Moss on Rocks: Evaluating biodeterioration and bioprotection of bryophytic growth on stone masonry

Katherine Jang

Wolfson College
University of Oxford

A thesis submitted for the degree of Doctor of Philosophy

Michaelmas Term 2020

Abstract

Lower plants and organisms growing on cultural heritage sites have been identified as key sources of biodeterioration and degradation of the underlying substrates. Within this field, bryophytes (mosses) have been relatively under-researched and the effects of their growth on heritage sites is comparatively unknown.

The main aim of this thesis is to characterize the impacts of moss growth on historic limestone masonry, and to determine if their presence on built structures can be categorized as having either an overall bioprotective or biodeteriorative effect on built structures. This thesis addresses the objectives and three primary research questions related to the perceptions of moss growth, visualizing the moss-lithobiontic interface, and moss impacts on moisture regimes using a mixed-methods approach involving field and lab analyses. To address the first objective, it provides a qualitative exploratory survey of built heritage experts and visitors about their perceptions of moss growth on cultural heritage. To address the second objective, the thesis develops a workflow to visualize the impacts of moss on limestone. To address the third objective the thesis uses a range of field and lab-based analyses to investigate the impacts of moss on water regimes on limestone and mortar surfaces. It uses both weathered laboratory samples of limestone and in-situ limestone walls and cementitious mortar to evaluate moss impacts under a range of conditions.

The project is based on research at several built heritage sites in Oxfordshire, England, including the UNESCO World Heritage site Blenheim Palace, Kelmscott Manor, and Oxford Botanic Gardens. It investigates the of impact one of the world's most common mosses, *Brachythecium rutabulum* on a variety of wall structures at these built heritage sites, and on some experimental limestone blocks with known colonisation histories.

Key findings from this project uncover both aesthetic and tangible impacts of moss colonisation on built heritage. Findings from the survey showed that both visitors and built heritage experts like the aesthetic qualities of mosses on historic stonework, and feel that removal of moss should only occur if clear biodeteriorative impacts are found. The survey also highlighted the need for further research on how mosses affect the underlying materials. The thesis also explored a possible workflow method for utilizing weathered samples from cultural heritage sites, and found visual evidence of mosses acting as secondary colonisers within lichen perithecial pits. Key scientific findings from this project are that mosses play a role in increasing both surface and subsurface water absorption and uptake, and that removing mosses from weathered surfaces may be more damaging than leaving them in-situ. Additional findings are that mosses may play a role in 'shielding' underlying substrates from light rainfall events. The evaluated findings show initial evidence that in most cases, moss growth is not an indicator of serious damage, and in some cases is neutral or even protective.

The research project has contributed to advancing the knowledge of moss impacts on cultural heritage, and in creating a set of methods and protocols for investigating the moss-rock interface. The findings also have implications for conservation decisions regarding the cleaning and maintenance of mosses on cultural heritage.

Moss on Rocks: Evaluating biodeterioration and bioprotection of bryophytic growth on stone masonry



Katherine Jang

Wolfson College

University of Oxford

A thesis submitted for the degree of

Doctor of Philosophy

Michaelmas Term 2020

Acknowledgements

Personal

This work could not have been completed without the support and help from my friends, family, and colleagues. I would like to specifically mention my colleagues from the School of Geography and the Environment and the Geolabs. To Dr Mona Edwards and Hong Zhang, without your guidance I would have never figured out the best way to 'snake' the sealant for Karsten tubes!

To my friends and family, thank you so much for your support and love throughout these long four years. My parents, Calvin and Esther, and brother Chris always kept me in good spirits from across the pond. To my partner Charlie, I owe a great debt for your amazing patience and constant 'tealiveries.' I can't imagine making this DPhil journey alone, so I thank you for being with me every step of the way.

Finally, I would be remiss without expressing deep gratitude to my supervisor Professor Heather Viles. Thank you for your guidance and gentle nudges throughout these four years. I can say unequivocally that your input and advice has given me more confidence both personally and as a scientist.

THANK YOU ALL!

Institutional

I would also like to thank the Centre for Doctoral Training in Science and Engineering in Arts, Heritage and Archaeology (SEAHA CDT) for providing the Research Training and Support Grant which helped make this project possible. Additional thanks goes to my SEAHA industry sponsors and partners, Amanda Potts and Trevor Proudfoot (d. 2019) at Cliveden Conservation. Acknowledgement for financial support also goes to Wolfson College, the School of Geography and the Environment, and the British Bryological Society.

Many thanks to Dr Julie Eklund, for giving me permission to use her samples from a previous research project. These samples and her input on biological growth were invaluable to this research project.

I am also grateful to Kelmscott Manor, Blenheim Palace, and Oxford Botanic Gardens for their permission to use their sites and for assistance during site visits.

Abstract

Lower plants and organisms growing on cultural heritage sites have been identified as key sources of biodeterioration and degradation of the underlying substrates. Within this field, bryophytes (mosses) have been relatively under-researched and the effects of their growth on heritage sites is comparatively unknown.

The main aim of this thesis is to characterize the impacts of moss growth on historic limestone masonry, and to determine if their presence on built structures can be categorized as having either an overall bioprotective or biodeteriorative effect on built structures. This thesis addresses the objectives and three primary research questions related to the perceptions of moss growth, visualizing the moss-lithobiontic interface, and moss impacts on moisture regimes using a mixed-methods approach involving field and lab analyses. To address the first objective, it provides a qualitative exploratory survey of built heritage experts and visitors about their perceptions of moss growth on cultural heritage. To address the second objective, the thesis develops a workflow to visualize the impacts of moss on limestone. To address the third objective the thesis uses a range of field and lab-based analyses to investigate the impacts of moss on water regimes on limestone and mortar surfaces. It uses both weathered laboratory samples of limestone and in-situ limestone walls and cementitious mortar to evaluate moss impacts under a range of conditions.

The project is based on research at several built heritage sites in Oxfordshire, England, including the UNESCO World Heritage site Blenheim Palace, Kelmscott Manor, and Oxford Botanic Gardens. It investigates the of impact one of the world's most common mosses, *Brachythecium rutabulum* on a variety of wall structures at these built heritage sites, and on some experimental limestone blocks with known colonisation histories.

