

19 **Revisiting and reanalysing the concept of bioreceptivity 25 years on**  
20

21 P. Sanmartín <sup>1,2,\*</sup>, A.Z. Miller <sup>3</sup>, B. Prieto <sup>2</sup>, H. Viles <sup>1</sup>  
22  
23  
24  
25

- 26 1. School of Geography and the Environment, University of Oxford, South Parks  
27 Road, Oxford OX1 3QY, UK  
28  
29  
30 2. Departamento de Edafología e Química Agrícola. Facultade de Farmacia.  
31 Universidade de Santiago de Compostela, 15782 - Santiago de Compostela, Spain  
32  
33  
34 3. Laboratório HERCULES, Universidade de Évora, Largo Marquês de Marialva 8,  
35  
36 Évora, 7000-676, Portugal  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47

48 \*Corresponding author: Patricia Sanmartín (P. Sanmartín)  
49

50 Telephone: +34 881814984 Fax: +34 881 815106  
51

52 E-mail address: [patricia.sanmartin@usc.es](mailto:patricia.sanmartin@usc.es)  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65

## 1 **Abstract**

2 2020 marks 25 years since Olivier Guillitte defined the term ‘bioreceptivity’, to describe  
3 the ability of a building material to be colonised by living organisms. Although Guillitte  
4 noted in his 1995 paper that several issues required further investigation, to the best of  
5 our knowledge the bioreceptivity concept has not been restated, reviewed, reanalysed or  
6 updated since then. The present paper provides an opinionated exposition of the status  
7 and utility of the bioreceptivity concept for built heritage science and conservation in  
8 the light of current knowledge, aimed to stimulate further discussion. A bibliometric  
9 analysis highlights the key dimensions of the past 25 years of published research,  
10 showing that the term bioreceptivity has been widely used in the field of built cultural  
11 heritage. In our reanalysis of the concept, special attention is devoted to the six types of  
12 bioreceptivity (primary, secondary, tertiary, intrinsic, extrinsic and semi-extrinsic)  
13 articulated by Guillitte in 1995. We propose that field-based studies of bioreceptivity  
14 are urgently needed, and that the intrinsic, extrinsic and semi-extrinsic types of  
15 bioreceptivity should be dropped, and a new category (quaternary bioreceptivity) added.  
16 Additionally, we propose that bioreceptivity in submerged and subsoil environments  
17 should also be considered. Bioreceptivity remains an important concept for managing  
18 both new build and built heritage, as it provides the key to understanding the drivers and  
19 patterns of biological colonisation of building materials.

20

21 **Keywords:** Biodeterioration; Biological colonisation; colonisation management;  
22 cultural heritage; further discussion; opinionated exposition.

23

## 24 1. Introduction

25 The colonisation of built cultural heritage by plants and microbes is an important part  
26 of building ecology, and its understanding is crucial for research into, and practical  
27 management of, the deterioration and conservation of building materials. In order to  
28 answer the question ‘what controls the colonisation and growth of organisms on  
29 buildings and structures?’ three sets of factors need to be considered which relate to  
30 the properties of the organisms themselves (including dispersal mechanisms, growth  
31 requirements, etc), the characteristics of the environment (including climatic  
32 conditions and microclimatic parameters, such as solar exposure, shading and water  
33 availability), and the properties of the building materials (including physical and  
34 chemical characteristics). Guillitte’s concept of bioreceptivity, defined as the potential  
35 of the material to be colonised by living organisms (Guillitte 1995), provides a neat  
36 and popular way to conceptualise the third of those sets of factors. According to  
37 Guillitte (1995), it complements another concept that has been less commonly used in  
38 building ecology, ‘accessibility’. This plant ecology term was introduced by Heimans  
39 (1954) to define the totality of conditions prevailing at a certain locality, that may  
40 influence the possibility of diaspores to reach that spot and settle there. As Guillitte  
41 (1995) wrote: ‘Whereas this concept [referring to accessibility] relates to the  
42 colonisation potential of the environment, the bioreceptivity concept expresses the  
43 colonisation potential as defined by the characteristics of the material’.

44 The colonisation of building materials is a complex process as it ~~encompasses habitat~~  
45 ~~heterogeneity and~~ is dynamic in time and space due to the interrelationships among  
46 the colonising organisms, as well as between their populations, the inorganic substrate  
47 and the surrounding heterogeneous environment. In fact, biological colonisation  
48 patterns on built heritage are not constant, but periodic and are very likely to change

49 quickly as a result of different climate conditions, in particular alterations in  
50 temperature and precipitation (Macedo et al., 2009), as well as environmental  
51 chemical contaminants in polluted air and precipitation (Schiavon, 2002). It is  
52 important to emphasise that the potential of the material to be colonised by living  
53 organisms - its bioreceptivity - (Guillitte, 1995), is also dynamic as the chemical and  
54 physical characteristics of the substrate change over time as a result of exposure to  
55 weather and pollution conditions.

56 It is now timely, given the importance of an improved understanding of intrinsic  
57 material properties, their dynamism and their relation with external factors, to  
58 reconsider the concept of bioreceptivity 25 years after Guillitte originally articulated  
59 it. This paper aims to give an opinionated exposition (to stimulate further discussion)  
60 about Guillitte's concept of bioreceptivity 25 years on, investigating how it has been  
61 deployed mainly in the field of built cultural heritage science and conservation using a  
62 bibliometric survey, and reanalysing the concept by proposing some revisions and  
63 improvements.

## 64 **2. Revisiting bioreceptivity**

### 65 *2.1 Guillitte's ideas on bioreceptivity*

66 In 1995, Olivier Guillitte published the first two papers defining and analysing the  
67 concept of bioreceptivity: 'Bioreceptivity: a new concept for building ecology  
68 studies' (Guillitte, 1995) and 'Laboratory chamber studies and petrographical analysis  
69 as bioreceptivity assessment tools of building materials' (Guillitte and Dreesen,  
70 1995). While the idea that material properties influence what grows was not in itself  
71 novel, Guillitte proposed the term bioreceptivity to provide a neutral framing with no  
72 connotation of biological colonisation being negative, and also to shift the focus on to  
73 the influence of materials on organisms rather than the reverse, which until then had

74 monopolized the attention of researchers (Hueck, 1965). In his first publication  
75 (Guillitte, 1995), he proposed two definitions for the bioreceptivity concept, (1) 'the  
76 ability of a material to be colonised by living organisms' (expanded in 'the aptitude of  
77 a material (or any other inanimate object) to be colonised by one or several groups of  
78 living organisms without necessarily undergoing any biodeterioration'), (2) 'the  
79 totality of material properties that contribute to the establishment, anchorage and  
80 development of fauna and/or flora' (Guillitte, 1995). The purpose of these definitions  
81 was to link bioreceptivity to the process of colonisation and *in situ* development and  
82 multiplication of organisms, thus interpreting the material as a potential habitat where  
83 the conditions that define the niche of the species can be found and not as a mere  
84 transient or anchoring place for organisms. He aimed to distinguish bioreceptivity  
85 from other concepts related to biological growths on materials, such as biodegradation  
86 and biodeterioration (which usually have negative connotations).

87 Why did Guillitte coin the term 'bioreceptivity' rather than 'biosusceptibility'?  
88 Guillitte (1995) reviewed the term 'susceptibility' and its definition in the field of  
89 medicine and veterinary medicine, and used it as an analogy for his new concept in  
90 building ecology. In a footnote to his work, Guillitte explains that he opts for  
91 'receptivity' instead of 'susceptibility' based on the parallel with the biological  
92 concept 'receptivity' in English defined as 'the ability of a flower stigma to be  
93 fertilised by pollen grains through the pollen tube', and because the former translates  
94 in the same way into different languages. Hence he writes 'we suggest using the word  
95 'bioreceptivite' in French, 'Biorezeptivitt' in German, 'bioreceptiviteit' in Dutch,  
96 'bioreceptividad' in Spanish, 'bioreceptividade' in Portuguese and 'biorecettivith' in  
97 Italian' (Guillitte, 1995). Nevertheless, some papers published later have used the  
98 terms susceptibility to biological colonisation (Marques et al., 2015), bio-

99 susceptibility (Sterflinger et al., 2013), and biosusceptibility (Gu et al., 1998) to refer  
100 to the bioreceptivity of a material.

101 What factors did Guillitte include within the concept of bioreceptivity? According to  
102 Guillitte (1995) 'the precise role of the building material characteristics in the  
103 colonisation process is not fully understood, with the exception of acidity, whose  
104 influence on the taxonomic content of colonising organisms is well known'. For that  
105 reason he grouped all those material characteristics with no order of importance under  
106 the term 'bioreceptivity'. Moreover, as a first step in clarifying the relative  
107 importance of each intrinsic factor to the material's bioreceptivity, he performed,  
108 alongside Roland Dreesen (Guillitte and Dreesen, 1995), a comparative study of  
109 colonisation under laboratory conditions over a six-month period, using limestone,  
110 concrete, mortar and brick to demonstrate that 'the bioreceptivity of building  
111 materials is highly variable and that it is controlled primarily by their surface  
112 roughness, initial porosity and mineralogical nature' (Guillitte and Dreesen, 1995).

## 113 *2.2 Other linked concepts*

114 In contrast to bioreceptivity, the concept of biodeterioration has been around for much  
115 longer and applied to a much wider range of materials and circumstances. The most  
116 consolidated and widespread definition of biodeterioration is that offered by Hueck in  
117 1965 as 'any undesirable change in the properties of a material caused by the vital  
118 activities of organisms' (Hueck, 1965, p. 7). Biodeterioration can be classified into  
119 three categories: (i) physical or mechanical, (ii) chemical and (iii) aesthetic. The latter  
120 is limited to the visual effects of the presence of microorganisms and their products  
121 that alter the chromatic appearance. It seems that Guillitte did not consider this third  
122 category to be a form of deterioration, at least in the case of organisms growing on  
123 building materials. Indeed, he claimed that 'some authors consider the colour changes

124 to be aesthetically pleasing, credit them with a protective role against man- or  
125 weather-induced aggression and suggest that they have a cleansing effect which  
126 benefits the environment' (Guillitte, 1995). Such claims remain controversial. As  
127 Kumar and Kumar (1999) reported, climbing plants have long been considered to  
128 enhance the aesthetic value of built heritage such as ruins, as in some cases can the  
129 occurrence of algae and lichens (Martines, 1983). In several cases, the negligible  
130 (Gulotta et al., 2018; Sanmartín et al., 2020) or bioprotective (Ramírez et al., 2010;  
131 Cutler et al., 2013) role of pioneer algae and cyanobacteria (a phenomenon often  
132 referred to as “greening”, the first step in the sequential process of colonisation) on  
133 the physical integrity of stone has been proven, aside from the ability of algae to  
134 sequester CO<sub>2</sub> from atmospheric air (Prajapati et al., 2013). However, at present, it  
135 is frequently considered preferable to eliminate any kind of colonisation from  
136 building surfaces for reasons of preventive conservation and to create an impression  
137 of order, cleanliness and care of the structure or construction.

138 Biodeterioration covers many of the phenomena, processes or activities by organisms  
139 on building materials, but excludes those recognized as protective. Bioprotection, as  
140 conceptualised by researchers such as Carter and Viles (2005), is used to refer to the  
141 positive ways in which organisms growing on the surfaces of rocks and building  
142 materials protect the surface from other processes of weathering and erosion. For  
143 example, surface-dwelling organisms can physically protect the underlying surface  
144 from abrasion, act as a thermal blanket, absorb pollutants and prevent them from  
145 interacting with the surface, and mediate moisture regimes (Sternberg et al., 2010a  
146 and b).

### 147 *2.3 Bibliometric analysis of 25 years of bioreceptivity publications*

148 Bibliometric analysis was conducted on the 19<sup>th</sup> November 2020 to investigate trends  
149 in publications on bioreceptivity. An initial search of the peer-reviewed literature was  
150 performed using the term ‘Bioreceptivity’ in both the Web of Science  
151 (<https://www.webofknowledge.com/>) and Scopus (<https://www.scopus.com/>)  
152 databases. Considering the number of records obtained, the database of the Web of  
153 Science (WOS) was selected for a more detailed search on the topic. The terms  
154 ‘Bioreceptivity’, ‘Biosusceptibility’ or ‘Bio-susceptibility’ were searched in the WOS  
155 database and then combined with the keywords: ‘primary’, ‘secondary’, ‘tertiary’,  
156 ‘stone’, ‘concrete’, ‘mortars’, ‘tiles’, ‘bricks’, ‘ceramic’, ‘plastic’ or ‘glass’.

157 The visualization tool VOSviewer (Van Eck and Waltman, 2010) was used to provide  
158 co-occurrence maps of keywords, advocated for detecting emerging trends. Excel  
159 from Microsoft Office was also used for visualization of the bibliometric results.

160 A total of 174 records was obtained in the WOS database on the 19<sup>th</sup> of November  
161 2020 using the terms ‘Bioreceptivity’ ‘Biosusceptibility’ or ‘Bio-susceptibility’,  
162 which have been cited 3348 times. Figure 1 shows the number of bioreceptivity-  
163 related publications between 1995 and 2020 and the citations per year of those works.  
164 It is noticeable that the annual number of articles increased significantly in the last  
165 decade. The first peak of published articles was in 2009, followed by 2014 and 2018.  
166 After 2010, the number of publications steadily increased until 2018. The top 20  
167 journals include *International Biodeterioration and Biodegradation*, *Science of the*  
168 *Total Environment*, *Building and Environment*, *Construction and Building Materials*,  
169 *Biofouling*, etc. However, bioreceptivity publications were mainly concentrated in the  
170 first two journals. The total number of records on bioreceptivity obtained in the WOS  
171 database (174) was published in 68 journals. The highest number of bioreceptivity-  
172 related articles derives from European countries.



173 *[Figure 1: Annual trends in bioreceptivity publications and their citations from 1995*  
174 *to 2020 (Source: WOS, accessed 19<sup>th</sup> November 2020).]*

175 In order to find associations between keywords from bioreceptivity-related  
176 publications, a co-occurrence bioreceptivity keyword map was performed ranked in  
177 terms of number of articles (Fig. 2). This co-occurrence network analysis is effective  
178 for identifying groups of related terms of a specific topic, and for mapping the  
179 strength of the association between keywords, showing the potential combination with  
180 other research fields and knowledge, evidencing multidisciplinary. As shown in  
181 Figure 2, the term ‘bioreceptivity’ has the highest co-occurrence frequency with  
182 ‘biodeterioration’, indicating that bioreceptivity and biodeterioration are thoroughly  
183 related. In fact, several studies on bioreceptivity of building materials also include the  
184 identification of the biodeterioration patterns produced by the living organisms on the  
185 materials (Coutinho et al., 2016, 2019; Miller et al., 2008, 2010). This also explains  
186 the predominance of the keywords ‘biocide’, ‘biofilms’ and ‘biofouling’ (Fig. 2).

187 *[Figure 2: Co-occurrence bioreceptivity keyword map compiled by articles from the*  
188 *WOS database assigned to bioreceptivity on the 19<sup>th</sup> of November 2020, using the*  
189 *bibliometric mapping tool VOSviewer. Unit of analysis: all keywords. The size of the*  
190 *node represents the frequency of the keyword co-occurrence with other keywords. The*  
191 *colour of a keyword (node) is determined by the cluster to which the keyword belongs,*  
192 *meaning that a keyword usually occurs with the keywords from the same colour*  
193 *cluster.]*

194 After ‘biodeterioration’, the predominance of the keywords ‘algae’ and  
195 ‘cyanobacteria’ is explained as phototrophic microorganisms are pioneer colonisers of  
196 inorganic materials, such as stone, and are the most commonly used microorganisms  
197 in laboratory-based bioreceptivity experiments (Miller et al., 2012). In addition,

198 'fungi' and 'lichens' also have a high co-occurrence in bioreceptivity-related articles.  
199 Worth mentioning is the predominance of keywords related to the materials covered  
200 in bioreceptivity-related publications, such as 'stone', 'rocks', 'limestone', 'concrete'  
201 and 'mortar', as well as 'cultural-heritage', 'conservation' and 'monuments', which  
202 demonstrate that the term bioreceptivity is widely used in the field of built cultural  
203 heritage (Fig. 2). According to our bibliometric survey of research into bioreceptivity,  
204 stone is the most studied material and the focus of the most cited articles (Fig. 3). In  
205 contrast, few studies have been performed on the bioreceptivity of concrete, mortars,  
206 tiles, bricks, glass or plastic, compared with stone. Most of the case studies on  
207 bioreceptivity shown in Figure 3 rely on in-vitro (lab based) tests. In fact, the majority  
208 of papers was focused on primary bioreceptivity (Fig. 4) which has been almost  
209 exclusively studied under laboratory conditions (e.g. Prieto and Silva, 2005; Miller et  
210 al., 2008, 2010; Vázquez-Nion et al., 2018a).

