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Original article

Risk, hazard, and vulnerability for stone biodeterioration due to higher plants: The methodological proposal of a multifactorial index (RHV)

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ABSTRACT

The growth of higher plants on buildings and stone monuments can cause various biodeterioration phenomena. Along with careful management of higher plants in archeological sites and monumental areas, a comprehensive method for assessing the risk they pose to stone conservation still needs to be developed. We propose, therefore, a multi-factorial index of risk from higher plants which will evaluate relevant threats to stone structures and local conditions of vulnerability (RHV). We suggest associating such threats with the environmental conditions (defined by bioclimate and environmental context) and with the plant growth characteristics (defined by life forms, root systems and stem development features, ecological preference, and physiological characteristics). We also suggest associating vulnerability with edaphic factors (stone typology and colonization microsites) and with conservation status, including management activities. The proposed index was tested at a number of international sites in a bioclimatic gradient varying from a temperate climate (Lucca, Italy) to Mediterranean (Rome, Italy) and sub-Mediterranean xeric (Pasargadae, Iran) and tropical (Angkor, Cambodia) conditions. The results show how useful such an index can be in performing analytical assessments of the risk posed by ruderal plants in cultural heritage sites.

1. Introduction

The study of plant colonization on buildings and monuments often involves a specific focus on floristic features and how they vary over time [1–8] such as the ecological characteristics of species [9–11] as well as on plant communities [12–16] and on the microhabitats of ruderal plant settlements [17–19]. Increasing anthropic pressures in cities and at archeological sites has meant that the protection of biodiversity and the naturalistic features of flora has become a critical issue [20–23].

Conversely, the growth of higher plants on monuments is viewed negatively by cultural heritage conservators due the effects of weathering, which occurs when roots interact with stone structures [17–19]. Such damage arises trough exchange processes of hydrogen ions present on the root tips, (varying among pH 4 and 6 [24]), or through the net of colloidal particles, following the well-known lyotropic series ($Ba^{2+} > Ca^{2+} > Mg^{2+} > Cs^{+} > Rb^{+} > NH^{4+} > K^{+} > Na^{+} > Li^{+}$) and partly from the emission of various chemical exudate [24–29]. The mechanical pushing of root is, however, the main mechanism, and it arises from the increase in root diameter of wooden species and also from the physical alteration of the soil volume by radical absorption [25,30,31]. When these phenomena occur in the fissures or cracks of stones, they cause erosions by decreasing the cohesion between stones and increasing the size of the fissures and cracks [19,24,26,30].

Of all biodeterioration phenomena, in fact, the growth of higher plants on buildings and monuments has been recognized as a significant hazard for monuments [2,10,12,28,31,32]. Higher plants interact significantly with stone, especially in the case of certain woody species such as *Capparis spinosa* [33], *Ailanthus altissima* [26,34], *Ficus carica* [25], *Ficus elastica, Tetrameles nudiflora, Ceiba pentandra* [10,28]. These biodeterioration phenomena seem to be particularly pronounced in tropical regions, such as Meso-America [10,35], India, and SE Asia, where the abandonment of monuments and buildings gives way to fast higher plant colonization [10,28]. Even in arid or semi-arid bioclimates, though, higher plants can colonize pioneer substrata such as stones and buildings [19,36].

A risk assessment was performed at a UNESCO site [37] in order to evaluate natural and anthropic hazards, where several site-specific methodologies were developed. Studies of this kind sup-

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port comprehensive risk assessments and related management activities in archeological areas aimed at preventing the development of damaging circumstances [38]. It is, therefore, crucial to identify the risk parameters, defined as ‘hazard’ and ‘vulnerability’, and to assess their indicators [39,41–43]. Furthermore, it is useful to distinguish between ‘hazard’ and ‘danger’, a distinction which is not always correctly understood [44]. ‘Hazard’ is a circumstance where a threat is posed (in our case, to a monument), while ‘danger’ is a situation where the monument is put at risk or is susceptible to a possible hazard [45]. In general, and as proposed in previous studies [39,40], the risk of damage can be calculated by multiplying the values of factors that give rise to a hazard by the values of factors that cause vulnerability (Risk = Hazard × Vulnerability).

A general hazard index was proposed by Fitzner [46–48], primarily in reference to the weathering of surfaces, where biodeterioration phenomena were evaluated generically as “Biological colonization to crust” [48]. It is true that, when considering a hazard, generic damage can be taken into account but the identification of a specific risk obviously benefits from a better definition of the typology of damage. In his Monument Mapping Method (MMM) Fitzner [46–48] lists 25 possible typologies of damage called “weathering forms” (WF) at “level II”. In following his method regarding biodeterioration due to the growth of climbing plants on monuments, we have decided to use only 9 typologies of possible damage [49]. For a general assessment of hazards caused by plant colonization, Signorini [50] proposed a numerical index (HI) in the 1990s based on the most relevant characteristics of the plants present at a site such as life forms, invasiveness, and vigor, giving a numerical scale of increasing potential dangerousness. This hazard index was later applied to a number of archeological and monumental sites in Italy [5,22,51–55]. However, this index provides only a tentative and partial evaluation of risk, and contains some shortcomings in the evaluation of damage.

In particular, the values attributed to lichen and moss colonization as a whole do not seem to represent their fundamental interactions. A different index was subsequently proposed for lichens by Gazzano [56]. Recently, Motti et al. [58] proposed the Deteriogenic Index (DI), updating the previous HI and adding the cover degree for each species as an additional parameter. However, both indices ignore several of the parameters that influence hazard, including those related to a site’s environmental parameters or the ecology of the species examined. Also, they do not take into consideration the vulnerability of the substrate and, in particular, microsites of colonization, as highlighted by Lisci et al. [18] and, more recently, by Hosseini & Caneva [19]. A proper risk assessment also requires an evaluation of a heritage site’s vulnerability. ‘Vulnerability’ refers to a site’s susceptibility or exposure to a disturbance or threat, and is related to the inherent weakness of the monument in question [39,41–45]. In this context vulnerability is a result of the parameters that influence the site’s susceptibility to plant colonization. Due to the need for a more comprehensive evaluation of risk, such indices need to be improved.

1.1. Research aims

This paper aims to propose a more comprehensive risk assessment method regarding higher plant colonization at archeological sites and on monuments. The assessment will evaluate various hazard typologies, including intrinsic hazard parameters due to plant colonization and those related to environmental conditions as well as vulnerability resulting from stone and microsite characteristics and conservation status. This assessment proposal will be tested worldwide so as to take into consideration a diversity of bioclimatic conditions, building materials and microsites of growth.

2. Materials and methods

2.1. Classification of damages

With regard to plant colonization we suggest using Fitzner’s Monument Mapping Method (MMM) [46–48], but with a simplified list of possible damages that considers only the following types (Fig. 1), ordered according to incremental levels of interaction:

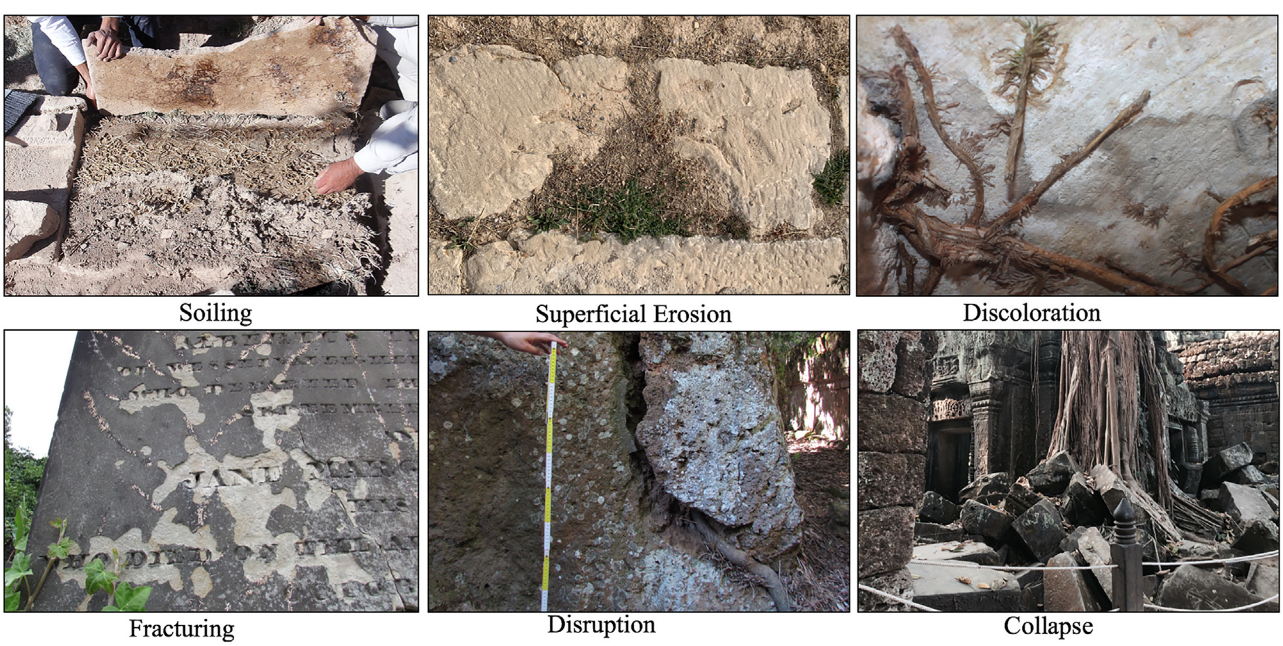

Fig. 1. Selection of weathering patterns which can be caused by higher plants: Soiling (SO) due to the growth of ephemeral plants at the Pasargadae site, Iran; Superficial erosion (SE) due to ephemeral plants at the Pasargadae site, Iran; Discoloration (DI) due to the exudates of aerial roots of *H. helix* at the Villa of Maxentius in Rome, Italy; Fracturing (FR) due to the aerial roots of *Hedera helix* in Glasgow cemetery, United Kingdom; Disruption (DS) due to woody species at the Etruscan Necropolis of Cerveteri, Italy; Collapse (CO) due to *Tetrameles nudiflora* R.Br. trees at the Angkor temple complex, Cambodia.

