Title

Deteriogenic flora of the Phlegraean Fields Archaeological Park: ecological analysis and management guidelines

Authors

Riccardo Motti¹, Giuliano Bonanomi¹, Adriano Stinca²

Affiliation

¹Department of Agricultural Sciences, University of Naples Federico II, Via Università 100, 80055 Portici (Naples), Italy

² Department of Environmental, Biological and Pharmaceutical Sciences and Technologies, University of Campania Luigi Vanvitelli, Via Vivaldi 43, 81100 Caserta, Italy.

Corresponding author

Corresponding author: Riccardo Motti Tel.: +39 081 2532014

E-mail address: motti@unina.it

Abstract

Biodeterioration, the alteration caused by living organisms, on historical buildings and stone monuments is a well-known problem affecting two-thirds of the world's cultural heritage. The study of the flora growing on wall surface is of particular importance for the assessment of the risk of biodeterioration of stone artifacts by vascular plants, and for maintenance planning. In this study, we investigate how rock type, exposure and inclination of the wall affect the biodeteriogenic flora at 13 sites of the Archaeological Park of the Phlegraean Fields located in the province of Naples, in southern Italy. For each site, we analysed randomly selected square areas with 2 x 2 m size, representing the different vegetation types in terms of vascular plant species cover. The total number of plant species recorded was 129, belonging to 43 families. *Erigeron sumatrensis*, *Sonchus tenerrimus*, and *Parietaria judaica* are the most commonly reported species, while *Capparis orientalis* is the species with the highest average coverage. Substrate type, exposure and surface inclination affect the floristic composition, with the average plant cover significantly higher on vertical surfaces and at western and southern exposure. All the main biodeteriogenic vascular plant species grow on more or less porous lythotype like yellow tufa, conglomerate and bricks. Finally, woody plants eradications methods are proposed by the tree cutting and local application of herbicides, to avoid stump and root sprouting and to minimize the dispersion of chemicals in the surrounding environment.

Key words

archaeological sites; biodeterioration; biological agents; bioreceptivity; conservation management; Hazard Index; higher plants; monument conservation

1. Introduction

In recent years, increasing attention has been paid to wall flora growing on archaeological and historical sites in the Mediterranean basin (Krigas et al., 1999; Spampinato et al., 2005; Iatrous et al., 2007; Motti and Stinca, 2011; Bartoli et al., 2017; Cicinelli et al., 2018; Dahmani et al., 2018). Although plants can in some cases be considered a protective resource for monuments (Miller, 2012; Erder, et al., 2013), in most cases they pose a severe threat to their conservation (Caneva et al., 2003; Celesti-Grapow and Blasi, 2004; Tjellén et al., 2015; Minissale et al., 2015).

Walls can be considered an extreme environment for plant life in many respects. Segal (1969) was the first to show that wall habitats show ecological features comparable with rocks in natural environments and could be described as artificial, highly selective ecosystems (Ellenberg, 1996; Laníková and Lososová, 2009; Francis, 2011).). Wall surfaces, particularly vertical sections, offer limited opportunities for root development, the accumulation of organic matter and mineral nutrients thus limiting edaphic development and, thereafter, plant establishment (Duchoslav, 2002; Francis, 2011). Physical and environmental characteristics of walls determine their capacity to act as habitat, and control the possibility of plants to colonise such man-made ecosystems. The factors which most influence the capacity of walls to function as habitat for vascular plants are wall size, construction materials, inclination, exposure and wall age (Francis, 2011).

Higher plant colonisation of stone monuments also depends on local factors such as human disturbance, microclimate in terms of temperature and humidity, and interaction with other plants (Segal, 1969; Kumbaric et al., 2012; Ceschin et al., 2016). Establishment of plant communities on walls generally depends on the level of disintegration of building materials, with the presence of crevices, fractures and interstices that promote root development and plant growth. Nevertheless, also the technology of wall building affects the growth of plant species which are able to colonise such artificial habitats (Duchoslav, 2002; Francis, 2011). Moreover, the vegetation surrounding the investigated site affects the composition and diversity of flora growing on stone structures (Duchoslav, 2002).

The Phlegraean Fields Archaeological Park (henceforth PFAF) was established in 2016 and includes 25 sites from the Graeco-Roman period spread over an area of about 8,000 hectares. The 25 archaeological sites include ancient settlements, villas, thermal baths, temples, amphitheatres and

tombs. The study sites are inserted in a complex landscape with several different habitats such as coastal and lake vegetation, Mediterranean scrubland, thermophilic and mesophilic woodland, grassland and low impact farmland (Motti and Ricciardi, 2008). Therefore, the investigated sites proved to be an interesting case study due to their great floristic richness, historical value and natural context. In the present study, we investigate the role of lithotype and microclimatic factors in terms of exposure and inclination of man-made structures in controlling the occurrence and distribution of vascular plants in stone monuments.

