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Revisiting and reanalysing the concept of bioreceptivity 25 years on

--Manuscript Draft--

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Abstract:	2020 marks 25 years since Olivier Guillitte defined the term 'bioreceptivity', to describe the ability of a building material to be colonised by living organisms. Although Guillitte noted in his 1995 paper that several issues required further investigation, to the best of our knowledge the bioreceptivity concept has not been restated, reviewed, reanalysed or updated since then. The present paper provides an opinionated exposition of the status and utility of the bioreceptivity concept for built heritage science and conservation in the light of current knowledge, aimed to stimulate further discussion. A bibliometric analysis highlights the key dimensions of the past 25 years of published research, showing that the term bioreceptivity has been widely used in the field of built cultural heritage. In our reanalysis of the concept, special attention is devoted to the six types of bioreceptivity (primary, secondary, tertiary, intrinsic, extrinsic and semi-extrinsic) articulated by Guillitte in 1995. We propose that field-based studies of bioreceptivity are urgently needed, and that the intrinsic, extrinsic and semi-extrinsic types of bioreceptivity should be dropped, and a new category (quaternary bioreceptivity) added. Additionally, we propose that bioreceptivity in submerged and subsoil environments should also be considered. Bioreceptivity remains an important concept for managing both new build and built heritage, as it provides the key to understanding the drivers and patterns of biological colonisation of building materials.
Response to Reviewers:	Santiago de Compostela, Spain 16 January, 2021 Associate Editor Science of the Total Environment Dear Prof. Dr. Daniel A. Wunderlin, We are sending you the second revised version of our manuscript entitled 'Revisiting and reanalysing the concept of bioreceptivity 25 years on' (Ms. Ref. No.: STOTEN-D-20-28779) written by myself, Ana Zélia Miller, Beatriz Prieto, and Heather Viles. In revising this paper, we have tried to fully address the comments made by the Reviewers via amendments in the text (showing tracked changes). We hope the manuscript will now be judged suitable for publication in Science of the Total Environment, and we look forward to hearing from you at your earliest convenience. Yours sincerely, Patricia Sanmartín, on behalf of the authors. RESPONSES TO THE REVIEWERS' COMMENTS: Reviewer 1 Dear Editor,

I am pleased to say that the authors have significantly improved their manuscript. They removed most of the manuscript's flaws and reworked most of the controversial passages. In particular, it was a good decision to remove the fragments about the relationship between biorespectivity and ecological succession. The authors decided to stick to their idea of redefining the tertiary biorespectivity (splitting it into two: new tertiary and quaternary) that I criticized. I still think this idea is a miss; I am not convinced by the authors' arguments. However, I believe that authors have a right to present their ideas as long as they are not nonsense. Especially since they classify their manuscript as a discussion article.
In conclusion, I recommend publication of the revised manuscript in the Science of the Total Environment after minor corrections. I am confident that the authors will deal with my comments with due diligence, and the editor will be able to accept the revised manuscript without sending it back to me.

DETAILED COMMENTS

Lines 44-45 of the revised manuscript - "habitat heterogeneity" is still not clear. In a narrow sense, habitat can be understood as a building material (e.g. see line 81). Here, the authors probably mean the surrounding environment. So, I propose changing "habitat heterogeneity" into "environmental heterogeneity". But the better option will be to remove "encompasses habitat heterogeneity" and end the sentence with "surrounding heterogeneous environment".
Response: We agree and appreciate the reviewer's comment. We have modified the sentence with the last suggested option.

Lines 228-229 - I suggest writing "the changes in material properties" instead of "changing material properties".
Response: Done.

Lines 231-235 - This sentence is difficult to understand. Consider rewriting.
Response: We agree with the reviewer that this sentence was unclear and have rewritten it as follows: “If, as Guillitte believed, the transition from primary to secondary bioreceptivity occurs as a result of both the activity of living organisms and abiotic processes, together or separately, then it is very difficult for researchers to produce realistic artificially weathered specimens in the laboratory on which to investigate secondary bioreceptivity “

Line 382 "quicker during" - It probably should be "quicker than during".
Response: Thanks. Done.

Line 384 - What do you mean by "new introduced material"? A chemical substance for protection of building material? Or building material coated with this substance? Or material other than stony material? Not clear.
Response: We have rephrased this sentence to add a clearer explanation (i.e. replaced “new introduced material” with “added materials such as consolidants and other surface treatments”.

Lines 383-388 - This surprised me. I thought that materials treated chemically (for protection) are generally less bioreceptive than not treated ones. This passage is not entirely clear to me. Maybe I should look at the papers cited, but the review is urgent, and there is no time for that. Consider rewriting.
Response: We have added some fuller examples to demonstrate the research findings showing enhanced bioreceptivity in these circumstance. The text has been adjusted accordingly and the new references added to the reference list. The relevant text now reads: “Several studies note that these new habitats are more bioreceptive than the original stony material (Bracci et al., 2002; Cappitelli et al., 2007). For example, in the Catacombs of Domitilla (Rome, Italy), a biocide treatment composed of quaternary ammonium compounds and octylisothiazolone sparked the proliferation of bacteria with high hydrolytic enzymatic activity (Urzì et al., 2016). In Campeche (Mexico), restored mortars composed of fatty acid promoted an early endolithic phototrophic colonization by cyanobacteria and bryophyte on the facade of San Roque church (Jurado and Miller et al., 2014). Surface treatments such as consolidants may also alter the physical properties of stony materials like the wetting-drying kinetics, leading to the material

	remaining damp for longer and hence its bioreceptivity increasing (Prieto et al., 2014)." Reviewer 2 All my comments have been taken into account and I hope that the manuscript will be published and will initiate an interesting scientific discussion. My recommendation is to accept for publication. Response: Many thanks. Reviewer 3 The paper revised can be accepted in the present form Response: Many thanks.

University of Santiago de Compostela

Spain

29 November, 2020

Dear editorial board of the journal *Science of the Total Environment*,

I hereby include a manuscript entitled **“Revisiting and reanalysing the concept of bioreceptivity 25 years on”**, written by myself, Ana Zélia Miller, Beatriz Prieto, and Heather Viles, to be submitted as **a discussion** for consideration of publication.

I would like to clarify that this work is a new version of a previous one, what was submitted as a ‘Review’ paper instead of a ‘Discussion’ paper. This new version reinforces the approach in the form of a discussion paper, including improvements after the criticisms received, and focusing the work more clearly on Cultural Heritage, which is the area of expertise of the four authors.

This paper was carried out between the universities of Oxford [UK], Santiago [Spain] and Évora [Portugal], and deals to give an opinionated exposition (to stimulate further discussion) about Guillitte’s concept of bioreceptivity 25 years on, investigating how it has been deployed mainly in the field of built cultural heritage science and conservation using a bibliometric survey, and reanalysing the concept by proposing some revisions and improvements.

Although Guillitte noted in his 1995 paper (published in *Science of the Total Environment*) that several issues required further investigation, the bioreceptivity concept has not been restated, reviewed, reanalysed or updated until now.

For these reasons, we think the study here presented fits the Aims and Scope of the journal *Science of the Total Environment* and hope it could be considered for publication.

All co-authors have seen and agree with the contents of the manuscript, and certify that the submission is an original work and is not under review neither being considered for publication elsewhere.

I hope that the editorial board will agree on the interest of this study.

Sincerely yours,
Patricia Sanmartín, on behalf of the authors.

Revisiting and reanalysing the concept of bioreceptivity 25 years on

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Santiago de Compostela, Spain

16 January, 2021

Associate Editor
Science of the Total Environment

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Reviewer 2

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Response: Many thanks.

Reviewer 3

The paper revised can be accepted in the present form

Response: Many thanks.

Abstract

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

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

1. Introduction

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

The colonisation of building materials is a complex process as it ~~encompasses habitat heterogeneity and~~ is dynamic in time and space due to the interrelationships among the colonising organisms, as well as between their populations, the inorganic substrate and the surrounding heterogeneous environment. In fact, biological colonisation patterns on built heritage are not constant, but periodic and are very likely to change quickly as a result of different climate conditions, in particular alterations in temperature and precipitation (Macedo et al., 2009), as well as environmental chemical contaminants in polluted air and precipitation (Schiavon, 2002). It is important to emphasise that the potential of the material to be colonised by living organisms - its bioreceptivity - (Guillitte, 1995), is also dynamic as the chemical and physical characteristics of the substrate change over time as a result of exposure to weather and pollution conditions.

