al., 2018).

Finally, management problems often derive from the lack of a legal framework on historic gardens. In some countries with garden and park tradition, such as the U.K., USA, France, Italy, Spain and Portugal, several sites are registered and protected. On the other hand, many other countries have no specific official policy or association regarding historic parks, gardens or landscapes. Lack of garden culture and education leads to everyday degradation and loss of historic parks and gardens and all related services and values (Athanasiadou, 2019).

#### *6.1.1. Strategies to solve problems of historic garden management*

"Entrance fees" are surely a main tool to give a monetary support to the garden management (Table 4); authors suggested to improve facilities to attract visitors such as recreational opportunities, security measures, behaviour and guidance of employees, parking facility and cleanliness (Bandaranayake, 1997; Saeed et al., 2017); even though the presence of visitors determines the issues reported in chapter 6.3.

As reported in Table 4, fees must be accompanied by practices of sustainable management, e.g. less time consuming and affordable. The first one is: "informing conservation plans realized by smart techniques" such as remote sensing and GIS applications to integrate the spatial component (topographic maps, orthophotos, physical plans, cadastral maps) and databases about botanic inventories and conservation treatments (Cazzani et al., 2019; Dix, 2014; Malinverni et al., 2019). Other strategies are "staff education and training" (Albericci, 2006; Lambert and Lovie, 2006; Andrianou and Papaioannou, 2019;) as well as "continuity of the staff personnel" (Martin, 2015; Sales, 2009; Yoon and Kwon, 2010). As previously discussed, informing staff implies raising their awareness on climate projections and extreme weather events (Martin, 2015) as well on other environmental and biotic current risks. Lambert and Lovie (2006) reported the positive experience of the 'Historic and Botanic Gardens Bursary Scheme' in the UK, which invested in the development of horticultural skills for the staff.

Sustainability also implies "water use efficiency", both for irrigation and water elements (Rozkošný et al., 2019) and of "waste management" (Pérez-Urrestarazu et al., 2018; Andrianou and Papaioannou, 2019).

Finally, regarding the lack of a specific legal frame for gardens in some countries, Athanasiadou et al. (2019) suggested two actions; first, "raising public awareness of the issue"; second, "taking advantage of existing legal documents", and creating new versions to prevent further

**Table 4**
Strategies for agents of threat related to anthropic causes; direct subjects of impact and references are also indicated.

| Threat | Impact on | Solutions | References |
|---|---|---|---|
| *Plant aging* | Plants & Monuments | COVE method for veteran trees; erecting fences to prevent compaction; well-performed pruning/pollarding; leaving the litter on the ground for nutrient releasing; realization of specific supports to fix great and unbalanced branches; sensors and remote sensing to monitor and create tree inventories; vegetative propagation of monumental trees. | Hayes, 2002;Nicolotti and Gonthier, 2004;Ferrini, 2006;Dix, 2014; Tomao et al., 2015;Ciaffi et al., 2018;Qiu et al., 2018;Cazzani et al., 2019;Malinverni et al., 2019;Woudstra, 2019;Pérez-Martín et al., 2021; |
| *Inadequate staff dimension, preparation and equipment* | Plants & Monuments | Education and training of staff especially in relation to changing environment; staff continuity. | Lambert and Lovie, 2006;Sales, 2009;Yoon and Kwon, 2010; Martin, 2015 |
| *Lack of funding* | Plants & Monuments | Smart techniques (e.g. remote sensing) to facilitate management; raising public awareness on historic garden benefits; entrance fees; improving facilities and attractiveness; sustainable and efficient management (i.e. water use). | Bandaranayake, 1997;Dix, 2014;Saeed et al., 2017; Pérez-Urrestarazu et al., 2018;Andrianou and Papaioannou, 2019; Cazzani et al., 2019;Malinverni et al., 2019;Rozkošný et al., 2019; |
| *Lack of legal framework (only for some countries)* | Plants & Monuments | Raising public awareness on historic garden benefits; taking advantage of existing legal documents. | Athanasiadou et al. 2019 |
| *Wrong visitor behaviours and vandalism* | Plants & Monuments | Restricting measures: limiting opening time, limiting visitor number, limiting group visits and timed ticketing; surveillance, panels explaining consequences of dangerous behaviours and sanctions; erecting fences around veteran trees. | Askwith, 1999;Connell, 2005;Yoon and Kwon, 2010;Hristov et al., 2018;Woudstra, 2019. |

loss and decay, and to address protection, conservation, restoration and management procedures.