Given the above considerations, the specific aims of the present work were to analyse the vascular flora detriogens of the PFAF and assess the risk of structural biodeterioration. Such knowledge is essential for the purposes of preserving the cultural landscape and for choosing appropriate management practices to prevent and eradicate vascular plants so as to minimise biodeterioration.

2. Materials and methods

2.1. Study sites

The Phlegraean area includes an insular part with the islands of Procida, Vivara and Ischia and a continental area, known as the Phlegraean Fields (Fig. 1). The area as a whole presents a highly articulated geomorphological configuration. In a very small area, bounded by a long coastline with beaches and rocky headlands, numerous volcanic calderas are interspersed with small lakes and plains. The area draws its origin from the eruption of 35,000 years ago, when a huge alkali trachytic ignimbrite followed by the subsequent collapse of the ancient volcano called Archiflegreo was released (Rosi et al., 1983). This phenomenon has produced a volcanic system with a complex hilly landscape, within which each peak represents the relict of ancient volcanic edifices, craters or eruptions.

Human settlements in the Phlegraean area, and especially in Cumae, date back to the III millennium BC. Founded by the Greeks in the 8th century BC, Cumae and its territory assumed great political and economic importance that allowed an expansion of its sphere of influence with the foundation of Dicearchia, the current Pozzuoli (Lombardo and Frisone, 2006). The maximum splendour of the Phlegraean area coincides with the end of the Republican age, when it became the focal point for the cultural and economic elite from Rome, and the whole territory is dotted with villas, palaces and sumptuous bath complexes (Maiuri, 1958).

The fall of the Roman Empire was followed by the decline of this area with the ruin of man-made structures already damaged by bradyseism. For many centuries, agriculture and silvi-pastoral

activities were dominant, although much of the farmland and forest has been lost to extensive and chaotic urbanisation in recent decades (Motti et al., 2004).

The climate of the Phlegraean fields is influenced by both its geographical position close to the Tyrrhenian Sea and its low altitude, reaching its maximum height at Mt. Sant'Angelo alla Corbara (319 m a.s.l.). Average rainfall (863 mm) and temperature (17.0 °C) in the area are typical of a Mediterranean climate, with a hot dry period between June and August. The whole Phlegraean flora now comprises approximately 750 taxa (Motti and Ricciardi, 2005). In our study, the floristic survey concerned 13 of the 25 sites included in the PFAF (Fig. 1; Tab. 1). The remaining sites were not surveyed because they are underwater or currently inaccessible.

Fig. 1. Study site (A), and location of the 13 selected sites in the PFAF (B)

Tab. 1. The 13 study sites selected in the PFAF area, their abbreviations and number of surveys carried out at each site

2.2. Data collection and analysis

The field surveys were carried out from March to September 2018. Overall, we carried out 143 vegetation surveys (Tab. 1). The number of surveys, having taken different types of substrate into account, was proportional to the size and plant cover of each site. In each survey, we analysed randomly selected 2 x 2 m sampling units to represent the different vegetation types in terms of plant cover and floristic diversity. For each sampling units the following data were supplied: site name, position (UTM coordinates), substrate, position (vertical or horizontal), exposure and floristic list with percentage cover for each species. The plant specimens were identified in the field except for dubious cases, which were later identified at the Laboratory of Applied Ecology of the Department of Agricultural Sciences of Portici, according to Pignatti (1982), Pignatti et al. (2017a; 2017b; 2018), and Tutin et al. (1964; 1980; 1993). The nomenclature follows the checklist of Italian vascular flora (Bartolucci et al., 2018; Galasso et al., 2018). Families are organised based on APG IV (2016) for angiosperms. To evaluate the hazard of deteriogenic species, for each taxon the hazard index (HI) was assigned according to Signorini (1995, 1996). Plant life form was classified according to Raunkiaer (1934), mostly verified by field observations. The chorotype was assigned according to

Pignatti et al. (2017a, 2017b, 2018). Herbarium specimens are deposited in the Herbarium Porticense (PORUN).

3. Results and discussion

3.1. Deteriogenic flora

In all, 129 plant species were recorded (Tab. S1), belonging to 43 families, of which the most species-rich are the Asteraceae (25 taxa), followed by the Poaceae (18 taxa) and Fabaceae (16 taxa).