211 *[Figure 3. Number of records for the combination of the term 'bioreceptivity' with the*  
212 *keywords related to building materials in the WOS database (accessed on the 19<sup>th</sup> of*  
213 *November 2020).]*

214 *[Figure 4. Number of records in the WOS database (accessed on the 19<sup>th</sup> of*  
215 *November 2020) for the keywords 'Primary bioreceptivity', 'Secondary*  
216 *bioreceptivity' and 'Tertiary bioreceptivity'.]*

### 217 **3. Reanalysing bioreceptivity**

#### 218 ***3.1 What is missing or often overlooked from Guillitte's ideas?***

219 When a material has not yet been exposed to colonisation and as long as its properties  
220 remain unchanged, bioreceptivity is defined as primary according to Guillitte, whilst  
221 when the material properties change it becomes secondary. Guillitte (1995) wrote:  
222 'For practical purposes, secondary bioreceptivity is often more important than primary

223 bioreceptivity'. This is especially true when we refer to built cultural heritage, whose  
224 materials have been exposed to weathering for long periods. However, as the current  
225 authors demonstrate in section 2.3, secondary bioreceptivity has hardly been studied,  
226 with the bulk of research focusing on primary bioreceptivity which probably is more  
227 useful in the architectural field for looking at 'new build'. There are several reasons  
228 that could explain why this has been true for 25 years. For example, it is not clear  
229 when ~~the changes in changing~~ material properties become significant for potential  
230 colonizers (breakpoint), and what criteria should be used to determine that breakpoint.  
231 How much must a given material be changed (physically and/or chemically) in order  
232 for its bioreceptivity to be defined as secondary? If, as Guillitte believed, the  
233 transition from primary to secondary bioreceptivity occurs as a result of both the  
234 activity of living organisms and abiotic processes, ~~together or separately in~~  
235 ~~combination or just one of them~~, then ~~how can researchers~~ it is very difficult for  
236 researchers to produce realistic artificially weathered specimens in the laboratory on  
237 which to investigate secondary bioreceptivity (Papida et al., 2000; Vázquez-Nion et  
238 al., 2018b)? Are field-based studies needed? There is also the issue that most natural  
239 building materials have already undergone change through weathering (for example  
240 on a quarry face) even before they are placed in a building (Silva et al., 1997), and so  
241 it is unclear whether bioreceptivity in such cases should be classified as primary or  
242 secondary.

243 Guillitte's concept of bioreceptivity is largely focused on the influence of small scale  
244 (mm to cm scale) factors intrinsic to different building materials. These are amenable  
245 to study in laboratory experiments and are the most obvious intrinsic factors to  
246 consider. However, once a material is exposed within a building façade or structure,  
247 other larger scale (cm to m) factors may have very important influences on

248 bioreceptivity (Viles and Ahmad, 2016). For example, a stone type used in  
249 architectural detailing such as balusters and string courses may have very different  
250 bioreceptivities within those two contexts, because of the influence of surface angle  
251 (in relation to vertical), aspect, and position on the building which i) exert important  
252 controls on water and thermal regimes and ii) modify primary bioreceptivity through  
253 weathering in different ways giving rise to different secondary bioreceptivity. In  
254 many ways, these larger scale influences can be seen as larger scale surface roughness  
255 (where the roughness applies to whole areas of masonry, facades or indeed an entire  
256 building). The potential importance of these larger scale factors can best be studied by  
257 well-designed field experiments. One of the remaining challenges about larger scale  
258 factors is to determine whether they are intrinsic or extrinsic in nature.

259 At present, the relative importance of each intrinsic characteristic on the  
260 bioreceptivity of the material has not been clarified. Some progress has been made for  
261 limestone and granite using laboratory-based methods. For granite, bioreceptivity is  
262 influenced by physical properties rather than chemical and mineralogical composition  
263 (Vázquez-Nion et al., 2018a). High open porosity, capillary water content and  
264 roughness are the intrinsic factors that most promote colonisation by phototrophs  
265 (Prieto and Silva, 2005; Vázquez-Nion et al., 2018a). For limestone, although surface  
266 roughness is a key factor, there is no consensus about the intrinsic material properties  
267 that most influence bioreceptivity (Miller et al., 2012). The concept of bioreceptivity  
268 has been extended to other materials, including ceramic tiles and glass, and is now  
269 fairly well accepted in the field of built cultural heritage (e.g. Rodrigues et al., 2014;  
270 Coutinho et al., 2016), but the key controlling factors remain unclear for many of  
271 these materials. For stained glass, chemical composition is most likely to influence  
272 the bioreceptivity to fungal growth as reported by Rodrigues et al. (2014). Coutinho et

273 al. (2016) demonstrated that tile bioreceptivity was influenced by water absorption by  
274 capillarity and water vapor permeability.

275 One further important aspect to consider is ‘bioreceptivity to what’? In essence,  
276 bioreceptivity is a relative not an absolute concept – relative to particular species or  
277 types of organisms. Guillitte (1995) indicated that in a controlled environment (e.g. a  
278 growth chamber in a laboratory with one cryptogam species) the absence of  
279 colonising cryptogams on the material means that the material is not bioreceptive to  
280 these cryptogams. In field studies, absence of colonising cryptogams means that the  
281 material is not bioreceptive to cryptogams present in the surrounding environment.  
282 This relative aspect of bioreceptivity is often overlooked, but has important practical  
283 implications. For example, when accelerated bioreceptivity studies under controlled  
284 conditions in the laboratory are carried out with a mixture of different colonising  
285 species belonging to different taxonomic groups (i.e. cyanobacteria, green algae,  
286 diatoms, mosses, etc.) a key question is how long to maintain the colonisation process  
287 because the speed of colonisation varies within and among different taxonomic  
288 groups, as well as, between materials. This was verified for the first time in the study  
289 of Guillitte and Dreesen (1995), where after two weeks the only colonisation observed  
290 was by pioneering green algae on concrete. After four weeks sandy limestone, brick  
291 and mortar showed the first signs of algae (which eventually disappeared, giving way  
292 to nitrophilous species), whereas concrete started being colonised by cyanobacteria  
293 and mosses. A month later, cyanobacteria became the most abundant coloniser on all  
294 materials. After 6 months, colonisation was very profuse on concrete and sandy  
295 limestone (but not in the compact and hard crinoidal limestone, which had the least  
296 vegetation cover of all materials), but brick and mortar were hardly colonised.

297 Furthermore, the diversity was wide, although filamentous cyanobacteria and at lesser  
298 extent some species of algae (*Anabaena* and *Oscillatoria*) were the most abundant.  
299 One missing point from Guillitte's ideas is how to express and quantify  
300 bioreceptivity. In the first experiment specifically designed to evaluate bioreceptivity,  
301 Guillitte and Dreesen (1995) characterised the bioreceptivity of two natural stone  
302 types and three manufactured materials by quantifying the vegetal cover after 9  
303 months of exposure to sprinkling with a nutrient-rich tap water containing a mixture  
304 of pioneer colonising plant diaspores. Percentage cover has been used to express  
305 bioreceptivity in subsequent experiments (Tomaselli et al., 2000, Miller et al., 2006,  
306 Escadeillas et al., 2007) allowing comparison between samples in the same  
307 experiment but not comparison between different experiments. The main problem  
308 derived from using % cover is that once 100% cover is reached the subsequent  
309 increase in colonization related to bioreceptivity cannot be quantified. Moreover,  
310 colonization in depth is not taken into account. To overcome these problems, the  
311 amount of chlorophyll *a* /surface unit has been used by other authors to express  
312 bioreceptivity (Prieto and Silva, 2005; Prieto et al., 2006). This way of expressing  
313 bioreceptivity allows comparison not only between samples but also between  
314 experiments, but has the disadvantage that it can only be used for phototrophs.  
315 Moreover, Guillitte did not establish how to unambiguously define and categorise the  
316 bioreceptivity of a material, although he pointed the need to remove any subjectivity  
317 attached to the concept and proposed developing a bioreceptivity index. Nowadays,  
318 this index has been developed but only for granitic rocks (Vázquez-Nion et al.,  
319 2018c).

### 320 ***3.2 Types of bioreceptivity on built heritage***

321 Bioreceptivity to primary colonisers where the material properties are not  
322 substantially modified, either by biotic or abiotic factors, is according to Guillitte  
323 (1995) the ‘primary bioreceptivity’, which according to the current authors is related  
324 to the intrinsic properties of a sound or fresh material after manipulation (extraction  
325 from the quarry and cut) for a final function (e.g. used in a construction) (Fig. 5).  
326 ‘Secondary bioreceptivity’ appears when the material properties evolve by weathering  
327 induced by environmental factors and/or colonisers (Fig. 5), and ‘tertiary  
328 bioreceptivity’ appears when human-induced factors are involved, such as cleaning or  
329 restoration interventions. Guillitte (1995) noted ‘any human activity affecting the  
330 material - consolidation, coating with a biocide or surface polishing - also modifies  
331 the initial or secondary characteristics of the properties of the material, inducing  
332 ‘tertiary bioreceptivity’’. However, cleaning the material affects its bioreceptivity in a  
333 completely different way than protecting it with chemicals. The current authors  
334 consider that adding a material, such as a consolidant or biocide-embedded coating,  
335 does not have the same effect on the material properties as brushing or polishing its  
336 surface, which modifies its surface roughness and colour, but does not introduce a  
337 component of a different nature. For this reason, we propose that Guillitte’s ‘tertiary  
338 bioreceptivity’ should be split into two, with ‘tertiary bioreceptivity’ used for human  
339 actions that cause physical changes to the material (such as by mechanical (with  
340 abrasives) and laser cleaning treatments), and ‘quaternary bioreceptivity’ used when  
341 new materials, as coatings or chemical products that can leave residues, are added.  
342 Table 1 summarises the key changes to Guillitte’s concept of bioreceptivity, and their  
343 rationales, that are proposed in this paper.

344 Although the addition of a new term (‘quaternary bioreceptivity’) could be seen as  
345 controversial and adding to complexity, we believe that it has practical benefits for

346 the use of bioreceptivity for understanding the deterioration of built heritage in  
347 highlighting different ways in which humans can affect the situation, in a way that is  
348 distinctive to the changes involved in secondary bioreceptivity. Furthermore, the  
349 concept of ‘quaternary bioreceptivity’ reduces complexity by replacing the terms, also  
350 defined by Guillitte but rarely used, of intrinsic, semi-extrinsic and extrinsic  
351 bioreceptivity. Guillitte (1995) defined intrinsic bioreceptivity as occurring ‘when  
352 colonisation depends mainly on the properties of the material, irrespective of  
353 exogenous contributions’. Many researchers consider ‘intrinsic’ and ‘primary’  
354 bioreceptivity as synonymous, probably because they see both natural weathering and  
355 human activities as exogenous contributions. We instead consider that Guillitte  
356 viewed exogenous contributions in a more narrow sense as additions to the material  
357 such as particles, organisms and substances. In this interpretation, all three types of  
358 bioreceptivity of a fresh, weathered and cleaned stony material, i.e. primary,  
359 secondary and tertiary bioreceptivity, may be seen as ‘intrinsic bioreceptivity’. It  
360 reinforces this idea that by ‘semi-extrinsic bioreceptivity’ Guillitte (1995) refers to  
361 situations when ‘colonisation depends directly and simultaneously on the properties  
362 of the material and on the deposits of exogenous substances’, where he used the term  
363 ‘deposit’ to refer to the exogenous contribution. For us, ‘semi-extrinsic bioreceptivity’  
364 would in some cases correspond to what we have called ‘quaternary bioreceptivity’.  
365 An extreme case of ‘quaternary bioreceptivity’, where only the bioreceptivity of the  
366 added exogenous material is of interest is what Guillitte (1995) called ‘extrinsic  
367 bioreceptivity’. We propose that intrinsic, extrinsic and semi-extrinsic bioreceptivity  
368 terms be dropped, and instead encourage the use of ‘intrinsic factors’ and ‘extrinsic  
369 factors’ related to the bioreceptivity of a material. Thus, roughness, porosity,  
370 mineralogical composition and colour of a material, for instance, will be intrinsic



371 factors related to bioreceptivity; while architectural factors, micro-temperature and  
372 micro-humidity on the material surface, and added materials (such as dead biomass,  
373 living organisms, dust, guano) are extrinsic factors related to bioreceptivity (Table 1).  
374 Figure 5 provides a visualization of how our conceptualisation of bioreceptivity builds  
375 on that of Guillitte (1995). The blue dashed arrows in figure 5 portray the ecological  
376 dynamism involved as material conditions change within the different categories  
377 (primary, secondary, tertiary and quaternary) and also as the situation switches from  
378 primary to secondary types. In the case of primary bioreceptivity, the communities  
379 should be dominated by fast-growing and well-dispersed species while in secondary  
380 bioreceptivity, these species will tend to be replaced by more competitive species  
381 which may have differing impacts on biodeterioration. Furthermore, in the case of  
382 tertiary bioreceptivity, changes in the ecological community should occur faster. This  
383 has been observed in several studies of tertiary bioreceptivity, where recolonisation  
384 after cleaning occurs quicker than during the primary bioreceptivity phase (Sohrabi et  
385 al., 2017). The same has been reported for the proposed new category of quaternary  
386 bioreceptivity, where ~~the added materials such as consolidants and other surface~~  
387 ~~treatments new introduced material~~ may become a new habitat for colonisers. Several  
388 studies note that these new habitats (generally much are more bioreceptive than the  
389 original stony material) for colonisers (Bracci et al., 2002; Cappitelli et al., 2007). For  
390 example, in the Catacombs of Domitilla (Rome, Italy), a biocide treatment composed  
391 of quaternary ammonium compounds and octylisothiazolone sparked the proliferation  
392 of bacteria with high hydrolytic enzymatic activity (Urzi et al., 2016). In Campeche  
393 (Mexico), restored mortars composed of fatty acid promoted an early endolithic  
394 phototrophic colonization by cyanobacteria and bryophyte on the facade of San  
395 Roque church (Jurado and Miller et al., 2014). Surface treatments such as

396 consolidants may also, ~~or may~~ alter the physical properties of stony materials like the  
397 wetting-drying kinetics, leading to the material remaining damp for longer and hence  
398 its bioreceptivity increases (Prieto et al., 2014). In future, an interesting area of  
399 research would be to explore these ecological dynamics in more detail and elucidate  
400 how communities of organisms living on built heritage change in tandem with the  
401 material changes. This could involve linking bioreceptivity to concepts of ecological  
402 succession.

403 *[Figure 5. Visualization of how our conceptualisation of bioreceptivity compares with*  
404 *that of Guillitte (1995).]*

### 405 ***3.3 Bioreceptivity of subaerial, submerged and subsoil built heritage***

406 While the concept of biodeterioration is considered in subaerial, submerged and  
407 subsoil environments, bioreceptivity is currently only explicitly considered in the  
408 former despite buildings possessing subsoil foundations and being affected by  
409 periodic flooding, as well as many archaeological sites being buried or immersed.  
410 However, this is only a conceptual issue because many studies have focused on how  
411 biodeterioration develops differently according to the type of material and how the  
412 intrinsic characteristics of a material affect its biocolonisation in submerged (mainly  
413 marine) and subsoil environments. For example, a comparative study of bioreceptivity  
414 between different building materials (marbles, limestones, ignimbrites, and bricks),  
415 similar to that of Guillitte and Dreesen (1995), but in a Mediterranean marine  
416 environment was carried out by Aloise et al. (2014) although they do not explicitly  
417 use the term bioreceptivity. Marble and limestone samples collected from the cities of  
418 Baiae and Portus Iulius (Naples, Italy), submerged since the 4th century AD, showed  
419 intense colonisation (high bioreceptivity) mainly by boring sponges, while  
420 ignimbrites in the same place presented a lower biological attack caused by serpulids

421 and bryozoans. In bricks, paste with volcanic aggregates was less bioreceptive,  
422 showing a greater resistance to biological colonisation, than that with quartz (Aloise  
423 et al., 2014). As is clear, different species were found on different substrates as a  
424 function of their composition. Similarly, differences in material colour have been  
425 shown to impact the short-term development of marine biofouling communities,  
426 influencing larval settlement and colonisation of invertebrates and algae (Dahlem et  
427 al., 1984; Satheesh and Wesley, 2010), and especially barnacles (Pomerat and Reiner,  
428 1942; Kon-ya and Miki, 1994; Robson et al., 2009; Prendergast, 2010). Most studies  
429 in this field have only tested black and white or grayscale substrates, thus showing  
430 only whether different responses arise due to the luminosity or lightness/darkness  
431 (Callow and Callow, 2000; Swain et al., 2006; Dobretsov et al., 2013; Cao et al.,  
432 2013). Other studies, instead, have also considered chroma and hue (Guenther et al.,  
433 2009; Ells et al., 2016; Li et al., 2017). Chroma (or saturation) is related to the  
434 intensity of colour, while hue, which refers to the dominant wavelength and  
435 represents redness, yellowness, greenness, blueness, etc., has been shown in  
436 perception studies to be the most important colour parameter (Berns, 2000; Prieto et  
437 al., 2018). Settlement of mussel *Mytilus coruscus* plantigrades was found to differ  
438 according to substrate colour (red, orange, blue, white, yellow and green) and was  
439 lowest on the biofilms formed on green surfaces, possibly because of a variation in  
440 the establishment of the underlying biofilm community (Li et al., 2017). In contrast,  
441 the hydroid *Ectopleura larynx* settled preferentially on black vs white substrates,  
442 whereas there were no significant differences between the remaining tested colours  
443 (yellow, red and blue; Guenther et al., 2009). These two examples show how  
444 differently various organisms respond to surface colour and highlight the need to  
445 investigate this response systematically.