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

2. Revisiting bioreceptivity

2.1 Guillitte's ideas on bioreceptivity

In 1995, Olivier Guillitte published the first two papers defining and analysing the concept of bioreceptivity: 'Bioreceptivity: a new concept for building ecology studies' (Guillitte, 1995) and 'Laboratory chamber studies and petrographical analysis as bioreceptivity assessment tools of building materials' (Guillitte and Dreesen, 1995). While the idea that material properties influence what grows was not in itself novel, Guillitte proposed the term bioreceptivity to provide a neutral framing with no connotation of biological colonisation being negative, and also to shift the focus on to the influence of materials on organisms rather than the reverse, which until then had monopolized the attention of researchers (Hueck, 1965). In his first publication (Guillitte, 1995), he proposed two definitions for the bioreceptivity concept, (1) 'the ability of a material to be colonised by living organisms' (expanded in ‘the aptitude of a material (or any other inanimate object) to be colonised by one or several groups of living organisms without necessarily undergoing any biodeterioration’), (2) ‘the totality of material properties that contribute to the establishment, anchorage and development of fauna and/or flora’ (Guillitte, 1995). The purpose of these definitions was to link bioreceptivity to the process of colonisation and *in situ* development and multiplication of organisms, thus interpreting the material as a potential habitat where the conditions that define the niche of the species can be found and not as a mere transient or anchoring place for organisms. He aimed to distinguish bioreceptivity from other concepts related to biological growths on materials, such as biodegradation and biodeterioration (which usually have negative connotations).

Why did Guillitte coin the term ‘bioreceptivity’ rather than ‘biosusceptibility’? Guillitte (1995) reviewed the term ‘susceptibility’ and its definition in the field of medicine and veterinary medicine, and used it as an analogy for his new concept in building ecology. In a footnote to his work, Guillitte explains that he opts for ‘receptivity’ instead of 'susceptibility' based on the parallel with the biological concept ‘receptivity’ in English defined as 'the ability of a flower stigma to be fertilised by pollen grains through the pollen tube', and because the former translates in the same way into different languages. Hence he writes ‘we suggest using the word ‘bioreceptivite’ in French, ‘Biorezeptivitlt’ in German, ‘bioreceptiviteit’ in Dutch, ‘bioreceptividad’ in Spanish, ‘bioreceptividade’ in Portuguese and ‘biorecettivith’ in Italian’ (Guillitte, 1995). Nevertheless, some papers published later have used the terms susceptibility to biological colonisation (Marques et al., 2015), biosusceptibility (Sterflinger et al., 2013), and biosusceptibility (Gu et al., 1998) to refer to the bioreceptivity of a material.

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

2.2 Other linked concepts

In contrast to bioreceptivity, the concept of biodeterioration has been around for much longer and applied to a much wider range of materials and circumstances. The most consolidated and widespread definition of biodeterioration is that offered by Hueck in 1965 as 'any undesirable change in the properties of a material caused by the vital activities of organisms' (Hueck, 1965, p. 7). Biodeterioration can be classified into three categories: (i) physical or mechanical, (ii) chemical and (iii) aesthetic. The latter is limited to the visual effects of the presence of microorganisms and their products that alter the chromatic appearance. It seems that Guillitte did not consider this third category to be a form of deterioration, at least in the case of organisms growing on building materials. Indeed, he claimed that 'some authors consider the colour changes to be aesthetically pleasing, credit them with a protective role against man- or weather-induced aggression and suggest that they have a cleansing effect which benefits the environment' (Guillitte, 1995). Such claims remain controversial. As Kumar and Kumar (1999) reported, climbing plants have long been considered to enhance the aesthetic value of built heritage such as ruins, as in some cases can the occurrence of algae and lichens (Martines, 1983). In several cases, the negligible (Gulotta et al., 2018; Sanmartín et al., 2020) or bioprotective (Ramírez et al., 2010; Cutler et al., 2013) role of pioneer algae and cyanobacteria (a phenomenon often referred to as "greening", the first step in the sequential process of colonisation) on the physical integrity of stone has been proven, aside from the ability of algae to sequestrate CO_2 from atmospheric air (Prajapati et al., 2013). However, at present, it is frequently considered preferable to eliminate any kind of colonisation from building surfaces for reasons of preventive conservation and to create an impression of order, cleanliness and care of the structure or construction.

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

2.3 Bibliometric analysis of 25 years of bioreceptivity publications

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

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

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

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

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

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

After 'biodeterioration', the predominance of the keywords 'algae' and 'cyanobacteria' is explained as phototrophic microorganisms are pioneer colonisers of inorganic materials, such as stone, and are the most commonly used microorganisms in laboratory-based bioreceptivity experiments (Miller et al., 2012). In addition, ‘fungi’ and ‘lichens’ also have a high co-occurrence in bioreceptivity-related articles. Worth mentioning is the predominance of keywords related to the materials covered in bioreceptivity-related publications, such as ‘stone’, ‘rocks’, ‘limestone’, ‘concrete’ and ‘mortar’, as well as ‘cultural-heritage’, ‘conservation’ and ‘monuments’, which demonstrate that the term bioreceptivity is widely used in the field of built cultural heritage (Fig. 2). According to our bibliometric survey of research into bioreceptivity, stone is the most studied material and the focus of the most cited articles (Fig. 3). In contrast, few studies have been performed on the bioreceptivity of concrete, mortars, tiles, bricks, glass or plastic, compared with stone. Most of the case studies on bioreceptivity shown in Figure 3 rely on in-vitro (lab based) tests. In fact, the majority of papers was focused on primary bioreceptivity (Fig. 4) which has been almost exclusively studied under laboratory conditions (e.g. Prieto and Silva, 2005; Miller et al., 2008, 2010; Vázquez-Nion et al., 2018a).

***[Figure 3**. Number of records for the combination of the term ‘bioreceptivity’ with the keywords related to building materials in the WOS database (accessed on the 19th of November 2020).]*

***[Figure 4.** Number of records in the WOS database (accessed on the 19th of November 2020) for the keywords ‘Primary bioreceptivity’, ‘Secondary bioreceptivity’ and ‘Tertiary bioreceptivity’.]*

3. Reanalysing bioreceptivity

3.1 What is missing or often overlooked from Guillitte’s ideas?

When a material has not yet been exposed to colonisation and as long as its properties remain unchanged, bioreceptivity is defined as primary according to Guillitte, whilst when the material properties change it becomes secondary. Guillitte (1995) wrote: 'For practical purposes, secondary bioreceptivity is often more important than primary bioreceptivity'. This is especially true when we refer to built cultural heritage, whose materials have been exposed to weathering for long periods. However, as the current authors demonstrate in section 2.3, secondary bioreceptivity has hardly been studied, with the bulk of research focusing on primary bioreceptivity which probably is more useful in the architectural field for looking at ‘new build’. There are several reasons that could explain why this has been true for 25 years. For example, it is not clear when the changes in ~~changing~~ material properties become significant for potential colonizers (breakpoint), and what criteria should be used to determine that breakpoint. How much must a given material be changed (physically and/or chemically) in order for its bioreceptivity to be defined as secondary? If, as Guillitte believed, the transition from primary to secondary bioreceptivity occurs as a result of both the activity of living organisms and abiotic processes, together or separately~~in combination or just one of them~~, then ~~how can researchers~~it is very difficult for researchers to produce realistic artificially weathered specimens in the laboratory on which to investigate secondary bioreceptivity (Papida et al., 2000; Vázquez-Nion et al., 2018b)? Are field-based studies needed? There is also the issue that most natural building materials have already undergone change through weathering (for example on a quarry face) even before they are placed in a building (Silva et al., 1997), and so it is unclear whether bioreceptivity in such cases should be classified as primary or secondary.

Guillitte’s concept of bioreceptivity is largely focused on the influence of small scale (mm to cm scale) factors intrinsic to different building materials. These are amenable to study in laboratory experiments and are the most obvious intrinsic factors to consider. However, once a material is exposed within a building façade or structure, other larger scale (cm to m) factors may have very important influences on bioreceptivity (Viles and Ahmad, 2016). For example, a stone type used in architectural detailing such as balusters and string courses may have very different bioreceptivities within those two contexts, because of the influence of surface angle (in relation to vertical), aspect, and position on the building which i) exert important controls on water and thermal regimes and ii) modify primary bioreceptivity through weathering in different ways giving rise to different secondary bioreceptivity. In many ways, these larger scale influences can be seen as larger scale surface roughness (where the roughness applies to whole areas of masonry, facades or indeed an entire building). The potential importance of these larger scale factors can best be studied by well-designed field experiments. One of the remaining challenges about larger scale factors is to determine whether they are intrinsic or extrinsic in nature.