Table 1
Set of general indicators for hazards related to the Environmental condition of the site.

Indicators / Values	Very Low	Low	Medium	High	Very high
	Class 1	Class 2	Class 3	Class 4	Class 5
1. Bioclimatic conditions (Bc)					
Polar; Tropical desertic; Medit. Desertic	X				
Tropical xeric; Medit. Xeric; Temperate xeric; Boreal xeric; B. continent.		X			
Medit. Pluvioseasonal; Temperate Continental; Boreal oceanic			X		
Temperate Oceanic				X	
Tropical pluvial					X
2. Environmental context (EC)					
Industrial, Urban (high pollution)	X	(X)			
Green spaces in polluted urban context		X			
Green spaces and Gardens in urban context			X		
Rural				X	
Forest					X

1. Very Low (VL); *Soiling* (SO) = Facilitation of soil deposits on stone surfaces (usually caused by the presence of small ephemeral plants that favor soil deposition but do not interact significantly with the surface; such phenomena can also be produced by other plants, but in association with additional phenomena)
2. Low (L); *2a Superficial erosion* (SE) = Detachment of small grain aggregates from the surface, or Granular disintegration (GD) (where interaction between plants and stone is not easily detectable, though with a measurable increase in roughness)
3. Low (L); *2b Discoloration* (DI) = Alteration of the original stone color (interaction between plants and substrate represented by the deposition of plant exudates or metabolites)
4. Medium (M); *Fracturing* (FR) = Development of fractures and fissures, some parallel to the surface (according to the type of stone), such as Back Weathering (BW) and Flaking (FL) (the interaction between plants and stone is detectable through the observation of such penetration activity, represented mainly by the presence of wooden roots or, occasionally, of perennial taproots)
5. High (H); *Disruption* (DS) = Development of significant damage resulting in Break Out (BO) or Detachment of large compact stone pieces of irregular shape (Crumbly Disintegration, CD); the interaction between plants and stone results in a visible detachment of materials, which can be detected only in the case of wooden roots)
6. Very High (VH) *Collapse* (CO) = Significant breakdown of the building structure (the growth of plants is so dangerous that it can give rise to severe structural damage of buildings).

2.2. A methodological proposal for plant colonization hazard assessment

For a comprehensive hazard evaluation, we suggest taking into account 6 separate indicators. Two of these are related to environmental factors (Table 1), such as Bioclimate (Bc) and the Environmental Context (EC), while the remaining four indicators are related to the characteristics of plant species such as Life Forms (LF), Root System (RS), Ecology (Ec) and Physiology (Ph) (Table 2). For each indicator we have grouped the main typologies of indicators into 5 hazard classes (Very Low=1; Low=2; Medium= 3; High= 4; Very High=5).

Hazards arising from the environmental location of the site and related bioclimatic information can be assessed simply by knowing its geographical location, whereas the hazards due to colonization of different species of plant can only be assessed after a careful field evaluation of their cover and characteristics.

2.2.1. Indicators of hazard related to the bioclimatic conditions of the site

Bioclimatic conditions exert a significant influence on biological colonization, since low temperature values and low pluviometry conditions reduce the potential for plant colonization and related biodeterioration phenomena [61]. Therefore, the bioclimate of a site is a primary factor when assessing the potential hazard of plant colonization. With regard to bioclimate we suggest referring to the classification proposed by Rivas Martinez et al. [62], which considers 14 main typologies, ranging from very low in polar or desert bioclimates to very high in tropical bioclimates [Appendix 1].

2.2.2. Hazard indicators related to the environmental context of the site

The local environmental conditions of a site influence the incidence of biological colonization on stone materials, since certain factors (high humidity, high input of seeds and biological propagules, high nutrients, adequate lighting and temperatures and pollution levels) favor or inhibit plant colonization potential [14,61,63,64]. Such factors vary from very low hazards in highly polluted areas to very high hazards in forests [Appendix 1]. Temperature and humidity favorable to the most invasive species are also relevant factors and are related to the specific ecology of the colonizing species (see also 2.2.5).

2.2.3. Hazard related to plant life forms

Plant life forms are based on their life cycle and the position of buds [65], and vary from ephemeral plants to vigorous trees. An assessment of these life forms is the first and foremost step in

Table 2
Set of general indicators for hazards linked to the Plants growth on monuments.

Indicators / Values	Very Low	Low	Medium	High	Very high
	Class 1	Class 2	Class 3	Class 4	Class 5
3. Life forms (LF)					
T: therophytes, annual grasses	X (S)	X (SE,D)			
H biennial (Hemicryptophytes)	X (S)	X (SE,D)	X (F)		
H perennial per G (Geophytes) Ch (Chamaephytes)	X (S)	X (SE,D)	X (F)		
Shrubs (Pcaesp: caespitose phanerophytes) and Lianas (Plian = lianose phanerophytes	X (S)	X (SE,D)	X (F)	X All (F*)	
Trees (Pscap: scapose phanerophytes	X (S)	X (SE,D)	X (F)	X All (F*)	X All (F,DS*,I)
4. Root systems and stem characters (RS)					
Fasciculate annual roots	X (S)	X (SE,D)			
Fasciculate perennial roots	X(S)	X(SE,D)			
Herbaceous Tap root and hypogean organs	X(S)	X(SE,D)	X ,(F)		
Wooden roots with limited growths	X (S)	X (SE,D	X ,(F)	X All (DS*)	
Wooden roots with long and vigorous roots	X (S)	X (SE,D	X ,(F)	X All (DS*)	X All (F,DS*I)
5. Ecological preference (Ec)					
Occasional ephemeral plants	X (S)				
Occasional perennial plants	X (S)	X(SE,D)			
Ruderal plants with wide tolerance	X (S)	X(SE,D)	X(F*)		
Plants with rocky habitat preference	X (S)	X (SE,D)	X All (F*)		
Plants of pioneer Forests	X (S)	X (SE,D)	X All (F*)	X All (DS*)	X All (F,DS*,I)
6. Physiological characteristics (Ph)					
Ephemeral plants with limited seedlings	X (S)	X (SE,D)			
Ephemeral plants with high seedlings	X (S)	X (SE*,D*)			
Perennial plants with limited vigor but high vegetative potentials and seedlings	X (S)	X (SE,D)	X (S,SE,D, F)		
Wooden plants with high vigor and low invasiveness	X (S)	X (SE,D)	X All (F*)	X All (F*)	
Wooden plants with high vigor and high invasiveness	X (S)	X (SE,D)	X All (F*)	X All (F*)	X All (F,DS*,I)

(Soiling (S), Superficial erosion (SE), Discoloration (D), Fracturing (F), Disruption (DS), Collapse (I).)
*Most probable typology.

establishing plant hazard. The hazard increases in proportion with the length of the plant life cycle, which is often related to a plant's soil penetration potential [Appendix 1].

2.2.4. Hazard related to a plant's root and stem characteristics

The development and strength of a plant's root system, and of its other subterranean organs, can vary widely, achieving very different lengths and creating differential damage as they grow [29–31,66–70]. In accordance with the indication of HI [50] and our own observations, we suggest a classification ranging from the very low hazard of fasciculate annual roots to the very high hazard of wooden roots with secondary polloniferous roots [Appendix 1].

2.2.5. Hazard related to the ecological preference of a plant

Habitat colonization is related to a plant's fitness for certain living conditions [19,59,71,72]. Archeological and built habitats constitute pioneer edaphic conditions, being composed of stones and not mature soils, usually with low humidity levels, low nutrients, and often a not insignificant overheating of surfaces [15,73]. Such ecological features are limiting factors for most plants, though not for ruderal or rocky species. The soil type and pH, then, are also relevant when considering the ecological preference of a plant. Suggested categories vary from occasional ephemeral species to plants belonging to shrubby and forest communities [Appendix 1].

