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Biodeteriogens at a southern Italian heritage site: Analysis and management of vascular flora on the walls of Villa Rufolo

Riccardo Motti [a], Giuliano Bonanomi [a], Adriano Stinca [b,*]

[a] Department of Agriculture, University of Naples Federico II, Via Università 100, 80055, Portici, Naples, Italy
[b] Department of Environmental, Biological and Pharmaceutical Sciences and Technologies, University of Campania Luigi Vanvitelli, Via Vivaldi 43, 81100, Caserta, Italy

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ABSTRACT

Colonisation of vascular plants on ancient historical buildings is known to cause severe damage. The aim of the present work was to analyse the deteriogenic vascular flora of Villa Rufolo in Ravello, one of the most famous heritage sites in southern Italy. The deteriogenic flora were analysed in terms of diversity, structure, chorology, origin and potential damage to the building. The hazard index (HI) was applied to evaluate the impact of the biodeteriogens in question. The total flora included 61 taxa with the prevalence of therophytes (42.6%) and widely distributed species (42.6%), mostly derived from natural or semi-natural environments in the surrounding area (95.1%). The plant colonisation pattern showed the presence of some very harmful but not very abundant vascular plants (6.6%), including *Ficus carica*, *Hedera helix* subsp. *helix*, *Capparis orientalis* and *Parthenocissus tricuspidata*. Analysing the potential deteriogenic impact of each species (DI), a new index proposed by the authors, it emerged that the most dangerous were *Centranthus ruber* subsp. *ruber* and *Parietaria judaica*. Methods for the eradication of the most damaging species are discussed and proposed.

1. Introduction

Worldwide, ancient remains are subjected to degradation and deterioration, and their preservation has become a source of concern for the scientific community. The deterioration of stone monuments is a natural and irreversible process and is the result of the combination of physical, chemical and biological factors (Warscheid and Braams, 2000). In recent years, the attention of biologists has been drawn to living organisms i.e. bacteria, algae, fungi, lichens, bryophytes and vascular plants, which colonise buildings, ruins, walls, artefacts, statues and columns on historical sites. Walls and other architectural structures are known to be an extreme environment for plant life in many respects. Limiting factors include the availability of safe sites for settlement, the hardness and alkalinity of the substrate, the scarcity of soil and moisture, and the large oscillation of substrate and air temperature (Segal, 1969). Nonetheless, walls can provide a key habitat for a wide range of vascular plants, mainly owing to their heterogeneity regarding building material, exposure and slope. In the case of abandonment or neglect, walls can host a rich plant diversity and also rare species. Significant examples for Italy are *Hieracium australe* Fr. subsp. *australe* (Asteraceae), a strictly localised Italian endemic of the Sforza Castle in Milan (Galasso et al., 2012), and *Centranthus macrosiphon* Boiss. (Valerianaceae), a naturalized alien on the Royal Palace of Portici (Stinca and Motti, 2009).

Establishment of higher plants generally requires crevices, fractures and interstices in the wall (Francis, 2010). The study of the flora growing on walls is of particular importance for assessing the risk of deterioration of man-made structures and for maintenance planning. Indeed, natural flora in monumental areas is often viewed with some concern because plants can damage monuments with their roots, can give the appearance of neglect, obstruct site access for visitors or conceal the monuments themselves (Kanellou et al., 2017). However, some species or plant communities may be worth protecting e.g. species included in Red Lists or in national and international nature conservation laws, and can confer a beneficial effect on the landscape. For these reasons, also in Italy, some recent works have focused on the relationship between vascular plants and stone monuments (e.g. Caneva et al., 2002; Celesti Grapow and Blasi, 2003; Minissale et al., 2015; Ceschin et al., 2016; Cicinelli et al., 2018; Celesti-Grapow and Ricotta, 2020). However, the results obtained are not applicable to the entire Italian cultural heritage. As a contribution to this still under-investigated field of research, the aim of the present work was to analyse the deteriogenic vascular flora of Villa Rufolo in Ravello. Villa Rufolo is one of the most famous heritage

* Corresponding author.
E-mail address: adriano.stinca@unicampania.it (A. Stinca).

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sites in southern Italy, whose construction dates back to the early 13th century. As the monumental complex has gardens with many exotic plants and is located on the Sorrento Peninsula, an area with a high degree of naturalness, we hypothesise a significant presence of deteriogenic plants coming from surrounding natural or semi-natural areas. These data are critical for the choice of appropriate preventive and eradication methods to ensure the conservation of this monument.

2. Materials and methods

2.1. Study site

Covering an area of about 12,000 m^2, Villa Rufolo and its gardens (40°38′57.7’’N, 14°36′43.06’’E) are situated in the centre of Ravello municipality at 365 m a.s.l. (Fig. 1A and B). The study site falls within the Monti Lattari Regional Park and the “Monti Lattari” Important Plant Area (code IPA CAMP 6; Blasi et al., 2010). Ravello, a small town on the Amalfi Coast on the southern slopes of the Sorrento Peninsula (province of Salerno, Campania region, South Italy), was founded in the 5th century AD as a haven from barbarian incursions. In recent years, it has become a very popular tourist destination and has been listed as a UNESCO World Heritage Site since 1996.