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

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

Furthermore, the diversity was wide, although filamentous cyanobacteria and at lesser extent some species of algae (*Anabaena* and *Oscillatoria*) were the most abundant.

One missing point from Guillitte's ideas is how to express and quantify bioreceptivity. In the first experiment specifically designed to evaluate bioreceptivity, Guillitte and Dreesen (1995) characterised the bioreceptivity of two natural stone types and three manufactured materials by quantifying the vegetal cover after 9 months of exposure to sprinkling with a nutrient-rich tap water containing a mixture of pioneer colonising plant diaspores. Percentage cover has been used to express bioreceptivity in subsequent experiments (Tomaselli et al., 2000, Miller et al., 2006, Escadeillas et al., 2007) allowing comparison between samples in the same experiment but not comparison between different experiments. The main problem derived from using % cover is that once 100% cover is reached the subsequent increase in colonization related to bioreceptivity cannot be quantified. Moreover, colonization in depth is not taken into account. To overcome these problems, the amount of chlorophyll *a* /surface unit has been used by other authors to express bioreceptivity (Prieto and Silva, 2005; Prieto et al., 2006). This way of expressing bioreceptivity allows comparison not only between samples but also between experiments, but has the disadvantage that it can only be used for phototrophs. Moreover, Guillitte did not establish how to unambiguously define and categorise the bioreceptivity of a material, although he pointed the need to remove any subjectivity attached to the concept and proposed developing a bioreceptivity index. Nowadays, this index has been developed but only for granitic rocks (Vázquez-Nion et al., 2018c).

3.2 Types of bioreceptivity on built heritage

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

Although the addition of a new term (‘quaternary bioreceptivity’) could be seen as controversial and adding to complexity, we believe that it has practical benefits for the use of bioreceptivity for understanding the deterioration of built heritage in highlighting different ways in which humans can affect the situation, in a way that is distinctive to the changes involved in secondary bioreceptivity. Furthermore, the concept of ‘quaternary bioreceptivity’ reduces complexity by replacing the terms, also defined by Guillitte but rarely used, of intrinsic, semi-extrinsic and extrinsic bioreceptivity. Guillitte (1995) defined intrinsic bioreceptivity as occurring 'when colonisation depends mainly on the properties of the material, irrespective of exogenous contributions’'. Many researchers consider ‘intrinsic’ and ‘primary’ bioreceptivity as synonymous, probably because they see both natural weathering and human activities as exogenous contributions. We instead consider that Guillitte viewed exogenous contributions in a more narrow sense as additions to the material such as particles, organisms and substances. In this interpretation, all three types of bioreceptivity of a fresh, weathered and cleaned stony material, i.e. primary, secondary and tertiary bioreceptivity, may be seen as ‘intrinsic bioreceptivity’. It reinforces this idea that by ‘semi-extrinsic bioreceptivity’ Guillitte (1995) refers to situations when ‘colonisation depends directly and simultaneously on the properties of the material and on the deposits of exogenous substances', where he used the term ‘deposit’ to refer to the exogenous contribution. For us, ‘semi-extrinsic bioreceptivity’ would in some cases correspond to what we have called ‘quaternary bioreceptivity’. An extreme case of ‘quaternary bioreceptivity’, where only the bioreceptivity of the added exogenous material is of interest is what Guillitte (1995) called ‘extrinsic bioreceptivity’. We propose that intrinsic, extrinsic and semi-extrinsic bioreceptivity terms be dropped, and instead encourage the use of ‘intrinsic factors’ and ‘extrinsic factors’ related to the bioreceptivity of a material. Thus, roughness, porosity, mineralogical composition and colour of a material, for instance, will be intrinsic factors related to bioreceptivity; while architectural factors, micro-temperature and micro-humidity on the material surface, and added materials (such as dead biomass, living organisms, dust, guano) are extrinsic factors related to bioreceptivity (Table 1).

Figure 5 provides a visualization of how our conceptualisation of bioreceptivity builds on that of Guillitte (1995). The blue dashed arrows in figure 5 portray the ecological dynamism involved as material conditions change within the different categories (primary, secondary, tertiary and quaternary) and also as the situation switches from primary to secondary types. In the case of primary bioreceptivity, the communities should be dominated by fast-growing and well-dispersed species while in secondary bioreceptivity, these species will tend to be replaced by more competitive species which may have differing impacts on biodeterioration. Furthermore, in the case of tertiary bioreceptivity, changes in the ecological community should occur faster. This has been observed in several studies of tertiary bioreceptivity, where recolonisation after cleaning occurs quicker than during the primary bioreceptivity phase (Sohrabi et al., 2017). The same has been reported for the proposed new category of quaternary bioreceptivity, where ~~the~~ added materials such as consolidants and other surface treatments ~~new introduced material~~ may become a new habitat for colonisers. Several studies note that these new habitats ~~(generally much~~are more bioreceptive than the original stony material~~) for colonisers~~ (Bracci et al., 2002; Cappitelli et al., 2007). For example, in the Catacombs of Domitilla (Rome, Italy), a biocide treatment composed of quaternary ammonium compounds and octylisothiazolone sparked the proliferation of bacteria with high hydrolytic enzymatic activity (Urzì et al., 2016). In Campeche (Mexico), restored mortars composed of fatty acid promoted an early endolithic phototrophic colonization by cyanobacteria and bryophyte on the facade of San Roque church (Jurado and Miller et al., 2014). Surface treatments such as consolidants may also ~~, or may~~ alter the physical properties of stony materials like the wetting-drying kinetics, leading to the material remaining damp for longer and hence its bioreceptivity increasing~~es~~ (Prieto et al., 2014). In future, an interesting area of research would be to explore these ecological dynamics in more detail and elucidate how communities of organisms living on built heritage change in tandem with the material changes. This could involve linking bioreceptivity to concepts of ecological succession.

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

3.3 Bioreceptivity of subaerial, submerged and subsoil built heritage

While the concept of biodeterioration is considered in subaerial, submerged and subsoil environments, bioreceptivity is currently only explicitly considered in the former despite buildings possessing subsoil foundations and being affected by periodic flooding, as well as many archaeological sites being buried or immersed. However, this is only a conceptual issue because many studies have focused on how biodeterioration develops differently according to the type of material and how the intrinsic characteristics of a material affect its biocolonisation in submerged (mainly marine) and subsoil environments. For example, a comparative study of bioreceptivity between different building materials (marbles, limestones, ignimbrites, and bricks), similar to that of Guillitte and Dreesen (1995), but in a Mediterranean marine environment was carried out by Aloise et al. (2014) although they do not explicitly use the term bioreceptivity. Marble and limestone samples collected from the cities of Baiae and Portus Iulius (Naples, Italy), submerged since the 4th century AD, showed intense colonisation (high bioreceptivity) mainly by boring sponges, while ignimbrites in the same place presented a lower biological attack caused by serpulids and bryozoans. In bricks, paste with volcanic aggregates was less bioreceptive, showing a greater resistance to biological colonisation, than that with quartz (Aloise et al., 2014). As is clear, different species were found on different substrates as a function of their composition. Similarly, differences in material colour have been shown to impact the short-term development of marine biofouling communities, influencing larval settlement and colonisation of invertebrates and algae (Dahlem et al., 1984; Satheesh and Wesley, 2010), and especially barnacles (Pomerat and Reiner, 1942; Kon-ya and Miki, 1994; Robson et al., 2009; Prendergast, 2010). Most studies in this field have only tested black and white or grayscale substrates, thus showing only whether different responses arise due to the luminosity or lightness/darkness (Callow and Callow, 2000; Swain et al., 2006; Dobretsov et al., 2013; Cao et al., 2013). Other studies, instead, have also considered chroma and hue (Guenther et al., 2009; Ells et al., 2016; Li et al., 2017). Chroma (or saturation) is related to the intensity of colour, while hue, which refers to the dominant wavelength and represents redness, yellowness, greenness, blueness, etc., has been shown in perception studies to be the most important colour parameter (Berns, 2000; Prieto et al., 2018). Settlement of mussel *Mytilus coruscus* plantigrades was found to differ according to substrate colour (red, orange, blue, white, yellow and green) and was lowest on the biofilms formed on green surfaces, possibly because of a variation in the establishment of the underlying biofilm community (Li et al., 2017). In contrast, the hydroid *Ectopleura larynx* settled preferentially on black vs white substrates, whereas there were no significant differences between the remaining tested colours (yellow, red and blue; Guenther et al., 2009). These two examples show how differently various organisms respond to surface colour and highlight the need to investigate this response systematically.