446 The main cause of deterioration in submerged marine environments is  
447 biodeterioration (Aloise et al., 2014; La Russa et al., 2015; Cámara et al., 2017). For  
448 *in situ* conservation of underwater cultural heritage a widely used technique is burial  
449 using marine sediments or burial materials, i.e. sandbags, concrete, or plastic  
450 geotextile (Bethencourt et al., 2018). Such burial should protect the material from  
451 environmental conditions in seawater, such as chemical composition of the water  
452 column, light regime, nutrient availability, waves and currents, however studies to  
453 date are inconclusive (Bethencourt et al., 2018). Other conservation activities involve  
454 the application of metal oxide nanoparticles to underwater stone surface (Ruffolo et  
455 al., 2017). In arid subaerial environments, where wind and rain are major agents of  
456 deterioration affecting archaeological remains and structures, burial or reburial in soil  
457 is likely to aid conservation. In the soil, buried materials like ceramics are in principle  
458 more bioreceptive than natural rocks due to their structure and porous matrix, able to  
459 retain humidity and heat (Guiamet et al., 2019). On the other hand, no  
460 microorganisms are able to degrade lignin anaerobically, so wooden materials are  
461 hardly bioreceptive in buried environments (Caneva et al., 2008). In addition, and as  
462 in subaerial environments, the pH of the material, combined with the alkaline or  
463 acidic conditions of the soil, is a key factor in bioreceptivity studies in buried  
464 environments. According to Caneva et al. (2008) this parameter, along with texture,  
465 concentration of soluble salts, clay and organic substances content, electrical  
466 conductivity and buffering capacity, gives a measure of the 'aggressivity' of the soils  
467 to the buried materials.

#### 468 ***3.4 Bioreceptivity and building-scale factors***

469 Because most bioreceptivity studies have been carried out in controlled, laboratory  
470 conditions, there is a need for further investigation of the larger-scale factors

471 influencing colonisation dynamics on real buildings and its relationship with  
472 bioreceptivity. As long as bioreceptivity of a material is defined by ‘the totality of  
473 material properties that contribute to the establishment, anchorage and development  
474 of fauna and/or flora’ those properties can be different for the same material  
475 depending on its position on the building. Introducing larger-scale factors to  
476 bioreceptivity brings complications, as it becomes hard to separate out intrinsic from  
477 extrinsic factors. Further research is needed to explore the influence of building-scale  
478 factors on bioreceptivity, colonization and biodeterioration.

479 The architectural geometry determines the microclimatic condition of each  
480 architectonic element. Those microclimatic conditions are related not only to the  
481 colonisation potential of the environment, but also to the colonisation potential of the  
482 material (bioreceptivity) as long as they modify the material properties. Thus, for  
483 instance, when a stone is emplaced within the façade of a building, the relationship  
484 between water (one of the most important factors in biological colonisation) and that  
485 stone type is going to differ from that defined in the laboratory because some rock  
486 properties related to the movement of water inside it change once the stone is set  
487 within a masonry and architectural context. For example, the porosity may differ from  
488 that measured in the laboratory on small, freshly cut specimens, as some of the porous  
489 space can be occupied by other materials (mortars), solutions, salts, etc., depending on  
490 location within the building. Another example is where stone surfaces receive runoff  
491 from building elements made of materials with biocide properties, such as copper,  
492 which can become a part of the stone surface and limit their bioreceptivity (Fig. 6). In  
493 contrast, stone surfaces located under tree canopies can receive nutrients washed off  
494 leaves which can enhance their bioreceptivity.

495 In several cases microclimate more than macroclimate exerts the major control on  
496 colonisation. Microclimatic conditions are themselves often highly influenced by the  
497 architectural geometry and complexity with, for example, sloping and horizontal  
498 surfaces likely to retain moisture more than vertical surfaces. Such is the case for the  
499 highly hydrophobic subaerial biofilm of the processional cloister of the Monastery of  
500 San Martiño Pinarío (Santiago de Compostela, NW Spain) mainly formed by  
501 *Apatococcus lobatus* (Chodat) J.B.Petersen (Chlorophyta). There, microbial cells with  
502 a thick cell wall occur in densely packed aggregates surrounded by the EPS matrix  
503 with an hydrophobic character associated with non-polar regions, which waterproof  
504 the cells and prevent dehydration. The hydrophobic character of the biofilm, in turn,  
505 influencing the bioreceptivity along the cloister walls, which is also determined by  
506 microclimate conditions that cause condensation on parts of the stone surface  
507 (Sanmartín et al., 2020). This study highlights the importance of the match between  
508 the particular species of colonisers and the potential area of colonisation.

509 *[Figure 6. Material in the surrounding space and architectural factors in influencing*  
510 *bioreceptivity. (a) Star of bronze (an alloy consisting primarily of copper) on the top*  
511 *of the structure plays a role as biocide in the Fountain of the Horses (Platerías*  
512 *Square, Santiago de Compostela, NW Spain); (b and c) Slope angle in buildings from*  
513 *Bristol and Oxford (UK) controlling hydrological pathways and, in turn, influencing*  
514 *bioreceptivity. Red arrows show the bioreceptivity patterns result of external factors.]*

#### 515 **4. Final considerations, conclusions and prospects**

516 Over the last 25 years, few studies have been carried out on bioreceptivity on  
517 materials *in situ* on built heritage. This has made bioreceptivity in practical terms a  
518 laboratory concept, which has allowed only partial investigation because many  
519 colonising organisms which are hard to cultivate in laboratory conditions (such as

520 lichens) have not been used. Also, in the studies conducted in controlled laboratory  
521 conditions the dynamism of bioreceptivity has been ignored, because primary,  
522 secondary or tertiary bioreceptivity have been studied in isolation. Although  
523 laboratory experiments could be designed to run for long enough to investigate  
524 primary and secondary bioreceptivity, better techniques need to be found to monitor  
525 the changing material properties during such experiments. A suite of non-destructive  
526 techniques (such as photogrammetry and laser scanning, portable hardness testing and  
527 moisture measurement devices) is now available which could provide such  
528 information in both long-term laboratory experiments and field-based exposure trials.  
529 Furthermore, the roles of both intrinsic (material properties) and extrinsic factors (e.g.  
530 microclimate, surrounding vegetation, architectural geometry, substances deposited  
531 but not integrated into the material) in the bioreceptivity of a material under  
532 laboratory conditions need to be assessed. While intrinsic properties are usually well-  
533 studied in laboratory experiments (e.g., Prieto and Silva, 2005; Vázquez-Nion et al.,  
534 2018a), extrinsic factors are rarely considered. Over time there is likely to be a  
535 changing balance between the relative important of intrinsic and extrinsic factors in  
536 controlling colonisation and determining bioreceptivity. Carefully designed laboratory  
537 experiments are needed to investigate the longer-term evolution of bioreceptivity.  
538 Well-designed field experiments are also required because many extrinsic factors  
539 cannot easily be simulated under laboratory conditions, and environmental conditions  
540 in the field may mask, or complicate, the bioreceptivity of the materials themselves  
541 (Barberousse et a., 2006; Manso et al., 2015).

542 In conclusion, the concept of bioreceptivity still has much to offer to scientists  
543 involved in understanding and management of the ecology of built heritage 25 years  
544 after it was first proposed. Along with biological and environmental factors, it forms a

545 trio of factors controlling colonisation of building surfaces, which in turn controls  
546 biodeteriorative, and bioprotective processes. The factors influencing colonisation are  
547 undoubtedly complex, but having a clearer understanding of concepts such as  
548 bioreceptivity helps to break the problem down into simpler component parts.  
549 Bibliometric analysis has shown that research on bioreceptivity over the past 25 years  
550 has been predominantly laboratory based and focused on primary bioreceptivity of  
551 building stones. This paper proposes some improvements and clarifications to the  
552 conceptual framework of Guillitte (summarised in Table 1), explores the parallels  
553 with ecological succession, and extends bioreceptivity to consider built heritage  
554 within submerged and subsoil environments. It also points out the need for additional  
555 well-designed field experiments to add to the valuable insights derived from  
556 laboratory studies and more fully explore the dynamic bioreceptivity of real building  
557 surfaces.

558

559



560 **Acknowledgements**

561 P. Sanmartín and B. Prieto thank the financial support of Xunta de Galicia grant  
562 ED431C 2018/32. A.Z. Miller acknowledges the support from the  
563 CEECIND/01147/2017 contract funded by Fundação para a Ciência e a Tecnologia  
564 (Portugal).

565

566 **References**

567 Aloise, P., Ricca, M., Russa, M.F., Ruffolo, S.A., Belfiore, C.M., Padeletti, G.,  
568 Crisci, G.M., 2014. Diagnostic analysis of stonematerials from underwater  
569 excavations: the case study of the Roman archaeological site of Baia (Naples, Italy).  
570 *Appl Phys A* 114, 655–662.

571 Barberousse, H., Tell, G., Yéprémian, C., Couté, A., 2006. Diversity of algae  
572 and cyanobacteria growing on buildings facades in France. *Algol Stud* 120, 81–105.

573 Berns, R.S., 2000. Billmeyer and Saltzman's principles of color technology.  
574 3rd ed. New York (USA): John Wiley & Sons. 272 pp.

575 Bethencourt, M., Fernández-Montblanc, T., Izquierdo, A., González-Duarte,  
576 M.M., Muñoz-Mas, C., 2018. Study of the influence of physical, chemical and  
577 biological conditions that influence the deterioration and protection of Underwater  
578 Cultural Heritage. *Sci Total Environ* 613, 98–114.

579 Bracci, S., Melo, M.J., Tiano, P., 2002. Comparative study on durability of  
580 different treatments on sandstone after exposure in natural environment. *The Silicates*  
581 *in Conservative Treatments. Tests, Improvements and Evaluation of Consolidating*  
582 *Performance*. In: *Proceedings of the International Congress*. Fondazione per le  
583 *Bioteconologie and Associazione Villa dell'Arte*, Torino, pp. 129–135.

584 Caneva, G., Nugari, M.P., Salvadori, O., 2008. Plant Biology for cultural  
585 heritage. Los Angeles: Getty Conservation Institute.

586 Cao, S., Wang, J., Zhang, Y., Chen, D., 2013. The effectiveness of an  
587 antifouling compound coating based on a silicone elastomer and colored phosphor  
588 powder against *Navicula* species diatom. *J Coat Technol Res* 10(3), 397–406.

589 Callow, M.E., Callow, J.A., 2000. Substratum location and zoospore  
590 behaviour in the fouling alga *Enteromorpha*. *Biofouling* 15, 49-56.

591 Cámara, B., Álvarez de Buergo, M., Bethencourt, M., Fernández-Montblanc,  
592 T., La Russa, M.F., Ricca, M., Fort, R., 2017. Biodeterioration of marble in an  
593 underwater environment. *Sci. Total Environ.* 609, 109–122.

594 Cappitelli, F., Principi, P., Pedrazzani, R., Toniolo, L., Sorlini, C., 2007.  
595 Bacterial and fungal deterioration of the Milan Cathedral marble treated with  
596 protective synthetic resins. *Sci Total Environ* 385(1-3), 172-181.

597 Carter, N.E.A., Viles, H.A., 2005. Bioprotection explored: the story of a little  
598 known earth surface process. *Geomorphology* 67(3-4), 273-281.

599 Coutinho, M.L., Miller, A.Z., Rogerio-Candelera, M.A., Mirão, J., Cerqueira  
600 Alves, L., Veiga, J.P., Águas, H., Pereira, S., Lyubchykg, A., Macedo, M.F., 2016.  
601 An integrated approach for assessing the bioreceptivity of glazed tiles to phototrophic  
602 microorganisms. *Biofouling* 32, 243-259.

603 Coutinho, M.L., Miller, A.Z., Phillips, A., Mirão, J., Dias, L., Rogerio-  
604 Candelera, M.A., Saiz-Jimenez, C., Martin-Sanchez, P.M., Cerqueira-Alves, L.,  
605 Macedo, M.F., 2019. Biodeterioration of majolica tiles by the fungus *Devriesia*  
606 *imbrexigena*. *Constr Build Mater* 212, 49-56.

607 Cutler, N.A., Viles, H.A., Ahmad, S., McCabe, S., Smith, B.J., 2013. Algal  
608 'greening' and the conservation of stone heritage structures. *Sci Total Environ* 442,  
609 152–164.

610 Dahlem, C., Moran, P.J., Grant, T.R., 1984. Larval settlement of marine  
611 sessile invertebrates on surfaces of different colour and position. *Ocean Sci Eng* 9,  
612 225-236.

613 Dobretsov, S., Abed, R.M.M., Voolstra, C.R., 2013. The effect of surface  
614 colour on the formation of marine micro and macrofouling communities. *Biofouling*  
615 29, 617-627.

616 Ells, V., Filip, N., Bishop, C.D., DeMont, M.E., Smith-Palmer, T., Wyeth,  
617 R.C., 2016. A true test of colour effects on marine invertebrate larval settlement. *J*  
618 *Exp Mar Bio Ecol* 483, 156-161.

619 Escadeillas, G., Bertron, A., Blanc, G., Dubosc, A., 2007. Accelerated testing  
620 of biological stain growth on external concrete walls. Part 1: Development of the  
621 growth tests. *Mater Struct* 40, 1061–71.

622 Gu, J.-D., Mitton, D.B., Ford, T.E., Mitchell, R., 1998. Microbial degradation  
623 of polymeric coatings measured by electrochemical impedance spectroscopy.  
624 *Biodegradation* 9, 39–45.

625 Guenther, J., Carl, C., Sunde, L.M., 2009. The effects of colour and copper on  
626 the settlement of the hydroid *Ectopleura larynx* on aquaculture nets in Norway.  
627 *Aquaculture* 292, 252–255.

628 Guillitte, O., 1995. Bioreceptivity: a new concept for building ecology studies.  
629 *Sci Total Environ* 167, 215–220.

630           Guillitte, O., Dreesen, R., 1995. Laboratory chamber studies and  
631 petrographical analysis as bioreceptivity assessment tools of building materials. *Sci*  
632 *Total Environ* 167, 365–374.

633           Guiamet, P.S., Soto, D.M., Schultz, M., 2019. Bioreceptivity of archeological  
634 ceramics in an arid region of northern Argentina. *Int. Biodeter Biodegr* 141, 2-9.

635           Gulotta, D., Villa, F., Cappitelli, F., Toniolo, L., 2018. Biofilm colonization of  
636 metamorphic lithotypes of a renaissance cathedral exposed to urban atmosphere. *Sci.*  
637 *Total Environ* 639, 1480–1490.

638           Heimans, J., 1954. L'accessibilite, terme nouveau en phytogeographie.  
639 *Vegetatio* 5-6, 142-146.

640           Hernández-Mariné, M., Roldán, M., Clavero, E., Canals, A., Ariño, X., 2001.  
641 Phototrophic biofilm morphology in dim light. The case of the Puigmoltó sinkhole.  
642 *Nova Hedwigia* 123, 237-253.

643           Hueck, H.J., 1965. The biodeterioration of materials as part of hylobiology.  
644 *Material und Organismen* 1(1), 5–34.

645           [Jurado, V., Miller, A., Cuezva, S., Fernandez-Cortes, A., Benavente, D.,](#)  
646 [Rogerio-Candelera, M., Reyes, J., Cañaveras, J., Sanchez-Moral, S., Saiz-Jimenez, C.,](#)  
647 [2014. Recolonization of mortars by endolithic organisms on the walls of San Roque](#)  
648 [church in Campeche \(Mexico\): A case of tertiary bioreceptivity. \*Constr Build Mater.\*](#)  
649 [53, 348–359.](#)

650           Kon-ya, K., Miki, W., 1994. Effects of environmental factors on larval  
651 settlement of the barnacle *Balanus amphitrite* reared in the laboratory. *Fisheries Sci*  
652 60, 563-565.

653           Kumar, R., Kumar, A.V., 1999. *Biodeterioration of Stone in Tropical*  
654 *Environments: An Overview*. The Getty Conservation Institute, Santa Monica, CA.

655 La Russa, M.F., Ricca, M., Belfiore, C.M., Ruffolo, S.A., Álvarez de Buergo,  
656 M., Crisci, G. M., 2015. The contribution of Earth Sciences to the preservation of  
657 underwater archaeological stone materials: an analytical approach. *Int J Conserv Sci*  
658 *6*, 335-348.

659 Li, Y., Guo, X., Chen, Y., Ding, D., Yang, J., 2017. Comparative analysis of  
660 biofilm community on different coloured substrata in relation to mussel settlement. *J*  
661 *Mar Biol Assoc UK* *97*, 81-89.

662 Macedo, M.F., Miller, A.Z., Dionísio, A., Saiz-Jimenez, C., 2009.  
663 Biodiversity of cyanobacteria and green algae on monuments in the Mediterranean  
664 Basin: an overview. *Microbiol-SGM* *155*, 3476-3490.

665 Manso, S., Calvo-Torras, M.A., De Belie, N., Segura, I., Aguado, A., 2015.  
666 Evaluation of natural colonisation of cementitious materials: effect of bioreceptivity  
667 and environmental conditions. *Sci Total Environ* *512-513*, 444-453.