### 6.2. *Tree senescence*

Many historic gardens have an ancient origin and trees sometimes date back to the time of the garden establishment. Even though the threat represented by tree senescence was not largely addressed in the revised literature (Fig. 1), the conservation of veteran trees represents a problem for garden managers (Ciaffi et al., 2018). Veteran trees represent a unique value from ecological, cultural, social and historic point of view (Nicolotti and Gonthier, 2004) but are often prone to decline. According to Manion's model, the decline of old trees is determined by three types of factors: predisposing factors (genetic and environmental factors), inciting factors (aggressive pathogens and pest attacks), and contributing factors (secondary agents able to kill trees in weak health condition, for example subjected to bark beetles and saprophytic fungi attacks) (Neely and Manion, 1991). Tree senescence, environmental and biological stressors may cause uprooting and stem failure (Pokorny et al., 2003) with detrimental effects on visitors, monuments, and buildings safety (Yoon and Kwon, 2010; Dobbs et al., 2011).

#### 6.2.1. *Strategies to manage tree senescence in historic gardens*

To avoid decline of veteran trees by limiting predisposing factors, simple measures can be supported, such as "erecting fences to prevent soil compaction", as reported for Bretton Park (Woudstra, 2019) (Table 4). Further measures are, for example, "leaving the litter on the ground" for releasing of nutrients (Hüttl et al., 2019), as well as the realization of specific "supports to fix great and unbalanced branches'' (Nicolotti and Gonthier, 2004). On the other hand, the use of machines with frequent passage on the soil and dendrosurgery practices carried out in the past seem to contribute to the decline and should be avoided (Fay, 2002).

Ciaffi et al. (2018) developed a multidisciplinary methodology for the "COnservation of VEteran trees within historic gardens" (COVE) and their management (Table 4). A main goal is to prevent the unnecessary removal or disfigurement of amenity trees, preserving the aesthetics of the garden as well as the microhabitats supplied by the old trees; the method i) recommends to vegetative propagate the specimen in order to maintain the genetic identity to mother plant ii) supports the evaluation of the tree asset of the garden together with the identification of risky trees in order to plan management practices, e.g. "pruning". Removing sick, broken, or dead branches may protect the trees by preventing the infection of decay-producer fungi (Gilman and Grabosky, 2006). Moreover, pruning by thinning may increase light diffusion and air movement throughout the crown (Harris and Bassuk, 1994). A frequently adopted practice in historic gardens is the pollarding, that is a pruning system involving the removal of the upper branches of a tree, which promotes the growth of a dense head of foliage and branches. According to Ferrini (2006), the three most important elements for successful renovation of older trees using pollarding are: 1. carefully designed pollard head locations, 2. anticipation of sprout weight under rain, ice, and wind conditions, and 3. consideration of current structural faults that could lead to catastrophic loss.

Unfortunately, pruning prescriptions are often mostly based on operational needs and short-term cost criteria (Campanella et al., 2009). If pruning is not properly performed, it can reduce natural defences against phytosanitary problems thus compromising tree's health and weakening wood structure, which may cause its breakage (Clark and Matheny, 2010). When trees are topped, overpruned or stressed, they produce weak epicormic shoots prone to mechanical failure (Hayes, 2002). Ferrini (2006) stressed that erroneous pruning can have negative effects on tree biomechanics by decreasing the safety factor, e.g. the quotient of the load capability and the actual load of a structure (Niklas, 1999, 2002). A specific index evaluates the risk of tree mechanical failure, namely the "composite tree risk index" (Tomao et al., 2015). This index takes into account the 'Hazard', representing the likelihood of tree failure, the 'Contact factor', i.e. the nature and the value of the target, and the 'Damage factor', i.e. the potential for injury or damage.