2.2.6. Hazard related to physiological characteristics (invasiveness and vigor) of a plant

Plant species have evolved different mechanisms to improve their potential for survival in a given habitat as well as developing significant reproductive fitness [72,74]. Clonal reproduction, such as seedling rate, describes physiological features that deter-

Table 3
Vulnerability classification of [a] substrate bioreceptivity (Sb) and associated to [b] Microsites of plant colonization (Ms).

↑ Increasing rate of porosity			Low	Medium	High
Mud brick Mud/clay mortar			Class4	Class 5	Class5
Fired brick	Gypsum Quicklime	Tuff Travertine	Class 3	Class 4	Class 4
	Hydrate lime Hydraulic lime	Limestone Sandstone	Class 3	Class 3	Class 4
	Pozzolan lime Portland cement	Granite, Basalt Gneiss, Slate	Class 2	Class 2	Class 3
	Concrete	Marble	Class 1	Class 1	Class 2

→ **Increasing rate of substrate deterioration**

[a]

Upper Part of Wall	Middle Part of Wall	Ground Level			
Horizontal			Class 4	Class 5	Class 5
Inclined	Horizontal		Class 3	Class 4	Class 5
Vertical	Inclined	Horizontal	Class 2	Class 3	Class 4
	Vertical	Inclined	Class 1	Class 2	Class 3
		Vertical	Class 1	Class 1	Class 2
			Cavities	Cracks Delamination	Fractures Surface covered by soil
			Mortar-Joints of Two Vertical	Dry-Joints of two vertical Mortar-Joints of two horizontal Mortar-Joints of horizontal with vertical/inclined	Dry-Joints of two horizontal Dry-Joints of horizontal with vertical/inclined

(Classes: 1= Very Low; 2= Low; 3= Medium; 4= High; 5= Very high).
The rate of colonization increases in relation to the ground level (Ground, Middle, Upper), inclination (Vertical, Inclined, Horizontal), and Typologies of Ms (i.e., Cavities, Cracks, Joints). **[b]**

(Classes: 1= Very Low; 2= Low; 3= Medium; 4= High; 5= Very high).
The rate of colonization increases in relation to the ground level (Ground, Middle, Upper), inclination (Vertical, Inclined, Horizontal), and Typologies of Ms (i.e., Cavities, Cracks, Joints).

mine the invasiveness and vigor of a species in colonizing a habitat [Appendix 1].

2.3. A methodological proposal for vulnerability assessment

Vulnerability related to plant colonization is here expressed through 3 parameters (indicators): the microsites of plant colonization (Ms), which can have a positive or a negative influence [59], the bioreceptivity of the substrate (Sb), which is an augmentative factor, and its deterioration rate (CS), which can be related to management practices [37]. Regarding the classification of vulnerability, we have again proposed 5 classes (1= Very Low; 2= Low; 3= Medium; 4= High; 5= Very high).

2.3.1. Vulnerability related to stone bioreceptivity (edaphic conditions)

The intrinsic physic-chemical properties of stone materials (e.g., surface roughness, mineral composition and overall porosity [75,76] are the primary factors in determining their bioreceptivity, i.e., their tendency to be colonized by living organisms [77,78]. Furthermore, exposure time determines a natural physic-chemical deterioration process resulting in porosity and bioreceptivity [77,78]. In addition to this, vulnerability increases over time because prolonged exposure increases the original porosity of materials (usually classified as low, medium, or high), and can lead to a higher classification (Table 3a). Substrate vulnerability increases both in relation to porosity values and to increasing deterioration rates,

Table 4
Set of indicators for Vulnerability linked to the site colonization conditions.

Indicators / values	Very Low	Low	Medium	High	Very high
	Class 1	Class 2	Class 3	Class 4	Class 5
7. Stone bioreceptivity (Sb)					
Stone with very low porosity and low degradation rate	x				
Stone with low porosity and increasing deterioration rate		x			
Stone with medium porosity and increasing deterioration rate			x		
Stone with high porosity and increasing deterioration rate				x	
Stone with very high porosity due to deterioration rate					x
8. Microsites (Ms)					
Crack, cavities and joints at ground level for vertical/inclined surface	x				
From cavities to fractures, and joints mainly in vertical/inclined surface with increased height of walls		x			
From cavities to fractures, and mainly in inclined surface with increased height of walls			x		
From cavities to fractures, and joints mainly in horizontal surface with increased height of walls				x	
From cavities to fractures, and joints at middle/upper level for horizontal/inclined surfaces					x
9. Conservation Status (CS)					
Protected site with regular plants control plan	x				
Protected site with plants control plan limited to some areas		x			
Protected site without regular plants control plan			x		
Abandonment for some years				x	
Abandonment for more than 10 years					x

with values ranging from very low (less than 1% porosity) to very high (more than 30% porosity) [Appendix 1].

2.3.2. Vulnerability related to microsites of growth (topographic conditions)

Different parts of the structure can be subject to different levels of vulnerability to plant colonization. Fissures, cracks, cavities and structural junctions in stone materials are microsites (Ms) of growth on stone surfaces because they trap nutrient-rich dust and organic material [16,79]. Lisci et al. [18] proposed their evaluation of risk factors, which was recently reassessed to include non-visible damage due to soiling [19]. In accordance with the latter contribution, we have looked at vulnerability to plant colonization based on 3 parameters intended to describe their settlement (Height, Inclination, and Typologies of Ms) (Table 3b) [Appendix 2]. We also suggest increasing the vulnerability level (raising by 1 class) in the presence of fragile architectural structures like mosaics, paintings, inscriptions, and statues.

2.3.3. Vulnerability related to conservation status

The conservation status of a monument is intimately connected to its management. For this reason maintenance is one of the most significant parameters when assessing the vulnerability of plant growth on historical structures and ruins [80,81]. Neglect and lack of maintenance are discriminating factors, and the vulnerability of substrates to plant colonization increases when there is no maintenance [73]. In general, abandonment and exposure to weathering agents favor biological colonization by bacteria, fungi, and lichens. This accelerates the deterioration of the structure, leading to the formation of a substrate that favors the germinating seeds of hardy pioneer plants. Atmospheric dust, bird excrement, plant remains, and human waste contribute to the enrichment of nutrients and to thin soil formation, encouraging the growth of other plants [17,18]. As shown in Table 5, we have suggested an average limit of 10 years in order to assessment the highest vulnerability conditions. This value seems suitable, especially for tropical sites, where dynamic evolution is seen to develop quickly. However, in temperate and Mediterranean climates, evolution towards woody vegetation needs a longer period of abandonment [17,18], and the vulnerability score can be lowered [Appendix 2].

The general set of vulnerability indicators with proposals for their classification is summarized in Table 4.

2.4. The quantitative application of the index of risk assessment (RHV) in relation to a plant, and its graphical representation

The main elements in the evaluation of plant colonization risks, procedure and the associated indicators of hazard and vulnerability are shown in Fig. 2.

Fig. 3 shows the values of potential damage linked to the nine suggested indicators, represented by nine points of a star (1 = Very Low (VL, i.e., limited to soiling); 2 = Low (L, i.e., only superficial erosion or discoloration); 3 = Medium (M, i.e., fracturing); 4 = High (H, i.e. disruption); 5 = Very High (VH, i.e. collapse).

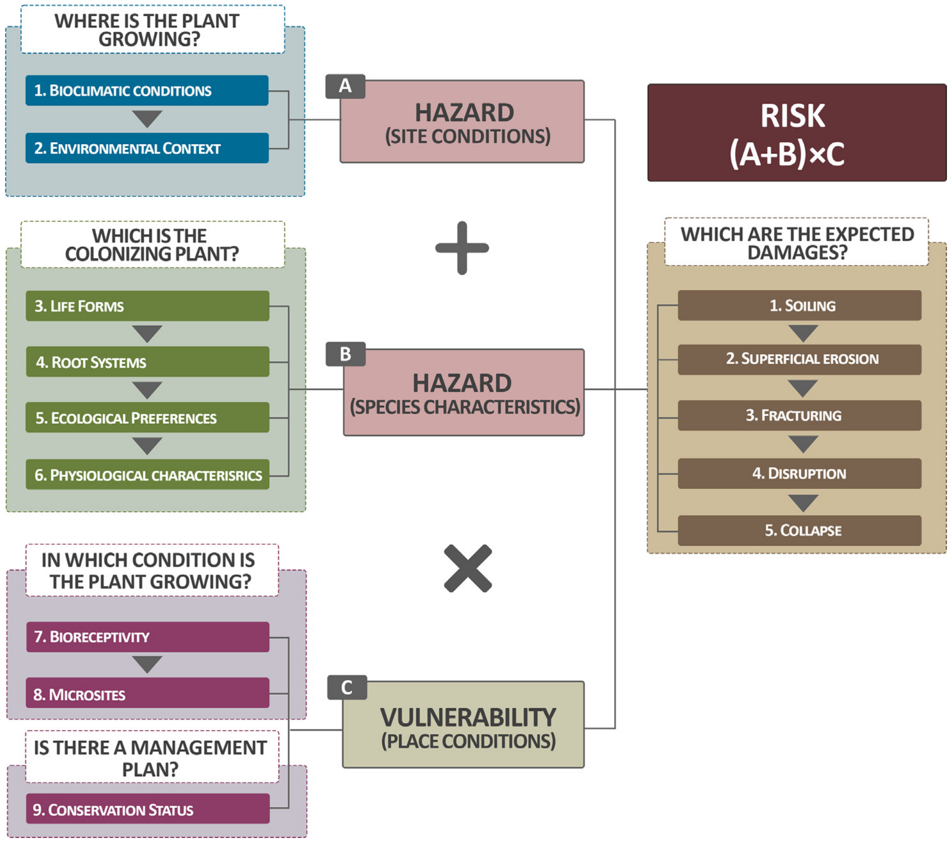

Fig. 2. The RHV model for the assessment of risk from higher plant colonization on buildings.