Key findings from this project uncover both aesthetic and tangible impacts of moss colonisation on built heritage. Findings from the survey showed that both visitors and built heritage experts like the aesthetic qualities of mosses on historic stonework, and feel that removal of moss should only occur if clear biodeteriorative impacts are found. The survey also highlighted the need for further research on how mosses affect the underlying materials. The thesis also explored a possible workflow method for utilizing weathered samples from cultural heritage sites, and found visual evidence of mosses acting as secondary colonisers within lichen perithecial pits.

Key scientific findings from this project are that mosses play a role in increasing both surface and subsurface water absorption and uptake, and that removing mosses from weathered surfaces may be more damaging than leaving them in-situ. Additional findings are that mosses may play a role in 'shielding' underlying substrates from light rainfall events. The evaluated findings show initial evidence that in most cases, moss growth is not an indicator of serious damage, and in some cases is neutral or even protective.

The research project has contributed to advancing the knowledge of moss impacts on cultural heritage, and in creating a set of methods and protocols for investigating the moss-rock interface. The findings also have implications for conservation decisions regarding the cleaning and maintenance of mosses on cultural heritage.

Contents

List of Figures **xi**

List of Tables **xiii**

Glossary **xv**

1 Introduction **1**
1.1 Motivation 1
1.2 Contribution 3
1.3 Structure of thesis and acknowledgement of SEAHA CDT 5

2 Background **9**
2.1 Defining the lithobiontic interface 10
2.2 Bioreceptivity, bioprotection and biodeterioration 11
2.3 Why bryophytes? 14
2.3.1 Endangered species 16
2.3.2 *Brachythecium rutabulum* 16
2.3.3 *Grimmia pulvinata* 17
2.4 How do we define 'impact'? 17
2.5 Stakeholders 19
2.6 Sites 19
2.6.1 Wytham Woods, Oxfordshire 20
2.6.2 Blenheim Palace, Oxfordshire 21
2.6.3 Kelmscott Manor, Oxfordshire 22
2.6.4 Oxford Botanic Gardens, Oxfordshire 23
2.6.5 Chipping Norton, Oxfordshire 24
2.6.6 Choice of sites 25
2.6.7 Methodology 26

3 Perceptions **27**
3.1 Perceptions of moss growth on historic buildings: Similarities and differences in opinion between public and experts and the implications for heritage conservation 28

3.2 Abstract . . . 28
3.3 Introduction . . . 28
3.4 Background . . . 31
3.5 Sites and People . . . 33
3.5.1 Visitor Survey . . . 33
3.5.2 Expert Opinion Survey . . . 35
3.6 Methods . . . 36
3.6.1 Questionnaire Format and Scope . . . 36
3.6.2 Data Analysis . . . 37
3.7 Results . . . 38
3.7.1 Participants' expertise in built heritage . . . 38
3.7.2 Participants as heritage visitors . . . 39
3.7.3 Participants' knowledge of moss . . . 40
3.7.4 Aesthetics of moss growth . . . 42
3.7.5 Perceptions of damage . . . 43
3.8 Discussion . . . 45
3.8.1 Further Questions . . . 46
3.9 Conclusions . . . 46
3.9.1 Key findings . . . 47
3.9.2 Implications for conservation . . . 47

4 Visualization & Workflow 49
4.1 Visualization workflow for analyzing moss impacts at the lithobiontic interface on limestone built heritage . . . 50
4.2 Abstract . . . 50
4.3 Introduction . . . 51
4.4 Materials and Methods . . . 57
4.4.1 Workflow . . . 57
4.4.2 Step 1 - Visual Assessment . . . 58
4.4.3 Step 2 - 3D Microscopy . . . 59
4.4.4 Step 3 - Optical Light Microscopy (OLM) . . . 60
4.4.5 Step 4 - Scanning Electron Microscopy (SEM) . . . 60
4.5 Results . . . 61
4.5.1 Step 1 Findings: Visual analysis/Condition assessment of sample blocks . . . 61
4.5.2 Step 2 Findings: Keyence 3D microscopy and profilometry . . . 63
4.5.3 Step 3 Findings: Optical light microscopy from polished thin sections of weathered sample limestone . . . 65

4.5.4 Step 4 Findings: SEM of cross-sections of weathered limestone 66
4.5.5 Evaluation of the proposed 4-Step workflow 71
4.6 Discussion 72
4.7 Conclusions 73

5 Moisture Regimes **75**
5.1 Moisture interactions between mosses and their underlying stone substrates 76
5.2 Abstract 76
5.3 Introduction 77
5.4 Aims and Objectives 81
5.5 Materials, Sites, and Methods 81
5.5.1 Materials 81
5.5.2 Sites 82
5.5.3 Methods 83
5.6 Results 86
5.6.1 How does aspect and microclimate influence moss growth: Kelmscott Manor temperature and relative humidity data . 86
5.6.2 How does moss growth influence microclimate fluctuations: Chipping Norton relative humidity and temperature data . 89
5.6.3 How does moss growth influence water uptake and evaporation rates: Mass data 92
5.6.4 Does moss growth influence water uptake at surface level: Protimeter data 93
5.6.5 Does moss growth influence water uptake at subsurface level: Karsten test data 94
5.7 Discussion 97
5.7.1 Limitations and scope of the project 97
5.7.2 Recommendations for further research 98
5.7.3 Relevance to built heritage management strategies 98
5.8 Conclusions 100

6 Discussion **103**
6.1 Structure of Discussion 103
6.2 How do built heritage experts and visitors view the presence of moss growth on historic buildings? 105
6.2.1 The three questions clearly identified as most in need of answering from both surveys are: 105
6.3 How can we visually characterize the deterioration and weathering processes of moss growth on limited samples of historic stone? . . . 107

6.4 How does moss growth affect moisture relations on stone substrates? 108
6.5 Typology of moss impacts 109
6.6 Can we characterize the impacts of moss growth on stone masonry: Bioprotection vs. Biodeterioration 112
6.7 Practical guidelines for treating moss 113
6.7.1 Ethics of doing nothing 115

7 Conclusions 117
7.1 Key findings 117
7.2 Lessons learned and opportunities for further research 119
7.3 Opportunities for further research 120