Composite tree risk index and COVE could be used in combination to create risk maps of the gardens, to guarantee visitor safety and monument conservation. Areas potentially dangerous can be forbidden to visitors.

### 6.3. User behaviours

The third potentially critical aspect linked to the anthropic nature of gardens is the visitors' impact, reported by authors from Europe and USA. More than 300 million people visit gardens worldwide per year (Silva and Carvalho, 2019). As anticipated in chapter 6.1.1, entrance fee, retail, and catering are the most immediate forms of economic contribution for gardens open to the public; however, the presence of people outside the staff implies two main issues: visitor safety (as mentioned in 6.2) and voluntary or involuntary damage to the plant component.

Several authors reported problems caused by high visitor frequency (Askwith, 1999; Connell, 2005; Yoon and Kwon, 2010) such as the excessive soil compaction (Woudstra, 2019). Only a few gardens were designed for sustaining a large number of people. These gardens were planned and established as public parks; instead, most historic gardens were designed as private and became public later on. The areas where the compaction causes the greatest damage are those under the canopy of the largest trees, used by visitors for shade. Soil compaction reduces water infiltration and hydraulic conductivity, which, in turn, contributes to increased waterlogging on flat terrain, runoff and erosion on slopes, as well as reduced oxygen and water availability for plant roots and microorganisms (Cambi et al., 2015).

In addition, vandalism is a common problem in gardens open to the public (Hristov et al., 2018). An interview with garden managers conducted in the UK revealed that 51 % of garden owners claim damages to the garden caused by visitors, mostly theft of garden material, both plants and stone artistic structures (Connell, 2005).

#### 6.3.1. Strategies for visitor behaviours in historic gardens

In order to limit problems related with visitors, some authors pointed out the opportunity to set a "maximum threshold of visitors", according to the garden characteristics (Yoon and Kwon, 2010; Askwith, 1999) (Table 4). "Erecting of fences around larger trees" to prevent compaction as done at Bretton Park (Woudstra, 2019) may dissuade visitors from creating an excessive load around the more fragile specimens. Connell (2005) reported about a study in the UK on 1223 garden managers, which released interviews about this issue. Thirty percent of them introduced measures for limiting visitors number, limiting opening time, and limiting visiting groups.

Regarding vandalism and wrong behaviours, solutions imply not only adequate "surveillance", but also arrangement of "panels warning about the consequences of dangerous behaviour and sanctions" (Hristov et al., 2018).

## 7. Biodeterioration agents

Biodeterioration was the most discussed cause regarding the conservation of historic gardens in the literature search (Fig. 1), probably due to a longer tradition to publish in English in this field. Plants, mosses and microorganisms (lichens, algae and bacteria) can affect the artistic structures, growing on walls, ruins, rocky surfaces, sculptures, and stone and marble artistic structures (Ceschin et al., 2016; Fineschi and Loreto, 2020) may degrade monuments, leading to aesthetic and structural deterioration (Tiano, 2001; Caneva et al., 2009).

### 7.1. Plants

Among vascular plants, trees represent the major risk for the artistic structures of the garden, indeed the issue is addressed by several publications referring on gardens located in Italy (Caneva, 1999; Caneva et al., 2009, 2006; Fineschi and Loreto, 2020). Tree impact on monuments is of particular concern in archaeological sites (Caneva and Roccardi, 1991) and can occur at below- and at above ground level.

Below the ground level, trees influence soil characteristics (hydrology, chemistry, structure) through the root system, which can develop both in depth and laterally for several meters (Ceschin et al., 2016). The damage to the artistic structures becomes significant when secondary diametrical growth proceeds, causing breaks and detachment within the structures (Caneva et al., 2006). Tree roots growing in zones with lower resistance, e.g. mortars between stones, may damage monuments, causing stone weathering (Fineschi and Loreto, 2020). Roots act not only mechanically but also chemically, the acidity of the rootlets may be a major agent of biodeterioration (Saiz-Jimenez, 1994).