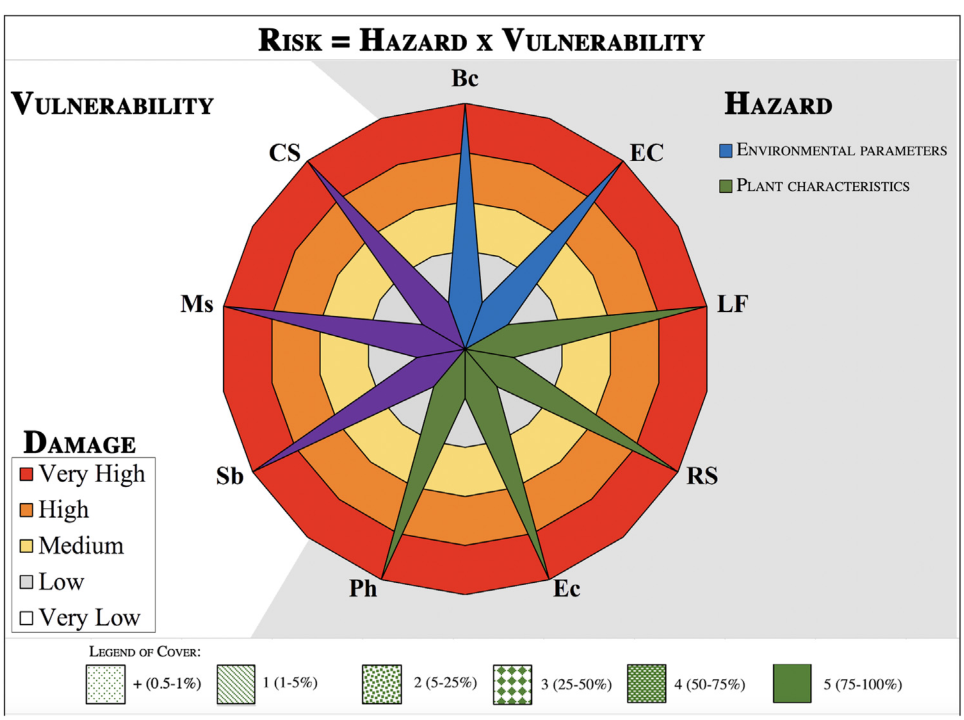

Fig. 3. Proposed graphical representation for the 9 parameters describing the risk from certain damage categories (5 classes from superficial erosion to collapse) resulting from plant growth. For hazard indicators (gray sector), we have shown the Environmental indicators (in blue: Bc 'Bioclimate'; EC' Environmental Context') and the Plant characteristic indicators (in green: LF 'Life Forms'; RS 'Root System'; Ec 'Ecological characteristics'; Ph 'Physiology'); for Vulnerability indicators (white sector) (in purple: Ms 'Microsite; Sb 'Substrate'; CS 'Conservation Status'). The cover values of plants are expressed by different graphical patterns, with an increasing intensity of color.

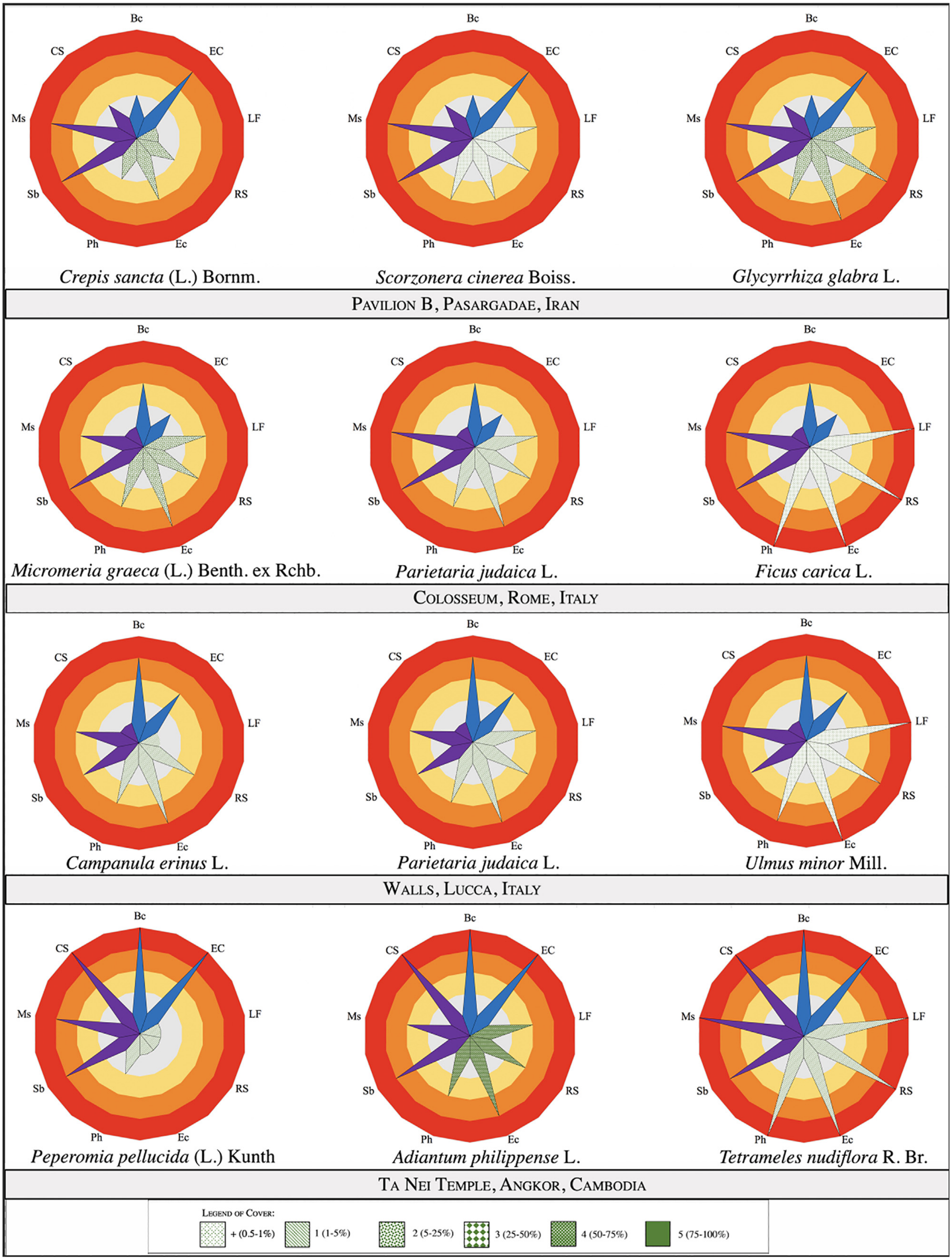

Fig. 4. Graphs of Risk from different species at different sites. In blue the Environmental indicators (Bc 'Bioclimate'; EC' Environmental Context'); in green the Plant characteristics indicators (LF 'Life Form'; RS 'Root System'; Ec 'Ecological characteristics'; Ph 'Physiology'); in purple the Vulnerability indicators (Ms 'Microsite; Sb 'Substrate'; CS 'Conservation Status').

Table 5
Risk assessment for selected plants colonization in different sites.