8 References 123

9 Appendices 143
9.1 A - Co-authors Statements 143
9.2 B - Survey Format 145

List of Figures

1.1 World map of bryophyte species richness 2
1.2 Thesis structure flowchart 6

2.1 Lithobiontic interface diagram 10
2.2 Distribution of Brachythecium rutabulum in Great Britain, GBIF . 16
2.3 OxRBL test site at Wytham Woods 20
2.4 Blenheim Palace exterior 21
2.5 Blenheim Palace boundary walls 22
2.6 Kelmscott Manor exterior 23
2.7 Oxford Botanic Gardens interior 24
2.8 St. Mary's Church, Chipping Norton, Oxfordshire exterior 25

3.1 Survey participants' self-reported built heritage experience 38
3.2 How often do survey participants visit historic buildings for leisure? 39
3.3 Collage of biological growth for survey identification 40
3.4 Survey participants' self-identified level of moss knowledge 41
3.5 Comparison between visitors and BH professionals, 'How do mosses affect the aesthetics of buildings?' 42
3.6 Comparison between visitors and BH professionals, whether mosses positively or negatively affect buildings 43
3.7 Comparison between visitors and BH professionals, how mosses specifically affect buildings. 44
3.8 Survey responses identifying further research questions 46

4.1 Diagram showing block sampling technique and workflow for analysing cross-sections of weathered material 58
4.2 Surface photographs of weathered blocks shown before surface clearing, at different percentages of moss coverage. 61
4.3 Surface topography mapping comparing freshly cut and weathered limestone surfaces 63
4.4 Comparison of polished thin cross-sections of weathered Jordan Basebed limestone samples at 40X magnification. 66

4.5 Direct and oblique angle SEM views of weathered limestone cross-sections . . . 67
4.6 SEM imaging showing bryophyte and lichen attachment mechanisms within stone matrix . . . 69
4.7 SEM imaging showing rhizoid disaggregation within stone matrix . 70

5.1 Acrocarpous and pleurocarpous moss morphology on a cementitious mortar capped wall at Kelmscott Manor, Lechlade UK. . . . 78
5.2 Known world distribution of Brachythecium rutabulum, GBIF . . . 79
5.3 Kelmscott Manor relative humidity microclimate monitoring (July-August 2019) . . . 87
5.4 Kelmscott Manor temperature microclimate monitoring (July-August 2019 . . . 88
5.5 Chipping Norton relative humidity microclimate monitoring (July-August 2019) . . . 90
5.6 Chipping Norton relative humidity microclimate monitoring (June-August 2019), showing moisture time lag . . . 91
5.7 Chipping Norton temperature microclimate monitoring (June-August 2019), no time lag . . . 91
5.8 Comparison of 4 test blocks with and without moss and their capacity to carry water. . . . 93
5.9 Surface moisture measurements on blocks with and without moss growth . . . 94
5.10 Karsten tube tests from field and lab showing water uptake from different substrate conditions . . . 95
5.11 Karsten tube tests on Chipping Norton limestone . . . 96
5.12 Karsten tube tests from field and lab showing water uptake from different materials . . . 97

6.1 Comparison of lichen and moss impacts . . . 113

List of Tables

2.1 Typology of moss impacts 18

4.1 Initial visual inspection results of moss coverage, biological growth (*B. rutabulum* (*B. rut*), black crustose lichen (BCL), green algae (GA)), and observed weathering on Jordan Basebed (JB) and Bowers Roach (BR) limestone 62
4.2 Keyence profilometry segment measurements, (Moss Weathered = MW, Lichen Weathered = LW, Lichen and Moss Weathered = LMW, Unweathered = U) where Δ Depth measures the difference between the lowest and highest points within 3.0 cm lengths across the surface 65
4.3 Average affected zonal depth findings for organic matter, data from SEM analysis 68

5.1 List of analyses, equipment and sites: How does moss growth influence moisture regimes? 83
5.2 Average daily range %RH Kelmscott Manor 87
5.3 Average daily temperature (°C) max, min, and range at Kelmscott Manor 88
5.4 Average daily range %RH comparing covered and uncovered iButtons 90
5.5 Average daily temperature (°C) max, min, and range at Chipping Norton, Covered vs Uncovered 91

6.1 Typology of moss impacts 110
6.2 Typology of moss impacts, revised 110

Glossary

Acrocarpous . . . . . One of the two growth forms of mosses. Described as circular, cushion-like, defined growths.

Algae . . . . . Informal term for a large group of photosynthetic eukaryotic organisms.

Biodeterioration . . . . Any undesirable change in the properties of a material caused by the action of biological agents such as fungi, beetle borers, termites, and marine borers.

Bioprotection . . . . . Role of biological agents in the protection of underlying materials (may be active or passive process).

Bryophyte . . . . . An informal group consisting of three divisions of non-vascular plants: liverworts, hornworts, and mosses. For the purposes of this research project, the terms bryophyte and moss will be used interchangeably.

Chelation . . . . . In relation to earth sciences, chelation refers to organic chelating agents that extract metal ions from rocks and minerals.

Cyanobacteria . . . . . Phylum of prokaryotes, they are photosynthetic bacteria that are generally blue-green in colour and found in aquatic environments.

Endolithic . . . . . Organism growing within or penetrating into the stone matrix.

Epilithic . . . . . Organism growing on the surface of stone.

Gametophyte . . . . . The sexual phase in the life cycle of plants and algae. In bryophytes, this is the most visible stage of the life cycle.

Hornwort . . . . . One of the smaller three divisions of the bryophyte group, also known as Anthocerotophyta.

Hypha . . . . . Filamentous structure of a fungus, oomycete, actinobacterium. In fungi, they comprise the main vegetative part of a fungus and are collectively referred to as a 'mycelium'.

Lichen . . . . . Composite organism that arises from algae or cyanobacteria and fungi. They are a non-vascular, slow-growing organism. Four primary growth forms; Fruticose, foliose, crustose, and leprose.

Lithobiont . . . . . Organism growing on or within a rock surface.

Lithobiontic interface . Zone in which lithobiontic organisms interact with the stone substrate.

Liverwort . . . . . One of the smaller three divisions of the bryophyte group, also known as Marchantiophyta.

Moss . . . . . Small, non-vascular plants from the division Bryophyta.

Perithecium . . . . . The spherical fruiting bodies of fungi and lichens.

Pleurocarpous . . . . . One of the two growth forms of mosses. Described as low-profile, carpeting, with amorphous edges.