668 Marques, J., Vázquez-Nion, D., Paz-Bermúdez, G., Prieto, B., 2015. The  
669 susceptibility of weathered versus unweathered schist to biological colonization in the  
670 Côa Valley Archaeological Park (north-east Portugal). *Environ. Microbiol.* *17*, 1805–  
671 1816.

672 Martines, G.G., 1983. Marmo e restauro dei monumenti antichi: Estetica delle  
673 rovine, degrado delle strutture all'aperto, un'ipotesi di lavoro. In *Marmo e Restauro.*  
674 *Situazioni e Prospettive*, Museo del Marmo, Carrara, Italy.

675 Miller, A., Dionísio, A., Macedo, MF., 2006. Primary bioreceptivity: a  
676 comparative study of different Portuguese lithotypes. *Int Biodeter Biodegr* *57*, 136–  
677 42.

678 Miller, A.Z., Laiz, L., Gonzalez, J.M., Dionisio, A., Macedo, M.F., Saiz-  
679 Jimenez, C., 2008. Reproducing stone monument photosynthetic-based colonization  
680 under laboratory conditions. *Sci Total Environ* 405, 278-285.

681 Miller, A.Z., Rogerio-Candelera, M.A., Laiz, L., Wierzchos, J., Ascaso, C.,  
682 Sequeira Braga, M.A., Hernández-Mariné, M., Maurício, A., Dionísio, A., Macedo,  
683 M.F., Saiz-Jimenez, C., 2010. Laboratory-induced endolithic growth in calcarenites:  
684 biodeteriorating potential assessment. *Microb Ecol* 60, 55-68.

685 Miller, A.Z., Sanmartín, P., Pereira-Pardo, L., Saiz-Jimenez, C., Dionísio, A.,  
686 Macedo, M.F., Prieto, B., 2012. Bioreceptivity of building stones: A review. *Sci Total*  
687 *Environ* 426, 1-12.

688 Papida, S., Murphy, W., May, E., 2000. Enhancement of physical weathering  
689 of building stones by microbial populations. *Int Biodeter Biodegr* 46, 305–317.

690 Pomerat, C.M., Reiner, E.R., 1942. The influence of surface angle and of light  
691 on the attachment of barnacles and other sedentary organisms. *Biol Bulletin* 82, 14-  
692 25.

693 Prajapati, S.K., Kaushik, P., Malik, A., Vijay, V.K., 2013. Phycoremediation  
694 coupled production of algal biomass, harvesting and anaerobic digestion: Possibilities  
695 and challenges. *Biotechnol. Adv* 31(8), 1408–1425.

696 Prendergast, G.S., 2010. Settlement and behavior of marine fouling organisms.  
697 In Duerr S. and Thomason J.C. (eds) *Biofouling*. Oxford: Wiley-Blackwell, pp. 30-  
698 51.

699 Prieto, B., Silva, B., 2005. Estimation of the potential bioreceptivity of  
700 granitic rocks from their intrinsic properties. *Int Biodeter Biodegr* 56, 206–215.

701 Prieto, B., Silva, B., Aira, N., Álvarez, L., 2006. Toward a definition of a  
702 bioreceptivity index for granitic rocks: perception of the change in appearance of the  
703 rock. *Int Biodeter Biodegr* 58, 150–154.

704 Prieto, B., Sanmartín, P., Silva, C., Vázquez-Nion, D., Silva, B., 2014.  
705 Deleterious effect plastic-based biocides on back-ventilated granite facades. *Int*  
706 *Biodeter Biodegr* 86, 19–24.

707 Prieto, B., Vázquez-Nion, D., Silva, B., Sanmartín, P., 2018. Shaping colour  
708 changes in a biofilm-forming cyanobacterium by modifying the culture conditions.  
709 *Algal Res.* 33, 173-181.

710 Ramírez, M., Hernández-Mariné, M., Novelo, E., Roldán, M., 2010.  
711 Cyanobacteria-containing biofilms from a Mayan monument in Palenque, Mexico.  
712 *Biofouling* 26, 399–409.

713 Robson, M.A., Williams, D., Wolff, K., Thomason, J.C., 2009. The effect of  
714 surface colour on the adhesion strength of *Elminius modestus* Darwin on a  
715 commercial non-biocidal antifouling coating at two locations in the UK. *Biofouling*  
716 25, 215-227.

717 Rodrigues, A., Gutierrez-Patricio, S., Miller, A.Z., Saiz-Jimenez, C., Wiley,  
718 R., Nunes, D., Vilarigues, M., Macedo, M.F., 2014. Fungal biodeterioration of stained  
719 glass windows. *Int Biodeterior Biodegr* 90, 152-160.

720 Ruffolo, S.A., Ricca, M., Macchia, A., La Russa, M.F., 2017. Antifouling  
721 coatings for underwater archaeological stone materials. *Prog Org Coat* 104, 64-71.

722 Sanmartín, P., Villa, F., Cappitelli, F., Balboa, S., Carballeira, R., 2020.  
723 Characterization of a biofilm and the pattern outlined by its growth on a granite built  
724 cloister in the Monastery of San Martiño Pinario (Santiago de Compostela, NW  
725 Spain). *Int Biodeter Biodegr* 147, 104871.

726 Satheesh, S., Wesley, S.G., 2010. Influence of substratum colour on the  
727 recruitment of macrofouling communities. *J Mar Biol Assoc UK* 90, 941-946.

728 Schiavon, N., 2002. Biodeterioration of calcareous and granitic building  
729 stones in urban environments. In: S. Siegesmund, T. Weiss, A. Vollbrecht (Eds.),  
730 *Natural Stone, Weathering Phenomena, Conservation Strategies and Case Studies*,  
731 205, Geological Society of London, London, pp. 195-205.

732 Silva, B., Prieto, B., Rivas, T., Sánchez-Biezma, M.J., Paz, G., Carballal, R.,  
733 1997. Rapid biological colonization of a granitic building by lichens. *Int Biodeter*  
734 *Biodegr* 40, 263–267.

735 Sohrabi, M., Favero-Longo, S.E., Pérez-Ortega, S., Ascaso, C., Haghghat, Z.,  
736 Talebian, M.H., Fadaei, H., de los Ríos, A., 2017. Lichen colonization and associated  
737 deterioration processes in Pasargadae, UNESCO world heritage site, Iran. *Int Biodeter*  
738 *Biodegr* 117, 171-182.

739 Sterflinger, K., Ettenauer, J., Piñar, G., 2013. Bio-susceptibility of materials  
740 and thermal insulation systems used for historical buildings. *Energy Procedia* 40,  
741 499–506.

742 Sternberg, T., Viles, H.A., Cathersides, A., 2010a. Evaluating the role of ivy  
743 (*Hedera helix*) in moderating wall surface microclimates and contributing to the  
744 bioprotection of historic buildings. *Build Environ* 46(2), 293-297.

745 Sternberg, T., Viles, H.A., Cathersides, A., Edwards, M., 2010b. Dust  
746 particulate absorption by ivy (*Hedera helix* L) on historic walls in urban  
747 environments. *Sci Total Environ* 409(1), 162-168.

748 Swain, G., Herpe, S., Ralston, E., Tribou, M., 2006. Short-term testing of  
749 antifouling surfaces: the importance of colour. *Biofouling* 22, 425-429.



750 Tomaselli, L., Lamenti, G., Bosco, M., Tiano, P., 2000 Biodiversity of  
751 photosynthetic microorganisms dwelling on stone monuments. *Int Biodeter Biodegr*  
752 46, 251–8.

753 [Urzi, C., De Leo, F., Krakova, L., Pangallo, D., Bruno, L., 2016. Effects of](#)  
754 [biocide treatments on the biofilm community in Domitilla's catacombs in Rome. \*Sci\*](#)  
755 [Total Environ 572, 252–262.](#)

756 Van Eck, N.J., Waltman, L., 2010. Software survey: VOSviewer, a computer  
757 program for bibliometric mapping. *Scientometrics* 84, 523-538.

758 Vázquez-Nion, D., Silva, B., Prieto, B., 2018a. Influence of the properties of  
759 granitic rocks on their bioreceptivity to subaerial phototrophic biofilms. *Sci. Total*  
760 *Environ* 610–611, 44–54.

761 Vázquez-Nion, D., Troiano, F., Sanmartín, P., Valagussa, C., Cappitelli, F.,  
762 Prieto, B., 2018b. Secondary bioreceptivity of granite: effect of salt weathering on  
763 subaerial biofilm growth. *Mater Struct* 51, 158.

764 Vázquez-Nion, D., Silva, B., Prieto, B., 2018c. Bioreceptivity index for  
765 granitic rocks used as construction material. *Sci. Total Environ* 663, 112-121.

766 Viles, H., Ahmad, H., 2016. Architectural controls on the bioreceptivity of  
767 sandstone to green algal colonization. ECBSM2016. European Conference on  
768 Biodeterioration of Stone Monuments - Second Edition. Cergy-Pontoise, France.  
769 November 17–18, 2016.

1    **Abstract**

2    2020 marks 25 years since Olivier Guillitte defined the term ‘bioreceptivity’, to describe  
3    the ability of a building material to be colonised by living organisms. Although Guillitte  
4    noted in his 1995 paper that several issues required further investigation, to the best of  
5    our knowledge the bioreceptivity concept has not been restated, reviewed, reanalysed or  
6    updated since then. The present paper provides an opinionated exposition of the status  
7    and utility of the bioreceptivity concept for built heritage science and conservation in  
8    the light of current knowledge, aimed to stimulate further discussion. A bibliometric  
9    analysis highlights the key dimensions of the past 25 years of published research,  
10   showing that the term bioreceptivity has been widely used in the field of built cultural  
11   heritage. In our reanalysis of the concept, special attention is devoted to the six types of  
12   bioreceptivity (primary, secondary, tertiary, intrinsic, extrinsic and semi-extrinsic)  
13   articulated by Guillitte in 1995. We propose that field-based studies of bioreceptivity  
14   are urgently needed, and that the intrinsic, extrinsic and semi-extrinsic types of  
15   bioreceptivity should be dropped, and a new category (quaternary bioreceptivity) added.  
16   Additionally, we propose that bioreceptivity in submerged and subsoil environments  
17   should also be considered. Bioreceptivity remains an important concept for managing  
18   both new build and built heritage, as it provides the key to understanding the drivers and  
19   patterns of biological colonisation of building materials.

20

21   **Keywords:** Biodeterioration; Biological colonisation; colonisation management;  
22   cultural heritage; further discussion; opinionated exposition.

23

## 24 **1. Introduction**

25 The colonisation of built cultural heritage by plants and microbes is an important part  
26 of building ecology, and its understanding is crucial for research into, and practical  
27 management of, the deterioration and conservation of building materials. In order to  
28 answer the question ‘what controls the colonisation and growth of organisms on  
29 buildings and structures?’ three sets of factors need to be considered which relate to  
30 the properties of the organisms themselves (including dispersal mechanisms, growth  
31 requirements, etc), the characteristics of the environment (including climatic  
32 conditions and microclimatic parameters, such as solar exposure, shading and water  
33 availability), and the properties of the building materials (including physical and  
34 chemical characteristics). Guillitte’s concept of bioreceptivity, defined as the potential  
35 of the material to be colonised by living organisms (Guillitte 1995), provides a neat  
36 and popular way to conceptualise the third of those sets of factors. According to  
37 Guillitte (1995), it complements another concept that has been less commonly used in  
38 building ecology, ‘accessibility’. This plant ecology term was introduced by Heimans  
39 (1954) to define the totality of conditions prevailing at a certain locality, that may  
40 influence the possibility of diaspores to reach that spot and settle there. As Guillitte  
41 (1995) wrote: ‘Whereas this concept [referring to accessibility] relates to the  
42 colonisation potential of the environment, the bioreceptivity concept expresses the  
43 colonisation potential as defined by the characteristics of the material’.

44 The colonisation of building materials is a complex process as it is dynamic in time  
45 and space due to the interrelationships among the colonising organisms, as well as  
46 between their populations, the inorganic substrate and the surrounding heterogeneous  
47 environment. In fact, biological colonisation patterns on built heritage are not  
48 constant, but periodic and are very likely to change quickly as a result of different

49 climate conditions, in particular alterations in temperature and precipitation (Macedo  
50 et al., 2009), as well as environmental chemical contaminants in polluted air and  
51 precipitation (Schiavon, 2002). It is important to emphasise that the potential of the  
52 material to be colonised by living organisms - its bioreceptivity - (Guillitte, 1995), is  
53 also dynamic as the chemical and physical characteristics of the substrate change over  
54 time as a result of exposure to weather and pollution conditions.

55 It is now timely, given the importance of an improved understanding of intrinsic  
56 material properties, their dynamism and their relation with external factors, to  
57 reconsider the concept of bioreceptivity 25 years after Guillitte originally articulated  
58 it. This paper aims to give an opinionated exposition (to stimulate further discussion)  
59 about Guillitte's concept of bioreceptivity 25 years on, investigating how it has been  
60 deployed mainly in the field of built cultural heritage science and conservation using a  
61 bibliometric survey, and reanalysing the concept by proposing some revisions and  
62 improvements.

## 63 **2. Revisiting bioreceptivity**

### 64 ***2.1 Guillitte's ideas on bioreceptivity***

65 In 1995, Olivier Guillitte published the first two papers defining and analysing the  
66 concept of bioreceptivity: 'Bioreceptivity: a new concept for building ecology  
67 studies' (Guillitte, 1995) and 'Laboratory chamber studies and petrographical analysis  
68 as bioreceptivity assessment tools of building materials' (Guillitte and Dreesen,  
69 1995). While the idea that material properties influence what grows was not in itself  
70 novel, Guillitte proposed the term bioreceptivity to provide a neutral framing with no  
71 connotation of biological colonisation being negative, and also to shift the focus on to  
72 the influence of materials on organisms rather than the reverse, which until then had  
73 monopolized the attention of researchers (Hueck, 1965). In his first publication

74 (Guillitte, 1995), he proposed two definitions for the bioreceptivity concept, (1) 'the  
75 ability of a material to be colonised by living organisms' (expanded in 'the aptitude of  
76 a material (or any other inanimate object) to be colonised by one or several groups of  
77 living organisms without necessarily undergoing any biodeterioration'), (2) 'the  
78 totality of material properties that contribute to the establishment, anchorage and  
79 development of fauna and/or flora' (Guillitte, 1995). The purpose of these definitions  
80 was to link bioreceptivity to the process of colonisation and *in situ* development and  
81 multiplication of organisms, thus interpreting the material as a potential habitat where  
82 the conditions that define the niche of the species can be found and not as a mere  
83 transient or anchoring place for organisms. He aimed to distinguish bioreceptivity  
84 from other concepts related to biological growths on materials, such as biodegradation  
85 and biodeterioration (which usually have negative connotations).

86 Why did Guillitte coin the term 'bioreceptivity' rather than 'biosusceptibility'?  
87 Guillitte (1995) reviewed the term 'susceptibility' and its definition in the field of  
88 medicine and veterinary medicine, and used it as an analogy for his new concept in  
89 building ecology. In a footnote to his work, Guillitte explains that he opts for  
90 'receptivity' instead of 'susceptibility' based on the parallel with the biological  
91 concept 'receptivity' in English defined as 'the ability of a flower stigma to be  
92 fertilised by pollen grains through the pollen tube', and because the former translates  
93 in the same way into different languages. Hence he writes 'we suggest using the word  
94 'bioreceptivite' in French, 'Biorezeptivittl' in German, 'bioreceptiviteit' in Dutch,  
95 'bioreceptividad' in Spanish, 'bioreceptividade' in Portuguese and 'biorecettivith' in  
96 Italian' (Guillitte, 1995). Nevertheless, some papers published later have used the  
97 terms susceptibility to biological colonisation (Marques et al., 2015), bio-

98 susceptibility (Sterflinger et al., 2013), and biosusceptibility (Gu et al., 1998) to refer  
99 to the bioreceptivity of a material.

100 What factors did Guillitte include within the concept of bioreceptivity? According to  
101 Guillitte (1995) 'the precise role of the building material characteristics in the  
102 colonisation process is not fully understood, with the exception of acidity, whose  
103 influence on the taxonomic content of colonising organisms is well known'. For that  
104 reason he grouped all those material characteristics with no order of importance under  
105 the term 'bioreceptivity'. Moreover, as a first step in clarifying the relative  
106 importance of each intrinsic factor to the material's bioreceptivity, he performed,  
107 alongside Roland Dreesen (Guillitte and Dreesen, 1995), a comparative study of  
108 colonisation under laboratory conditions over a six-month period, using limestone,  
109 concrete, mortar and brick to demonstrate that 'the bioreceptivity of building  
110 materials is highly variable and that it is controlled primarily by their surface  
111 roughness, initial porosity and mineralogical nature' (Guillitte and Dreesen, 1995).