HAZARD (and related hazard values)							VULNERABILITY (and related vulnerability values)		
Indicators of Environmental factors of Site		Plant species and (their index of cover)	Plant characteristics (Indicators for species)						
1.BC	1.EC		3.LF	4.RS	5.Ec	6.Ph	7.SB	8.MS	9.CS
Pavilion B, Pasargadae, Iran									
Medit xer 2	Rural 4	*Scorzonera cinerea* Boiss. (0.5)	H scap 3	Herb tap root 3	Ruderal 3	Perennial 3	Sands 4	G/h soil 4	Partial plant control 2
		Glycyrrhiza glabra L. (2)	G rhiz 3	Wood hypogean 4	Rocky 4	Perennial 3		Ground horizontal 4	
		Crepis sancta (L.) Bornm. (2)	T scap 1	Annual tap root 2	Ruderal 3	Ephemeral high seedl 2		Ground horizontal 4	
Colosseum, Rome, Italy									
Medit pluv 3	Green urban space 2	*Micromeria graeca* (L.) Benth. Ex Rchb. (2)	Ch suffr 3	Herb tap root 3	Ruderal 3	Perennial 3	Traver 4	Cavities inclined 3	Regular plant control 1
		Parietaria judaica L. (1)	H scap 3	Herb tap root 3	Rocky 4	Perennial 3		Joint vertical middle 4	
		Ficus carica L. (0.5)	P scap 5	Wooden pollonif. 5	Pioneer forest 5	Tree (high inv) 5		Joints vertical upper 4	
City Walls, Lucca, Italy									
Temp Oce 4	Urban Garden 3	*Campanula erinus* L. (1)	T scap 1	Herb tap root 3	Rocky 4	Perennial 3	Brick 3	Mortar joint inclined middle 3	regular plant control 1
		Parietaria judaica L. (1)	H scap 3	Herb tap root 3	Rocky 4	Perennial 3		Mortar joint inclined middle 3	
		Ulmus minor Mill. (0.5)	P scap 5	Wooden 4	Pioneer forest 5	Tree low inv. 4		Mortar joint inclined upper 4	
Ta Nei temple, Angkor, Cambodia									
Trop pluv 5	Forest 5	*Adiantum philippense* L. (4)	G rhiz 3	Hypogean org 3	Rocky 4	Perennial 3	Sands 4	Dry joint vertical middle 3	Abandon. more 10 years
		Tetrameles nudiflora (1)	P scap 5	Wooden pollonifer 5	Pioneer forest 5	Wooden high inv. 5		Horizontal upper fractures 5	
		Peperomia pellucida (L.) Kunth (1)	T scap 1	Annual Fasciculae 1	occasional ephemeral 1	Ephemeral high seed. 2		Ground horizontal soil 4	

The acronyms refer to: Bc = Bioclimate; EC = Environmental Context; LF = Life Forms; RS = Root System; Ec = Ecology; Ph = Physiology; Sb = Substrate; Ms = Microsite of plant colonization; CS = Conservation Status. The cover value refers to + = 0.5; 1 = 1–5%; 2 = 5–25%; 3 = 25–50%; 4 = 50–75%; 5 = 75–100%; Hazard and vulnerability indicators:1=Very Low, 2=Low, 3=Medium, 4=High, 5=Very High.

Table 6
The application of RHV to the analyzed sites.

Bc	EC	Species	Cv	LF	RS	Ec	Ph	Sb	Ms	CS	RISK	
Pavilion B, Pasargadae, Iran												
2	4										H_E	L-H (M)
		Scorzonera cinerea Boiss.	0,5	3	3	3	3				H_P	M-L
		Glycyrrhiza glabra L.	2,0	3	4	4	3					
		Crepis sancta (L.) Bornm.	2,0	1	2	3	2					
								4	4	2	V	L-H
								4	4	2		
								4	4	2		
Colosseum, Rome, Italy												
3	2										H_E	M-L
		Micromeria graeca (L.) Benth. Ex Rchb.	2,0	3	3	3	3				H_P	M with VH potential
		Parietaria judaica L.	1,0	3	3	4	3					
		Ficus carica L.	0,5	5	5	5	5					
								4	3	1	V	L-H
								4	4	1		
								4	4	1		
Walls, Lucca, Italy												
4	3										H_E	H-M
		Campanula erinus L.	1,0	1	3	4	3				H_P	M with VH potential
		Parietaria judaica L.	1,0	3	3	4	3					
		Ulmus minor Mill.	0,5	5	4	5	4					
								3	3	1	V	L-M
								3	3	1		
								3	4	1		
Ta Nei Temple, Angkor, Cambodia												
5	5										H_E	VH
		Peperomia pellucida (L.) Kunth	1,0	1	1	1	2				H_P	M-H with VH potential
		Adiantum philippense L.	4,0	3	3	4	3					
		Tetrameles nudiflora	1,0	5	5	5	5					
								4	3	5	V	H-VH
								4	5	5		
								4	4	5		

The acronyms refer to: Bc = Bioclimate; EC = Environmental Context; LF = Life Forms; RS = Root System; Ec = Ecology; Ph = Physiology; Sb = Substrate; Ms = Microsite of plant colonization; CS = Conservation Status; Cv = Cover; H_E = hazard related to the environmental conditions, V = vulnerability, H_P = hazard related to the plants. The cover value refers to + = 0.5; 1 = 1–5%; 2 = 5–25%; 3 = 25–50%; 4 = 50–75%; 5 = 75–100%; Hazard and vulnerability indicators:1=Very Low, 2=Low, 3=Medium, 4=High, 5=Very High.

We believe that when combining different types of parameters we cannot simply sum each global risk assessment value, therefore we prefer to illustrate them with an analytical representation. Furthermore, due to the heterogeneity of such assessments, it is quite impossible to give a homogenous numerical scale, so we have opted for classes instead of numbers.

In order to enhance the role of plant cover, we also suggest employing the usual scale of phytosociological analysis [60]: + = 0.5; 1 = 1–5%; 2 = 5–25%; 3 = 25–50%; 4 = 50–75%; 5 = 75–100%). Values are shown graphically using different gradations and color patterns for the 4 peaks of the stars that represent plant characteristics.

2.5. The application of RHV to a site

Similarly, when applying the RHV to a site, we suggest separating hazard values related to environmental conditions from those linked to plant colonization such as values regarding site vulnerability. The results will emphasize those values which appear to be common geographic and bioclimatic characteristics throughout the site, and at the same time will emphasize separately the parameters linked to other plants at the site. For each value, we suggest considering the average, such as the possible peaks.

2.6. Tested areas and species

In order to test the application of the proposed methodology we also selected four sites representative of different bioclimatic and environmental conditions, where we carried out in the past detailed observations and analysis. The chosen test areas were: Pavilion B, Pasargadae (Iran) [19], located in a *rural context in a Mediterranean xeric bioclimate;* the Colosseum in Rome (Italy) [82], located in an *urban context* in a *Mediterranean pluvio-seasonal bioclimate*; the walls of Lucca, (Italy) [83], surrounded by gardens in an urban context in a *Temperate Oceanic bioclimate*; Ta Nei temple, Angkor (Cambodia) [84], located in a woody area in a *Tropical pluvial bioclimate* (Appendix 3).

In each site, we also selected three plant species, presenting different hazard levels, that were identified through analytical keys of morphological features, using the local floras. Such comparison will highlight the differences between species and the hazards related to the same species at different sites.

3. Results

The application of the RHV assessment in the different test areas is shown in Table 5, where all of the observations and classifications have been collected together. The graphs in Fig. 4 analyze hazard and vulnerability separately, showing species with elevated hazards in the same environmental and vulnerability conditions. They also illustrate how different species at a site can produce different hazards according to their cover and characteristics, and how favorable bioclimatic conditions expose sites to increasingly dangerous conditions. Furthermore, they also show the relevance of vulnerability parameters (see the different hazards for *P. judaica* at the Rome and Lucca sites).

As shown in Table 6, when considering all four sites as a whole we observed average hazard values related to environmental conditions (HE) for Pavilion B in Pasargadae, and for the Colosseum as well as the walls of Lucca, but the tropical and forest conditions of Ta Nei Temple in Angkor led to high hazard values. The hazard values related to the presence of plants at Pasargadae also presented average values, whereas some plants at the Colosseum showed a high potential risk, which was even higher for plants at Angkor, where other plants had a very high potential risk. Vulnerability values at Pasargadae were, again, average, as were those at the Colosseum. Such values were low for the walls of Lucca walls and high for Ta Nei Temple in Angkor, mainly due to differences in site management.

4. Discussion

The complexity of evaluating hazards due to plant growth at archeological sites arises from the need to take into account several parameters. The hazard indices [46-50,57] that have previously been proposed are not comprehensive enough to address all of the relevant risk parameters. The wider view that we suggest (nine parameters rather than the previous three or four) provides a more realistic definition of risk. Both indices (HI and DI) constituted reliable starting points for the identification of potential danger caused by different plant species. However, the HI [50] as well as the subsequent DI in Motti et al. [57], both lack any evaluation of variability resulting from hazard associated with local bioclimatic conditions or of vulnerability associated with edaphic conditions where the plants grow [15,52]. Furthermore, we have avoided the more common method [51–54], of applying such indices to the calculation of a global numerical evaluation of risk based simply upon the presence and cover of species. The need for a sufficient evaluation of physiological and ecological factors adds further to such complexity. The influence of such factors explains the variations in aggressiveness for the substrate of the same plant when the geographical, bioclimatic, and edaphic conditions vary. For example, the influence on a plant of different bioclimatic conditions can explain discrepancies in the evaluations of dangerousness of ivy growing in the Mediterranean bioclimatic conditions of central-southern Italy [49,85] compared to those observed in the cold-humid temperate conditions of England [86,87]. The ecological preference of a species provides a clear indication of its potential ability to establish itself in a given location, with archeological areas and monumental sites providing optimal conditions for ruderal plants [19,71,72].