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

3.4 Bioreceptivity and building-scale factors

Because most bioreceptivity studies have been carried out in controlled, laboratory conditions, there is a need for further investigation of the larger-scale factors influencing colonisation dynamics on real buildings and its relationship with bioreceptivity. As long as bioreceptivity of a material is defined by ‘the totality of material properties that contribute to the establishment, anchorage and development of fauna and/or flora’ those properties can be different for the same material depending on its position on the building. Introducing larger-scale factors to bioreceptivity brings complications, as it becomes hard to separate out intrinsic from extrinsic factors. Further research is needed to explore the influence of building-scale factors on bioreceptivity, colonization and biodeterioration.

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

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

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

4. Final considerations, conclusions and prospects

Over the last 25 years, few studies have been carried out on bioreceptivity on materials *in situ* on built heritage. This has made bioreceptivity in practical terms a laboratory concept, which has allowed only partial investigation because many colonising organisms which are hard to cultivate in laboratory conditions (such as lichens) have not been used. Also, in the studies conducted in controlled laboratory conditions the dynamism of bioreceptivity has been ignored, because primary, secondary or tertiary bioreceptivity have been studied in isolation. Although laboratory experiments could be designed to run for long enough to investigate primary and secondary bioreceptivity, better techniques need to be found to monitor the changing material properties during such experiments. A suite of non-destructive techniques (such as photogrammetry and laser scanning, portable hardness testing and moisture measurement devices) is now available which could provide such information in both long-term laboratory experiments and field-based exposure trials.

Furthermore, the roles of both intrinsic (material properties) and extrinsic factors (e.g. microclimate, surrounding vegetation, architectural geometry, substances deposited but not integrated into the material) in the bioreceptivity of a material under laboratory conditions need to be assessed. While intrinsic properties are usually well-studied in laboratory experiments (e.g., Prieto and Silva, 2005; Vázquez-Nion et al., 2018a), extrinsic factors are rarely considered. Over time there is likely to be a changing balance between the relative important of intrinsic and extrinsic factors in controlling colonisation and determining bioreceptivity. Carefully designed laboratory experiments are needed to investigate the longer-term evolution of bioreceptivity. Well-designed field experiments are also required because many extrinsic factors cannot easily be simulated under laboratory conditions, and environmental conditions in the field may mask, or complicate, the bioreceptivity of the materials themselves (Barberousse et a., 2006; Manso et al., 2015).

In conclusion, the concept of bioreceptivity still has much to offer to scientists involved in understanding and management of the ecology of built heritage 25 years after it was first proposed. Along with biological and environmental factors, it forms a trio of factors controlling colonisation of building surfaces, which in turn controls biodeteriorative, and bioprotective processes. The factors influencing colonisation are undoubtedly complex, but having a clearer understanding of concepts such as bioreceptivity helps to break the problem down into simpler component parts. Bibliometric analysis has shown that research on bioreceptivity over the past 25 years has been predominantly laboratory based and focused on primary bioreceptivity of building stones. This paper proposes some improvements and clarifications to the conceptual framework of Guillitte (summarised in Table 1), explores the parallels with ecological succession, and extends bioreceptivity to consider built heritage within submerged and subsoil environments. It also points out the need for additional well-designed field experiments to add to the valuable insights derived from laboratory studies and more fully explore the dynamic bioreceptivity of real building surfaces.

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Abstract

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

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

1. Introduction

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

The colonisation of building materials is a complex process as it is dynamic in time and space due to the interrelationships among the colonising organisms, as well as between their populations, the inorganic substrate and the surrounding heterogeneous environment. In fact, biological colonisation patterns on built heritage are not constant, but periodic and are very likely to change quickly as a result of different climate conditions, in particular alterations in temperature and precipitation (Macedo et al., 2009), as well as environmental chemical contaminants in polluted air and precipitation (Schiavon, 2002). It is important to emphasise that the potential of the material to be colonised by living organisms - its bioreceptivity - (Guillitte, 1995), is also dynamic as the chemical and physical characteristics of the substrate change over time as a result of exposure to weather and pollution conditions.

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

2. Revisiting bioreceptivity

2.1 Guillitte's ideas on bioreceptivity

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

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

Why did Guillitte coin the term ‘bioreceptivity’ rather than ‘biosusceptibility’? Guillitte (1995) reviewed the term ‘susceptibility’ and its definition in the field of medicine and veterinary medicine, and used it as an analogy for his new concept in building ecology. In a footnote to his work, Guillitte explains that he opts for ‘receptivity’ instead of 'susceptibility' based on the parallel with the biological concept ‘receptivity’ in English defined as 'the ability of a flower stigma to be fertilised by pollen grains through the pollen tube', and because the former translates in the same way into different languages. Hence he writes ‘we suggest using the word ‘bioreceptivite’ in French, ‘Biorezeptivitlt’ in German, ‘bioreceptiviteit’ in Dutch, ‘bioreceptividad’ in Spanish, ‘bioreceptividade’ in Portuguese and ‘biorecettivith’ in Italian’ (Guillitte, 1995). Nevertheless, some papers published later have used the terms susceptibility to biological colonisation (Marques et al., 2015), biosusceptibility (Sterflinger et al., 2013), and biosusceptibility (Gu et al., 1998) to refer to the bioreceptivity of a material.

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

2.2 Other linked concepts

In contrast to bioreceptivity, the concept of biodeterioration has been around for much longer and applied to a much wider range of materials and circumstances. The most consolidated and widespread definition of biodeterioration is that offered by Hueck in 1965 as ‘any undesirable change in the properties of a material caused by the vital activities of organisms’ (Hueck, 1965, p. 7). Biodeterioration can be classified into three categories: (i) physical or mechanical, (ii) chemical and (iii) aesthetic. The latter is limited to the visual effects of the presence of microorganisms and their products that alter the chromatic appearance. It seems that Guillitte did not consider this third category to be a form of deterioration, at least in the case of organisms growing on building materials. Indeed, he claimed that ‘some authors consider the colour changes to be aesthetically pleasing, credit them with a protective role against man- or weather-induced aggression and suggest that they have a cleansing effect which benefits the environment' (Guillitte, 1995). Such claims remain controversial. As Kumar and Kumar (1999) reported, climbing plants have long been considered to enhance the aesthetic value of built heritage such as ruins, as in some cases can the occurrence of algae and lichens (Martines, 1983). In several cases, the negligible (Gulotta et al., 2018; Sanmartín et al., 2020) or bioprotective (Ramírez et al., 2010; Cutler et al., 2013) role of pioneer algae and cyanobacteria (a phenomenon often referred to as "greening", the first step in the sequential process of colonisation) on the physical integrity of stone has been proven, aside from the ability of algae to sequestrate CO_2 from atmospheric air (Prajapati et al., 2013). However, at present, it is frequently considered preferable to eliminate any kind of colonisation from building surfaces for reasons of preventive conservation and to create an impression of order, cleanliness and care of the structure or construction.

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

2.3 Bibliometric analysis of 25 years of bioreceptivity publications

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

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

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

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

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

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

After ‘biodeterioration’, the predominance of the keywords ‘algae’ and ‘cyanobacteria’ is explained as phototrophic microorganisms are pioneer colonisers of inorganic materials, such as stone, and are the most commonly used microorganisms in laboratory-based bioreceptivity experiments (Miller et al., 2012). In addition, 'fungi' and 'lichens' also have a high co-occurrence in bioreceptivity-related articles. Worth mentioning is the predominance of keywords related to the materials covered in bioreceptivity-related publications, such as 'stone', 'rocks', 'limestone', 'concrete' and 'mortar', as well as 'cultural-heritage', 'conservation' and 'monuments', which demonstrate that the term bioreceptivity is widely used in the field of built cultural heritage (Fig. 2). According to our bibliometric survey of research into bioreceptivity, stone is the most studied material and the focus of the most cited articles (Fig. 3). In contrast, few studies have been performed on the bioreceptivity of concrete, mortars, tiles, bricks, glass or plastic, compared with stone. Most of the case studies on bioreceptivity shown in Figure 3 rely on in-vitro (lab based) tests. In fact, the majority of papers was focused on primary bioreceptivity (Fig. 4) which has been almost exclusively studied under laboratory conditions (e.g. Prieto and Silva, 2005; Miller et al., 2008, 2010; Vázquez-Nion et al., 2018a).