Villa Rufolo dates back to the 13th century, and was mentioned by Giovanni Boccaccio in his Decameron (1348–1353). In 1851 the villa was bought by the Scottish philanthropist Francis Neville Reid, an expert on botany and ancient art, who restored both the villa itself and the gardens, giving life to today’s layout. The gardens provided the inspiration for Richard Wagner in 1880 for the setting of the enchanted garden of Klingsor in his opera Parsifal. Since 2007, the management of this heritage site has been entrusted to the Ravello Foundation and every year the site attracts over 250,000 visitors. Since 1953, the villa has been the venue for the world-famous summer festival of music known as the Ravello Festival.

The main building material of the architectural structures of Villa Rufolo consists of Mesozoic limestone from the Lattari Mountains. The limestone blocks are joined with mortar and sometimes covered by plaster consisting mainly of sand, pozzolan, lime and/or cement.

Climate (temperature and rainfall data from Agerola meteorological station, about 6 km from Villa Rufolo) is referable to the Mediterranean type, with average monthly temperatures ranging from 6 °C in winter to 21 °C in summer. Annual precipitation exceeds 1100 mm and occurs mainly in the autumn-winter period (Stinca et al., 2020). Given the proximity of the Tyrrhenian Sea and the modest elevations reached by the site of Ravello, snowfall is very rare and negligible for practical purposes in defining the climate of the area.

2.2. Data collection and analysis

Despite periodic maintenance, the walls of the villa, especially those hard to reach by workers, show extensive plant colonisation (Fig. 1C and D) and potential deterioration problems. Our list of flora was based on field investigation carried out from March 2016 to April 2017. The vascular plants observed in the study site were identified in the field except for dubious cases, which were collected and later identified at the

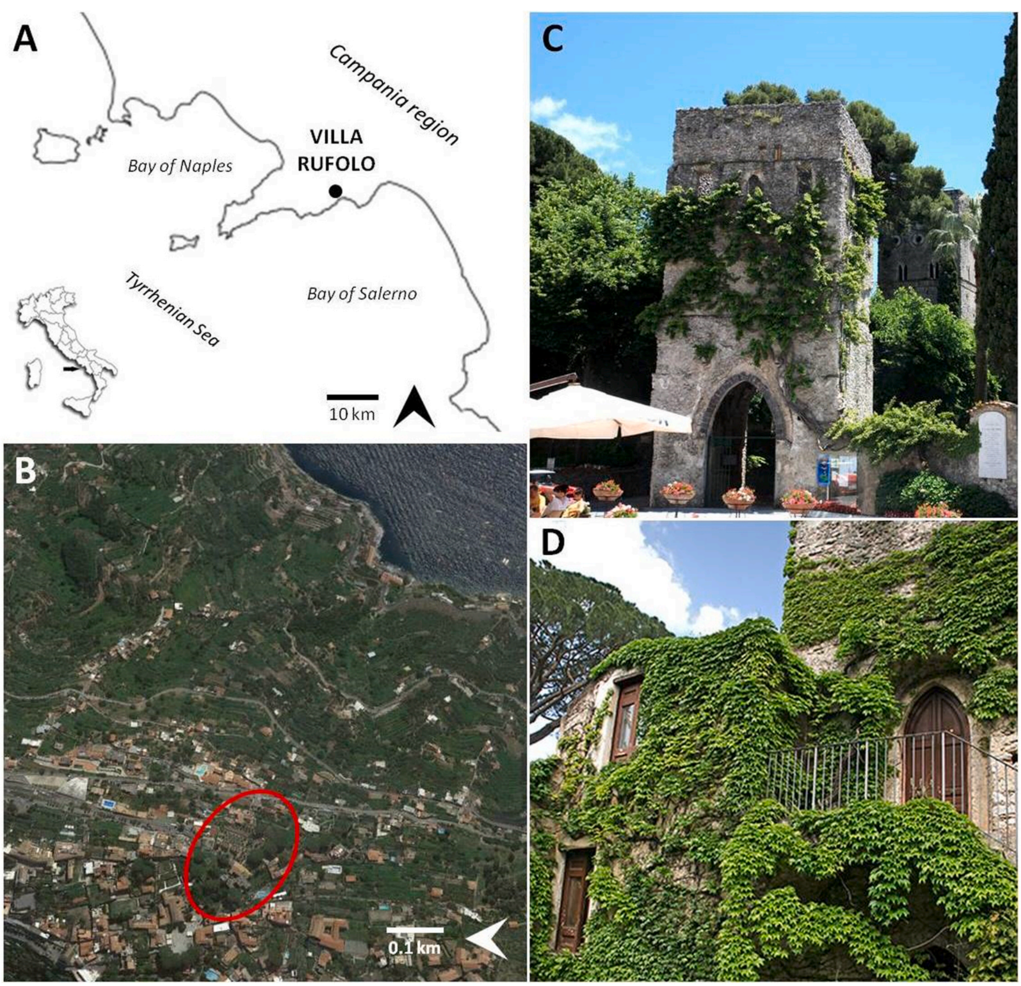

Fig. 1. Location in southern Italy and Campania of Villa Rufolo (A). Aerial view of Ravello with study site pinpointed in red (B). Some deteriogenic vascular plants colonising the architectural structures (C: *Hedera helix* subsp. *helix*; D: *Parthenocissus tricuspidata*).