Furthermore, and as previously observed [88], if the indices proposed for the quantification of the deteriogenic impact of microorganisms and plants are to be useful, they will require an agreed standardization of reference parameters and methods for the assessment of the factors involved.

In our opinion the usefulness of such an approach in establishing risk arises from the distinctions between different hazard and vulnerability conditions. For the first parameter, a clear distinction can be made between external hazard factors (bioclimate and local conditions), which can vary greatly according to geographical and topographical conditions, and hazards related to the characteristics of the plants growing on the site, which constitute the typical 'features' of the plant (see the different patterns related to the species shown in Fig. 4). Each site has specific hazard conditions and vulnerability resulting from its conservation status (parameters 1, 2, and 9), for example with regard to the specific qualities of certain species (compare the similar pattern of a site and the difference between plants in Fig. 4 and Table 5). When comparing a site like Pasargadae in an arid bioclimatic region with Angkor in a tropical region, the H_E displays notably different values ranging from low to very high, as does the potential H_P. Vulnerability, on the other hand, varies according to local conditions, particularly with regard to microsites of growth and the local management of plants. In this way, when comparing the sites analyzed in Rome and Lucca, where the H_P values were similar, hazards due to environment (H_E) and vulnerability clearly play a key role in defining the total risk for the site. Rome, however, has a bioclimate with a period of drought stress, which results in a lower potential hazard with respect to that of Lucca; the type of substrate and the microsites where the plants were growing determined a greater vulnerability than those observed on the walls of Lucca, leading to a higher potential risk condition. Consequently, such RHV index evaluations seem appropriate for a careful management plan which takes into consideration the risk of plants growing on monuments.

Even though an increasing number of papers stress the importance of careful management of plants in archeological sites in order to avoid damage [19,89], we cannot ignore the fact that archeological areas often become a refuge for plants and animals disrupted by human activities [90,91]. Finally we would like to emphasize that a comprehensive management plan requires, in addition to such assessments, an evaluation of a site's naturalistic and, ideally, its cultural values [11,22]. Some typical wall species, in fact, have a limited spread in natural habitats highlighting the importance of these areas as secondary stations for rare and threatened species, and their removal should take place only if they cause a non-negligible risk to cultural heritage [80,92].

5. Conclusion

Different weathering agents can pose a risk to heritage conservation in outdoor conditions. Of all the various biodeteriogens, the growth of higher plants is a major threat. Despite this, indices that provide a method for the calculation of a plant species' dangerousness are few in number and suffer from several limitations. The proposed risk index (RHV) takes into consideration several parameters that represent hazards resulting from general site conditions and the colonization of plants, such as the parameters influencing vulnerability in a local context. By analyzing these various parameters separately, the resulting evaluations will make it possible to prioritize interventions for the removal of dangerous species. This index will be a useful tool for the management of plants growing at archeological or monumental sites.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.culher.2023.05.032.