## 112 *2.2 Other linked concepts*

113 In contrast to bioreceptivity, the concept of biodeterioration has been around for much  
114 longer and applied to a much wider range of materials and circumstances. The most  
115 consolidated and widespread definition of biodeterioration is that offered by Hueck in  
116 1965 as 'any undesirable change in the properties of a material caused by the vital  
117 activities of organisms' (Hueck, 1965, p. 7). Biodeterioration can be classified into  
118 three categories: (i) physical or mechanical, (ii) chemical and (iii) aesthetic. The latter  
119 is limited to the visual effects of the presence of microorganisms and their products  
120 that alter the chromatic appearance. It seems that Guillitte did not consider this third  
121 category to be a form of deterioration, at least in the case of organisms growing on  
122 building materials. Indeed, he claimed that 'some authors consider the colour changes

123 to be aesthetically pleasing, credit them with a protective role against man- or  
124 weather-induced aggression and suggest that they have a cleansing effect which  
125 benefits the environment' (Guillitte, 1995). Such claims remain controversial. As  
126 Kumar and Kumar (1999) reported, climbing plants have long been considered to  
127 enhance the aesthetic value of built heritage such as ruins, as in some cases can the  
128 occurrence of algae and lichens (Martines, 1983). In several cases, the negligible  
129 (Gulotta et al., 2018; Sanmartín et al., 2020) or bioprotective (Ramírez et al., 2010;  
130 Cutler et al., 2013) role of pioneer algae and cyanobacteria (a phenomenon often  
131 referred to as “greening”, the first step in the sequential process of colonisation) on  
132 the physical integrity of stone has been proven, aside from the ability of algae to  
133 sequester CO<sub>2</sub> from atmospheric air (Prajapati et al., 2013). However, at present, it  
134 is frequently considered preferable to eliminate any kind of colonisation from  
135 building surfaces for reasons of preventive conservation and to create an impression  
136 of order, cleanliness and care of the structure or construction.

137 Biodeterioration covers many of the phenomena, processes or activities by organisms  
138 on building materials, but excludes those recognized as protective. Bioprotection, as  
139 conceptualised by researchers such as Carter and Viles (2005), is used to refer to the  
140 positive ways in which organisms growing on the surfaces of rocks and building  
141 materials protect the surface from other processes of weathering and erosion. For  
142 example, surface-dwelling organisms can physically protect the underlying surface  
143 from abrasion, act as a thermal blanket, absorb pollutants and prevent them from  
144 interacting with the surface, and mediate moisture regimes (Sternberg et al., 2010a  
145 and b).

### 146 *2.3 Bibliometric analysis of 25 years of bioreceptivity publications*

147 Bibliometric analysis was conducted on the 19<sup>th</sup> November 2020 to investigate trends  
148 in publications on bioreceptivity. An initial search of the peer-reviewed literature was  
149 performed using the term ‘Bioreceptivity’ in both the Web of Science  
150 (<https://www.webofknowledge.com/>) and Scopus (<https://www.scopus.com/>)  
151 databases. Considering the number of records obtained, the database of the Web of  
152 Science (WOS) was selected for a more detailed search on the topic. The terms  
153 ‘Bioreceptivity’, ‘Biosusceptibility’ or ‘Bio-susceptibility’ were searched in the WOS  
154 database and then combined with the keywords: ‘primary’, ‘secondary’, ‘tertiary’,  
155 ‘stone’, ‘concrete’, ‘mortars’, ‘tiles’, ‘bricks’, ‘ceramic’, ‘plastic’ or ‘glass’.

156 The visualization tool VOSviewer (Van Eck and Waltman, 2010) was used to provide  
157 co-occurrence maps of keywords, advocated for detecting emerging trends. Excel  
158 from Microsoft Office was also used for visualization of the bibliometric results.

159 A total of 174 records was obtained in the WOS database on the 19<sup>th</sup> of November  
160 2020 using the terms ‘Bioreceptivity’ ‘Biosusceptibility’ or ‘Bio-susceptibility’,  
161 which have been cited 3348 times. Figure 1 shows the number of bioreceptivity-  
162 related publications between 1995 and 2020 and the citations per year of those works.

163 It is noticeable that the annual number of articles increased significantly in the last  
164 decade. The first peak of published articles was in 2009, followed by 2014 and 2018.  
165 After 2010, the number of publications steadily increased until 2018. The top 20  
166 journals include *International Biodeterioration and Biodegradation*, *Science of the*  
167 *Total Environment*, *Building and Environment*, *Construction and Building Materials*,  
168 *Biofouling*, etc. However, bioreceptivity publications were mainly concentrated in the  
169 first two journals. The total number of records on bioreceptivity obtained in the WOS  
170 database (174) was published in 68 journals. The highest number of bioreceptivity-  
171 related articles derives from European countries.



172 *[Figure 1: Annual trends in bioreceptivity publications and their citations from 1995*  
173 *to 2020 (Source: WOS, accessed 19<sup>th</sup> November 2020).]*

174 In order to find associations between keywords from bioreceptivity-related  
175 publications, a co-occurrence bioreceptivity keyword map was performed ranked in  
176 terms of number of articles (Fig. 2). This co-occurrence network analysis is effective  
177 for identifying groups of related terms of a specific topic, and for mapping the  
178 strength of the association between keywords, showing the potential combination with  
179 other research fields and knowledge, evidencing multidisciplinary. As shown in  
180 Figure 2, the term ‘bioreceptivity’ has the highest co-occurrence frequency with  
181 ‘biodeterioration’, indicating that bioreceptivity and biodeterioration are thoroughly  
182 related. In fact, several studies on bioreceptivity of building materials also include the  
183 identification of the biodeterioration patterns produced by the living organisms on the  
184 materials (Coutinho et al., 2016, 2019; Miller et al., 2008, 2010). This also explains  
185 the predominance of the keywords ‘biocide’, ‘biofilms’ and ‘biofouling’ (Fig. 2).

186 *[Figure 2: Co-occurrence bioreceptivity keyword map compiled by articles from the*  
187 *WOS database assigned to bioreceptivity on the 19<sup>th</sup> of November 2020, using the*  
188 *bibliometric mapping tool VOSviewer. Unit of analysis: all keywords. The size of the*  
189 *node represents the frequency of the keyword co-occurrence with other keywords. The*  
190 *colour of a keyword (node) is determined by the cluster to which the keyword belongs,*  
191 *meaning that a keyword usually occurs with the keywords from the same colour*  
192 *cluster.]*

193 After ‘biodeterioration’, the predominance of the keywords ‘algae’ and  
194 ‘cyanobacteria’ is explained as phototrophic microorganisms are pioneer colonisers of  
195 inorganic materials, such as stone, and are the most commonly used microorganisms  
196 in laboratory-based bioreceptivity experiments (Miller et al., 2012). In addition,

197 'fungi' and 'lichens' also have a high co-occurrence in bioreceptivity-related articles.  
198 Worth mentioning is the predominance of keywords related to the materials covered  
199 in bioreceptivity-related publications, such as 'stone', 'rocks', 'limestone', 'concrete'  
200 and 'mortar', as well as 'cultural-heritage', 'conservation' and 'monuments', which  
201 demonstrate that the term bioreceptivity is widely used in the field of built cultural  
202 heritage (Fig. 2). According to our bibliometric survey of research into bioreceptivity,  
203 stone is the most studied material and the focus of the most cited articles (Fig. 3). In  
204 contrast, few studies have been performed on the bioreceptivity of concrete, mortars,  
205 tiles, bricks, glass or plastic, compared with stone. Most of the case studies on  
206 bioreceptivity shown in Figure 3 rely on in-vitro (lab based) tests. In fact, the majority  
207 of papers was focused on primary bioreceptivity (Fig. 4) which has been almost  
208 exclusively studied under laboratory conditions (e.g. Prieto and Silva, 2005; Miller et  
209 al., 2008, 2010; Vázquez-Nion et al., 2018a).

210 *[Figure 3. Number of records for the combination of the term 'bioreceptivity' with the*  
211 *keywords related to building materials in the WOS database (accessed on the 19<sup>th</sup> of*  
212 *November 2020).]*

213 *[Figure 4. Number of records in the WOS database (accessed on the 19<sup>th</sup> of*  
214 *November 2020) for the keywords 'Primary bioreceptivity', 'Secondary*  
215 *bioreceptivity' and 'Tertiary bioreceptivity'.]*

### 216 **3. Reanalysing bioreceptivity**

#### 217 ***3.1 What is missing or often overlooked from Guillitte's ideas?***

218 When a material has not yet been exposed to colonisation and as long as its properties  
219 remain unchanged, bioreceptivity is defined as primary according to Guillitte, whilst  
220 when the material properties change it becomes secondary. Guillitte (1995) wrote:  
221 'For practical purposes, secondary bioreceptivity is often more important than primary

222 bioreceptivity'. This is especially true when we refer to built cultural heritage, whose  
223 materials have been exposed to weathering for long periods. However, as the current  
224 authors demonstrate in section 2.3, secondary bioreceptivity has hardly been studied,  
225 with the bulk of research focusing on primary bioreceptivity which probably is more  
226 useful in the architectural field for looking at 'new build'. There are several reasons  
227 that could explain why this has been true for 25 years. For example, it is not clear  
228 when the changes in material properties become significant for potential colonizers  
229 (breakpoint), and what criteria should be used to determine that breakpoint. How  
230 much must a given material be changed (physically and/or chemically) in order for its  
231 bioreceptivity to be defined as secondary? If, as Guillitte believed, the transition from  
232 primary to secondary bioreceptivity occurs as a result of both the activity of living  
233 organisms and abiotic processes, together or separately, then it is very difficult for  
234 researchers to produce realistic artificially weathered specimens in the laboratory on  
235 which to investigate secondary bioreceptivity (Papida et al., 2000; Vázquez-Nion et  
236 al., 2018b)? Are field-based studies needed? There is also the issue that most natural  
237 building materials have already undergone change through weathering (for example  
238 on a quarry face) even before they are placed in a building (Silva et al., 1997), and so  
239 it is unclear whether bioreceptivity in such cases should be classified as primary or  
240 secondary.

241 Guillitte's concept of bioreceptivity is largely focused on the influence of small scale  
242 (mm to cm scale) factors intrinsic to different building materials. These are amenable  
243 to study in laboratory experiments and are the most obvious intrinsic factors to  
244 consider. However, once a material is exposed within a building façade or structure,  
245 other larger scale (cm to m) factors may have very important influences on  
246 bioreceptivity (Viles and Ahmad, 2016). For example, a stone type used in

247 architectural detailing such as balusters and string courses may have very different  
248 bioreceptivities within those two contexts, because of the influence of surface angle  
249 (in relation to vertical), aspect, and position on the building which i) exert important  
250 controls on water and thermal regimes and ii) modify primary bioreceptivity through  
251 weathering in different ways giving rise to different secondary bioreceptivity. In  
252 many ways, these larger scale influences can be seen as larger scale surface roughness  
253 (where the roughness applies to whole areas of masonry, facades or indeed an entire  
254 building). The potential importance of these larger scale factors can best be studied by  
255 well-designed field experiments. One of the remaining challenges about larger scale  
256 factors is to determine whether they are intrinsic or extrinsic in nature.

257 At present, the relative importance of each intrinsic characteristic on the  
258 bioreceptivity of the material has not been clarified. Some progress has been made for  
259 limestone and granite using laboratory-based methods. For granite, bioreceptivity is  
260 influenced by physical properties rather than chemical and mineralogical composition  
261 (Vázquez-Nion et al., 2018a). High open porosity, capillary water content and  
262 roughness are the intrinsic factors that most promote colonisation by phototrophs  
263 (Prieto and Silva, 2005; Vázquez-Nion et al., 2018a). For limestone, although surface  
264 roughness is a key factor, there is no consensus about the intrinsic material properties  
265 that most influence bioreceptivity (Miller et al., 2012). The concept of bioreceptivity  
266 has been extended to other materials, including ceramic tiles and glass, and is now  
267 fairly well accepted in the field of built cultural heritage (e.g. Rodrigues et al., 2014;  
268 Coutinho et al., 2016), but the key controlling factors remain unclear for many of  
269 these materials. For stained glass, chemical composition is most likely to influence  
270 the bioreceptivity to fungal growth as reported by Rodrigues et al. (2014). Coutinho et

271 al. (2016) demonstrated that tile bioreceptivity was influenced by water absorption by  
272 capillarity and water vapor permeability.

273 One further important aspect to consider is ‘bioreceptivity to what’? In essence,  
274 bioreceptivity is a relative not an absolute concept – relative to particular species or  
275 types of organisms. Guillitte (1995) indicated that in a controlled environment (e.g. a  
276 growth chamber in a laboratory with one cryptogam species) the absence of  
277 colonising cryptogams on the material means that the material is not bioreceptive to  
278 these cryptogams. In field studies, absence of colonising cryptogams means that the  
279 material is not bioreceptive to cryptogams present in the surrounding environment.  
280 This relative aspect of bioreceptivity is often overlooked, but has important practical  
281 implications. For example, when accelerated bioreceptivity studies under controlled  
282 conditions in the laboratory are carried out with a mixture of different colonising  
283 species belonging to different taxonomic groups (i.e. cyanobacteria, green algae,  
284 diatoms, mosses, etc.) a key question is how long to maintain the colonisation process  
285 because the speed of colonisation varies within and among different taxonomic  
286 groups, as well as, between materials. This was verified for the first time in the study  
287 of Guillitte and Dreesen (1995), where after two weeks the only colonisation observed  
288 was by pioneering green algae on concrete. After four weeks sandy limestone, brick  
289 and mortar showed the first signs of algae (which eventually disappeared, giving way  
290 to nitrophilous species), whereas concrete started being colonised by cyanobacteria  
291 and mosses. A month later, cyanobacteria became the most abundant coloniser on all  
292 materials. After 6 months, colonisation was very profuse on concrete and sandy  
293 limestone (but not in the compact and hard crinoidal limestone, which had the least  
294 vegetation cover of all materials), but brick and mortar were hardly colonised.

295 Furthermore, the diversity was wide, although filamentous cyanobacteria and at lesser  
296 extent some species of algae (*Anabaena* and *Oscillatoria*) were the most abundant.  
297 One missing point from Guillitte's ideas is how to express and quantify  
298 bioreceptivity. In the first experiment specifically designed to evaluate bioreceptivity,  
299 Guillitte and Dreesen (1995) characterised the bioreceptivity of two natural stone  
300 types and three manufactured materials by quantifying the vegetal cover after 9  
301 months of exposure to sprinkling with a nutrient-rich tap water containing a mixture  
302 of pioneer colonising plant diaspores. Percentage cover has been used to express  
303 bioreceptivity in subsequent experiments (Tomaselli et al., 2000, Miller et al., 2006,  
304 Escadeillas et al., 2007) allowing comparison between samples in the same  
305 experiment but not comparison between different experiments. The main problem  
306 derived from using % cover is that once 100% cover is reached the subsequent  
307 increase in colonization related to bioreceptivity cannot be quantified. Moreover,  
308 colonization in depth is not taken into account. To overcome these problems, the  
309 amount of chlorophyll *a* /surface unit has been used by other authors to express  
310 bioreceptivity (Prieto and Silva, 2005; Prieto et al., 2006). This way of expressing  
311 bioreceptivity allows comparison not only between samples but also between  
312 experiments, but has the disadvantage that it can only be used for phototrophs.  
313 Moreover, Guillitte did not establish how to unambiguously define and categorise the  
314 bioreceptivity of a material, although he pointed the need to remove any subjectivity  
315 attached to the concept and proposed developing a bioreceptivity index. Nowadays,  
316 this index has been developed but only for granitic rocks (Vázquez-Nion et al.,  
317 2018c).

### 318 ***3.2 Types of bioreceptivity on built heritage***

319 Bioreceptivity to primary colonisers where the material properties are not  
320 substantially modified, either by biotic or abiotic factors, is according to Guillitte  
321 (1995) the ‘primary bioreceptivity’, which according to the current authors is related  
322 to the intrinsic properties of a sound or fresh material after manipulation (extraction  
323 from the quarry and cut) for a final function (e.g. used in a construction) (Fig. 5).  
324 ‘Secondary bioreceptivity’ appears when the material properties evolve by weathering  
325 induced by environmental factors and/or colonisers (Fig. 5), and ‘tertiary  
326 bioreceptivity’ appears when human-induced factors are involved, such as cleaning or  
327 restoration interventions. Guillitte (1995) noted ‘any human activity affecting the  
328 material - consolidation, coating with a biocide or surface polishing - also modifies  
329 the initial or secondary characteristics of the properties of the material, inducing  
330 ‘tertiary bioreceptivity’’. However, cleaning the material affects its bioreceptivity in a  
331 completely different way than protecting it with chemicals. The current authors  
332 consider that adding a material, such as a consolidant or biocide-embedded coating,  
333 does not have the same effect on the material properties as brushing or polishing its  
334 surface, which modifies its surface roughness and colour, but does not introduce a  
335 component of a different nature. For this reason, we propose that Guillitte’s ‘tertiary  
336 bioreceptivity’ should be split into two, with ‘tertiary bioreceptivity’ used for human  
337 actions that cause physical changes to the material (such as by mechanical (with  
338 abrasives) and laser cleaning treatments), and ‘quaternary bioreceptivity’ used when  
339 new materials, as coatings or chemical products that can leave residues, are added.  
340 Table 1 summarises the key changes to Guillitte’s concept of bioreceptivity, and their  
341 rationales, that are proposed in this paper.