Herbarium Porticense (PORUN, acronym according to Thiers, 2020), according to Pignatti (1982), Pignatti et al. (2017a, 2017b, 2018, 2019) and Tutin et al. (1968, 1972, 1976, 1980, 1993). Nomenclature and taxa delimitation follow the checklist of Italian vascular flora (Bartolucci et al., 2018; Galasso et al., 2018) and recent updates.

The main features of the deteriogenic plant community established in the study site were analysed in terms of diversity, structure, chorology and origin using species richness, life forms (Pignatti et al., 2017a, 2017b, 2018), chorotypes (Peruzzi et al., 2015; Pignatti et al., 2017a, 2017b, 2018; Bartolucci et al., 2018) and their presence as cultivated in the gardens and spread by propagules on its architectural structures (CS) or present in natural or semi-natural environments of the Sorrento Peninsula (NE), respectively. For the alien taxa, the status of naturalization in Campania was indicated according to Galasso et al. (2018). As reported in previous studies (e.g. Celesti-Grapow and Blasi, 2004; Castellano et al., 2007; Motti and Stinca, 2011; Caneva et al., 2018; Motti and Bonanomi, 2018), to evaluate the hazard of biodeteriogens for the villa, each taxon was assigned a hazard index (HI; Signorini, 1995, 1996). HI was originally proposed to assess the potential risks due to plants in the context of monument conservation, and it is based on plant life form, invasiveness, vigour, size and shape of the root system, with values ranging between 0 (lowest hazard) to 10 (highest hazard). Applied to a floristic list, the limit of HI is that it does not take into account the abundance of each species. It is therefore not possible to carry out a quantitative hazard assessment of the flora growing at a specific site. Here, to better quantify the hazard of each species we propose a new index called the Deteriogenic Index (DI). The DI value ranges from 0 to 60 and is the result of the multiplication between the hazard index of a single species (HI_i) and the abundance of a single species (A_i; expressed by the following scale: 1 = <1%, 2 = 1–5%, 3 = 6–25%, 4 = 26–50%, 5 = 51–75%, 6 = 76–100%; Braun-Blanquet, 1964). Moreover, we propose a refinement of the HI that takes into account the total vascular flora: $HItot_{av}$. The value of $HItot_{av}$ ranged from 0 to 60 and was calculated with the following equation:

$$HI_{tot_{av}} = \frac{\sum_{i=1}^{K} HI_i A_i}{K}$$

where k is the total number of the species found in the study area.

One-way analysis of variance (ANOVA) was applied to test the effect of plant life form and chorotype on HI of a single species. The significance was evaluated at $p < 0.05$ using the Tukey HSD test. Furthermore, Pearson's correlation analysis was employed to identify the relationship between the A value and HI ($p < 0.05$).

3. Results

3.1. Deteriogenic vascular flora: diversity, structure, chorology and origin

The deteriogenic vascular flora found on the architectural structures of Villa Rufolo included 61 taxa (Table 1). There were three pteridophytes i.e. *Adiantum capillus-veneris*, *Asplenium ceterach* subsp. *ceterach* and *Polypodium cambricum*, and 58 angiosperms. The most species-rich family was the Asteraceae (12 taxa), followed by the Poaceae (5), Brassicaceae and Plantaginaceae (4).

The life form spectrum, defining the plant community structure, showed a prevalence of therophytes (42.6%), followed by hemicryptophytes (24.6%), chamaephytes (14.8%), geophytes (9.8) and phanerophytes (8.2%) (Table 1).

The total flora detected at the study site was characterized by a prevalence of widely distributed species (42.6%, of which 16.4% were aliens species, 16.4% cosmopolitan and 6.5% doubtful aliens) compared to the other chorological types: Mediterranean (36.1%, comprising 19.7% euri-Mediterranean and 16.4% steno-Mediterranean), Eurasian (11.5%), Italian endemics (8.2%) and Atlantic species (1.6%) (Table 1).

Regarding the origin of biodeteriogens, only three species that are currently cultivated in the gardens of Villa Rufolo have spread to its architectural structures i.e. *Acanthus mollis* subsp. *mollis*, *Parthenocissus tricuspidata* and *Tagetes erecta*. In other words, 95.1% of the deteriogenic vascular flora came from the natural or semi-natural environments of the surrounding area (Table 1).

3.2. Deteriogenic vascular flora: impact on the monument

Of the species growing on the walls of Villa Rufolo, 54.1% were not very hazardous (HI 0–3), 39.3% were quite hazardous (HI 4–6), and 6.6% were very hazardous (HI 7–10; i.e. *Capparis orientalis*, *Ficus carica*, *Hedera helix* subsp. *helix* and *Parthenocissus tricuspidata*) (Table 1).

As regards their abundance (A) on the architectural structures of the villa, 72.1% of the species were rare or of scarce abundance, 23.0% were of medium abundance and 4.9% were very abundant, namely *Campanula fragilis* subsp. *fragilis*, *Centranthus ruber* subsp. *ruber* and *Parietaria judaica* (Table 1).

On analysing the potential deteriogenic impact of each species, it emerged that the most dangerous were *Centranthus ruber* subsp. *ruber* and *Parietaria judaica* (DI = 15), followed by *Capparis orientalis* and *Hedera helix* subsp. *helix* (DI = 14) (Table 1). The average hazard index of the total vascular flora ($HItot_{av}$) in the study site was 4.4 ± 3.9.