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

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

3. Reanalysing bioreceptivity

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

When a material has not yet been exposed to colonisation and as long as its properties remain unchanged, bioreceptivity is defined as primary according to Guillitte, whilst when the material properties change it becomes secondary. Guillitte (1995) wrote: 'For practical purposes, secondary bioreceptivity is often more important than primary bioreceptivity'. This is especially true when we refer to built cultural heritage, whose materials have been exposed to weathering for long periods. However, as the current authors demonstrate in section 2.3, secondary bioreceptivity has hardly been studied, with the bulk of research focusing on primary bioreceptivity which probably is more useful in the architectural field for looking at ‘new build’. There are several reasons that could explain why this has been true for 25 years. For example, it is not clear when the changes in material properties become significant for potential colonizers (breakpoint), and what criteria should be used to determine that breakpoint. How much must a given material be changed (physically and/or chemically) in order for its bioreceptivity to be defined as secondary? If, as Guillitte believed, the transition from primary to secondary bioreceptivity occurs as a result of both the activity of living organisms and abiotic processes, together or separately, then it is very difficult for researchers to produce realistic artificially weathered specimens in the laboratory on which to investigate secondary bioreceptivity (Papida et al., 2000; Vázquez-Nion et al., 2018b)? Are field-based studies needed? There is also the issue that most natural building materials have already undergone change through weathering (for example on a quarry face) even before they are placed in a building (Silva et al., 1997), and so it is unclear whether bioreceptivity in such cases should be classified as primary or secondary.

Guillitte’s concept of bioreceptivity is largely focused on the influence of small scale (mm to cm scale) factors intrinsic to different building materials. These are amenable to study in laboratory experiments and are the most obvious intrinsic factors to consider. However, once a material is exposed within a building façade or structure, other larger scale (cm to m) factors may have very important influences on bioreceptivity (Viles and Ahmad, 2016). For example, a stone type used in architectural detailing such as balusters and string courses may have very different bioreceptivities within those two contexts, because of the influence of surface angle (in relation to vertical), aspect, and position on the building which i) exert important controls on water and thermal regimes and ii) modify primary bioreceptivity through weathering in different ways giving rise to different secondary bioreceptivity. In many ways, these larger scale influences can be seen as larger scale surface roughness (where the roughness applies to whole areas of masonry, facades or indeed an entire building). The potential importance of these larger scale factors can best be studied by well-designed field experiments. One of the remaining challenges about larger scale factors is to determine whether they are intrinsic or extrinsic in nature.

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

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

Furthermore, the diversity was wide, although filamentous cyanobacteria and at lesser extent some species of algae (*Anabaena* and *Oscillatoria*) were the most abundant.

One missing point from Guillitte's ideas is how to express and quantify bioreceptivity. In the first experiment specifically designed to evaluate bioreceptivity, Guillitte and Dreesen (1995) characterised the bioreceptivity of two natural stone types and three manufactured materials by quantifying the vegetal cover after 9 months of exposure to sprinkling with a nutrient-rich tap water containing a mixture of pioneer colonising plant diaspores. Percentage cover has been used to express bioreceptivity in subsequent experiments (Tomaselli et al., 2000, Miller et al., 2006, Escadeillas et al., 2007) allowing comparison between samples in the same experiment but not comparison between different experiments. The main problem derived from using % cover is that once 100% cover is reached the subsequent increase in colonization related to bioreceptivity cannot be quantified. Moreover, colonization in depth is not taken into account. To overcome these problems, the amount of chlorophyll *a* /surface unit has been used by other authors to express bioreceptivity (Prieto and Silva, 2005; Prieto et al., 2006). This way of expressing bioreceptivity allows comparison not only between samples but also between experiments, but has the disadvantage that it can only be used for phototrophs. Moreover, Guillitte did not establish how to unambiguously define and categorise the bioreceptivity of a material, although he pointed the need to remove any subjectivity attached to the concept and proposed developing a bioreceptivity index. Nowadays, this index has been developed but only for granitic rocks (Vázquez-Nion et al., 2018c).

3.2 Types of bioreceptivity on built heritage

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

Although the addition of a new term (‘quaternary bioreceptivity’) could be seen as controversial and adding to complexity, we believe that it has practical benefits for the use of bioreceptivity for understanding the deterioration of built heritage in highlighting different ways in which humans can affect the situation, in a way that is distinctive to the changes involved in secondary bioreceptivity. Furthermore, the concept of ‘quaternary bioreceptivity’ reduces complexity by replacing the terms, also defined by Guillitte but rarely used, of intrinsic, semi-extrinsic and extrinsic bioreceptivity. Guillitte (1995) defined intrinsic bioreceptivity as occurring 'when colonisation depends mainly on the properties of the material, irrespective of exogenous contributions’'. Many researchers consider ‘intrinsic’ and ‘primary’ bioreceptivity as synonymous, probably because they see both natural weathering and human activities as exogenous contributions. We instead consider that Guillitte viewed exogenous contributions in a more narrow sense as additions to the material such as particles, organisms and substances. In this interpretation, all three types of bioreceptivity of a fresh, weathered and cleaned stony material, i.e. primary, secondary and tertiary bioreceptivity, may be seen as ‘intrinsic bioreceptivity’. It reinforces this idea that by ‘semi-extrinsic bioreceptivity’ Guillitte (1995) refers to situations when ‘colonisation depends directly and simultaneously on the properties of the material and on the deposits of exogenous substances', where he used the term ‘deposit’ to refer to the exogenous contribution. For us, ‘semi-extrinsic bioreceptivity’ would in some cases correspond to what we have called ‘quaternary bioreceptivity’. An extreme case of ‘quaternary bioreceptivity’, where only the bioreceptivity of the added exogenous material is of interest is what Guillitte (1995) called ‘extrinsic bioreceptivity’. We propose that intrinsic, extrinsic and semi-extrinsic bioreceptivity terms be dropped, and instead encourage the use of ‘intrinsic factors’ and ‘extrinsic factors’ related to the bioreceptivity of a material. Thus, roughness, porosity, mineralogical composition and colour of a material, for instance, will be intrinsic factors related to bioreceptivity; while architectural factors, micro-temperature and micro-humidity on the material surface, and added materials (such as dead biomass, living organisms, dust, guano) are extrinsic factors related to bioreceptivity (Table 1).

Figure 5 provides a visualization of how our conceptualisation of bioreceptivity builds on that of Guillitte (1995). The blue dashed arrows in figure 5 portray the ecological dynamism involved as material conditions change within the different categories (primary, secondary, tertiary and quaternary) and also as the situation switches from primary to secondary types. In the case of primary bioreceptivity, the communities should be dominated by fast-growing and well-dispersed species while in secondary bioreceptivity, these species will tend to be replaced by more competitive species which may have differing impacts on biodeterioration. Furthermore, in the case of tertiary bioreceptivity, changes in the ecological community should occur faster. This has been observed in several studies of tertiary bioreceptivity, where recolonisation after cleaning occurs quicker than during the primary bioreceptivity phase (Sohrabi et al., 2017). The same has been reported for the proposed new category of quaternary bioreceptivity, where added materials such as consolidants and other surface treatments may become a new habitat for colonisers. Several studies note that these new habitats are more bioreceptive than the original stony material (Bracci et al., 2002; Cappitelli et al., 2007). For example, in the Catacombs of Domitilla (Rome, Italy), a biocide treatment composed of quaternary ammonium compounds and octylisothiazolone sparked the proliferation of bacteria with high hydrolytic enzymatic activity (Urzì et al., 2016). In Campeche (Mexico), restored mortars composed of fatty acid promoted an early endolithic phototrophic colonization by cyanobacteria and bryophyte on the facade of San Roque church (Jurado and Miller et al., 2014). Surface treatments such as consolidants may also alter the physical properties of stony materials like the wetting-drying kinetics, leading to the material remaining damp for longer and hence its bioreceptivity increasing (Prieto et al., 2014). In future, an interesting area of research would be to explore these ecological dynamics in more detail and elucidate how communities of organisms living on built heritage change in tandem with the material changes. This could involve linking bioreceptivity to concepts of ecological succession.