342 Although the addition of a new term (‘quaternary bioreceptivity’) could be seen as  
343 controversial and adding to complexity, we believe that it has practical benefits for

344 the use of bioreceptivity for understanding the deterioration of built heritage in  
345 highlighting different ways in which humans can affect the situation, in a way that is  
346 distinctive to the changes involved in secondary bioreceptivity. Furthermore, the  
347 concept of ‘quaternary bioreceptivity’ reduces complexity by replacing the terms, also  
348 defined by Guillitte but rarely used, of intrinsic, semi-extrinsic and extrinsic  
349 bioreceptivity. Guillitte (1995) defined intrinsic bioreceptivity as occurring 'when  
350 colonisation depends mainly on the properties of the material, irrespective of  
351 exogenous contributions'. Many researchers consider ‘intrinsic’ and ‘primary’  
352 bioreceptivity as synonymous, probably because they see both natural weathering and  
353 human activities as exogenous contributions. We instead consider that Guillitte  
354 viewed exogenous contributions in a more narrow sense as additions to the material  
355 such as particles, organisms and substances. In this interpretation, all three types of  
356 bioreceptivity of a fresh, weathered and cleaned stony material, i.e. primary,  
357 secondary and tertiary bioreceptivity, may be seen as ‘intrinsic bioreceptivity’. It  
358 reinforces this idea that by ‘semi-extrinsic bioreceptivity’ Guillitte (1995) refers to  
359 situations when ‘colonisation depends directly and simultaneously on the properties  
360 of the material and on the deposits of exogenous substances’, where he used the term  
361 ‘deposit’ to refer to the exogenous contribution. For us, ‘semi-extrinsic bioreceptivity’  
362 would in some cases correspond to what we have called ‘quaternary bioreceptivity’.  
363 An extreme case of ‘quaternary bioreceptivity’, where only the bioreceptivity of the  
364 added exogenous material is of interest is what Guillitte (1995) called ‘extrinsic  
365 bioreceptivity’. We propose that intrinsic, extrinsic and semi-extrinsic bioreceptivity  
366 terms be dropped, and instead encourage the use of ‘intrinsic factors’ and ‘extrinsic  
367 factors’ related to the bioreceptivity of a material. Thus, roughness, porosity,  
368 mineralogical composition and colour of a material, for instance, will be intrinsic



369 factors related to bioreceptivity; while architectural factors, micro-temperature and  
370 micro-humidity on the material surface, and added materials (such as dead biomass,  
371 living organisms, dust, guano) are extrinsic factors related to bioreceptivity (Table 1).  
372 Figure 5 provides a visualization of how our conceptualisation of bioreceptivity builds  
373 on that of Guillitte (1995). The blue dashed arrows in figure 5 portray the ecological  
374 dynamism involved as material conditions change within the different categories  
375 (primary, secondary, tertiary and quaternary) and also as the situation switches from  
376 primary to secondary types. In the case of primary bioreceptivity, the communities  
377 should be dominated by fast-growing and well-dispersed species while in secondary  
378 bioreceptivity, these species will tend to be replaced by more competitive species  
379 which may have differing impacts on biodeterioration. Furthermore, in the case of  
380 tertiary bioreceptivity, changes in the ecological community should occur faster. This  
381 has been observed in several studies of tertiary bioreceptivity, where recolonisation  
382 after cleaning occurs quicker than during the primary bioreceptivity phase (Sohrabi et  
383 al., 2017). The same has been reported for the proposed new category of quaternary  
384 bioreceptivity, where added materials such as consolidants and other surface  
385 treatments may become a new habitat for colonisers. Several studies note that these  
386 new habitats are more bioreceptive than the original stony material (Bracci et al.,  
387 2002; Cappitelli et al., 2007). For example, in the Catacombs of Domitilla (Rome,  
388 Italy), a biocide treatment composed of quaternary ammonium compounds and  
389 octylisothiazolone sparked the proliferation of bacteria with high hydrolytic  
390 enzymatic activity (Urzi et al., 2016). In Campeche (Mexico), restored mortars  
391 composed of fatty acid promoted an early endolithic phototrophic colonization by  
392 cyanobacteria and bryophyte on the facade of San Roque church (Jurado and Miller et  
393 al., 2014). Surface treatments such as consolidants may also alter the physical

394 properties of stony materials like the wetting-drying kinetics, leading to the material  
395 remaining damp for longer and hence its bioreceptivity increasing (Prieto et al.,  
396 2014). In future, an interesting area of research would be to explore these ecological  
397 dynamics in more detail and elucidate how communities of organisms living on built  
398 heritage change in tandem with the material changes. This could involve linking  
399 bioreceptivity to concepts of ecological succession.

400 [*Figure 5. Visualization of how our conceptualisation of bioreceptivity compares with*  
401 *that of Guillitte (1995).]*

### 402 **3.3 Bioreceptivity of subaerial, submerged and subsoil built heritage**

403 While the concept of biodeterioration is considered in subaerial, submerged and  
404 subsoil environments, bioreceptivity is currently only explicitly considered in the  
405 former despite buildings possessing subsoil foundations and being affected by  
406 periodic flooding, as well as many archaeological sites being buried or immersed.  
407 However, this is only a conceptual issue because many studies have focused on how  
408 biodeterioration develops differently according to the type of material and how the  
409 intrinsic characteristics of a material affect its biocolonisation in submerged (mainly  
410 marine) and subsoil environments. For example, a comparative study of bioreceptivity  
411 between different building materials (marbles, limestones, ignimbrites, and bricks),  
412 similar to that of Guillitte and Dreesen (1995), but in a Mediterranean marine  
413 environment was carried out by Aloise et al. (2014) although they do not explicitly  
414 use the term bioreceptivity. Marble and limestone samples collected from the cities of  
415 Baiae and Portus Iulius (Naples, Italy), submerged since the 4th century AD, showed  
416 intense colonisation (high bioreceptivity) mainly by boring sponges, while  
417 ignimbrites in the same place presented a lower biological attack caused by serpulids  
418 and bryozoans. In bricks, paste with volcanic aggregates was less bioreceptive,

419 showing a greater resistance to biological colonisation, than that with quartz (Aloise  
420 et al., 2014). As is clear, different species were found on different substrates as a  
421 function of their composition. Similarly, differences in material colour have been  
422 shown to impact the short-term development of marine biofouling communities,  
423 influencing larval settlement and colonisation of invertebrates and algae (Dahlem et  
424 al., 1984; Satheesh and Wesley, 2010), and especially barnacles (Pomerat and Reiner,  
425 1942; Kon-ya and Miki, 1994; Robson et al., 2009; Prendergast, 2010). Most studies  
426 in this field have only tested black and white or grayscale substrates, thus showing  
427 only whether different responses arise due to the luminosity or lightness/darkness  
428 (Callow and Callow, 2000; Swain et al., 2006; Dobretsov et al., 2013; Cao et al.,  
429 2013). Other studies, instead, have also considered chroma and hue (Guenther et al.,  
430 2009; Ells et al., 2016; Li et al., 2017). Chroma (or saturation) is related to the  
431 intensity of colour, while hue, which refers to the dominant wavelength and  
432 represents redness, yellowness, greenness, blueness, etc., has been shown in  
433 perception studies to be the most important colour parameter (Berns, 2000; Prieto et  
434 al., 2018). Settlement of mussel *Mytilus coruscus* plantigrades was found to differ  
435 according to substrate colour (red, orange, blue, white, yellow and green) and was  
436 lowest on the biofilms formed on green surfaces, possibly because of a variation in  
437 the establishment of the underlying biofilm community (Li et al., 2017). In contrast,  
438 the hydroid *Ectopleura larynx* settled preferentially on black vs white substrates,  
439 whereas there were no significant differences between the remaining tested colours  
440 (yellow, red and blue; Guenther et al., 2009). These two examples show how  
441 differently various organisms respond to surface colour and highlight the need to  
442 investigate this response systematically.

443 The main cause of deterioration in submerged marine environments is  
444 biodeterioration (Aloise et al., 2014; La Russa et al., 2015; Cámara et al., 2017). For  
445 *in situ* conservation of underwater cultural heritage a widely used technique is burial  
446 using marine sediments or burial materials, i.e. sandbags, concrete, or plastic  
447 geotextile (Bethencourt et al., 2018). Such burial should protect the material from  
448 environmental conditions in seawater, such as chemical composition of the water  
449 column, light regime, nutrient availability, waves and currents, however studies to  
450 date are inconclusive (Bethencourt et al., 2018). Other conservation activities involve  
451 the application of metal oxide nanoparticles to underwater stone surface (Ruffolo et  
452 al., 2017). In arid subaerial environments, where wind and rain are major agents of  
453 deterioration affecting archaeological remains and structures, burial or reburial in soil  
454 is likely to aid conservation. In the soil, buried materials like ceramics are in principle  
455 more bioreceptive than natural rocks due to their structure and porous matrix, able to  
456 retain humidity and heat (Guiamet et al., 2019). On the other hand, no  
457 microorganisms are able to degrade lignin anaerobically, so wooden materials are  
458 hardly bioreceptive in buried environments (Caneva et al., 2008). In addition, and as  
459 in subaerial environments, the pH of the material, combined with the alkaline or  
460 acidic conditions of the soil, is a key factor in bioreceptivity studies in buried  
461 environments. According to Caneva et al. (2008) this parameter, along with texture,  
462 concentration of soluble salts, clay and organic substances content, electrical  
463 conductivity and buffering capacity, gives a measure of the 'aggressivity' of the soils  
464 to the buried materials.

#### 465 ***3.4 Bioreceptivity and building-scale factors***

466 Because most bioreceptivity studies have been carried out in controlled, laboratory  
467 conditions, there is a need for further investigation of the larger-scale factors

468 influencing colonisation dynamics on real buildings and its relationship with  
469 bioreceptivity. As long as bioreceptivity of a material is defined by ‘the totality of  
470 material properties that contribute to the establishment, anchorage and development  
471 of fauna and/or flora’ those properties can be different for the same material  
472 depending on its position on the building. Introducing larger-scale factors to  
473 bioreceptivity brings complications, as it becomes hard to separate out intrinsic from  
474 extrinsic factors. Further research is needed to explore the influence of building-scale  
475 factors on bioreceptivity, colonization and biodeterioration.

476 The architectural geometry determines the microclimatic condition of each  
477 architectonic element. Those microclimatic conditions are related not only to the  
478 colonisation potential of the environment, but also to the colonisation potential of the  
479 material (bioreceptivity) as long as they modify the material properties. Thus, for  
480 instance, when a stone is emplaced within the façade of a building, the relationship  
481 between water (one of the most important factors in biological colonisation) and that  
482 stone type is going to differ from that defined in the laboratory because some rock  
483 properties related to the movement of water inside it change once the stone is set  
484 within a masonry and architectural context. For example, the porosity may differ from  
485 that measured in the laboratory on small, freshly cut specimens, as some of the porous  
486 space can be occupied by other materials (mortars), solutions, salts, etc., depending on  
487 location within the building. Another example is where stone surfaces receive runoff  
488 from building elements made of materials with biocide properties, such as copper,  
489 which can become a part of the stone surface and limit their bioreceptivity (Fig. 6). In  
490 contrast, stone surfaces located under tree canopies can receive nutrients washed off  
491 leaves which can enhance their bioreceptivity.

492 In several cases microclimate more than macroclimate exerts the major control on  
493 colonisation. Microclimatic conditions are themselves often highly influenced by the  
494 architectural geometry and complexity with, for example, sloping and horizontal  
495 surfaces likely to retain moisture more than vertical surfaces. Such is the case for the  
496 highly hydrophobic subaerial biofilm of the processional cloister of the Monastery of  
497 San Martiño Pinarío (Santiago de Compostela, NW Spain) mainly formed by  
498 *Apatococcus lobatus* (Chodat) J.B.Petersen (Chlorophyta). There, microbial cells with  
499 a thick cell wall occur in densely packed aggregates surrounded by the EPS matrix  
500 with an hydrophobic character associated with non-polar regions, which waterproof  
501 the cells and prevent dehydration. The hydrophobic character of the biofilm, in turn,  
502 influencing the bioreceptivity along the cloister walls, which is also determined by  
503 microclimate conditions that cause condensation on parts of the stone surface  
504 (Sanmartín et al., 2020). This study highlights the importance of the match between  
505 the particular species of colonisers and the potential area of colonisation.

506 [**Figure 6.** *Material in the surrounding space and architectural factors in influencing*  
507 *bioreceptivity. (a) Star of bronze (an alloy consisting primarily of copper) on the top*  
508 *of the structure plays a role as biocide in the Fountain of the Horses (Platerías*  
509 *Square, Santiago de Compostela, NW Spain); (b and c) Slope angle in buildings from*  
510 *Bristol and Oxford (UK) controlling hydrological pathways and, in turn, influencing*  
511 *bioreceptivity. Red arrows show the bioreceptivity patterns result of external factors.]*

#### 512 **4. Final considerations, conclusions and prospects**

513 Over the last 25 years, few studies have been carried out on bioreceptivity on  
514 materials *in situ* on built heritage. This has made bioreceptivity in practical terms a  
515 laboratory concept, which has allowed only partial investigation because many  
516 colonising organisms which are hard to cultivate in laboratory conditions (such as

517 lichens) have not been used. Also, in the studies conducted in controlled laboratory  
518 conditions the dynamism of bioreceptivity has been ignored, because primary,  
519 secondary or tertiary bioreceptivity have been studied in isolation. Although  
520 laboratory experiments could be designed to run for long enough to investigate  
521 primary and secondary bioreceptivity, better techniques need to be found to monitor  
522 the changing material properties during such experiments. A suite of non-destructive  
523 techniques (such as photogrammetry and laser scanning, portable hardness testing and  
524 moisture measurement devices) is now available which could provide such  
525 information in both long-term laboratory experiments and field-based exposure trials.  
526 Furthermore, the roles of both intrinsic (material properties) and extrinsic factors (e.g.  
527 microclimate, surrounding vegetation, architectural geometry, substances deposited  
528 but not integrated into the material) in the bioreceptivity of a material under  
529 laboratory conditions need to be assessed. While intrinsic properties are usually well-  
530 studied in laboratory experiments (e.g., Prieto and Silva, 2005; Vázquez-Nion et al.,  
531 2018a), extrinsic factors are rarely considered. Over time there is likely to be a  
532 changing balance between the relative important of intrinsic and extrinsic factors in  
533 controlling colonisation and determining bioreceptivity. Carefully designed laboratory  
534 experiments are needed to investigate the longer-term evolution of bioreceptivity.  
535 Well-designed field experiments are also required because many extrinsic factors  
536 cannot easily be simulated under laboratory conditions, and environmental conditions  
537 in the field may mask, or complicate, the bioreceptivity of the materials themselves  
538 (Barberousse et a., 2006; Manso et al., 2015).

539 In conclusion, the concept of bioreceptivity still has much to offer to scientists  
540 involved in understanding and management of the ecology of built heritage 25 years  
541 after it was first proposed. Along with biological and environmental factors, it forms a

542 trio of factors controlling colonisation of building surfaces, which in turn controls  
543 biodeteriorative, and bioprotective processes. The factors influencing colonisation are  
544 undoubtedly complex, but having a clearer understanding of concepts such as  
545 bioreceptivity helps to break the problem down into simpler component parts.  
546 Bibliometric analysis has shown that research on bioreceptivity over the past 25 years  
547 has been predominantly laboratory based and focused on primary bioreceptivity of  
548 building stones. This paper proposes some improvements and clarifications to the  
549 conceptual framework of Guillitte (summarised in Table 1), explores the parallels  
550 with ecological succession, and extends bioreceptivity to consider built heritage  
551 within submerged and subsoil environments. It also points out the need for additional  
552 well-designed field experiments to add to the valuable insights derived from  
553 laboratory studies and more fully explore the dynamic bioreceptivity of real building  
554 surfaces.

555

556



557 **Acknowledgements**

558 P. Sanmartín and B. Prieto thank the financial support of Xunta de Galicia grant  
559 ED431C 2018/32. A.Z. Miller acknowledges the support from the  
560 CEECIND/01147/2017 contract funded by Fundação para a Ciência e a Tecnologia  
561 (Portugal).

562

563 **References**

564 Aloise, P., Ricca, M., Russa, M.F., Ruffolo, S.A., Belfiore, C.M., Padeletti, G.,  
565 Crisci, G.M., 2014. Diagnostic analysis of stonematerials from underwater  
566 excavations: the case study of the Roman archaeological site of Baia (Naples, Italy).  
567 *Appl Phys A* 114, 655–662.

568 Barberousse, H., Tell, G., Yéprémian, C., Couté, A., 2006. Diversity of algae  
569 and cyanobacteria growing on buildings facades in France. *Algol Stud* 120, 81–105.

570 Berns, R.S., 2000. Billmeyer and Saltzman's principles of color technology.  
571 3rd ed. New York (USA): John Wiley & Sons. 272 pp.

572 Bethencourt, M., Fernández-Montblanc, T., Izquierdo, A., González-Duarte,  
573 M.M., Muñoz-Mas, C., 2018. Study of the influence of physical, chemical and  
574 biological conditions that influence the deterioration and protection of Underwater  
575 Cultural Heritage. *Sci Total Environ* 613, 98–114.