Erigeron sumatrensis (HI=2) is the most commonly reported species in the 143 samples (Fig. 2), followed by *Sonchus tenerrimus* (HI=5), *Parietaria judaica* (HI=5) and *Dittrichia viscosa* subsp. *viscosa* (HI=5). Among the ten species with the maximum average cover, seven show woody habits, with a Hazard Index between 5 and 10. *Capparis orientalis* (HI=8) is the species with the highest average cover (Fig. 3) followed by *Dittrichia viscosa* subsp. *viscosa* (HI=5) and *Spartium junceum* (HI=8).

Fig. 2. List of the 12 most commonly recorded species in the 143 sampling units (number of records for each species).

Fig. 3. Cover of the 10 most abundant species in the 143 sampling units

The normal chorological spectrum (Fig. 4) revealed the prevalence of Mediterranean species (33.7%), of which the most representative are euri-Mediterranean (62.8%) vs. steno-Mediterranean (37.2%). Widely distributed species are well-represented (35.7%), of which alien species amount to 30.4%. These data are similar to those of the floristic list of the whole Phlegraean Fields area (Motti and Ricciardi, 2005).

The archaeological sites of the PACS are located in a floristic context dominated by species associated with agricultural environments, as well as by woody species typical of Mediterranean tufaceous coastal hill ecosystems (Motti and Ricciardi, 2008). Our data indicate that the flora growing on stone structures partially reflects this kind of vegetation. Hence the floristic composition of the PACS is influenced by its proximity to natural areas (Duchoslav, 2002; Migliozi et al., 2010).

Fig. 4. Normal chorological spectrum of the flora of the Phlegraean Fields Archaeological Park (PFAF) compared with that of the flora of the whole area of the Phlegraean Fields (PF) (Motti and Ricciardi, 2005)

The life form spectrum (Fig. 5A) shows a prevalence of Therophytes (48.4%) and Hemicryptophytes (28.6%) at all study sites, but these life forms have no predominant cover (Fig. 5B). Woody life forms (Phanerophytes and Chamaephytes), which include the most deteriogenic species, account for 22.2% of the total frequency and 60.3% of total cover. The relationship between therophytes and hemicryptophytes (T/H ratio: 1.7) is influenced by human disturbance, which promotes the spread of short-lived species (Motti and Stinca 2011), as well as by climate.

Fig. 5 Plant life-form spectrum of the vascular flora (A) and percentage cover of different plant life forms (B) in the 143 sampling units (T=Therophytes; P=Phanerophytes; H = Hemicryptophytes; Ch = Chamaephytes).

3.2. Deteriogenic flora: the role of inclination, exposure and substrate type

Wall inclination affects the amount of direct solar radiation reaching the substrate and, indirectly, air and soil temperatures (Wieser and Tausz, 2007). Previous studies reported that horizontal surfaces, which provide better growing conditions, usually host a higher plant cover compared to vertical walls (Caneva et al., 1992; Lisci et al., 2003; Ceschin et al., 2016; Motti and Bonanomi, 2018). Vertical walls are often considered to be like desert habitats with a high degree of aridity, and the stone surfaces exposed to direct sunlight can reach extremely high temperatures (Garty, 1990). In contrast with previous results, in our study sites the average plant cover (Fig. 6A) was significantly higher on vertical surfaces (Fig. 7A). As shown also by Duchoslav (2002), Therophytes were more common on horizontal surfaces, while Hemicryptophytes, Chamaephytes and Phanerophytes, the most biodeteriogenic life forms, grow rather on vertical surfaces (Fig. 7B). This could be explained by the greater ability of the latter life forms to absorb water from greater depths (Kumbaric et al., 2012; Caneva et al., 2009). Alternatively, the high frequency and cover of Therophytes on flat surfaces and the widespread occurrence of woody plants on vertical surfaces could be explained by the different

effort exerted for cleaning. Indeed, vertical surfaces are more difficult for workers to reach and are therefore subject to less intense and less frequent removal of vegetation.

Fig. 6. Percentage cover (A), and percentage cover of life forms (B) on horizontal (H) and vertical (V) surfaces in the study sites. Values are averages of the 143 sampling units.

Among the species with the highest hazard index ($HI > 5$), *Ficus carica*, *Matthiola incana*, *Pistacia lentiscus*, *Capparis orientalis*, *Reichardia picroides*, *Rubus ulmifolius* and *Artemisia arborescens* show a higher abundance on vertical surfaces. By contrast, *Spartium junceum*, *Rhamnus alaternus* and *Reseda alba* are almost indifferent to surface inclination, while *Ailanthus altissima* grows almost exclusively over horizontal substrates (Fig. 7).