The HI of each species was significantly affected by the plant life form (ANOVA, Tukey HSD test $p < 0.00001$) (Fig. 2A). The species with the highest impact were phanerophytes, with an average HI of 7.2 ± 1.8, followed by the chamaephytes (4.7 ± 0.5), hemicryptophytes (4.2 ± 0.9), geophytes (2.8 ± 0.4) and therophytes (1.2 ± 1.1). HI was not significantly affected by the chorotype (ANOVA, Tukey HSD test $p = 0.09$) (Fig. 2B). However, on the walls of Villa Rufolo, Italian endemic species had a higher average impact (5.0 ± 0.7) in comparison to the other chorological types (steno-Mediterranean 3.2 ± 1.9, euri-Mediterranean 2.1 ± 2.0, Eurasian 3.9 ± 2.2, wide distribution 3.0 ± 2.3). Pearson's correlation analysis highlighted a weak correlation between the A value and HI ($r = 0.187$, $p = 0.15$) (Fig. 3).

4. Discussion

4.1. Features of the deteriogenic vascular flora

Overall, we found 61 deteriogenic vascular plant taxa on the architectural structures of Villa Rufolo. This value is much higher that recorded in a similar study carried out in four castles situated in the Naples metropolitan area (61 vs 24) (Motti and Bonanomi, 2018). This is surprising considering the similar climatic conditions and the lower bioreceptivity (Guillite, 1995) of the limestone walls of Villa Rufolo, due to their limited porosity and high hardness compared to volcanic tuff and plaster, very commonly used for instance in castles in the province of Naples (Motti and Bonanomi, 2018). The latter materials facilitates water penetration and retains moisture for longer compared to other substrates. Indeed, bioreceptivity is higher for porous rocks and those with a rough surface, such properties adsorbing and retaining more water (Kumbaric et al., 2012; Korkanç and Savran, 2015). That said, a crucial role in the colonisation of deteriogenic species was undoubtedly played by the discontinuities present between the constituent elements of the walls in the villa. Most of the walls observed were vertical or very inclined and showed more or less deep cavities between the bricks where the substrate required for plant growth had accumulated. According to Lisci and Pacini (1993) and Hosseini and Caneva (2021), plant colonisation of crevices and cavities in vertical walls is quite difficult because of the severe environmental conditions that limit plant establishment and growth. Therefore, we hypothesise the role of other environmental factors that can promote extensive plant colonisation on the stone walls of Villa Rufolo. Although we cannot exclude the "maintenance" variable, our data support the hypothesis that most of the deteriogenic plants of Villa Rufolo come from the surrounding natural or semi-natural

Table 1
Inventory of the deteriogenic vascular flora surveyed in Villa Rufolo. For each taxon we report the main synonym (if present), family, plant life form, chorotype, origin (CS: cultivated in the gardens of Villa Rufolo and spread on its architectural structures; NE: also present in natural or semi-natural environments of the Sorrento Peninsula), hazard index (HI; from 0 to 10), abundance (A; from 1 to 6) and potential deteriogenic impact of the population of a single species on the building (DI; from 0 to 60).