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

3.3 Bioreceptivity of subaerial, submerged and subsoil built heritage

While the concept of biodeterioration is considered in subaerial, submerged and subsoil environments, bioreceptivity is currently only explicitly considered in the former despite buildings possessing subsoil foundations and being affected by periodic flooding, as well as many archaeological sites being buried or immersed. However, this is only a conceptual issue because many studies have focused on how biodeterioration develops differently according to the type of material and how the intrinsic characteristics of a material affect its biocolonisation in submerged (mainly marine) and subsoil environments. For example, a comparative study of bioreceptivity between different building materials (marbles, limestones, ignimbrites, and bricks), similar to that of Guillitte and Dreesen (1995), but in a Mediterranean marine environment was carried out by Aloise et al. (2014) although they do not explicitly use the term bioreceptivity. Marble and limestone samples collected from the cities of Baiae and Portus Iulius (Naples, Italy), submerged since the 4th century AD, showed intense colonisation (high bioreceptivity) mainly by boring sponges, while ignimbrites in the same place presented a lower biological attack caused by serpulids and bryozoans. In bricks, paste with volcanic aggregates was less bioreceptive, showing a greater resistance to biological colonisation, than that with quartz (Aloise et al., 2014). As is clear, different species were found on different substrates as a function of their composition. Similarly, differences in material colour have been shown to impact the short-term development of marine biofouling communities, influencing larval settlement and colonisation of invertebrates and algae (Dahlem et al., 1984; Satheesh and Wesley, 2010), and especially barnacles (Pomerat and Reiner, 1942; Kon-ya and Miki, 1994; Robson et al., 2009; Prendergast, 2010). Most studies in this field have only tested black and white or grayscale substrates, thus showing only whether different responses arise due to the luminosity or lightness/darkness (Callow and Callow, 2000; Swain et al., 2006; Dobretsov et al., 2013; Cao et al., 2013). Other studies, instead, have also considered chroma and hue (Guenther et al., 2009; Ells et al., 2016; Li et al., 2017). Chroma (or saturation) is related to the intensity of colour, while hue, which refers to the dominant wavelength and represents redness, yellowness, greenness, blueness, etc., has been shown in perception studies to be the most important colour parameter (Berns, 2000; Prieto et al., 2018). Settlement of mussel *Mytilus coruscus* plantigrades was found to differ according to substrate colour (red, orange, blue, white, yellow and green) and was lowest on the biofilms formed on green surfaces, possibly because of a variation in the establishment of the underlying biofilm community (Li et al., 2017). In contrast, the hydroid *Ectopleura larynx* settled preferentially on black vs white substrates, whereas there were no significant differences between the remaining tested colours (yellow, red and blue; Guenther et al., 2009). These two examples show how differently various organisms respond to surface colour and highlight the need to investigate this response systematically.

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

3.4 Bioreceptivity and building-scale factors

Because most bioreceptivity studies have been carried out in controlled, laboratory conditions, there is a need for further investigation of the larger-scale factors influencing colonisation dynamics on real buildings and its relationship with bioreceptivity. As long as bioreceptivity of a material is defined by 'the totality of material properties that contribute to the establishment, anchorage and development of fauna and/or flora' those properties can be different for the same material depending on its position on the building. Introducing larger-scale factors to bioreceptivity brings complications, as it becomes hard to separate out intrinsic from extrinsic factors. Further research is needed to explore the influence of building-scale factors on bioreceptivity, colonization and biodeterioration.

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

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

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

4. Final considerations, conclusions and prospects

Over the last 25 years, few studies have been carried out on bioreceptivity on materials *in situ* on built heritage. This has made bioreceptivity in practical terms a laboratory concept, which has allowed only partial investigation because many colonising organisms which are hard to cultivate in laboratory conditions (such as lichens) have not been used. Also, in the studies conducted in controlled laboratory conditions the dynamism of bioreceptivity has been ignored, because primary, secondary or tertiary bioreceptivity have been studied in isolation. Although laboratory experiments could be designed to run for long enough to investigate primary and secondary bioreceptivity, better techniques need to be found to monitor the changing material properties during such experiments. A suite of non-destructive techniques (such as photogrammetry and laser scanning, portable hardness testing and moisture measurement devices) is now available which could provide such information in both long-term laboratory experiments and field-based exposure trials.

Furthermore, the roles of both intrinsic (material properties) and extrinsic factors (e.g. microclimate, surrounding vegetation, architectural geometry, substances deposited but not integrated into the material) in the bioreceptivity of a material under laboratory conditions need to be assessed. While intrinsic properties are usually well-studied in laboratory experiments (e.g., Prieto and Silva, 2005; Vázquez-Nion et al., 2018a), extrinsic factors are rarely considered. Over time there is likely to be a changing balance between the relative important of intrinsic and extrinsic factors in controlling colonisation and determining bioreceptivity. Carefully designed laboratory experiments are needed to investigate the longer-term evolution of bioreceptivity. Well-designed field experiments are also required because many extrinsic factors cannot easily be simulated under laboratory conditions, and environmental conditions in the field may mask, or complicate, the bioreceptivity of the materials themselves (Barberousse et a., 2006; Manso et al., 2015).

In conclusion, the concept of bioreceptivity still has much to offer to scientists involved in understanding and management of the ecology of built heritage 25 years after it was first proposed. Along with biological and environmental factors, it forms a trio of factors controlling colonisation of building surfaces, which in turn controls biodeteriorative, and bioprotective processes. The factors influencing colonisation are undoubtedly complex, but having a clearer understanding of concepts such as bioreceptivity helps to break the problem down into simpler component parts. Bibliometric analysis has shown that research on bioreceptivity over the past 25 years has been predominantly laboratory based and focused on primary bioreceptivity of building stones. This paper proposes some improvements and clarifications to the conceptual framework of Guillitte (summarised in Table 1), explores the parallels with ecological succession, and extends bioreceptivity to consider built heritage within submerged and subsoil environments. It also points out the need for additional well-designed field experiments to add to the valuable insights derived from laboratory studies and more fully explore the dynamic bioreceptivity of real building surfaces.

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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 Larger or building-scale factors
Extrinsic	Extrinsic factors**	Extrinsic bioreceptivity dropped, replaced by extrinsic factors	Surface deposits such as oil, dust, organic particulates, pollutants, guano, and also dead biomass and living organisms*** Locational characteristics such as angle of surface, aspect, height above ground (factors which affect moisture and thermal regimes) Larger or building-scale factors
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

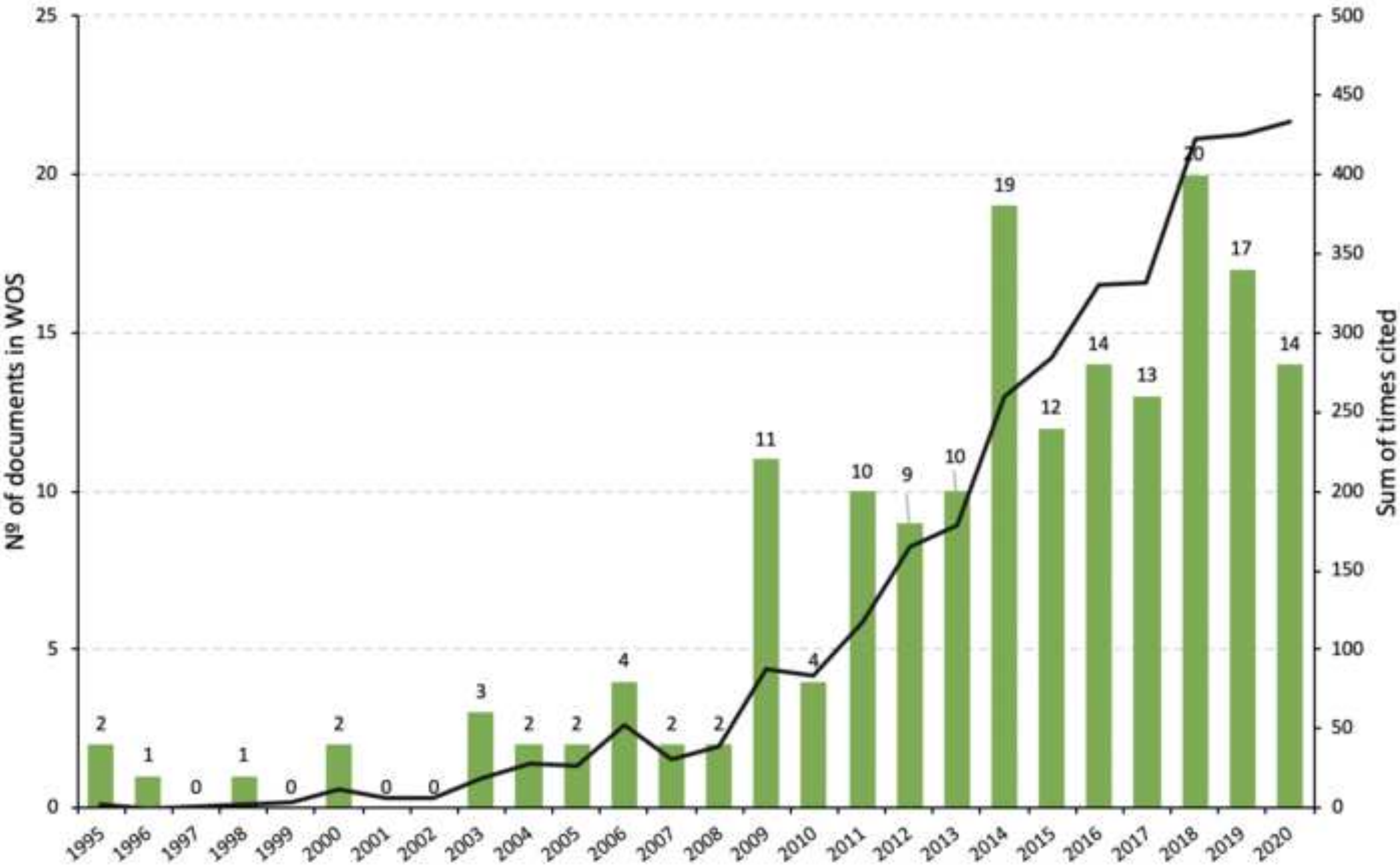
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Figure 2