Fig. 7. Relative cover of the 11 species with the highest HI in relation to inclination (H= horizontal; V=vertical). Values are averages in the 143 sampling units.

In the Mediterranean climate context, with its long summer drought, exposure plays a major role in causing differentiation in biological colonisation (Caneva and Ceschin, 2009). At mid latitudes of the northern hemisphere, south-facing slopes receive more direct solar radiation and can be expected to be much warmer and drier than other exposures.

In the study area, plant cover was highest on western and eastern-exposed walls (Fig. 8A). Phanerophytes, which are woody plants that may reach a considerable size and have an extensive root system (Pacini and Signorini, 2009), were recorded mainly on western and eastern exposures (Fig. 8B). By contrast, herbaceous species (hemicryptophytes and therophytes) grow preferentially on south-facing slopes. The southern slopes reproduce the general life strategies of plants found in the Mediterranean climatic area where drought-avoiding annuals predominate and herbaceous perennials, which die back to the ground surface during the summer drought, are also common (Mooney and Dunn, 1970). The woody species grow under less dry exposure (East and West) and are almost all evergreen trees and shrubs, which tolerate the less intense drought that occurs over such exposures. Moreover, as highlighted by Callaway (2007), stones can act as an inanimate “nurse” structure, promoting the establishment and growth of plants and acting as a temperature buffer. In this perspective, southerly exposure may be more favourable for plant growth due to the larger amount of solar radiation, especially during autumn and winter (Motti and Bonanomi, 2018).

Fig. 8. Plant cover (A, average of the 143 sampling units) and cover of different life forms (B) in relation to exposure

Natural stones are the main element of the archaeological heritage and are subject to biodeterioration: they are mostly located outdoors and the processes of deterioration affecting them are the same that play an essential role in pedogenesis (Pinna and Salvadori, 2009). Effusive magmatic rocks such as yellow tuff, piperno and basalt represent the most common stony substrates in the PFAF. Instead, the man-made structures mainly consist of the following materials: i) *opus reticulatum*, consisting of a sand and lime mortar mix into which diamond-shaped bricks of tuff were positioned (Wilson, 2006); ii) *opus latericium* walls, built with clay-fired bricks bonded with mortar. In both cases, the bricks constitute the external parts of the wall, while the inner section is filled with a conglomerate of mortar, tuff and lapillus (Talamo P., *in verbis*).

Fig. 9. Selected images of the most common substrates found in the PFAF (A=Yellow tuff; B= *Opus latericium*; C=*Opus reticulatum*; D=Basalt; E=Piperno; F=Conglomerate).

Other non-effusive stones can be found in the study area, including marble and vitreous mosaics. Since tuff and mortar have a relatively high porosity (Kumbaric et al., 2012), they allow higher water penetration and are more likely to retain moisture compared to other lithotypes. On the above basis, we could partially explain the differences in plant cover among different substrates (Fig. 10A), which reaches the highest values on yellow tuff followed by conglomerate, *opus latericium* and *opus reticulatum*.

Fig. 10. Plant cover (A) and growth habit cover (B) in relation to substrate. Values are averages from the 143 sampling units

As shown in Fig. 9B, the less porous lithotypes like marble, basalt and mosaic are mainly colonised by herbaceous species, while woody species grow preferentially on volcanic rocks and structures with a higher moisture content. We speculate that therophytes can adapt to hard and non-porous substrates because their vegetative period is limited to autumn and winter when water shortage is not a limiting factor. Instead, perennial plants require porous substrates that store water, thus allowing survival also during the summer drought.

All the main deteriogenic vascular plant species grow on more or less porous substrates (Fig. 10): none of them thrive on marble, basalt or mosaics. Some species (e.g. *Rubus ulmifolius*, *Rhamnus*

alaternus) are quite indifferent to the lithotype, while others, such as *Ailanthus altissima*, *Spartium junceum*, *Matthiola incana* and *Artemisia arborescens*, preferentially grow on yellow tuff.

Fig. 11. Relative cover of the 11 species with the highest HI in relation to substrates. Values are averages of the 143 sampling units.