Taxon	Family	Plant life form	Chorotype	Origin	HI	Abundance	DI
Acanthus mollis* L. subsp. *mollis	Acanthaceae	Hemicryptophyta scaposa	Doubtful alien [Mediterranean]	CS	4	1	4
***Adiantum capillus-veneris* L.**	Pteridaceae	Geophyta rhizomatosa	Palaeotropical	NE	3	2	6
***Allium neapolitanum* Cirillo**	Amaryllidaceae	Geophyta bulbosa	Steno-Mediterranean	NE	2	1	2
Anisantha madritensis* (L.) Nevski subsp. *madritensis [≡ *Bromus madritensis* L. subsp. *madritensis*]	Poaceae	Therophyta scaposa	Euri-Mediterranean	NE	0	1	0
***Antirrhinum siculum* Mill.**	Plantaginaceae	Hemicryptophyta scaposa	Endemic	NE	6	1	6
Arabis collina* Ten. subsp. *collina	Brassicaceae	Hemicryptophyta scaposa	Orophyte S-European	NE	4	1	4
***Artemisia annua* L.**	Asteraceae	Therophyta scaposa	Invasive alien [E Europe, W and C Asia]	NE	4	1	4
Asplenium ceterach* L. subsp. *ceterach [= *Ceterach officinarum* Willd. subsp. *officinarum*]	Aspleniaceae	Hemicryptophyta rosulata	Eurasian	NE	3	1	3
***Borago officinalis* L.**	Boraginaceae	Therophyta scaposa	Euri-Mediterranean	NE	4	1	4
Campanula fragilis* Cirillo subsp. *fragilis	Campanulaceae	Chamaephyta suffrutescentia	Endemic	NE	4	3	12
***Capparis orientalis* Veill.** [= *Capparis spinosa* L. subsp. *rupestris* (Sm.) Nyman]	Capparaceae	Nano-Phanerophyta	Eurasian	NE	7	2	14
***Capsella rubella* Reut.**	Brassicaceae	Therophyta scaposa	Euri-Mediterranean	NE	1	1	1
***Cardamine hirsuta* L.**	Brassicaceae	Therophyta scaposa	Cosmopolitan	NE	3	2	6
Catapodium rigidum* (L.) C.E.Hubb. subsp. *rigidum	Poaceae	Therophyta scaposa	Euri-Mediterranean	NE	0	2	0
Centranthus ruber* (L.) DC. subsp. *ruber	Valerianaceae	Chamaephyta suffrutescentia	Steno-Mediterranean	NE	5	3	15
Clinopodium nepeta* (L.) Kuntze subsp. *nepeta [≡ *Calamintha nepeta* (L.) Savi subsp. *nepeta*]	Lamiaceae	Chamaephyta suffrutescentia	Steno-Mediterranean	NE	5	2	10
Crepis neglecta* L. subsp. *neglecta	Asteraceae	Therophyta scaposa	Euri-Mediterranean	NE	2	1	2
Cymbalaria muralis* G.Gaertn., B.Mey. & Scherb. subsp. *muralis	Plantaginaceae	Hemicryptophyta caespitosa	S-European	NE	4	2	8
Daucus carota* L. subsp. *carota	Apiaceae	Hemicryptophyta biennia	Palaeotemperate	NE	3	1	3
Dittrichia viscosa* (L.) Greuter subsp. *viscosa	Asteraceae	Chamaephyta suffrutescentia	Euri-Mediterranean	NE	5	1	5
***Dolichandra unguis-cati* (L.) L.G.Lohmann** [≡ *Macfadyena unguis-cati* (L.) A.H.Gentry]	Bignoniaceae	Phanerophyta lianosa	Casual alien [N, C and S America]	NE	5	1	5
***Erigeron karvinskianus* DC.**	Asteraceae	Hemicryptophyta scaposa	Invasive alien [N, C and S America]	NE	4	2	8
***Erigeron sumatrensis* Retz.**	Asteraceae	Therophyta scaposa	Invasive alien [S America]	NE	3	1	3
***Euphorbia peplus* L.**	Euphorbiaceae	Therophyta scaposa	Cosmopolitan	NE	1	1	1
Festuca danthonii* Asch. & Graebn. subsp. *danthonii [= *Vulpia ciliata* Dumort.]	Poaceae	Therophyta caespitosa	Subcosmopolitan	NE	0	1	0
***Ficus carica* L.**	Moraceae	Phanerophyta scaposa	Mediterranean-Turanian	NE	10	1	10
Fumaria capreolata* L. subsp. *capreolata	Papaveraceae	Therophyta scaposa	Euri-Mediterranean	NE	1	1	1
***Galinsoga quadriradiata* Ruiz & Pav.** [= *G. ciliata* (Raf.) S.F.Blake]	Asteraceae	Therophyta scaposa	Invasive alien [N, C and S America]	NE	1	1	1
Galium lucidum* All. subsp. *lucidum	Rubiaceae	Hemicryptophyta scaposa	Euri-Mediterranean	NE	4	2	8
***Galium murale* (L.) All.**	Rubiaceae	Therophyta scaposa	Steno-Mediterranean	NE	1	1	1
***Geranium rotundifolium* L.**	Geraniaceae	Therophyta scaposa	Palaeotemperate	NE	2	1	2
Hedera helix* L. subsp. *helix	Araceae	Phanerophyta lianosa	Subatlantic	NE	7	2	14
***Helichrysum litoreum* Guss.**	Asteraceae	Chamaephyta suffrutescentia	Endemic	NE	5	1	5
***Heliotropium europaeum* L.**	Heliotropiaceae	Therophyta scaposa	Mediterranean-Turanian	NE	1	1	1
***Hordeum murinum* L. subsp. *leporinum* (Link) Arcang.**	Poaceae	Therophyta scaposa	Euri-Mediterranean	NE	0	1	0
***Ipomoea indica* (Burm.) Merr.** [= *I. acuminata* (Vahl) Roem. & Schult.]	Convolvulaceae	Geophyta rhizomatosa	Invasive alien [Tropical Asia, S America]	NE	3	1	3
***Jacobaea maritima* (L.) Pelser & Meijden subsp. *bicolor* (Willd.) B.Nord. & Greuter**	Asteraceae	Chamaephyta suffrutescentia	Endemic	NE	5	1	5
***Linaria purpurea* (L.) Mill.**	Plantaginaceae	Hemicryptophyta scaposa	Endemic	NE	5	1	5
***Lobularia maritima* (L.) Desv.**	Brassicaceae	Chamaephyta suffrutescentia	Steno-Mediterranean	NE	4	1	4
Lysimachia arvensis* (L.) U.Manns & Anderb. subsp. *arvensis [≡ *Anagallis arvensis* L. subsp. *arvensis*]	Primulaceae	Therophyta scandentia	Cosmopolitan	NE	1	1	1
***Mercurialis annua* L.**	Euphorbiaceae	Therophyta scaposa	Palaeotemperate	NE	1	2	2
Micromeria graeca* (L.) Benth. ex Rchb. subsp. *graeca	Lamiaceae	Chamaephyta suffrutescentia	Steno-Mediterranean	NE	4	2	8
***Oxalis corniculata* L.**	Oxalidaceae	Hemicryptophyta reptantia	Doubtful alien [Cosmopolitan]	NE	4	1	4
***Oxalis latifolia* Kunth**	Oxalidaceae	Geophyta bulbosa	Naturalized alien [N, C and S America]	NE	3	1	3

(*continued on next page*)

Table 1 (*continued*)