Rhizoid . . . . . Filamentous or rootlike structures of bryophytes and algae.

Seta . . . . . Morphological structure of moss which refers to the stalk supporting the capsule (sporangium).

Sporangium . . . . . Enclosure in which spores are formed in plants, fungi, and mosses.

I am going to have a long talk with Bombadil; such a talk as I have not had in all my time. He is a moss-gatherer, and I have been a stone doomed to rolling. But my rolling days are ending, and now we shall have much to say to one another.

— J.R.R. Tolkien, *The Return of the King*

1 Introduction

Contents

1.1 Motivation 1
1.2 Contribution 3
1.3 Structure of thesis and acknowledgement of SEAHA CDT 5

1.1 Motivation

Mosses, also known as bryophytes, are a common sight on many historic buildings and sites, as well as in the natural environment. For some, the sight of moss on buildings or in the natural environment is so commonplace that it may be overlooked. For others, mosses conjure images of remote and idyllic landscapes, or are linked to deterioration and decay.

Mosses are ubiquitous organisms, found on all seven continents, even Antarctica, and survive in harsh environments that are not tolerated by vascular plants. Their prevalence in the natural environment is mirrored by their survival in the built environment, where they are found growing on rural sites such as monuments and ruins, as well as urban environments. The tenacious nature of mosses is such that

they are commonly found growing in cracks and crevices in pavements in urban environments and on well-traveled paths.

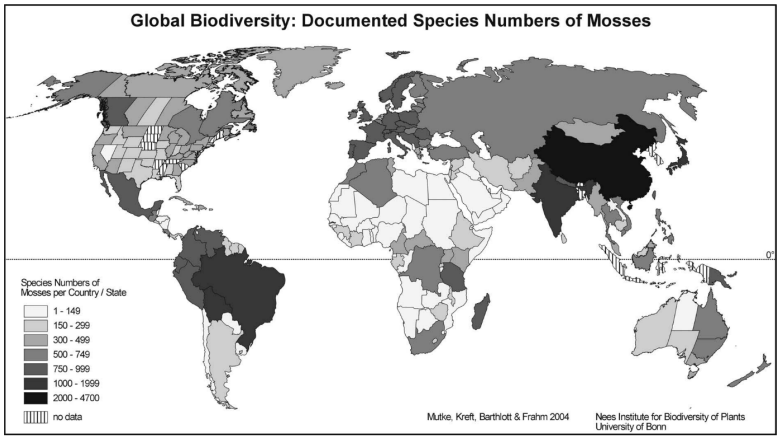


Figure 1.1: Mosses as documented in literature. Please note that total species numbers per country/state are given without referring to a standard area. Mutke and Barthlott 2007, p 529.

The widespread nature of mosses make them a particularly fascinating subject of study in the field of biogeomorphology, which studies the relationship and impact of plants and organisms on the processes of landscape formation. The field of biogeomophology and cultural heritage research investigates the impact of biological growth on the lifespan, deteriorioration, and protection of built heritage structures (Viles 2019). Within this field of research, several organisms are commonly cited as having a dominant effect on underlying substrates. These impacts, defined as generally positive or negative, include epilithic and endolithic organisms (Viles et al. 2008).

Research focused on biogeomorphology and cultural heritage has historically focused on organisms such as lichens, cyanobacteria and algae. This research project aims to investigate and characterise the impacts of moss growth on substrates to better understand the relationship between mosses and their environment.

The presence of biological growth on cultural heritage is a well-documented phenomenon, with primarily negative consequences for both the physical and chemical deterioration of built heritage materials, while also affecting the visual aesthetics (Bartoli 2014). The term biodeterioration describes the “physical or

chemical damage caused by biological agents on structural materials and occurs through the formation of biofilms" and can refer to multiple types of biological growths including vascular plants, lichens, fungi, bryophytes, algae, and cyanobacteria (Herrera et al. 2009, p. 75). In particular, impacts on moisture regimes are concerns when discussing moss colonisation (Garcia-Rowe and Saiz-Jimenez 1991). However, research has also uncovered possible benefits to biological colonisation such as protection from mechanical weathering (Chen et al. 2000). Despite research findings showing the possible benefits of biological growths on built heritage, it is still a commonly held belief that biological growths on cultural heritage negatively impact visual aesthetics, or are a visual indicator of underlying problems such as excess moisture (Garcia-Rowe and Saiz-Jimenez 1991). Biocides and mitigation strategies for biological greening have been studied, and are well- accepted as part of conservation management strategies for cultural heritage (Silva et al. 2017).

Previous research projects have mainly studied the lithobiontic interface of cultural heritage from the perspective of lichen growth (Garcia-Rowe and Saiz-Jimenez 1991; McIlroy de la Rosa et al. 2012). The biomechanical and biochemical mechanisms of weathering of lichen growth are well-researched and documented, however, there isn't the same depth of understanding for mosses. This is not to say that mosses are less prevalent or widespread as lichens, as they are listed as one of the primary forms of biological growth patterns on cultural heritage by ICOMOS, simply that this topic is under-researched (ICOMOS-ISCS 2008). This research project seeks to understand the process of biological colonisation of mosses on a deeper level, and to characterize the effects of their growth on cultural heritage. Taking the large amount of data and research into lichens into account, methods and standards for this research project have been appropriated from previous research studies on other types of biological growths including lichens (McIlroy de la Rosa et al. 2012).

1.2 Contribution

The overall aim of this research project is to provide a balanced assessment of the effects of bryophytic growth on cultural heritage sites in Britain, with a focus on

limestone and cementitious mortar in the natural and built environment. It will attempt to analyze the physical effects of rhizoid penetration on the substrate, and to quantify and typify the chemical and physical changes that the colonisation creates. The research will evaluate evidence for both biodeteriorative and bioprotective roles of bryophytes, using a combination of laboratory and field experiments and on-site monitoring.

The main aim of the thesis is to characterize the impacts of moss growth on stone masonry, and to determine if their presence on built structures can be categorized as having either an overall bioprotective or biodeteriorative effect on built structures. Along with investigations of a set of previously weathered limestone blocks, three primary case study sites have been carefully chosen to illustrate real-world effects of moss growth on historic buildings. In order to fulfill the main project aim, three primary research questions have been devised to address the different aspects of moss growth on stone built heritage.