576 Bracci, S., Melo, M.J., Tiano, P., 2002. Comparative study on durability of  
577 different treatments on sandstone after exposure in natural environment. *The Silicates*  
578 *in Conservative Treatments. Tests, Improvements and Evaluation of Consolidating*  
579 *Performance. In: Proceedings of the International Congress. Fondazione per le*  
580 *Bioteconologie and Associazione Villa dell'Arte, Torino, pp. 129–135.*

581 Caneva, G., Nugari, M.P., Salvadori, O., 2008. Plant Biology for cultural  
582 heritage. Los Angeles: Getty Conservation Institute.

583 Cao, S., Wang, J., Zhang, Y., Chen, D., 2013. The effectiveness of an  
584 antifouling compound coating based on a silicone elastomer and colored phosphor  
585 powder against *Navicula* species diatom. *J Coat Technol Res* 10(3), 397–406.

586 Callow, M.E., Callow, J.A., 2000. Substratum location and zoospore  
587 behaviour in the fouling alga *Enteromorpha*. *Biofouling* 15, 49-56.

588 Cámara, B., Álvarez de Buergo, M., Bethencourt, M., Fernández-Montblanc,  
589 T., La Russa, M.F., Ricca, M., Fort, R., 2017. Biodeterioration of marble in an  
590 underwater environment. *Sci. Total Environ.* 609, 109–122.

591 Cappitelli, F., Principi, P., Pedrazzani, R., Toniolo, L., Sorlini, C., 2007.  
592 Bacterial and fungal deterioration of the Milan Cathedral marble treated with  
593 protective synthetic resins. *Sci Total Environ* 385(1-3), 172-181.

594 Carter, N.E.A., Viles, H.A., 2005. Bioprotection explored: the story of a little  
595 known earth surface process. *Geomorphology* 67(3-4), 273-281.

596 Coutinho, M.L., Miller, A.Z., Rogerio-Candelera, M.A., Mirão, J., Cerqueira  
597 Alves, L., Veiga, J.P., Águas, H., Pereira, S., Lyubchykg, A., Macedo, M.F., 2016.  
598 An integrated approach for assessing the bioreceptivity of glazed tiles to phototrophic  
599 microorganisms. *Biofouling* 32, 243-259.

600 Coutinho, M.L., Miller, A.Z., Phillips, A., Mirão, J., Dias, L., Rogerio-  
601 Candelera, M.A., Saiz-Jimenez, C., Martin-Sanchez, P.M., Cerqueira-Alves, L.,  
602 Macedo, M.F., 2019. Biodeterioration of majolica tiles by the fungus *Devriesia*  
603 *imbrexigena*. *Constr Build Mater* 212, 49-56.

604 Cutler, N.A., Viles, H.A., Ahmad, S., McCabe, S., Smith, B.J., 2013. Algal  
605 'greening' and the conservation of stone heritage structures. *Sci Total Environ* 442,  
606 152–164.

607 Dahlem, C., Moran, P.J., Grant, T.R., 1984. Larval settlement of marine  
608 sessile invertebrates on surfaces of different colour and position. *Ocean Sci Eng* 9,  
609 225-236.

610 Dobretsov, S., Abed, R.M.M., Voolstra, C.R., 2013. The effect of surface  
611 colour on the formation of marine micro and macrofouling communities. *Biofouling*  
612 29, 617-627.

613 Ells, V., Filip, N., Bishop, C.D., DeMont, M.E., Smith-Palmer, T., Wyeth,  
614 R.C., 2016. A true test of colour effects on marine invertebrate larval settlement. *J*  
615 *Exp Mar Bio Ecol* 483, 156-161.

616 Escadeillas, G., Bertron, A., Blanc, G., Dubosc, A., 2007. Accelerated testing  
617 of biological stain growth on external concrete walls. Part 1: Development of the  
618 growth tests. *Mater Struct* 40, 1061–71.

619 Gu, J.-D., Mitton, D.B., Ford, T.E., Mitchell, R., 1998. Microbial degradation  
620 of polymeric coatings measured by electrochemical impedance spectroscopy.  
621 *Biodegradation* 9, 39–45.

622 Guenther, J., Carl, C., Sunde, L.M., 2009. The effects of colour and copper on  
623 the settlement of the hydroid *Ectopleura larynx* on aquaculture nets in Norway.  
624 *Aquaculture* 292, 252–255.

625 Guillitte, O., 1995. Bioreceptivity: a new concept for building ecology studies.  
626 *Sci Total Environ* 167, 215–220.

627           Guillitte, O., Dreesen, R., 1995. Laboratory chamber studies and  
628 petrographical analysis as bioreceptivity assessment tools of building materials. *Sci*  
629 *Total Environ* 167, 365–374.

630           Guiamet, P.S., Soto, D.M., Schultz, M., 2019. Bioreceptivity of archeological  
631 ceramics in an arid region of northern Argentina. *Int. Biodeter Biodegr* 141, 2-9.

632           Gulotta, D., Villa, F., Cappitelli, F., Toniolo, L., 2018. Biofilm colonization of  
633 metamorphic lithotypes of a renaissance cathedral exposed to urban atmosphere. *Sci.*  
634 *Total Environ* 639, 1480–1490.

635           Heimans, J., 1954. L'accessibilite, terme nouveau en phytogeographie.  
636 *Vegetatio* 5-6, 142-146.

637           Hernández-Mariné, M., Roldán, M., Clavero, E., Canals, A., Ariño, X., 2001.  
638 Phototrophic biofilm morphology in dim light. The case of the Puigmoltó sinkhole.  
639 *Nova Hedwigia* 123, 237-253.

640           Hueck, H.J., 1965. The biodeterioration of materials as part of hylobiology.  
641 *Material und Organismen* 1(1), 5–34.

642           Jurado, V., Miller, A., Cuezva, S., Fernandez-Cortes, A., Benavente, D.,  
643 Rogerio-Candelera, M., Reyes, J., Cañaveras, J., Sanchez-Moral, S., Saiz-Jimenez, C.,  
644 2014. Recolonization of mortars by endolithic organisms on the walls of San Roque  
645 church in Campeche (Mexico): A case of tertiary bioreceptivity. *Constr Build Mater.*  
646 53, 348–359.

647           Kon-ya, K., Miki, W., 1994. Effects of environmental factors on larval  
648 settlement of the barnacle *Balanus amphitrite* reared in the laboratory. *Fisheries Sci*  
649 60, 563-565.

650           Kumar, R., Kumar, A.V., 1999. *Biodeterioration of Stone in Tropical*  
651 *Environments: An Overview*. The Getty Conservation Institute, Santa Monica, CA.

652 La Russa, M.F., Ricca, M., Belfiore, C.M., Ruffolo, S.A., Álvarez de Buergo,  
653 M., Crisci, G. M., 2015. The contribution of Earth Sciences to the preservation of  
654 underwater archaeological stone materials: an analytical approach. *Int J Conserv Sci*  
655 *6*, 335-348.

656 Li, Y., Guo, X., Chen, Y., Ding, D., Yang, J., 2017. Comparative analysis of  
657 biofilm community on different coloured substrata in relation to mussel settlement. *J*  
658 *Mar Biol Assoc UK* *97*, 81-89.

659 Macedo, M.F., Miller, A.Z., Dionísio, A., Saiz-Jimenez, C., 2009.  
660 Biodiversity of cyanobacteria and green algae on monuments in the Mediterranean  
661 Basin: an overview. *Microbiol-SGM* *155*, 3476-3490.

662 Manso, S., Calvo-Torras, M.A., De Belie, N., Segura, I., Aguado, A., 2015.  
663 Evaluation of natural colonisation of cementitious materials: effect of bioreceptivity  
664 and environmental conditions. *Sci Total Environ* *512-513*, 444-453.

665 Marques, J., Vázquez-Nion, D., Paz-Bermúdez, G., Prieto, B., 2015. The  
666 susceptibility of weathered versus unweathered schist to biological colonization in the  
667 Côa Valley Archaeological Park (north-east Portugal). *Environ. Microbiol.* *17*, 1805–  
668 1816.

669 Martines, G.G., 1983. Marmo e restauro dei monumenti antichi: Estetica delle  
670 rovine, degrado delle strutture all'aperto, un'ipotesi di lavoro. In *Marmo e Restauro.*  
671 *Situazioni e Prospettive*, Museo del Marmo, Carrara, Italy.

672 Miller, A., Dionísio, A., Macedo, MF., 2006. Primary bioreceptivity: a  
673 comparative study of different Portuguese lithotypes. *Int Biodeter Biodegr* *57*, 136–  
674 42.

675 Miller, A.Z., Laiz, L., Gonzalez, J.M., Dionisio, A., Macedo, M.F., Saiz-  
676 Jimenez, C., 2008. Reproducing stone monument photosynthetic-based colonization  
677 under laboratory conditions. *Sci Total Environ* 405, 278-285.

678 Miller, A.Z., Rogerio-Candelera, M.A., Laiz, L., Wierzchos, J., Ascaso, C.,  
679 Sequeira Braga, M.A., Hernández-Mariné, M., Maurício, A., Dionísio, A., Macedo,  
680 M.F., Saiz-Jimenez, C., 2010. Laboratory-induced endolithic growth in calcarenites:  
681 biodeteriorating potential assessment. *Microb Ecol* 60, 55-68.

682 Miller, A.Z., Sanmartín, P., Pereira-Pardo, L., Saiz-Jimenez, C., Dionísio, A.,  
683 Macedo, M.F., Prieto, B., 2012. Bioreceptivity of building stones: A review. *Sci Total*  
684 *Environ* 426, 1-12.

685 Papida, S., Murphy, W., May, E., 2000. Enhancement of physical weathering  
686 of building stones by microbial populations. *Int Biodeter Biodegr* 46, 305–317.

687 Pomerat, C.M., Reiner, E.R., 1942. The influence of surface angle and of light  
688 on the attachment of barnacles and other sedentary organisms. *Biol Bulletin* 82, 14-  
689 25.

690 Prajapati, S.K., Kaushik, P., Malik, A., Vijay, V.K., 2013. Phycoremediation  
691 coupled production of algal biomass, harvesting and anaerobic digestion: Possibilities  
692 and challenges. *Biotechnol. Adv* 31(8), 1408–1425.

693 Prendergast, G.S., 2010. Settlement and behavior of marine fouling organisms.  
694 In Duerr S. and Thomason J.C. (eds) *Biofouling*. Oxford: Wiley-Blackwell, pp. 30-  
695 51.

696 Prieto, B., Silva, B., 2005. Estimation of the potential bioreceptivity of  
697 granitic rocks from their intrinsic properties. *Int Biodeter Biodegr* 56, 206–215.

698 Prieto, B., Silva, B., Aira, N., Álvarez, L., 2006. Toward a definition of a  
699 bioreceptivity index for granitic rocks: perception of the change in appearance of the  
700 rock. *Int Biodeter Biodegr* 58, 150–154.

701 Prieto, B., Sanmartín, P., Silva, C., Vázquez-Nion, D., Silva, B., 2014.  
702 Deleterious effect plastic-based biocides on back-ventilated granite facades. *Int*  
703 *Biodeter Biodegr* 86, 19–24.

704 Prieto, B., Vázquez-Nion, D., Silva, B., Sanmartín, P., 2018. Shaping colour  
705 changes in a biofilm-forming cyanobacterium by modifying the culture conditions.  
706 *Algal Res.* 33, 173-181.

707 Ramírez, M., Hernández-Mariné, M., Novelo, E., Roldán, M., 2010.  
708 Cyanobacteria-containing biofilms from a Mayan monument in Palenque, Mexico.  
709 *Biofouling* 26, 399–409.

710 Robson, M.A., Williams, D., Wolff, K., Thomason, J.C., 2009. The effect of  
711 surface colour on the adhesion strength of *Elminius modestus* Darwin on a  
712 commercial non-biocidal antifouling coating at two locations in the UK. *Biofouling*  
713 25, 215-227.

714 Rodrigues, A., Gutierrez-Patricio, S., Miller, A.Z., Saiz-Jimenez, C., Wiley,  
715 R., Nunes, D., Vilarigues, M., Macedo, M.F., 2014. Fungal biodeterioration of stained  
716 glass windows. *Int Biodeterior Biodegr* 90, 152-160.

717 Ruffolo, S.A., Ricca, M., Macchia, A., La Russa, M.F., 2017. Antifouling  
718 coatings for underwater archaeological stone materials. *Prog Org Coat* 104, 64-71.

719 Sanmartín, P., Villa, F., Cappitelli, F., Balboa, S., Carballeira, R., 2020.  
720 Characterization of a biofilm and the pattern outlined by its growth on a granite built  
721 cloister in the Monastery of San Martiño Pinario (Santiago de Compostela, NW  
722 Spain). *Int Biodeter Biodegr* 147, 104871.

723 Satheesh, S., Wesley, S.G., 2010. Influence of substratum colour on the  
724 recruitment of macrofouling communities. *J Mar Biol Assoc UK* 90, 941-946.

725 Schiavon, N., 2002. Biodeterioration of calcareous and granitic building  
726 stones in urban environments. In: S. Siegesmund, T. Weiss, A. Vollbrecht (Eds.),  
727 *Natural Stone, Weathering Phenomena, Conservation Strategies and Case Studies*,  
728 205, Geological Society of London, London, pp. 195-205.

729 Silva, B., Prieto, B., Rivas, T., Sánchez-Biezma, M.J., Paz, G., Carballal, R.,  
730 1997. Rapid biological colonization of a granitic building by lichens. *Int Biodeter*  
731 *Biodegr* 40, 263–267.

732 Sohrabi, M., Favero-Longo, S.E., Pérez-Ortega, S., Ascaso, C., Haghghat, Z.,  
733 Talebian, M.H., Fadaei, H., de los Ríos, A., 2017. Lichen colonization and associated  
734 deterioration processes in Pasargadae, UNESCO world heritage site, Iran. *Int Biodeter*  
735 *Biodegr* 117, 171-182.

736 Sterflinger, K., Ettenauer, J., Piñar, G., 2013. Bio-susceptibility of materials  
737 and thermal insulation systems used for historical buildings. *Energy Procedia* 40,  
738 499–506.

739 Sternberg, T., Viles, H.A., Cathersides, A., 2010a. Evaluating the role of ivy  
740 (*Hedera helix*) in moderating wall surface microclimates and contributing to the  
741 bioprotection of historic buildings. *Build Environ* 46(2), 293-297.

742 Sternberg, T., Viles, H.A., Cathersides, A., Edwards, M., 2010b. Dust  
743 particulate absorption by ivy (*Hedera helix* L) on historic walls in urban  
744 environments. *Sci Total Environ* 409(1), 162-168.

745 Swain, G., Herpe, S., Ralston, E., Tribou, M., 2006. Short-term testing of  
746 antifouling surfaces: the importance of colour. *Biofouling* 22, 425-429.



747 Tomaselli, L., Lamenti, G., Bosco, M., Tiano, P., 2000 Biodiversity of  
748 photosynthetic microorganisms dwelling on stone monuments. *Int Biodeter Biodegr*  
749 46, 251–8.

750 Urzì, C., De Leo, F., Krakova, L., Pangallo, D., Bruno, L., 2016. Effects of  
751 biocide treatments on the biofilm community in Domitilla’s catacombs in Rome. *Sci*  
752 *Total Environ* 572, 252–262.

753 Van Eck, N.J., Waltman, L., 2010. Software survey: VOSviewer, a computer  
754 program for bibliometric mapping. *Scientometrics* 84, 523-538.

755 Vázquez-Nion, D., Silva, B., Prieto, B., 2018a. Influence of the properties of  
756 granitic rocks on their bioreceptivity to subaerial phototrophic biofilms. *Sci. Total*  
757 *Environ* 610–611, 44–54.

758 Vázquez-Nion, D., Troiano, F., Sanmartín, P., Valagussa, C., Cappitelli, F.,  
759 Prieto, B., 2018b. Secondary bioreceptivity of granite: effect of salt weathering on  
760 subaerial biofilm growth. *Mater Struct* 51, 158.

761 Vázquez-Nion, D., Silva, B., Prieto, B., 2018c. Bioreceptivity index for  
762 granitic rocks used as construction material. *Sci. Total Environ* 663, 112-121.

763 Viles, H., Ahmad, H., 2016. Architectural controls on the bioreceptivity of  
764 sandstone to green algal colonization. ECBSM2016. European Conference on  
765 Biodeterioration of Stone Monuments - Second Edition. Cergy-Pontoise, France.  
766 November 17–18, 2016.

**Table 1.** Correspondence of previous (1995) to current (2020) bioreceptivity-related terms and summary of changes enacted, further explained with descriptions and examples.