Taxon	Family	Plant life form	Chorotype	Origin	HI	Abundance	DI
Oxalis pes-caprae **L.**	Oxalidaceae	Geophyta bulbosa	Invasive alien [S Africa]	NE	3	1	3
Papaver rhoeas **L. subsp.** ***rhoeas***	Papaveraceae	Therophyta scaposa	Doubtful alien (probably E Mediterranean)	NE	1	1	1
Parietaria judaica **L.**	Urticaceae	Hemicryptophyta scaposa	Euri-Mediterranean	NE	5	3	15
Parietaria lusitanica **L. subsp.** ***lusitanica***	Urticaceae	Therophyta reptantia	Steno-Mediterranean	NE	1	1	1
Parthenocissus tricuspidata **(Siebold & Zucc.) Planch.**	Vitaceae	Phanerophyta lianosa	Naturalized alien [E Asia]	CS	7	1	7
Polypodium cambricum **L.**	Polypodiaceae	Hemicryptophyta rosulata	Euri-Mediterranean	NE	3	1	3
Reichardia picroides **(L.) Roth**	Asteraceae	Hemicryptophyta scaposa	Steno-Mediterranean	NE	6	1	6
Salpichroa origanifolia **(Lam.) Baill.**	Solanaceae	Chamaephyta suffrutescentia	Invasive alien [S America]	NE	5	1	5
Senecio vulgaris **L. subsp.** ***vulgaris***	Asteraceae	Therophyta scaposa	Cosmopolitan	NE	1	1	1
Setaria italica **(L.) P.Beauv. subsp.** ***viridis*** **(L.) Thell.**	Poaceae	Therophyta scaposa	Doubtful alien (uncertain origin)	NE	0	1	0
Solanum nigrum **L.**	Solanaceae	Therophyta scaposa	Cosmopolitan	NE	1	2	2
Sonchus oleraceus **L.**	Asteraceae	Hemicryptophyta scaposa	Cosmopolitan	NE	4	2	8
Tagetes erecta **L.** [= *T. patula* L.]	Asteraceae	Therophyta scaposa	Casual alien [N America]	CS	1	1	1
Trachelium caeruleum **L. subsp.** ***caeruleum***	Campanulaceae	Hemicryptophyta scaposa	Naturalized alien [W Mediterranean]	NE	4	1	4
Umbilicus horizontalis **(Guss.) DC.**	Crassulaceae	Geophyta bulbosa	Steno-Mediterranean	NE	3	1	3
Urtica membranacea **Poir.**	Urticaceae	Therophyta scaposa	Steno-Mediterranean	NE	1	2	2
Veronica cymbalaria **Bodard subsp.** ***cymbalaria***	Plantaginaceae	Therophyta scaposa	Euri-Mediterranean	NE	0	1	0

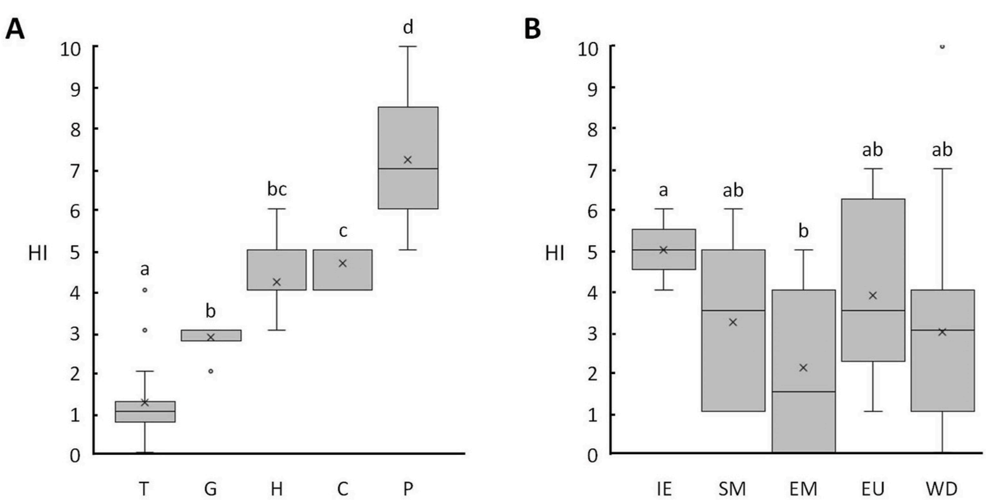

Fig. 2. Variations of HI of a single species in (A) plant life forms (T: therophytes; G: geophytes; H: hemicryptophytes; C: chamaephytes; P: phanerophytes) and (B) chorological types (IE: Italian endemics; SM: steno-Mediterranean; EM: euri-Mediterranean; EU: Eurasian; WD: wide distribution, including alien species) (total values; rectangles define 25th and 75th percentiles, horizontal lines show median values, whiskers indicate extreme values, symbols " × " indicate the average value). Different letters indicate significant differences (Tukey test, $p < 0.05$).