The objectives and research questions posed by this project include:

1. How do built heritage experts and visitors view the presence of moss growth on historic buildings?

    - To examine the perceptions of moss growth on built heritage, identify the aesthetic impacts of moss growth, and identify gaps in knowledge, and examine how these opinions might inform future conservation policy and conservation management plans.

2. How can we visually characterize the deterioration and weathering processes of moss growth on limited samples of historic stone? Previous evaluations of biological growth at heritage sites noted that mosses were secondary colonisers which are more impactful than other types of biological growth in terms of deterioration (Morillas et al. 2019, p. 1380), and if confirmed may influence management strategies for cultural heritage sites.

    - To provide a workflow with complementary visual analyses which characterizes the physical impacts of moss growth.

3. How does moss growth affect moisture relations on stone substrates? As discussed earlier, moisture relations have been identified in previous research as a key concern of moss growth on cultural heritage (Garcia-Rowe and Saiz-Jimenez 1991).

    - To examine the difference in surface moisture, water absorption, and humidity fluctuations on areas with and without mosses.

To address these research questions, this project has been designed using a mixture of natural and social science methods to create an interdisciplinary project methodology. The project approaches these questions using both field and lab analyses, along with a desk-based analysis of the values framework regarding biological growth on cultural heritage. To do this, a range of cultural heritage sites in England have been identified that exemplify natural and cultural heritage values at the local, national, and international scale. These selected sites serve as field sites for non-destructive tests on stonework, microclimate monitoring experiments, and locations for the visitor opinion survey on mosses.

It is expected that the results of this research will benefit not only the cultural heritage sector, but also the wider built environment, and the natural environment in terms of geomorphology.

1.3 Structure of thesis and acknowledgement of SEAHA CDT

This thesis structure is structured using a three-paper format to address the main objectives and three primary research questions. Chapter 1 sets the scene and addresses the motivation behind the project and its contribution to research, while Chapter 2 reviews the relevant literature and assesses gaps in research. While this chapter assesses the current research landscape, it is important to note that due to the format of this thesis, some of the relevant material may also be found in the introductory sections of the subsequent paper chapters 3, Chapter 4, and Chapter 5 and will be referenced rather than repeated in this chapter.

Chapters 3, Chapter 4, and Chapter 5 are the paper chapters which explore the main research questions of the thesis. Chapter 3 addresses the research question, "How do built heritage experts and visitors view the presence of moss growth on historic buildings?" Chapter 4 addresses the second research question, "How can we visually characterize the deterioration and weathering processes of moss growth on limited samples of historic stone?" Chapter 5 addresses the third research question, "How does moss growth affect moisture relations on stone substrates?"

The discussion Chapter 6 assembles the key findings from the three main research questions and presents a discussion regarding the overall effects of moss growth on cultural heritage. The conclusion Chapter 7 will then address lessons learned from this research project moving forward, and suggests areas for further research.

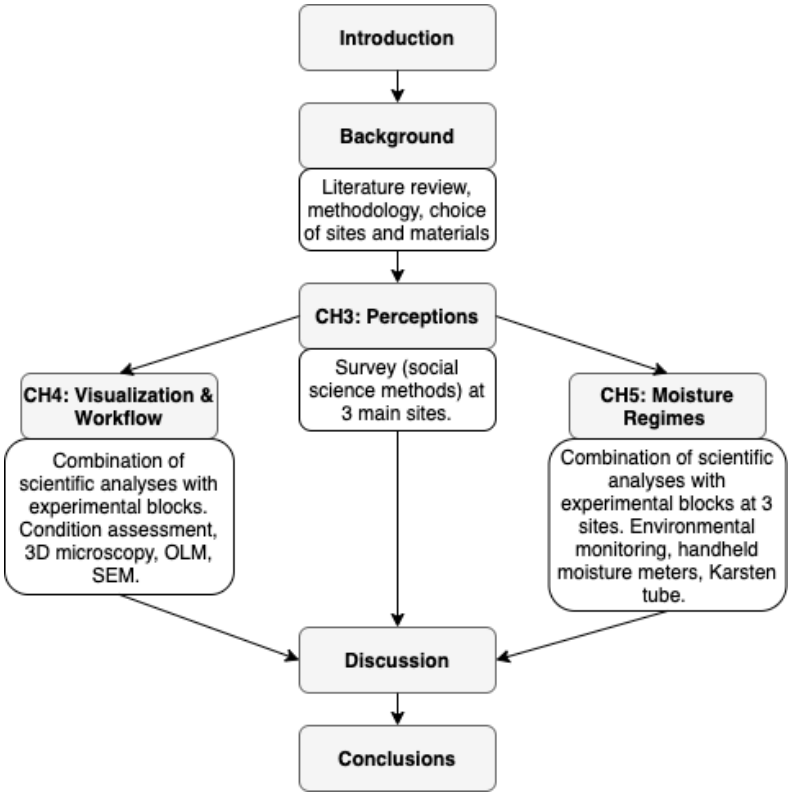


Figure 1.2: Thesis structure flowchart

Fig. 1.2 explains the flow and structure of the thesis. It shows how the background, literature review, and Chapter 3 feed into Chapters 4 and 5. The knowledge gained in the three paper-based chapters is then distilled and discussed in Chapters 6 and 7.

Throughout the DPhil process at the University of Oxford, the project has had the opportunity to receive feedback in the form of assessments and examinations at the Transfer of Status and Confirmation of Status reviews. Certain aspects of the methodology and data analysis of the papers have been amended due to the feedback which has been taken on board from these assessments. In particular, more robust data analysis has been added to Chapter 3 to include t-Tests from survey responses, and further data analysis has been added to Chapter 5 Moisture Regimes to analyze the impact of mosses on moisture relations. Additional laboratory and field-based analyses had been planned due to feedback from the Confirmation of Status examination, such as revisiting the SEM imaging to quantify instances of biological growth on the weathered samples, but had to be cancelled due to COVID 19 disruptions to research.

Additionally, this thesis was compiled using LaTeX, which gives the reader more functionality. When using the PDF file the user should be able to select Chapter titles, Figures, and Tables, highlighted with a red box, and that should direct the user to the correct information.