Plant growth on walls can be therefore interpreted as a dynamic process with weeds that may alter the physical conditions of the substrate in which they thrive (Fisher 1972), also through progressive disintegration of building materials. Biochemical deterioration results from assimilatory processes, where the organism uses the stone surface as a source of nutrition, and from dissimilatory processes, where the organism produces a variety of metabolites that react chemically with the stone surface (Mortland et al., 1956; Caneva and Altieri, 1988). Carbon dioxide, produced through roots respiration, changes into carbonic acid [H_2CO_3] in an aqueous environment. The carbonic acid reacts with calcium carbonate [CaCO_3] and magnesium [MgCO_3] insoluble present in several substrates, forming calcium bicarbonate [$\text{Ca}(\text{HCO}_3)_2$] and magnesium [$\text{Mg}(\text{HCO}_3)_2$] soluble (Mishra et al., 1995; Pinna and Salvadori, 2005).

Plants exploit and help to create microenvironments suitable for plant growth, (Allsopp et al., 2004) and pre-existing plant cover favours the establishment of other taxa, also protecting them against evaporation and regulating relative humidity (Segal, 1969). In this sense, the first plants that colonise the walls mainly have a herbaceous growth habit and could be considered pioneer species playing a key role in stone weathering: their strong fasciculate root system creates or widens crevices in which soil is formed, providing organic matter and nutrients that promote succession of typical vegetation for the biogeographic region concerned (Segal, 1969; Duchoslav, 2002).

3.3. Plant deterioration and management guidelines

The plant average cover for each site is shown in Fig. 12, from which it can be seen that sites like the Temple of Apollo, Flavian Amphitheatre, Baia Castle, the Sacellum and Piscina Mirabilis need urgent maintenance to eliminate the most deteriorogen vascular plants so as to minimise the risk of severe structural damage. In the other sites of the complex, although the plant cover is lower, periodic assessment of case-by-case situations is required.

Fig. 12. Plant cover (%) in the 13 study sites

Weed control in archaeological sites is complex and costly since proper conservation of man-made structures, the environment and the natural landscape has to be taken into account. Current practice at PFAF sites to manage undesirable vegetation relies mainly on mowing by the use of brush-cutters. This practice is strongly discouraged by archaeologists as it can cause additional deterioration to walls. Moreover, many species, especially shrubs and trees, are not completely eliminated because only the above-ground portion is cut. In recent years alternative non-chemical methods for weed control, including flame weeding and soil solarization, have been proposed (Papafotiou et al., 2016; Papafotiou et al., 2010). These treatments are often more expensive than chemical weed control due to higher treatment frequency and greater energy consumption than chemical weed control, resulting in a lower cost/benefit ratio (Kempenaar et al., 2002). Selective use of herbicides is, in our opinion, the most efficient and least costly practice for controlling and eradicating woody vascular plants, especially on vertical surfaces.

In many woody plants (e.g. *Ailanthus altissima*, *Capparis orientalis*) manual cutting generally stimulates stump and root sprouting due to the loss of apical dominance, such that cutting must be followed by local herbicide treatment (Caneva et al., 1996; Burch and Zedaker, 2003). The techniques suggested for this purpose are tree cutting and local application of herbicide by injection or by painting, allowing the herbicide to translocate throughout the roots and/or rhizome of the plant (Mendes et al., 2017) while maintaining the integrity of the remaining plant community.

These techniques involve the application of chemicals (e.g. glyphosate, imazapyr) directly on the plant, with no dispersion in the surrounding environment and minimising product quantities. Stem injection consists in making a cut (or a hole by drilling) downward at an angle of ~45 degrees through the bark, 4 to 8 cm long, and then injecting a small amount of herbicide (DiTomaso and Kyser, 2007). The cut stump method, instead, involves cutting off the plant completely at its base using a chainsaw. The herbicide solution is then painted onto the exposed surface.

The choice of the most appropriate technique is made on the basis of the structural and physiological features of the species, age and size of the specimen, and the position of the plant in relation to the wall. According to Caneva et al. (2009), these practices should be followed by wall consolidation because, with the death of the living roots, collapses and structural damage could arise.

4. Conclusions

Our data provided useful information for understanding the role of abiotic factors (substrate, position, exposure) in determining plant growth. The eradication methods proposed in the present paper constitute an example of a multidisciplinary approach to restoration practices, in which collaboration

between agronomists, archaeologists and masonry experts is desirable. The ultimate goal is to apply efficient techniques with no undesirable side effects on the substrate.

Acknowledgements

We are very grateful to Paolo Giulierini, Director of the PFAF, and the technical-administrative staff who shared knowledge with us and for their logistical support. The authors wish to thank Pierfrancesco Talamo, archaeologist at the PFAF, for information concerning man-made structures. Stefano Emrick collaborated in field research. Mark Walters revised the English language version.