At the aboveground level, a first issue is the monument and building safety in case of lack of tree stability (Fineschi and Loreto, 2020). On the other hand, in specific cases at above level, trees and vines rather than causing biodeterioration, could provide a certain degree of bioprotection for monuments by acting as a barrier against weathering and thermal stress and by reducing erosion or even improve the aesthetic value of a monument (Viles et al., 2011; Kowarik et al., 2016; Salvadori and Municchia, 2016).

#### 7.1.1. Strategies for the management of plants affecting monuments

When dealing with the tree effect on plants at the belowground level the first step is the detection of the contact between the tree roots and the monument. This can be investigated with sensors such as "georadar" as done for urban trees (Stokes et al., 2002) (Table 5). This procedure could take advantage of "three-dimensional root models"; unfortunately, such models are available only for central European countries while they are missing in other biogeographic regions where heritage site conservation is a main issue as well (Caneva et al., 2009). If the risk of the contact is confirmed, authors have contrasting opinions on the possible strategies to be adopted. The "use of plant growth regulators'', e.g. to suppress shoot growth, was generally not supported mainly because of high quantities of water required as hormone carriers that may have collateral effects on underground environments (Caneva et al., 2009) as well as the "arrangement of physical barriers" for technical (effects of humidity at the root level) and economic problems (Biddle, 1998). Other possible strategies are "pruning" and "felling" (Biddle, 1998; Caneva et al., 2009) (Table 5). Pruning can reduce the water uptake, as the vigour of trees; hence it may be considered in the lower risk situations, with an ongoing commitment to maintain the plant size (Biddle, 1998); such choice must consider the recommendations listed in chapter 6.2. Considering tree felling as a solution can be suggested with precautions: roots, after dying, create holes inside the material where water may channel easily; those zones become a weak point in structures, hence, a parallel consolidation treatment can be necessary (Caneva et al., 2006). Celesti-Grapow and Ricotta (2021) underlined that tree felling can inflict considerable damage on monuments and tree removal from areas utilised by citizens creates tensions for the cultural connection existing between people and plants, especially in urban context. The species reproductive traits can be crucial in the decision to remove the plant or not the plant. Felling trees of species with a high colonizing potential (wind- or bird-dispersed) is supported by the literature experiences on Roman heritage sites (Caneva et al., 2009; Celesti-Grapow and Ricotta, 2021). Such species are often associated to detrimental effects on monuments mostly because their propagules can easily reach the monuments surface, where their control is particularly difficult, e.g. *Ailanthus altissima* (Mill.) Swingle; while the use of biocides reported in literature to avoid a re-growth process is no longer applicable being prohibited by law in most countries.

Finally, as mentioned in chapter 6.2.1 the use of "tree risk index" to prevent the risk of damages for the artistic structures due to tree stability is recommended (Tomao et al., 2015).

### 7.2. Biofilms: lichens, mosses, algae, fungi and bacteria

Biofilm formation (or patinas) are responsible for aesthetic damages, such as colour and/or shape modification; mechanical and chemical damages (i.e. thermo-hygric properties) can occur on the surface as well as in the inner zone of stone artistic structures and bring to the monument decay in the long term (Scheerer et al., 2009; Cicinelli et al., 2018;

**Table 5**
Strategies for agents of threat related to the management of biodeterioration agents; direct subjects of impact and references are also indicated.