1995	2020	Changes enacted	Description, cases and examples
Primary	Primary*	Definition improved	A sound or fresh material after manipulation (extraction from the quarry and cut) for a final function (e.g. be used in a construction)
Secondary	Secondary*	Definition improved	Material weathered by environmental factors and/or colonisers. This weathering can be artificially induced through accelerated ageing tests with solar or UV radiation, rain, humidity, temperature, pollutants, salts, etc
Tertiary	Tertiary*	Split into 2 types of bioreceptivity: leaving tertiary for when the material is cleaned, and using quaternary when materials are added and integrated into the starting material	Mechanical cleaning techniques (Brushing, washing with water, grinding), laser cleaning methodologies
	Quaternary*	Described as a new bioreceptivity type. Related to a coated or treated material, where the added materials have been permanently or semi-permanently integrated into the original material	Water repellents, biocides, consolidants, cleaning agents that leave residues, painting, stucco, plaster
Intrinsic	Intrinsic factors**	Intrinsic bioreceptivity dropped, replaced by intrinsic factors	Porosity, surface roughness, mineralogy, geochemistry, permeability, surface hardness, colour, pH <a href="#">Larger or building-scale factors</a>
Extrinsic	Extrinsic factors**	Extrinsic bioreceptivity dropped, replaced by extrinsic factors	Surface deposits such as oil, dust, organic particulates, pollutants, guano, <a href="#">and also dead biomass and living organisms***</a> Locational characteristics such as angle of surface, aspect, height above ground (factors which affect moisture and thermal regimes) <a href="#">Larger or building-scale factors</a>
Semi-extrinsic		Dropped term	
	In subaerial environment		Buildings, monuments and structures in outdoor environment
	In submerged environment	Inclusion of this environment in bioreceptivity studies	Archaeological sites immersed, floodprone area in buildings
	In subsoil environment	Inclusion of this environment in bioreceptivity studies	Archaeological sites buried, building foundations

\*Under lab conditions the material is inoculated with living organisms, under field conditions it is placed onsite and exposed to the environment (in some cases also inoculated outdoors).

\*\*According to current authors extrinsic and intrinsic factors potentially affecting the colonization at all stages (Primary to Quaternary) – rather than Guillitte who related them as producing different pathways.

\*\*\*[Because the presence of one organism may make it easier for others to enter the community.](#)

Figure 1

[Click here to access/download;Figure;Fig 1.png](#)

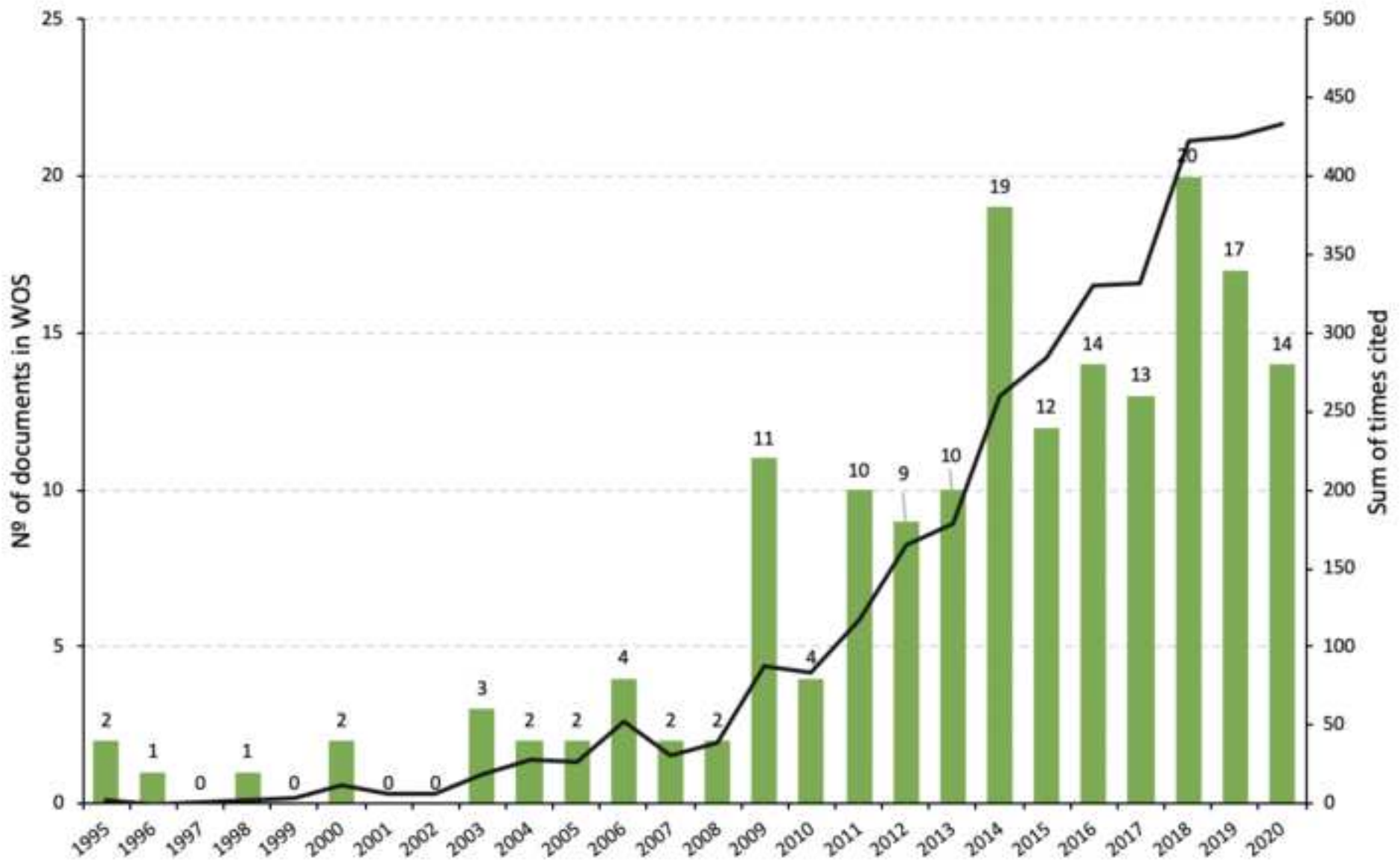
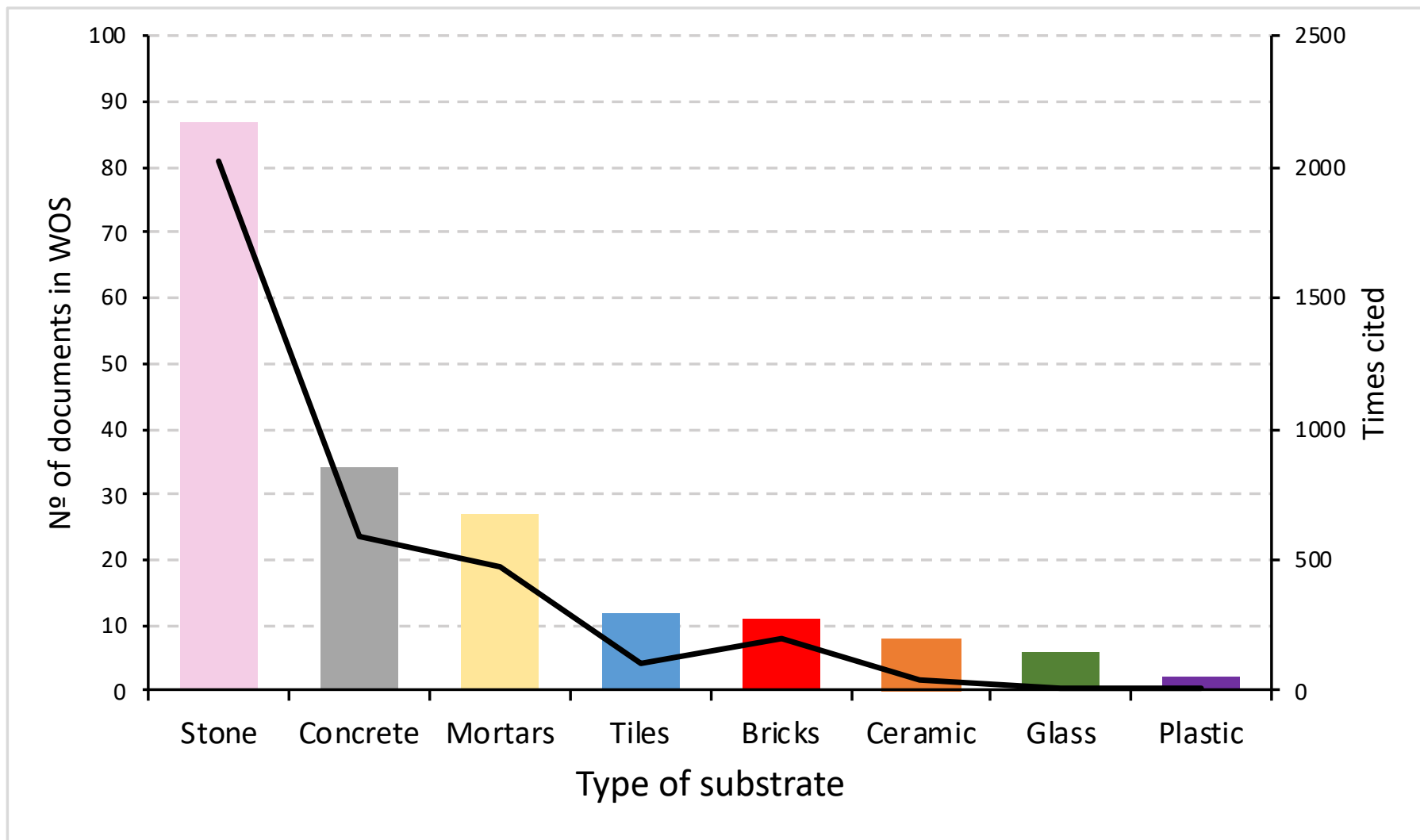
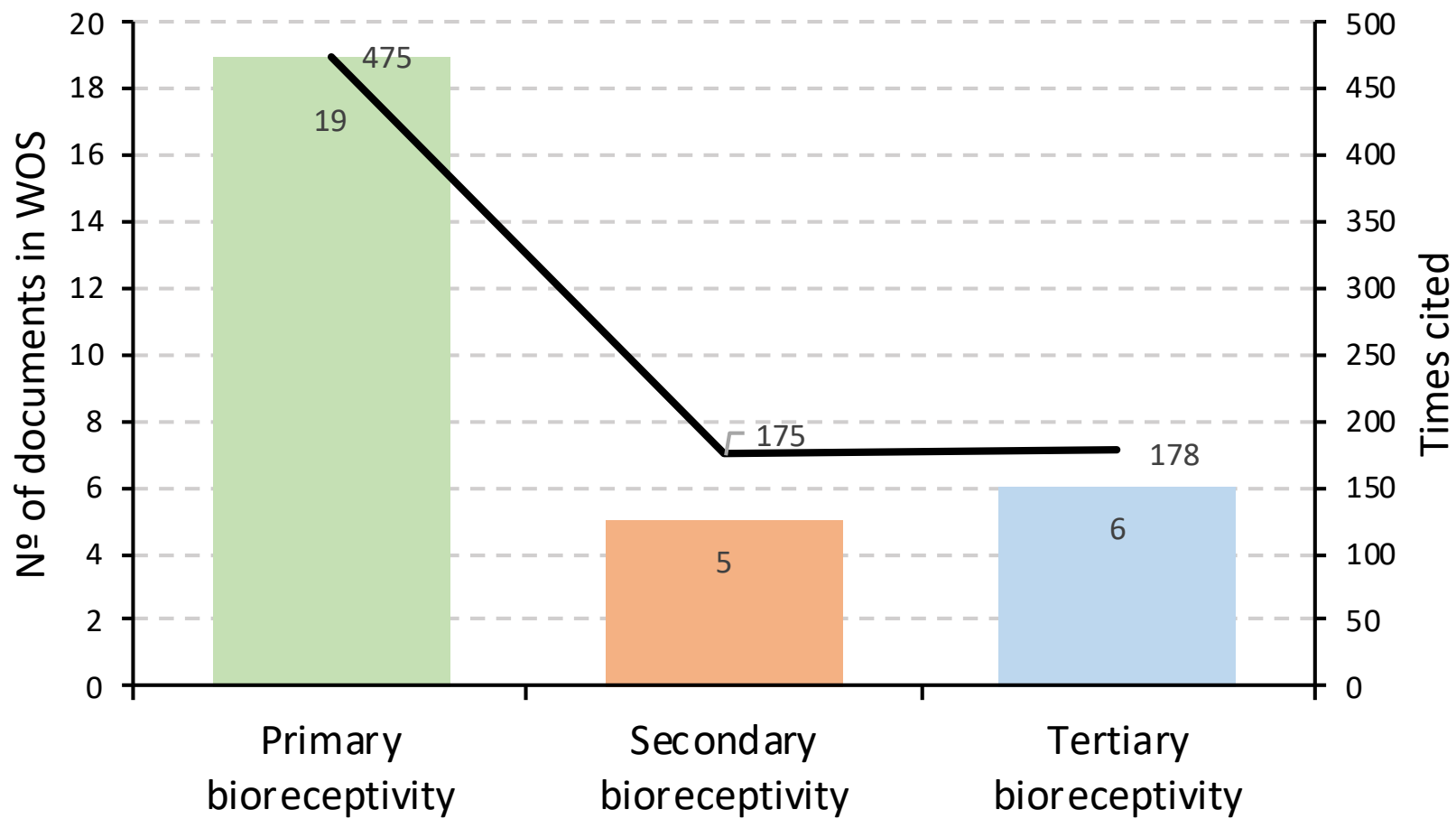


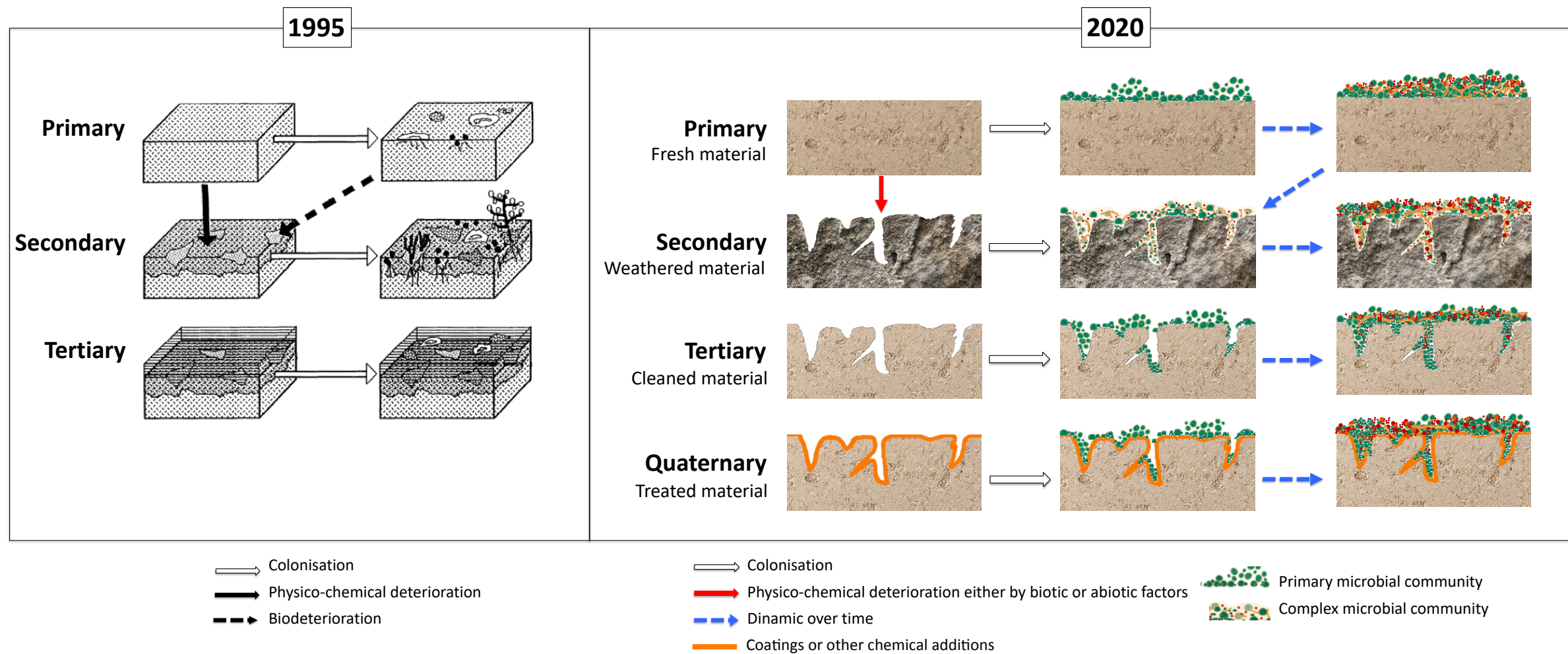


Figure 3













University of Santiago de Compostela

Spain

29 November, 2020

Disclosure of potential conflict of interest

The authors declare that they have no conflicts of interest.

Patricia Sanmartín, on behalf of the authors

Patricia Sanmartín

Departamento de Edafoloxía e Química Agrícola  
Facultade de Farmacia. Pavillón A - Soto. Campus Vida  
Universidade de Santiago de Compostela  
15782 Santiago de Compostela (A Coruña). SPAIN.  
Tel : +34 881814984  
E-mail: [patricia.sanmartin@usc.es](mailto:patricia.sanmartin@usc.es)  
<http://webspersoais.usc.es/persoais/patricia.sanmartin/>