References

- Allsopp D, Seal KJ, Gaylarde CC. Introduction to biodeterioration, second ed. Cambridge University Press; 2004.
- Bartolucci F, Peruzzi L, Galasso G, Albano A, Alessandrini A, Ardenghi NMG, et al. An updated checklist of the vascular flora native to Italy. *Plant Biosyst.* 2018;152(2):179-303.
- Burch PL, Zedaker SM. Removing the invasive tree *Ailanthus altissima* and restoring natural cover. *Journal of Arboriculture.* 2003;29:18–24.
- Callaway RM. Positive Interactions and Interdependence in Plant Communities. Springer, Dordrecht, NL; 2007.
- Caneva G, Altieri A. Biochemical mechanisms of stone weathering induced by plant growth. In: *Proceedings of the 6th international congress on deterioration and conservation of stone.* Nicholas Copernicus University Press, Torun, Poland; 1988. p. 32-44.
- Caneva G, Ceschin S. Ecology of biodeterioration. In: *Plant Biology for Cultural Heritage. Biodeterioration and Conservation.* 2009;35-58.
- Caneva G, De Marco G, Dinelli A, Vinci M. The wall vegetation of the roman archaeological areas. *Science and technology for cultural heritage.* 1992;1:217-226.
- Caneva G, Galotta G, Cancellieri L, Savo V. Tree roots and damages in the Jewish catacombs of Villa Torlonia (Roma). *J Cult Herit.* 2009;10(1):53-62.
- Caneva G, Pacini A, Celesti-Grappow L, Ceschin S. The Colosseum's use and state of abandonment as analysed through its flora. *Int Biodeterior Biodegradation.* 2003;51:211–219.
- Caneva G., Benelli F., Bartoli F., Cicinelli E. Safeguarding natural and cultural heritage on Etruscan tombs (La Banditaccia, Cerveteri, Italy). *Rendiconti Lincei. Scienze Fisiche e Naturali.* 2018;29(4):891-907.
- Celesti-Grappow L, Blasi C. The Role of Alien and Native Weeds in the Deterioration of Archaeological Remains in Italy. *Weed Technology.* 2004;18(sp1), 1508-1514.
- Ceschin S, Bartoli F, Salerno G, Zuccarello V, Caneva G. Natural habitats of typical plants growing on ruins of Roman archaeological sites (Rome, Italy). *Plant Biosyst.* 2016;150(5):866-875.

- 378 Chase MW, Christenhusz MJM, Fay MF, Byng JW, et al. An update of the angiosperm phylogeny
379 group classification for the orders and families of flowering plants: APG IV. Bot J Linn Soc.
380 2016;181(1):1-20.
- 381 Cicinelli E, Salerno G, Caneva G, 2018. An assessment methodology to combine the preservation of
382 biodiversity and cultural heritage: the San Vincenzo al Volturno historical site (Molise, Italy).
383 Biodivers Conserv. 27(5):1073-1093.
- 384 Dahmani J, Benharbit M, Fassar M, Hajila R, Zidane L, Magri N., Belahbib N. Vascular plants census
385 linked to the biodeterioration process of the Portuguese city of Mazagan in El Jadida,
386 Morocco. Journal of King Saud University-Science; 2018.
- 387 DiTomaso JM., Kyser GB. Control of *Ailanthus altissima* using stem herbicide application
388 techniques. Arboric Urban For. 2007;33(1):55.
- 389 Duchoslav M. Flora and vegetation of stony walls in East Bohemia (Czech Republic). Preslia-Praha.
390 2002;74(1):1-26.
- 391 Ellenberg H. Vegetation Mitteleuropas mit den Alpen in: Ökologischer, dynamischer und historischer
392 Sicht Verlag. Eugen Ulmer, Stuttgart 5; 1996
- 393 Erder E, Gürsan-Salzman A, Miller NF. A Conservation Management Plan for Gordion and its
394 Environs Conservation and Management of Archaeological Sites. 2013;15(3-4):329–347.
- 395 Fisher GG. Weed damage to materials and structures. International Biodeterioration Bulletin.
396 1972;8:101-103.
- 397 Francis RA. Wall ecology: A frontier for urban biodiversity and ecological engineering. Prog Phys
398 Geogr. 2011;35(1):43-63.
- 399 Galasso G, Conti F, Peruzzi L, Ardenghi NMG, Banfi E, Celesti-Grapow, et al. An updated checklist
400 of the vascular flora alien to Italy. Plant Biosyst. 2018;152(3):556-592.
- 401 Garty J. Influence of epilithic microorganisms on the surface temperature of building walls. Can J
402 Bot. 1990. 68(6):1349-1353.
- 403 Iatrou G, Trigas P, Pettas N. The vascular flora of Akrokorinthos Castle and its surrounding area (NE
404 Peloponnese, Greece). Phytologia Balcanica. 2007;13(1):83-93.
- 405 Kempenaar C, Spijke, JH., Vermeulen GD, Lotz LAP. Rational weed control on hard surfaces, Laar
406 HHv, Proc 12th Eur Weed Res Soc (EWRS) Symposium, EWRS Wageningen, The Netherlands;
407 2002. p 162–163.
- 408 Krigas N, Lagiou E, Hanlidou E, Kokkini S. The vascular flora of the Byzantine Walls of Thessaloniki
409 (N Greece). Willdenowia. 1999;77-94.
- 410 Kumbaric A, Ceschin S, Zuccarello V, Caneva G. Main ecological parameters affecting the
411 colonization of higher plants in the biodeterioration of stone embankments of Lungotevere (Rome).
412 Int Biodeterior Biodegrad. 2012;72:31–41.
- 413 Laníková D, Lososová Z. Rocks and walls: natural versus secondary habitats Folia Geobot. 2009;44
414 (3):263–280.
- 415 Lisci M, Monte M, Pacini E. Lichens and higher plants on stone: a review. Int Biodeterior Biodegrad.
416 2003;51:1–17.
- 417 Lombardo M, Frisone F. Colonie di colonie: le fondazioni sub-coloniali greche tra colonizzazione e
418 colonialismo. Atti del Convegno Internazionale di studi (sezione "Tra sub-colonia ad epoikia: il caso
419 di Neapolis"), Lecce 22-24 giugno 2006, Congedo Ed.,
- 420 Maiuri A. I Campi Flegrei, III ed.; 1958 Roma p. 19-61.