| Threat | Impact on | Solutions | References |
|---|---|---|---|
| *Plants* | Monuments | Development of dimensional root models coupled with use of sensors (e.g. georadar); evaluation of tree risk index; pruning; felling considering structure consolidation; avoiding plant removal or pruning when providing bioprotection to the monument. | Biddle, 1998;Stokes et al., 2002;Caneva et al., 2009, 2006; Tomao et al., 2015;Celesti-Grapow and Ricotta, 2021 |
| *Mosses* | Monuments | Mechanic removal only when necessary; considering the improvement of the aesthetic value caused by mosses before removing. | Tiano, 2001 |
| *Lichens* | Monuments | Applying biocide and mechanical methods (air abrasive or hard brushes) without removing the lichen thallus; before using biocide check the interference with supporting material and the effectiveness on the patina removal; adopting prevention and maintenance programmes. | Tiano, 2001;Gorbushina et al., 2002;Stupar et al., 2014a, 2014b;Coutinho et al., 2016;Rosado et al., 2017;Cennamo et al., 2018 |
| *Algae, bacteria, fungi* | Monuments | Biocide cleaning with rigid brushes; before using biocide check the interference with the supporting material and the effectiveness on the patina removal; evaluating sustainable treatments, e.g. electromagnetic radiations, essential oil application; adopting prevention and maintenance programmes. | Tiano, 2001;Gorbushina et al., 2002;Stupar et al., 2014a, 2014b;Coutinho et al., 2016;Rosado et al., 2017;Cennamo et al., 2018 |

Li et al., 2017; Toreno et al., 2018). Such agent of threat was the most represented in our bibliographic search (Fig. 1) in 10 different countries in Europe and Asia.

Biodeteriogens are mosses, lichens, algae, fungi and bacteria. To detect the species that form the biofilm, a traditional method is to cultivate samples on agar and recognize the species by microscopic analysis (Lamenti et al., 2000). However, recently, the use of metagenomic analysis of the throughput sequencing is largely supported (Coutinho et al., 2016; Li et al., 2017; Dyda et al., 2018). Lamenti and colleagues (2000), by observing the colonisation of restored ornamental marble statues in the Boboli Gardens in Florence (Italy) by photosynthetic micro-organisms, found that a green microalga *Coccomyx*a was the first colonizer. Later, the biofilms were enriched by cyanobacterial forms, which became dominant. In about six years, a photosynthetic microbial community, structurally similar to that occurring on the unrestored statues was regenerated. Algae that colonize cultural heritage belong to the green algae group Chlorophyta, they confer a bright green or dull-blackish colour on the stone surfaces. Cyanobacteria, widely present on stone material, form biofilms on rock surfaces that are green under humid conditions and blackish when dry (Pinna, 2017).

Old parks and gardens provide suitable habitats for bryophytes, becoming important biodiversity refuges as emerged by the study of Godovičová et al. (2020) who surveyed a total of 14 historical parks and gardens in urban and rural areas of Slovakia.

While mosses, bacteria and algae are only responsible for aesthetic alterations, under particular climatic conditions, such as high humidity, some species of fungi can be extremely erosive and may penetrate inside stone, marble, and antiqueue glass (Sterflinger et al., 2018). Black meristematic fungi colonising stones, known as ‘rock inhabiting fungi’, such as *Coniosporium* Link and *Knufia* L.J. Hutchison & Unter., are a wide group of black pigmented fungi with melanin inside the cells most widespread on stone monuments in Mediterranean basin, especially marble statues (Isola et al., 2016; De Leo et al., 2019).

However, researches showed that lichens are the main responsible for stone substrata biodeterioration within a relatively short timescale (Nascimbene and Salvadori, 2008). Deterioration is attributed to physical (e.g. pressure induced by expansion and contraction of the thalli, adhesion of rhizines, penetration of hyphae) and chemical mechanisms (Nascimbene and Salvadori, 2008). They produce large numbers of secondary metabolites, especially oxalates, which play a role in biogeochemical weathering of rocks and in soil formation; oxalates significantly contribute to the bulk and composition of the thallus itself and persists as encrustation after the lichen’s death (Seaward, 2015).

#### 7.2.1. *Strategies to control biofilms in historic gardens*

Mosses can be simply “mechanically removed” even though it is not always recommendable since they often increase the aesthetic value of monuments. Regarding lichens, the suggested measure is to “remove only the body of lichen” with biocide and mechanical methods (air abrasive or hard brushes) without removing its thallus to avoid damage to the stone surface Tiano (2001). Similarly, patinas formed by algae, bacteria and fungi can be eliminated by “brushing stone with biocide cleaning”. Tiano (2001) recommended to carry out a “preliminary check” of the interference on the support material and the effectiveness on the patina removal, before using biocide products. Several authors tested the different biocide for their inhibition potential (e.g. Coutinho et al., 2016; Rosado et al., 2017). In addition, novel and more sustainable techniques compared to traditional ones adopted in cultural heritage conservation, were also investigated. Among these, the use of high-strength “electromagnetic radiation” in the radiofrequency band, non-invasive for the artistic structure and non-dangerous for operators and the environment (Cennamo et al., 2018) or the use of “essential oils”, i.e. extracted from *Helichrysum italicum* (Roth) G. Don (Stupar et al., 2014a) or *Origanum vulgare* L. (Stupar et al., 2014b).