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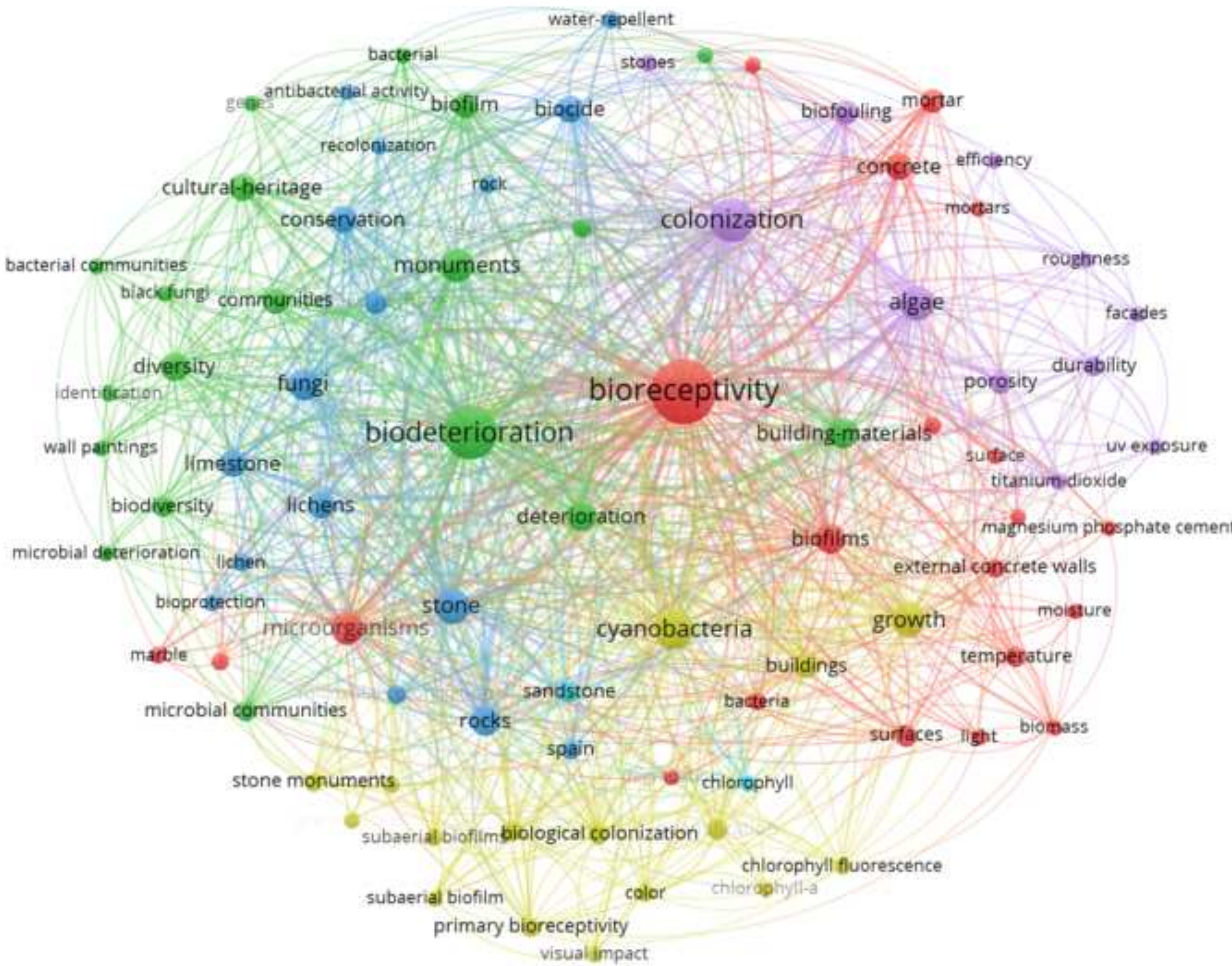