This project is a part of the Science and Engineering in Arts, Heritage and Archaeology Centre for Doctoral Training (SEAHA CDT) and was supported by the SEAHA CDT Research Training Support Grant (RTSG). SEAHA CDT is an EPSRC funded centre for doctoral training which focuses on cross-disciplinary heritage science research. SEAHA CDT students come into heritage science from a diversity of disciplines, from physics and engineering, to more humanities and social science-based backgrounds. Students from SEAHA CDT are supported by their supervisors and the SEAHA CDT board, but they also have a unique opportunity to engage with their industry and heritage partners. For this project, the industry and heritage partners were Amanda Potts, formerly of John Simpson Architects, and Trevor Proudfoot (d. 2019) at Cliveden Conservation. The development of this project was heavily based upon methods and initial findings from the author's MSc thesis (2015), "The degradative effects of moss and moisture on historic roof structures," University College London.

I died for beauty, but was scarce
Adjusted in the tomb,
When one who died for truth was lain
In an adjoining room.

He questioned softly why I failed?
"For beauty," I replied.
"And I for truth - the two are one;
We brethren are," he said.

And so, as kinsmen met a night,
We talked between the rooms.
Until the moss had reached our lips,
And covered up our names.

— Emily Dickinson, 1890

2 Background

Contents

2.1 Defining the lithobiontic interface 10
2.2 Bioreceptivity, bioprotection and biodeterioration . . . 11
2.3 Why bryophytes? 14
2.3.1 Endangered species 16
2.3.2 *Brachythecium rutabulum* 16
2.3.3 *Grimmia pulvinata* 17
2.4 How do we define 'impact'? 17
2.5 Stakeholders 19
2.6 Sites 19
2.6.1 Wytham Woods, Oxfordshire 20
2.6.2 Blenheim Palace, Oxfordshire 21
2.6.3 Kelmscott Manor, Oxfordshire 22
2.6.4 Oxford Botanic Gardens, Oxfordshire 23
2.6.5 Chipping Norton, Oxfordshire 24
2.6.6 Choice of sites 25
2.6.7 Methodology 26

The following chapter reviews the scope of the literature and gives an overview of the current research being done in the field of biogeomorophology and moss research. The chapter evaluates multiple studies and research projects beginning from the early 1990's regarding the effect of lichens, and likewise cyanobacteria, algal growth, and higher plants on stonework and cultural heritage. It finds that there appears to be a relative scarcity of moss-specific research in this field.

Due to the three-paper format of this thesis, some relevant information may also be found in the introductory sections of chapters 3, 4, and 5.

2.1 Defining the lithobiontic interface

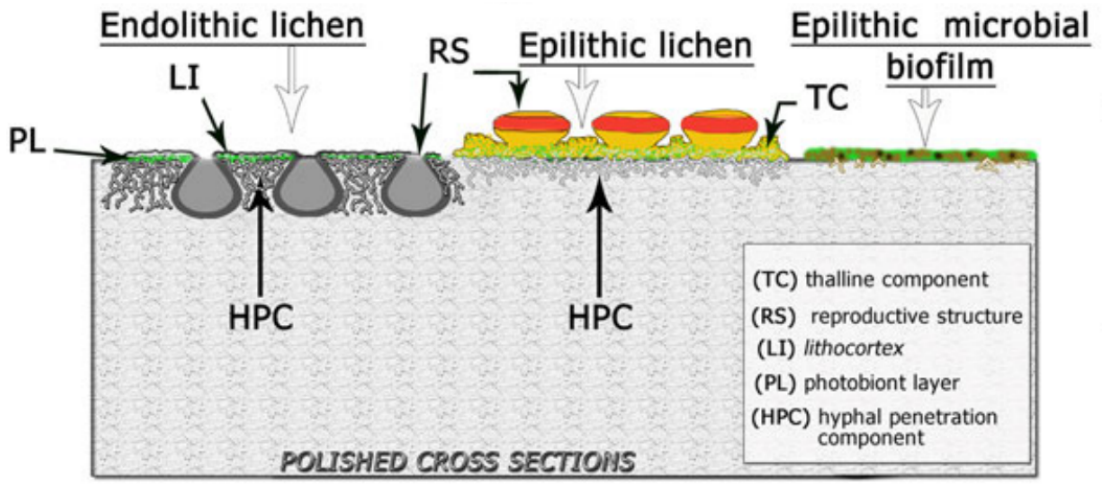


Figure 2.1: Endolithic and epilithic organisms colonising the lithobiontic interface, Morando et al. 2017, p 1667

The lithobiontic interface or zone, as defined in previous research, is area in which organisms interact with their underlying substrates and is a key concept to introduce when discussing the growth of any organism on substrates. Several different types of organisms may be found colonising this interface, including endo and epilithic lichens, cyanobacteria, algae, fungi, and bryophytes (Trovão et al. 2019). This zone may be superficial or extend several mm below the substrate surface, depending on the specific organism, seen in Fig 2.1. In particular, several species of crustose lichens (both endo and epilithic in nature) were observed to have hyphal penetration between 1-3 mm below the surface of Portland and Botticino limestone (Morando et al. 2017). This lithobiontic interface is very important when it comes to biodeterioration because it defines the zone in which metabolic processes occur. Physical weathering may be accelerated in this zone due to increased disaggregation of the stone matrix due to hyphal penetration, and chemical weathering may also be increased due to the deposition of chelating materials such as oxalic acids and oxalate crystal

formation (Owczarek-ko et al. 2020). When it comes to bryophyte attachment mechanisms and the possible extent of the lithobiontic interface, they attach to the substrate through small structures called rhizoids (Hanson and Rice 2014). According to a previous research project which investigated the efficacy of cleaning and conservation treatments on ancient stone stelae, moss 'fragments' were found within the stone substrate even after cleaning, suggesting that the moss-lithobiontic interface may extend below the surface (Savkovic et al. 2016). Despite this, the author is unaware of any research or projects which solely focus on the effects of moss growth on the lithobiontic interface and the possible impacts on cultural heritage.