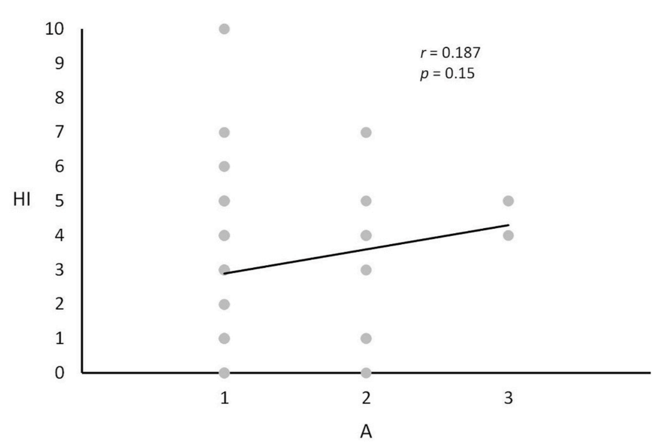

Fig. 3. Correlation (Pearson's r coefficient and associated p value) between the species abundance value (A; from 1 to 6) and hazard index of a single species (HI; from 0 to 10).

areas. Indeed, 95.1% of the surveyed deteriogenic vascular flora was present in the other environments of the Sorrento Peninsula like Mediterranean maquis and evergreen woodland. Many of the detected species are known to be able to spread their propagules over long distances using wind e.g. *Dittrichia viscosa* subsp. *viscosa*, *Erigeron sumatrensis*, *Jacobaea maritima* subsp. *bicolor* and *Centranthus ruber* subsp. *ruber*, or animal vectors e.g. *Ficus carica*, *Hedera helix* subsp. *helix*, *Capparis orientalis*, *Helichrysum litoreum*, *Oxalis corniculata*, *Parthenocissus tricuspidata* and *Reichardia picroides*. Therefore, it would appear that the main biodeterioration problems occur in monuments located in environments conducive to the development of vascular plants (e.g. Motti and Stinca, 2011).

In our survey, HI was significantly affected by the plant life form. This result is confirmed by the visible damage produced on the walls of the villa i.e. cracking, deformation, and detachment of limestone blocks and plasters, by woody plants and particularly by phanerophytes like *Ficus carica*. Interestingly, ornamental trees grown in gardens and distant from the walls, e.g. *Pinus pinea*, can also damage them. Indeed, the growing roots are able to develop enormous physical pressure, through both direct mechanical action and indirect effects of water absorption from the soil surrounding the foundations of monuments (Biddle, 2001; Trotta et al., 2020). Damage to underground archaeological structure is also frequent in historical sites (Caneva et al., 2006, 2009).

Our results are in agreement with those obtained by Motti and Stinca (2011) at the Royal Palace of Portici, also in terms of plant community structure. In both monuments, the relationship between therophytes and hemicryptophytes (T/H ratio) is very similar (Villa Rufolo 1.7 vs Royal Palace of Portici 1.9). In Villa Rufolo, the considerable presence of chamaephytes may be related to the surrounding natural vegetation which serves as a reservoir of deteriogenic species, such as the Italian endemics *Campanula fragilis* subsp. *fragilis*, *Helichrysum litoreum* and *Jacobaea maritima* subsp. *bicolor*. All these are widely distributed taxa on the limestone cliffs of the Sorrento Peninsula and were detected on the villa walls. The above evidence supports the hypothesis that wall plant species come mainly from rocky habitats (Ceschin et al., 2016).

The large presence of alien species could be related to human impact, and is in line with the trend of increasing pressure of alien species in the Sorrento Peninsula and the wider region of Campania (e.g. Stinca and Motti, 2013; Stinca et al., 2016; 2017; Motti et al., 2018; Stinca, 2019; Del Guacchio et al., 2020). Indeed, a recent study conducted at 26 ancient sites in Rome that had been surveyed repeatedly since the 1940s revealed an increase in woody non-native species (Celesti-Grapow and Ricotta, 2020).

One of the most surprising findings in our research was the absence of *Ailanthus altissima* (Mill.) Swingle (Simaroubaceae) on the architectural structures of Villa Rufolo, a very common exotic tree on the Sorrento Peninsula where it has unfortunately invaded both natural and anthropogenic environments. *Ailanthus altissima*, also known as tree of heaven, has proved to be damaging to ancient buildings and among archaeological remains due to its rapid growth, aggressive root system and clonal reproduction (Almeida et al., 1994; Celesti-Grapow and Blasi, 2004; Motti et al., 2020; Trotta et al., 2020). It was also recently included among the invasive species of European Union concern (EU Regulation, 2019/1262).

The total flora found in Villa Rufolo comprised many non-dangerous and very abundant species, as well as a few very harmful vascular plants of low abundance. This pattern of plant colonisation pattern explains the weak correlation between the species abundance value and HI. In agreement with previous findings (e.g. Caneva et al., 1991; Mishra et al., 1995), *Ficus carica*, *Hedera helix* subsp. *helix* and *Capparis orientalis* are potentially very damaging species for historical buildings. *Ficus carica* (HI = 10; DI = 10), commonly known as fig, was the most dangerous vascular plant observed at Villa Rufolo. It can be found on various substrates, in different water availability and light conditions (Lisci and Pacini, 1993), and can cause severe damage due to the expansion of its root system. Being a plant with many ethnobotanical uses (Salerno et al., 2017), its challenge to the conservation of architectural structures is often neglected.