Figure 3

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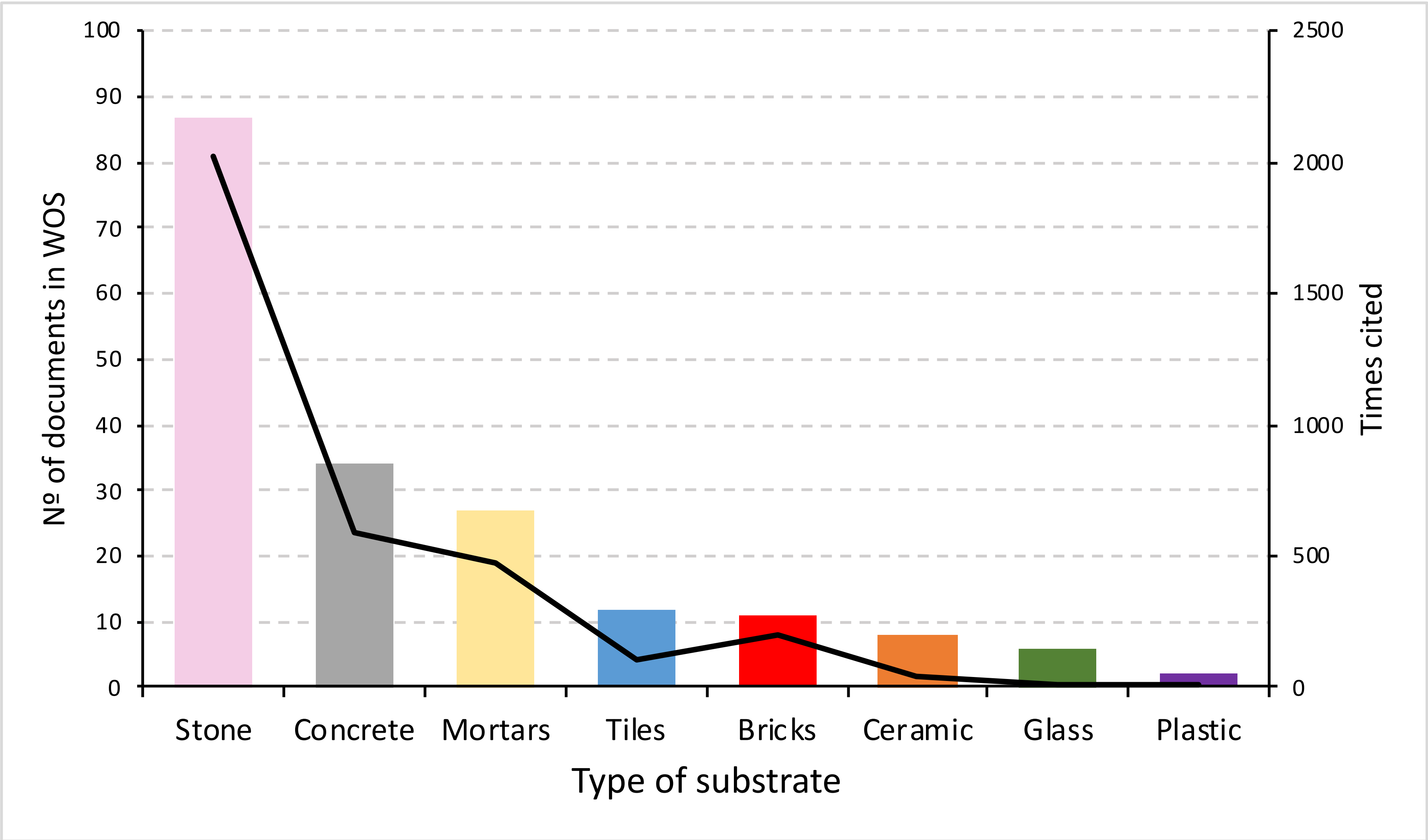
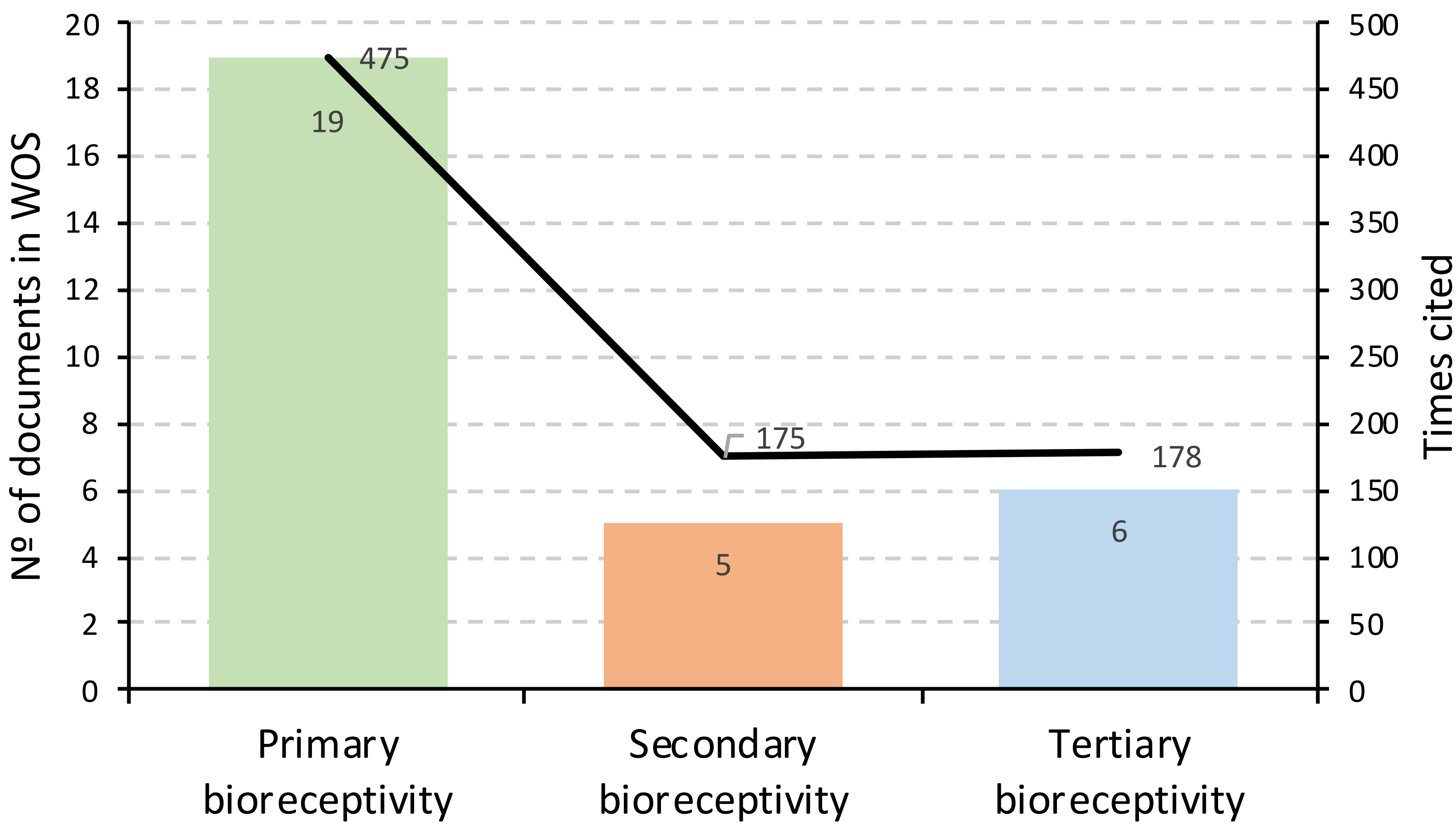


Figure 4



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Primary bioreceptivity
Secondary bioreceptivity
Tertiary bioreceptivity

Figure 5

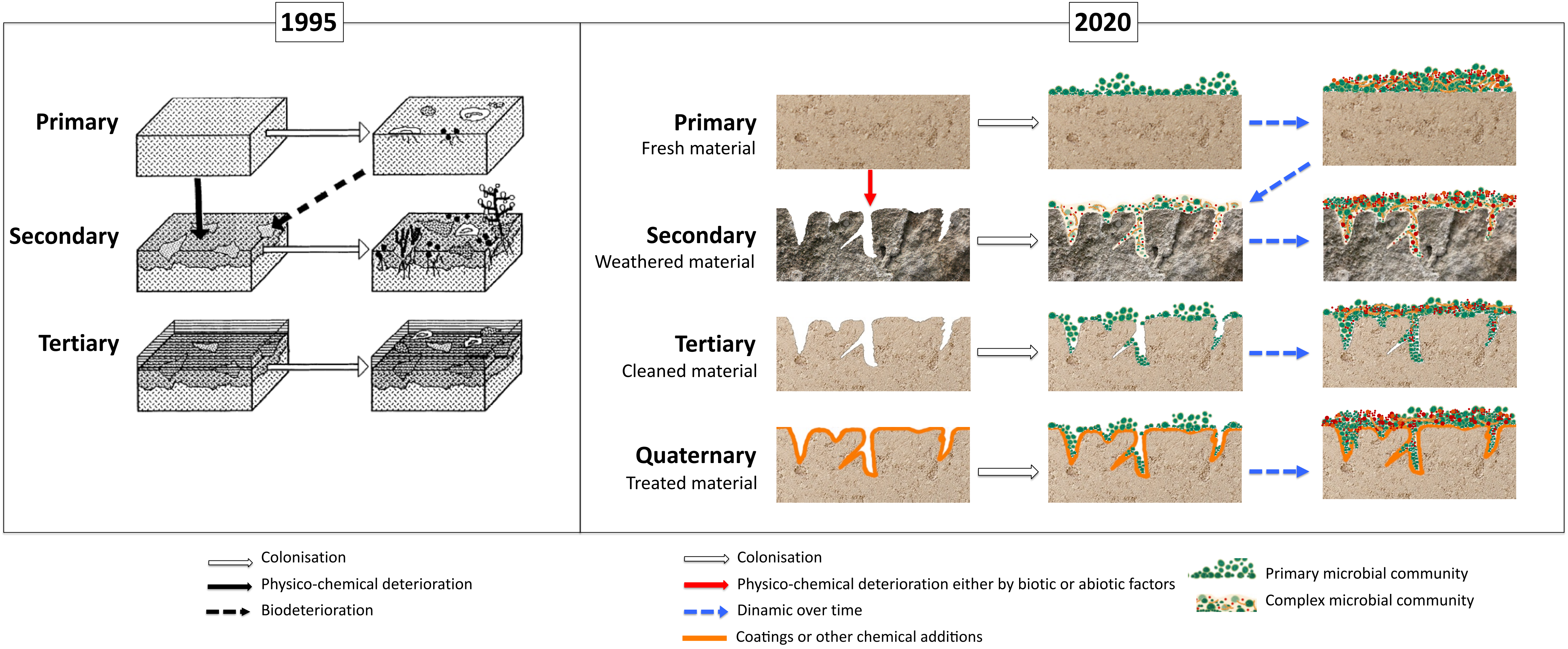
1995
2020
Primary
Secondary
Tertiary
Primary
Fresh material
Secondary
Weathered material
Tertiary
Cleaned material
Quaternary
Treated material
Colonisation
Physico-chemical deterioration
Biodeterioration
Colonisation
Physico-chemical deterioration either by biotic or abiotic factors
Dinamic over time
Coatings or other chemical additions
Primary microbial community
Complex microbial community

Figure 6

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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

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