To prevent the destructive processes induced by microorganisms, several control measures can be recommended. Among these: (1) the surface of marble and limestone monuments should be mechanically cleaned without applying organic substances, (2) the monuments can be treated with biocides specific to the contaminating microflora and neutral to the stone, and (3) the disintegrating parts of the monuments should be fixed with specially chosen impregnating compounds (Gorbushina et al., 2002). In general, Nascimbeni and Salvadori (2008) underlined the difficulties to prevent biological recolonization over the long term after restoration and recommended the adoption of maintenance programs more effective than a complete restoration.

## 8. Conclusions

Historic gardens are complex systems of high ecological, economic, cultural, artistic and historic value. These systems are increasingly under pressure due to multiple and interacting factors, both biotic and abiotic. Hence, managers should be aware, trained, and responsible to preserve them for the next generations. In this review, we summarised the major threats, encountered in literature from 1990 up to 2021, in the management of the plant component of single gardens, and we reported and discussed the adopted solutions.

The problem of biodeterioration was the most widely discussed topic and new solutions such as the use of sensors to detect tree roots and novel techniques to remove biofilms have been recently adopted.

Pathogen/pest attacks and climate change were first and second in importance in recent years. Both represent a risk, particularly for some tree species that are typical of historic gardens in given regions. Indeed, a key aspect of the adaptation process to both factors is the species composition of the garden vegetation. This work recognizes the need to find solutions that can meet the need to conserve the original composition of the garden and the traditional practices while favouring its adaptation to a rapidly changing environment. Since changes in plant species composition are currently taking place in a more or less controlled way in many gardens, planning and driving the replacement of some tree specimens is necessary to preserve the original scheme and design of the historic garden. Moreover, we showed that an effective and sustainable management can take advantage from the use of informative and risk maps realized through smart techniques (e.g. remote sensing) and a multidisciplinary knowledge ranging from plant biology to cultural heritage conservation. The information presented in this review goes in this direction and hopes to provide a useful tool for managers of historic gardens.

## Funding

This work was supported by Regione Toscana (POR FSE 2014-2020) and Fondazione Cassa di Risparmio di Firenze in the framework of EFFORT project (Efficientamento della salvaguardia e valorizzazione dei Giardini storici).

## CRediT authorship contribution statement

**E. Carrari:** Conceptualization. **C. Aglietti:** Data curation, Writing – review & editing. **A. Bellandi:** Writing – review & editing. **C. Dibari:** Supervision, Writing – review & editing. **F. Ferrini:** Methodology, Supervision, Writing – review & editing. **S. Fineschi:** Supervision, Writing – review & editing. **P. Galeotti:** Writing – review & editing. **A. Giuntoli:** Supervision, Writing – review & editing. **R. Manganelli Del Fa:** Writing – review & editing. **M. Moriondo:** Supervision, Writing – review & editing. **M. Mozzo:** Funding acquisition, Writing – review & editing. **G. Padovan:** Data curation, Writing – review & editing. **C. Riminesi:** Supervision, Writing – review & editing. **F. Selvi:** Supervision, Writing – review & editing. **M. Bindi:** Conceptualization, Writing – review & editing, Funding acquisition.

## 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.

## Data Availability

Data will be made available on request.

## Acknowledgements

Authors wish to thank Regione Toscana, Fondazione Cassa di Risparmio di Firenze and Direzione Regionale Musei della Toscana, in particular the staff of Villa la Petraia and Villa Castello for the support during the project.

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