2.2 Bioreceptivity, bioprotection and biodeterioration

Previous research from biomorphological studies on cultural heritage have noted several key concepts regarding biological growth on stonework, identified as; bioreceptivity, bioprotection, and biodeterioration. Bioreceptivity is defined as "the aptitude of a material... to be colonised by one or more groups of organisms without necessarily undergoing and biodeterioration" (Guillitte 1995, p. 216) and is generally characterized by the structure and chemical composition of the stone substrate. In this work, Guillitte describes bioreceptivity as a concept which evolves over time, where pioneer colonisers may alter the receptivity of a material to be more attractive to subsequent organisms. Certain organisms have been commonly demonstrated to be primary colonisers, such as epilithic lichens, while others such as bryophytes have been observed to be secondary or tertiary colonisers.

Biodeterioration, which is defined as, "any undesirable change in the properties of a material caused by the action of biological agents" is a concept that has been observed to occur with many organisms growing on cultural heritage sites (Dungani et al. 2019). Biodeterioration encompasses mechanical and chemical processes which occur due to the growth and metabolic processes of organisms on substrates, and can generally be attributed to the impacts of their attachment mechanisms, metabolic byproducts of growth, and the alterations in microclimate conditions within the

surface and near-surface zones produced by the presence of lithobiontic organisms. Biomechanical weathering, which can involve the swelling and shrinking of endolithic cyanobacteria as a result of wetting and drying cycles and thus furthering physical disaggregation of the stone matrix, is a well-documented process with other types of biological growth including lichens, cyanobacteria, fungi, and algae (Abe et al. 2014; Adamo and Pietro, 2000; Andersen et al. 2016; Antonelli et al. 2015; Chen et al. 2000; Savcović et al. 2016). In addition to physical weathering, biological growth contributes to chemical weathering of the substrate via metabolic processes and the excretion of oxalic acids, which contributes to chelation and the formation of oxalate crusts and patinas (Herrera et al. 2004/2009). These interactions between the biological growths and the substrate have been demonstrated to increase the rate of physical and chemical degradation and decrease the lifespan of historic buildings (Ricci et al. 2016).

On the other hand, bioprotection is a concept which is defined as the ability of organisms to contribute to the protection of the underlying substrate. Bioprotection may be "active (e.g., by producing a protective patina or crust on a rock surface) or passive (e.g., by providing an umbrella-like effect)" (Carter and Viles 2005, p. 279). More recent research has found biological growth may in fact play a role in bioprotection of the underlying substrate. Research done at the Oxford Resilient Buildings and Landscapes Laboratory (OxRBL) on ivy noted that plants play a role in moderating the temperature fluctuations at the wall surface, and protect it against freeze-thaw degradation (Sternberg et al. 2011; Coombes et al. 2018). The Spanish Research Council (CSIC) has noted that lichens can protect fragile mosaics from the same effects as well as airborne pollutant deposition (Ariño et al. 1995; Sternberg et al. 2010; Casoli et al. 2016). In addition, the oxalate crust may play an important role in preventing surface erosion and surface weathering (Slavík et al. 2016). It has been noted that the interaction between organisms and their underlying substrates is complex and multilayered, with the overall effect lying somewhere on a spectrum between fully biodeteriorative and fully bioprotective (Favero-Longo and Viles 2020).

There is a current debate in the scientific community on whether mosses have an overall negative or positive role in built heritage (Bartoli et al. 2014; Di Bonaventura, et al. 1999). When it comes to conservation advice from heritage bodies, mosses are generally treated as biodeteriogens which negatively affect the physical and chemical state of the substrate. Lichen research has found that hyphae "penetrate into the rock via intergranular boundaries at ≥0.002-0.003 mm/year" and contribute to biomechanical weathering beneath growths due to "expansion and contraction of the thallus related to wetting and drying cycles" (Lee and Parsons 1999, p. 386). As moss grows more quickly than lichens, it is predicted that the effects of biomechanical weathering may be more severe, however, these hypotheses have not been explored in further empirical research projects (Bartoli et al. 2014).

Although biodeterioration on cultural heritage sites is a well-researched field in terms of other types of biological growth explored in this review, very little research has been done on mosses and cultural heritage sites. This is possibly due to the fact that mosses are more loosely attached to the substrate than lichens or other lithobionts and can be more easily removed removed from historic surfaces. Mosses may not be viewed as permanently impacting the aesthetic presentation of historic environments and therefore deemed less worthy of being researched. There appears to be a scarcity in empirical research on the impacts of its growth on substrates, as well as a lack of development of appropriate methods and agreed protocols for investigating the moss-lithobiontic interface.

For the purposes of this project, it appears appropriate to adapt relevant methodologies and analyses from other research projects which evaluate the impacts of other organisms on historic buildings. In particular, the morphology and scale of endolithic and epilithic lichens are observed to be the most similar in structure to bryophytes, and taking into account the wealth of previous studies on the lichen-rock interface make them a sensible choice to adapt previous methodologies and analyses for this project. Chelation and acidification of the stone substrate (although outside the scope of this project), hyphal penetration, as well as moisture retention and

thermal response are all processes of deterioration that appear to be commonly observed in both lichens and mosses.

2.3 Why bryophytes?

Bryophytes are non-vascular plants that are found on all seven continents, and are commonly found in environments that vascular plants would not be able to tolerate. According to the British Bryological Society, there are 20,000 recorded species worldwide, and around 1,000 species in the United Kingdom (British Bryological Society). Their scale ranges from microscopic to over a metre in height. Mosses thrive in both rural and urban environments (Stevenson and Hill 2008), and are commonly associated with damp microclimates (Ruiz et al. 2019). Bryophytes are separated into three divisions; mosses (division Bryophyta), hornworts (division Anthocerotophyta), and liverworts (division Marchantiophyta). However, mosses are by far the most numerous division and most literature uses the terms bryophytes and mosses interchangeably.

Bryophytes have two primary growth habits, described as acrocarpous and pleurocarpous. Acrocarpous mosses have been described as cushion-like, pillowy, and have circular growth patterns. Out of the two growth forms, they are the slower growing form and they are often more loosely attached to their underlying substrates. In the United Kingdom, some of the most common acrocarpous species are *Grimmia pulvinata* which can commonly be found on wall tops, and *Schistidium acrocarpum*, which can be found in urban areas on concrete and calcareous substrates such as limestone walls. Pleurocarpous mosses have been described as flat and creeping growth patterns, with amorphous edges. They are faster growing than acrocarpous mosses and are more tightly bound to their underlying substrates. In the United Kingdom some of the most common pleurocarpous mosses are the species *Brachythecium rutabulum, Kindbergia praelonga*, and *Rhynchostegium confertum*, which are found commonly in lawns, garden borders, and at the base of walls.