421 Mendes KF, Silveira RF., Inoue MH, Tornisiello VL. Procedures for Detection of Resistant Weeds
422 Using ¹⁴C-Herbicide Absorption, Translocation, and Metabolism. In *Herbicide Resistance in Weeds*
423 and Crops. IntechOpen; 2017.

424 Migliozi A, Cona F, Di Gennaro A, Mingo A, Saracino A, Mazzoleni S. Land-use management and
425 changes in campania region (southern Italy): examples from ten regional state forestS In: *Proceedings*
426 *of IUFRO–Forest Landscapes and Global Change-New Frontiers in Management, Conservation and*
427 *Restoration*; 2002. p. 21–27.

428 Miller NF. Working with Nature to Preserve Site and Landscape at Gordion. In: Rose CB, ed. *The*
429 *Archaeology of Phrygian Gordion, Royal City of Midas*. Philadelphia, PA: University of
430 Pennsylvania Museum of Archaeology; 2012 p. 243–258.

431 Minissale P, Trigilia A, Brogna F, Sciandrello S Plants and vegetation in the archaeological park of
432 Neapolis of Syracuse (Sicily, Italy): a management effort and also an opportunity for better enjoyment
433 of the site. *Conservation and Management of Archaeological Sites* 2015;17(4):340-369.

434 Mishra AK, Garg KL, Jain KK, Kamlakar G, Rao VP. Microbiological deterioration of stone: An
435 overview. In: Kamlakar, G., Rao, V.P. (Eds.), *Conservation, preservation and restoration: traditions,*
436 *trends and techniques*. Birla Archeological and Cultural Research Institute, Hyderabad. 1995 p. 217-
437 228.

438 Mooney HA, Dunn EL. Convergent evolution of Mediterranean-climate evergreen sclerophyll
439 shrubs. *Evolution*. 1970;24(2):292-303.

440 Mortland MM, Lawton K, Uehara G. Alteration of biotite to vermiculite by plant growth. *Journal of*
441 *Soil Science*. 1956;82:477-481.

442 Motti R, Stinca A Analysis of the biodeteriogenic vascular flora at the Royal Palace of Portici in
443 southern Italy. *Int Biodeterior Biodegradation*. 2011;65(8), 1256-1265.

444 Motti R, Bonanomi G. Vascular plant colonisation of four castles in southern Italy: Effects of
445 substrate bioreceptivity, local environment factors and current management. *Int Biodeterior*
446 *Biodegradation*. 2018;133:26-33.