Hedera helix subsp. *helix* (HI = 7; DI = 14), also known as ivy, is a climbing, woody evergreen species native to the Mediterranean-Atlantic region. It is one of the plants most commonly found growing on buildings in the Euro-Mediterranean area (Bartoli et al., 2017). The species can reach up to 30 m in height, its root diameter can attain 20 cm, and it can climb with the help of its adventitious aerial roots, thereby damaging walls (Elinç et al., 2013). However, some studies have demonstrated that ivy cover changes temperature and relative humidity compared to adjacent exposed surfaces, suggesting that this species can have a bioprotective role. Indeed an ivy canopy can reduce extremes of temperature and relative humidity, thereby contributing to building conservation. Furthermore, *H. helix* subsp. *helix* may reduce decay processes on stone walls by absorbing fine and ultra-fine particles that would ordinarily accelerate rock weathering (e.g. Francis, 2010; Sternberg et al., 2010, 2011; Viles et al., 2011).

Capparis orientalis (HI = 7; DI = 14), known as caper, is a very common shrub growing in rocky habitats of the Sorrento Peninsula. Here, the chasmophytic vegetation consists of plant communities that colonise the cracks and fissures of more or less vertical rocks. In this environment, water and nutrients are limiting and environmental conditions are very stressful for vascular plants in terms of temperature oscillation, strong winds and long periods of moisture shortage. However, thanks to a deep mycorrhizal root system, caper can successfully grow on infertile substrates and cope with severe environmental abiotic stresses (Pugnaire and Esteban, 1991). It is therefore one of the common species on the walls of historic monuments in Campania (Motti and Stinca, 2011; Motti and Bonanomi, 2018; Motti et al., 2020).

Parthenocissus tricuspidata (HI = 7; DI = 7), commonly known as Japanese ivy, is a popular ornamental liana native to East Asia and very common in the gardens of the Sorrento Peninsula. It climbs with its branched tendrils which end in adhesive discs that attach themselves quite strongly to walls or other supports. A single mature adhesive disc has an average attached area of about 1.22 mm^2 and an adhesive force of about 13.7 N (He et al., 2010). The numerous tendrils, if detached from the walls, cause serious damage.

Among the very abundant species in the study site, in addition to deterioration problems, *Centranthus ruber* subsp. *ruber* (HI = 5; DI = 15) has a great ability to adapt to different environments, modifying leaf morpho-functional traits following anthropogenic impact (De Micco et al., 2020), while *Parietaria judaica* (HI = 5; DI = 15) can make visits to the villa physically uncomfortable as its pollen is known to elicit severe pollinosis in many areas of the world (Fotiou et al., 2011; Mardones et al., 2013).

4.2. Management of the deteriogenic vascular flora

Management of deteriogenic plants in historical sites represents an emerging challenge for the conservation of such monuments. This is a highly complex problem, particularly when such species are of phytogeographical interest and grow on walls located in protected natural areas (Cicinelli et al., 2018), such as Villa Rufolo which lies within the Monti Lattari Regional Park. It should also be borne in mind that some management actions (e.g. uprooting and use of brushcutters) can inflict considerable damage on monuments.

Based on the above description, it would appear necessary to eradicate the woody species with HI ≥ 7 from the walls of the villa, also to avoid possible major structural problems in the future. For these plants (i.e. *Capparis orientalis*, *Ficus carica*, *Hedera helix* subsp. *helix* and *Parthenocissus tricuspidata*), felling must be followed by a herbicide treatment applied to the stump to avoid re-growth (Caneva et al., 1996). Three possible treatment techniques are suggested for this purpose: i. stem injection; ii. tree cutting and stump application of herbicide; iii. tree cutting and stump injection of herbicide. All these techniques involve the application of herbicides directly on the plant, with minimal dispersion in the surrounding environment. Stem injection consists in making a cut or a hole, and then injecting a small amount of herbicide (DiTomaso and Kyser, 2007). The cut stump method involves cutting off the plant completely at its base and a herbicide solution being then painted onto the exposed surface. The stump injection method is very similar to the cut stump treatment but the herbicide is injected. These treatments allow the herbicide to translocate throughout the roots and/or rhizome of the plant (Mendes et al., 2017). 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 position of the plant in relation to the wall. According to Caneva et al. (2009), tree felling should be followed by the consolidation of the walls, because, with the death of the living roots, collapses and structural damage could arise.

Only for the species with DI ≥ 14, i.e. *Centranthus ruber* subsp. *ruber* and *Parietaria judaica*, the use of herbicide solution is prescribed, painted directly on the leaves to avoid environmental dispersion. Moreover, the periodic use of anti-germinative products applied directly in the wall cracks would be a good practice. Finally, the finding of some Italian endemics (i.e. *Antirrhinum siculum*, *Campanula fragilis* subsp. *fragilis*, *Helichrysum litoreum*, *Jacobaea maritima* subsp. *bicolor* and *Linaria purpurea*; all with HI < 7 and DI < 14) on the walls of Villa Rufolo opens up new horizons for the implementation of the tourist offer of the site. These plants, which are currently included in the IUCN Red List of the Italian Flora (Orsenigo et al., 2018) also have ornamental characteristics which are highly appreciated. Therefore, they should not be uprooted and could be enhanced by affixing information plaques.

5. Conclusions

The purpose of floristic research in monumental and archaeological areas should be both to conserve artefacts from the most deteriogenic plant taxa, and to protect rare plant or those of phytogeographical interest. Our findings offered an insight into the deteriogenic vascular flora growing in Villa Rufolo, one of the most important heritage sites in Italy. In the study site we highlighted the role of the surrounding natural vegetation as a reservoir of biodeteriogens. This floristic analysis is also intended as a starting point for the preventive control of plants, aimed at conservation of the site in question.

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.

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