References

[1] L. Celesti Grapow, G. Caneva, A. Pacini, La Flora dell'Anfiteatro Flavio (Roma), Webbia 56 (2001) 321–324.
[2] N. Krigas, E. Lagiou, E. Hanlidou, S. Kokkini, The vascular flora of the Byzantine Walls of Thessaloniki (N Greece), Willdenowia 29 (1999) 77–94, doi:10.3372/wi.29.2907.
[3] G. Caneva, M. Cutini, A. Pacini, M. Vinci, Analysis of the colosseum's floristic changes during the last four centuries, Plant Biosyst. 136 (2002) 291–311, doi:10.1080/11263500212331351199.
[4] V.A. Dos Reis, J.A. Lombardi, R.A. De Figueiredo, Diversity of vascular plants growing on walls of a Brazilian city, Urban Ecosyst. 9 (2006) 39–43, doi:10.1007/s11252-006-5528-1.
[5] R. Motti, A. Stinca, Analysis of the biodeteriogenic vascular flora at the Royal Palace of Portici in southern Italy, Int. Biodeterior. Biodegrad. 65 (2011) 1256–1265, doi:10.1016/j.ibiod.2010.03.010.
[6] L.R.G. Torres, A.C. Pérez, V.P. Álvarez-Rivera, L.C. Romero, Colonización de la piedra por plantas vasculares en edificaciones monumentales de la Habana Vieja, Rev. Del. Jardín Botánico Nac. 23 (2002) 243–247 http://www.jstor.org/stable/42597424.
[7] L. Celesti Grapow, S. Pignatti, E. Pignatti, Analisi della flora dei siti archeologici di Roma, Allionia 32 (1993) 113–118.
[8] F. Lucchese, E. Pignatti, La vegetazione nelle aree archeologiche di Roma e della Campagna Romana, Quad. Bot. Amb. Appl. 20 (2009) 3–89.
[9] S. Segal, Ecological Notes on Wall Vegetation, Springer, Dordrecht, 1969, doi:10.2307/3543223.
[10] G. Caneva, O. Salvadori, S. Ricci, S. Ceschin, Ecological analysis and biodeterioration processes over time at the Hieroglyphic Stairway in the Copàn (Honduras) archaeological site, Plant Biosyst. (2005) 295–310, doi:10.1080/11263500500343353.
[11] S. Ceschin, G. Salerno, G. Caneva, Multitemporal floristic analysis on a humid area in Rome's archaeological site as indicator for environmental change, Environ. Monit. Assess. 149 (2009) 29–42, doi:10.1007/s10661-008-0180-2.
[12] G. Caneva, G. De Marco, M.A. Pontrandolfi, Plant communities on the walls of Venosa Castle (Basilicata, Italy) as biodeteriogens and bioindicators, in: Conserv. Stone Other Mater. Proc. Int. RILEM/UNESCO Cong". "Conservation Stone Other Mater. Res. Held UNESCO Headquarters, Paris, June 29-July 1, 1993, pp. 263–270.
[13] V. Altay, I.I. Oezyigit, C. Yarci, Urban ecological characteristics and vascular wall flora on the Anatolian side of Istanbul, Turkey, Maejo, Int. J. Sci. Technol. 4 (2010) 483–495.
[14] A. Kumbaric, S. Ceschin, V. Zuccarello, G. Caneva, Main ecological parameters affecting the colonization of higher plants in the biodeterioration of stone embankments of Lungotevere (Rome), Int. Biodeterior. Biodegrad. 72 (2012) 31–41, doi:10.1016/j.ibiod.2012.02.009.
[15] S. Ceschin, F. Bartoli, G. Salerno, V. Zuccarello, G. Caneva, Natural habitats of typical plants growing on ruins of Roman archaeological sites (Rome, Italy), Plant Biosyst. 150 (2016) 866–875, doi:10.1080/11263504.2014.990536.
[16] M. Korkanç, A. Savran, Impact of the surface roughness of stones used in historical buildings on biodeterioration, Constr. Build. Mater. 80 (2015) 279–294, doi:10.1016/j.conbuildmat.2015.01.073.
[17] M. Lisci, E. Pacini, Plants growing on the Walls of Italian Towns 1. Sites and distribution, Phyt. (Horn, Austria) 33 (1) (1993) 15–26.
[18] M. Lisci, M. Monte, E. Pacini, Lichens and higher plants on stone: a review, Int. Biodeterior. Biodegrad. 51 (1) (2003) 1–17, doi:10.1016/S0964-8305(02)00071-9.
[19] Z. Hosseini, G. Caneva, Evaluating hazard conditions of plant colonization in Pasargadae World Heritage Site (Iran) as a tool of biodeterioration assessment, Int. Biodeterior. Biodegrad. 160 (2021) 105216, doi:10.1016/j.ibiod.2021.105216.
[20] G. Capotorti, E. Del Vico, E. Lattanzi, A. Tilia, L. Celesti-Grapow, Exploring biodiversity in a metropolitan area in the Mediterranean region: the urban and suburban flora of Rome (Italy), Plant Biosyst. 147 (2013) 174–185, doi:10.1080/11263504.2013.771715.
[21] O. Valkó, K. Tóth, A. Kelemen, T. Miglécz, S. Radócz, J. Sonkoly, B. Tóthmérész, P. Török, B. Deák, Cultural heritage and biodiversity conservation - plant introduction and practical restoration on ancient burial mounds, Nat. Conserv. (2018) 65–80, doi:10.3897/natureconservation.24.20019.
[22] E. Cicinelli, G. Salerno, G. Caneva, An assessment methodology to combine the preservation of biodiversity and cultural heritage: the San Vincenzo al Volturno historical site (Molise, Italy), Biodivers. Conserv. 27 (2018) 1073–1093, doi:10.1007/s10531-017-1480-z.
[23] M. Panitsa, P. Trigas, D. Kontakos, A.T. Valli, G. Iatrou, Natural and cultural heritage interaction: aspects of plant diversity in three East Peloponnesian castles (Greece) and conservation evaluation, Plant Biosyst. (2021) 1–15, doi:10.1080/11263504.2021.1889701.
[24] G. Caneva, A. Altieri, Biochemical mechanisms of stone weathering induced by plant growth, in: VIth Int. Congr. Deterior. Conserv. Stone Proc. Torun, 12-14. 09. 1988 = VIe Congrè Int. Sur l'alteration La Conserv. La Pierres Actes, 1988, pp. 32–44.
[25] G. Caneva, G. Galotta, L. Cancellieri, V. Savo, Tree roots and damages in the Jewish catacombs of Villa Torlonia (Roma), J. Cult. Herit. 10 (2009) 53–62, doi:10.1016/j.culher.2008.04.005.
[26] G. Trotta, V. Savo, E. Cicinelli, M. Carboni, G. Caneva, Colonization and damages of Ailanthus altissima (Mill.) Swingle on archaeological structures: evidence from the Aurelian Walls in Rome (Italy), Int. Biodeterior. Biodegrad. 153 (2020) 105054, doi:10.1016/j.ibiod.2020.105054.
[27] D. Isola, F. Bartoli, S. Langone, S. Ceschin, L. Zucconi, G. Caneva, Plant DNA barcode as a tool for root identification in hypogea: the case of the Etruscan tombs of Tarquinia (central Italy), Plants 10 (2021) 1138, doi:10.3390/plants10061138.
[28] A.K. Mishra, K.K. Jain, K.L. Garg, Role of higher plants in the deterioration of historic buildings, Sci. Total Environ. 167 (1995) 375–392, doi:10.1016/0048-9697(95)04597-T.
[29] Y.M. Elgohary, M.M.A. Mansour, M.Z.M. Salem, Assessment of the potential effects of plants with their secreted biochemicals on the biodeterioration of archaeological stones, Biomass Convers. Biorefinery (2022) 1–15, doi:10.1007/s13399-022-03300-8.
[30] P.G. Biddle, Tree root damage to buildings an arboriculturst's experience, Arboric. J. 3 (6) (1979) 397–412, doi:10.1080/03071375.1979.10590552.
[31] G. Caneva, S. Ceschin, G. De Marco, Mapping the risk of damage from tree roots for the conservation of archaeological sites: the case of the Domus Aurea, Rome, Conserv, Manag. Archaeol. Sites 7 (2006) 163–170, doi:10.1179/135050306793137403.
[32] G. Caneva, A. Roccardi, Harmful flora in the conservation of Roman monuments, in: Biodeterior. Cult. Prop. Proc. Int. Conf. Biodeterior. Cult. Prop. Febr. 20-25, 1989, Held Natl. Res. Lab. Conserv. Cult. Prop. Collab. with ICCROM, 1991.
[33] S. Rhizopoulou, G. Kapolas, In situ study of deep roots of *Capparis spinosa* L. during the dry season: evidence from a natural "rhizotron" in the ancient catacombs of Milos Island (Greece), J. Arid Environ. 119 (2015) 212–218, doi:10.1016/j.jaridenv.2015.03.010.
[34] M.T. Almeida, T. Mouga, P. Barracosa, The weathering ability of higher plants. The case of *Ailanthus altissima* (Miller) Swingle, Int. Biodeterior. Biodegrad. 33 (1994) 333–343, doi:10.1016/0964-8305(94)90011-6.
[35] J.M.G. De Miguel, L. Sanchez-Castillo, J.J. Ortega-Calvo, J.A. Gil, C. Saiz-Jimenez, Deterioration of building materials from the Great Jaguar Pyramid at Tikal, Guatemala, Build. Environ. 30 (1995) 591–598, doi:10.1016/0360-1323(94)00055-W.
[36] J. Dahmani, M. Benharbit, M. Fassar, R. Hajila, L. Zidane, N. Magri, N. Belahbib, Vascular plants census linked to the biodeterioration process of the Portuguese city of Mazagan in El Jadida, Morocco, J. King Saud Univ. - Sci. 32 (2020), doi:10.1016/j.jksus.2018.10.015.
[37] A. Paolini, A. Vafadari, G. Cesaro, M.Santana Quintero, K. van Balen, O. Vileikis, L. Fakhoury, Risk Management at Heritage Sites: a Case Study of the Petra World Heritage Site, UNESCO Amman Office, Amman, 2012.
[38] G. Caneva, A botanical approach to the planning of archaeological, parks in Italy, Conserv. Manag. Archaeol. Sites 3 (1999) 127–134, doi:10.1179/135050399793138590.
[39] S. Yıldırım Esen, A.G. Bilgin Altınöz, Assessment of risks on a territorial scale for archaeological sites in İzmir, Int. J. Archit. Herit. 12 (2018) 951–980, doi:10.1080/15583058.2017.1423133.
[40] S. Kumpulainen, Vulnerability concepts in hazard and risk assessment, Spec. Pap. Geol. Surv. Finl. (2006).
[41] C. Daly, A framework for assessing the vulnerability of archaeological sites to climate change: theory, development, and application, Conserv. Manag. Archaeol. Sites. 16 (2014) 268–282, doi:10.1179/1350503315Z.00000000086.
[42] J. McCarthy, O. Canziani, N. Leary, D. Dokken, K. White, Climate Change 2001: Impacts, Adaptation, and Vulnerability, Cambridge University Press, Cambridge, 2001.
[43] A.N. Martins, A.A. Pereira, C. Forbes, J.L.M.P. de Lima, D. Matos, Risk to cultural heritage in Baixa Pombalina (Lisbon Downtown) - a transdisciplinary approach to exposure and drivers of vulnerability, Int. J. Archit. Herit. 15 (2021) 1058–1080, doi:10.1080/15583058.2020.1745322.
[44] S.L. Young, J.W. Brelsford, M.S. Wogalter, Judgments of hazard, risk, and danger. Do they differ? Proc. Hum. Factors Soc. (1990) 503–507, doi:10.1177/154193129003400515.
[45] H. Merkelsen, The constitutive element of probabilistic agency in risk: a semantic analysis of risk, danger, chance, and hazard, J. Risk Res. 14 (2011) 881–897, doi:10.1080/13669877.2011.571781.
[46] B. Fitzner, K. Heinrichs, R. Kownatzki, Weathering forms at natural stone monuments - classification, mapping and evaluation, Int. Zeitschrift Für Bauinstandsetz. 3 (1997) 105–124.
[47] B. Fitzner, K. Heinrichs, Damage diagnosis at stone monuments - weathering forms, damage categories and damage indices, Acta Univ. Carolinae, Geol. 45 (2001).
[48] B. Fitzner, Documentation and evaluation of stone damage on monuments, in: 10th Int. Congr. Deterior. Conserv. Stone, 2004, pp. 677–690.
[49] F. Bartoli, F. Romiti, G. Caneva, Aggressiveness of *Hedera helix* L. growing on monuments: evaluation in Roman archaeological sites and guidelines for a general methodological approach, Plant Biosyst. 151 (2017) 866–877, doi:10.1080/11263504.2016.1218969.
[50] M.A. Signorini, L'indice di pericolosità: un contributo del botanico al controllo della vegetazione infestante nelle aree monumentali, Inf. Bot. Ital. 28 (1996) 7–14 doi.org/10.2/JQUERY.MIN.JS.
[51] A. Guglielmo, P. Pavone, V. Tomaselli, G. Spampinato, Analisi Della Flora E Della