447 Motti R, Maisto A, Migliozi A, Mazzoleni S. Agricultural and forestal landscape changes of the
448 Phlegrean Fields during the XX century. *Italian Botanist*. 2004;36 (2):577-583

449 Motti R, Ricciardi M. La flora dei campi Flegrei (Golfo di Pozzuoli, Campania, Italia). *Webbia*.
450 2005;60(2):395-476.

451 Motti R., Ricciardi M. Il paesaggio vegetale. Campi Flegrei, atlante della biodiversità. Electa, Napoli;
452 2008.

453 Pacini E, Signorini MA. Vascular plants. In: *Plant Biology for Cultural Heritage Biodeterioration and*
454 *Conservation*. 87-96; 2009.

455 Papafotiou M, Kanellou E, Economou G. 2010. Alternative practices for vegetation management in
456 archaeological sites - the case of Eleusis. *Acta Horti*. 2010;881:879–883.

457 Papafotiou M, Kanellou E, Economou G. Integrated design and management of vegetation at
458 archaeological sites to protect monuments and enhance the historical landscape. In *VI International*
459 *Conference on Landscape and Urban Horticulture* 1189 (pp. 1-10); 2016.

460 Pignatti S, Guarino R, La Rosa M. *Flora d'Italia*, Vol. 1. Edagricole, Bologna; 2017a.

461 Pignatti S, Guarino R, La Rosa M. *Flora d'Italia*, Vol. 2. Edagricole, Bologna; 2017b.

462 Pignatti S, Guarino R, La Rosa M. *Flora d'Italia*, Vol. 3. Edagricole, Bologna; 2018

463 Pignatti S. *Flora d'Italia* 1-3. Edagricole, Bologna; 1982.

464 Pinna D, Salvadori O. Meccanismi generali dei processi di biodeterioramento. In: Caneva G. Nugari
 465 M.P. Salvadori O. (Eds.) *La Biologia Vegetale per i Beni Culturali* vol. I. Nardini Editore Firenze.
 466 2002; p. 15-34.

467 Pinna D, Salvadori O. Stone and related materials. *Plant Biology for Cultural Heritage.*
 468 *Biodeterioration and Conservation*, 87-96; 2009.

469 Raunkiaer C. *The Life Forms and Statistical Plant Geography*. Oxford Clarendon Press; 1934.

470 Rosi M, Sbrana A, Principe C. The Phlegraean Fields: structural evolution, volcanic history and
 471 eruptive mechanisms. *Journal of Volcanology and Geothermal Research*. 1983;17(1-4):273-288.

472 Segal S. *Ecological Notes on wall Vegetation*. Springer-Science+Business Media, BV; 1969

473 Signorini MA. L'indice di Pericolosità: un contributo del botanico al controllo della vegetazione
 474 infestante nelle aree monumentali. *Informatore Botanico Italiano*. 1996;28:7-14.

475 Signorini MA. Lo studio e il controllo della vegetazione infestante nei siti archeologici. Una proposta
 476 metodologica. L'area archeologica di Fiesole. Rilievi e ricerche per la conservazione. Alinea ed.,
 477 Firenze, 41-46; 1995.

478 Spampinato G, Guglielmo A, Pavone P, Tomaselli V. Analisi della flora e della vegetazione delle
 479 aree archeologiche della Sicilia orientale finalizzata alla tutela e valorizzazione dei manufatti
 480 architettonici. *Informatore Botanico Italiano*. 2005;37, 830-831:1, parte B

481 Tjelldén AKE, Kristiansen SM, Matthiesen H, Pedersen O. Impact of roots and rhizomes on wetland
 482 archaeology: a review. *Conservation and management of Archaeological Sites*. 2015;17(4):370-391.

483 Tutin TG, Burges NA, Chater AO, Edmondson JR, Heywood VH, Moore DM et al. (EdS). *Flora*
 484 *Europaea* 1, second ed. Cambridge University Press; 1993.

485 Tutin TG, Heywood VH, Burges NA, Valentine DH, Walters SM, Webb, DA (EdS). *Flora Europaea*
 486 1-5. Cambridge University Press; 1964 and 1980.

487 Wieser G, Tausz M. *Trees at Their Upper Limit: Treelife Limitation at the alpine Timberline*, vol. 5
 488 Springer, Dordrecht, NL; 2007.

489 Wilson A. The economic impact of technological advances in the Roman construction industry.
 490 *Innovazione tecnica e progresso economico nel mondo romano*, 225-236; 2006.

491

492

Figure

Figure

Figure

Figure

A

B

Figure

Figure

Figure

Figure

A

B

C

D

E

F

Figure

Figure

Figure

Figure