Vegetazione Delle Aree Archeologiche Della Sicilia Orientale Finalizzata Alla Tutela E Valorizzazione Dei Manufatti Architettonici, Inf. Bot. Ital. Boll. Della Soc. Bot. Ital. 37 (2005) 226–228.
[52] F. Corbetta, P. Pavone, G. Spampinato, V. Tomaselli, A. Trigilia, Studio della vegetazione dell'area archeologica della Neapolis (Siracusa, Sicilia) finalizzato alla conservazione dei manufatti architettonici, Fitosociologia 39 (2002) 3–24.
[53] G. Caneva, F. Bartoli, Botanical planning and lichen control for the conservation of gravestones in Jewish urban cemeteries in north-eastern Italy, Isr. J. Plant Sci. 64 (2017) 210–223, doi:10.1080/07929978.2017.1288425.
[54] G. Caneva, F. Benelli, F. Bartoli, E. Cicinelli, Safeguarding natural and cultural heritage on Etruscan tombs (La Banditaccia, Cerveteri, Italy), Rend. Lincei 29 (2018) 891–907, doi:10.1007/s12210-018-0730-7.
[55] M.E. Mascaro, G. Pellegrino, A.M. Palermo, Analysis of biodeteriogens on architectural heritage. An approach of applied botany on a gothic building in southern Italy, Sustain 14 (2022) 34, doi:10.3390/su14010034.
[56] C. Gazzano, S.E. Favero-Longo, E. Matteucci, A. Roccardi, R. Piervittori, Index of Lichen Potential Biodeteriogenic Activity (LPBA): a tentative tool to evaluate the lichen impact on stonework, Int. Biodeterior. Biodegrad. 63 (2009) 836–843, doi:10.1016/j.ibiod.2009.05.006.
[57] R. Motti, G. Bonanomi, A. Stinca, Biodeteriogens at a southern Italian heritage site: analysis and management of vascular flora on the walls of Villa Rufolo, Int. Biodeterior. Biodegrad. 162 (2021) 105252, doi:10.1016/j.ibiod.2021.105252.
[58] R. Motti, G. Bonanomi, Vascular plant colonization of four castles in southern Italy: effects of substrate bioreceptivity, local environment factors and current management, Int. Biodeterior. Biodegrad. 133 (2018) 26–33, doi:10.1016/j.ibiod.2018.06.004.
[59] Z. Hosseini, G. Zangari, M. Carboni, G. Caneva, Substrate preferences of ruderal plants in colonizing stone monuments of the Pasargadae world heritage site, Iran, Sustain 13 (2021) 9381, doi:10.3390/su13169381.
[60] J. Braun-Blanquet, Plant Sociology. The Study of Plant Communities, 1st ed., McGraw-Hill Book Co., New York and London, 1932.
[61] G. Caneva, A. Pacini, Biodeterioration problems in relation to geographical and climatic contexts, in: G. Caneva, M. Nugari, O. Salvadori (Eds.), Plant Biol. Cult. Herit. – Biodeterior. Conserv., The Getty Conservation Institute, Los Angeles, 2008, pp. 227–230.
[62] S. Rivas-Martínez, S. Rivas-Sáenz, A. Penas-Merino, Worldwide bioclimatic classification system, Glob. Geobot. 1 (2011) 1–634, doi:10.5616/gg110001.
[63] R. Kumar, A.V. Kumar, Biodeterioration of Stone in Tropical Environments : an Overview, Getty Conservation Institute, Los Angles, 1999.
[64] G. Caneva, M.P. Nugari, O. Salvadori, Plant Biology for Cultural Heritage: Biodeterioration and Conservation, The Getty Publications, Los Angeles, 2008.
[65] T. Just, C. Raunkiaer, The life forms of plants and statistical plant geography, Am. Midl. Nat. (1934) 15, doi:10.2307/2419902.
[66] G. Biddle, Tree root damage to buildings, in: Shallow Foundation and Soil Properties Committee Sessions at ASCE Civil Engineering Conference 2001, Houston, Texas, United States, 2001, pp. 1–23, doi:10.1061/40592(270)1. October 10-13.
[67] V. Navarro, M. Candel, A. Yustres, J. Sánchez, J. Alonso, Trees, soil moisture and foundation movements, Comput. Geotech. 36 (2009) 810–818, doi:10.1016/j.compgeo.2009.01.008.
[68] V. Navarro, M. Candel, Á. Yustres, J. Alonso, B. García, Trees, lateral shrinkage and building damage, Eng. Geol. 108 (3–4) (2009) 189–198, doi:10.1016/j.enggeo.2009.07.006.
[69] R.M. Aiken, A.J.M. Smucker, Root system regulation of whole plant growth, Annu. Rev. Phytopathol. 34 (1996) 325–346, doi:10.1146/annurev.phyto.34.1.325.
[70] L. Kutschera, Root Atlas of Central European Weeds and Crop. Plants of Arable Land, DLG Verlag, Frankfurt am Main, Germany, 1960 https://www.cabdirect.org/cabdirect/abstract/19622300166 (accessed October 26, 2022).
[71] J.P. Grime, Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory, Am. Nat. 111 (1977) 1169–1194, doi:10.1086/283244.
[72] F.A. Bazzaz, Habitat selection in plants, Am. Nat. 137 (1991) 116–130, doi:10.1086/285142.
[73] G. Caneva, A. Pacini, L. Celesti Grapow, S. Ceschin, The Colosseum's use and state of abandonment as analysed through its flora, Int. Biodeterior. Biodegrad. 51 (2003) 211–219, doi:10.1016/S0964-8305(02)00173-7.
[74] W.G. Abrahamson, A comment on vegetative and seed reproduction in plants, Evolution (N. Y) 33 (1979) 527 -519, doi:10.2307/2407641.
[75] N. Brace, M. Voegle, H. Pratt, Porosity. Permeability, and their relationship in Granite. Basalt, and Tuff, ONWI/E512-02900/TR-10, report prepared for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH, October, 1982.
[76] E. Borrelli, Porosity, in: E. Borrelli, G. Chiari, M.L. Tabasso, J.M. Teutonico, G. Torraca, A. Urland (Eds.), ARC Lab. Handb. Porosity, Salts, Bind. Colour, ICCROM, Rome, 1999, pp. 1–20. https://www.iccrom.org/sites/default/files/ICCROM_14_ARCLabHandbook01_en.pdf.
[77] O. Guillitte, Bioreceptivity: a new concept for building ecology studies, Sci. Total Environ. 167 (1995), doi:10.1016/0048-9697(95)04582-L.
[78] A.Z. Miller, P. Sanmartín, L. Pereira-Pardo, A. Dionísio, C. Saiz-Jimenez, M.F. Macedo, B. Prieto, Bioreceptivity of building stones: a review, Sci. Total Environ. 426 (2012) 1–12, doi:10.1016/J.SCITOTENV.2012.03.026.
[79] D. Láníková, Z. Lososová, Rocks and walls: natural versus secondary habitats, Folia Geobot. 44 (2009) 263–280, doi:10.1007/S12224-009-9045-X/TABLES/6.
[80] S. Ceschin, M. Cutini, G. Caneva, Contributo alla conoscenza della vegetazione delle aree archeologiche romane (Roma), Fitosociologia 43 (1) (2006) 97–139.
[81] S. Ceschin, G. Caneva, A. Kumbaric, Biodiversità ed emergenze floristiche nelle aree archeologiche romane, Webbia 61 (2006) 133–144, doi:10.1080/00837792.2006.10670797.
[82] G. Caneva, G. De Marco, A. Dinelli, M. Vinci, Le classi Parietarietea diffusae (Rivas-Mart ́ınez, 1964) Oberd. 1977 e Adiantetea Br.-Bl. 1947 nelle aree archeologiche romane, Fitosociologia 29 (1995) 165–179.
[83] G. Caneva, P.E. Tomei, Un giardino verticale sulle Mura di Lucca: Mi/u-rabilia, Gangemi Editore spa (2017) ISBN: 978-88- 492-3499-2.
[84] G. Caneva, F. Bartoli, A. Casanova Municchia, O. Salvatori, Y. Futagami, Biodeterioration patterns of different biological colonization of Ta Nei Temple, Angkor, in: Report on the Biodeterioration of Stone Monuments in Angkor - Results of the Joint Research Project at Ta Nei Temple, 2014, pp. 124–131.
[85] Z.K. Elinç, T. Korkut, L.G. Kaya, *Hedera helix* L. and damages in Tlos ancient city, Int. J. Dev. Sustain. 2 (2013) 333–346.
[86] T. Sternberg, H. Viles, A. Cathersides, Evaluating the role of ivy (*Hedera helix*) in moderating wall surface microclimates and contributing to the bioprotection of historic buildings, Build. Environ. 46 (2011) 293–297, doi:10.1016/j.buildenv.2010.07.017.
[87] H. Viles, T. Sternberg, A. Cathersides, Is ivy good or bad for historic walls? J. Archit. Conserv. 17 (2011) 25–41, doi:10.1080/13556207.2011.10785087.
[88] S.E. Favero-Longo, H.A. Viles, A review of the nature, role and control of lithobionts on stone cultural heritage: weighing-up and managing biodeterioration and bioprotection, World J. Microb. Biot. 36 (2020) 1–18, doi:10.1007/s11274-020-02878-3.
[89] Y. Gunasdi, O. Aksakal, L. Kemaloglu, Biodeterioration of some historical monuments in Erzurum by vascular plants, Int. Biodeterior. Biodegrad. 176 (2023) 105530, doi:10.1016/j.ibiod.2022.105530.
[90] G. Albani Rocchetti, F. Bartoli, E. Cicinelli, F. Lucchese, G. Caneva, Linking man and nature: relictual forest coenosis with *Laurus nobilis* L. and *Celtis australis* L. in Antica *Lavinium*, Italy, Sustainability 14 (1) (2021) 56, doi:10.3390/su14010056.
[91] S.Z. Heneidy, Y.M. Al-Sodany, L.M. Bidak, A.M. Fakhry, S.K. Hamouda, M.W. Halmy, S.A. Alrumman, D.A. Al-Bakre, E.M. Eid, S.M. Toto, Archeological sites and relict landscapes as refuge for biodiversity: case study of Alexandria City, Egypt, Sustainability 14 (4) (2022) 2416, doi:10.3390/su14042416.
[92] E. Cicinelli, G. Zangari, F. Bartoli, D. Isola, F. Lucchese, G. Caneva, Protecting monuments and plant biodiversity in archaeological sites: the case of the Etruscan necropolis of "Monterozzi" (Tarquinia, central Italy), Acta Hortic. (2022) 123–128, doi:10.17660/ACTAHORTIC.2022.1345.16.