Previous cultural heritage research projects have identified mosses as one of the common lower plant forms colonising built heritage on different continents. As

studied in the cases in medieval castles in Germany (Steinbauer et al. 2013), to tenth century rock-carved Buddha statues in Korea (Lee et al. 2010), the 18th century Church of Veracruz in Colombia (Hererra et al. 2014), The Sacred Rock in Machu Piccu, Peru (Morillas et al. 2019), and Roman bridges in the Iberian Peninsula (Pozo-Antonio et al. 2016). The incredible variety and biogeographic spread of mosses make them suitable subjects for cultural heritage research.

To the author's knowledge, very few cultural heritage research projects focusing on the lithobiontic interface have chosen to study mosses as the primary organism of interest. The seminal work studying the impact of mosses on cultural heritage was done by Garcia-Rowe and Saiz-Jimenez (1991) surveying three Spanish cathedrals in Salamanca, Seville, and Toledo. They noted that mosses and lichens exploit the same ecological niche, and that they commonly act as pioneer colonisers prior to vascular plant succession. Mosses were observed to colonise mortars and contribute to disintegration due to rhizoid penetration (Garcia-Rowe and Saiz-Jimenez 1991). When studying biological colonisation on the ruins of Angkor temples (Cambodia), mosses were observed to contribute to decohesion and through optical microscopy the depth of rhizoid penetration was measured to 2.46 mm in one sample (Bartoli et al. 2014). Additional work at the Ta Nei Temple (Cambodia) noted that sandstone's surface hardness when covered with mosses was lower than that of surfaces covered in lichens, and had almost 30% lower surface hardness than fresh sandstone (Kuchitsu 2007). Other research has simply correlated moss growth with visual signs of deterioration or damage, as in Lee et al. (2010) and Pozo-Antonio et al. (2016) which associate moss growth and areas of moisture or high relative humidity.

Speaking generally, there does not seem to be an agreed set of protocols or methods to study or visualize the impacts of mosses on cultural heritage. There also appears to be a gap in empirical research studying mosses and their relation to moisture on cultural heritage despite mosses being visually correlated to wetter areas on built heritage in previous studies. Although methods have been developed to non-destructively test moisture absorption in cultural heritage, such as Karsten tube tests, these methods have not been applied to substrates with moss growth. Investigations

into the moss lithobiontic interface have been brief, as in the case of Bartoli et al. (2014), and there is scope to analyze moss impacts on different substrates.

2.3.1 Endangered species

When researching mosses on cultural heritage, practitioners should be mindful of protected and endangered species, since balancing natural conservation with built heritage conservation adds a layer of complexity to managing cultural heritage sites. In the United Kingdom, there are known endangered and vulnerable species of bryophytes. Some species of moss exist in a tiny geographic area, such as *Ditrichum cornubicum*, also known as Cornish Path-Moss, which was first discovered in 1963 and has since been found in only two other locations within Bodmin Moor, Cornwall, UK. The full list can be found on the Red List for Bryophytes with the most up-to-date list covering England, Scotland, Wales and the Isle of Man, but excluding Ireland, Northern Ireland and the Channel Islands (Hodgetts 2011). This list covers species that fall under the 6 threat categories, ranging from vulnerable to extinct.

2.3.2 *Brachythecium rutabulum*

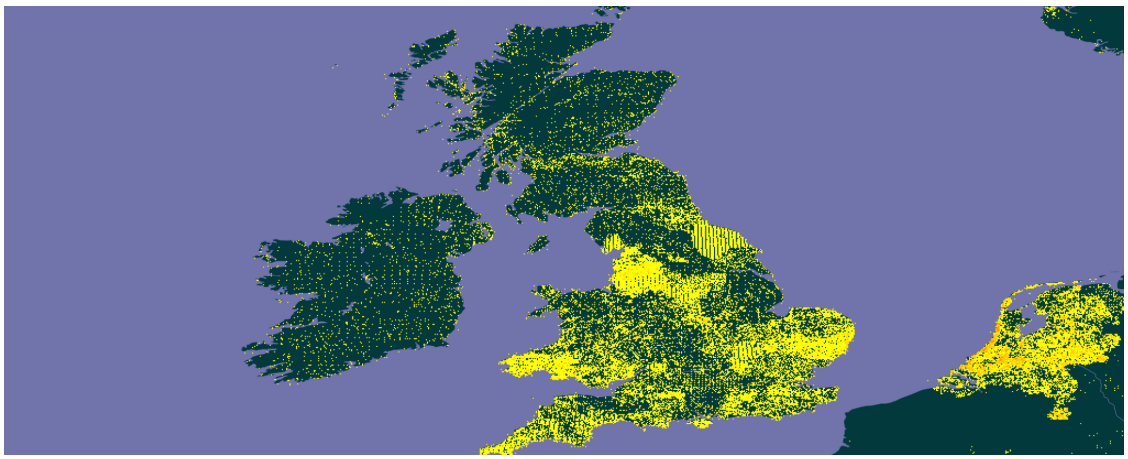


Figure 2.2: Distribution of Brachythecium rutabulum in Great Britain, GBIF

This project has chosen to focus on the species *Brachythecium rutabulum*, due to its biogeographical prevalence and dominance in the United Kingdom, North America, and Europe as seen in the GBIF data Fig 5.2. Fig 2.2 shows its relative

spread in Great Britain. *B. rutabulum*, also known as Rough-Stalked Feather-Moss, is one of the most commonly found species of mosses in the United Kingdom (Preston et al. 2010). It is commonly found colonising calcareous stone substrates, wood, co-mingling with planted lawns, and in patches of soil. In a detailed survey of King's Lynn, Norfolk UK, *B. rutabulum* was cited as one of the most common species of bryophytes surveyed, indicating that they survive and thrive in urban environments in the UK as well as rural (Stevenson and Hill 2008). This survey found that *B. rutabulum* was one of the three most common pleurocarpous mosses found in arable fields, along with *Kindbergia praelonga* and *Oxyrrhynchium hians*. As a pleurocarpous moss, *B. rutabulum* is often found in medium to large patches of growth, making them easy to recognize and monitor for growth during site visits.

2.3.3 *Grimmia pulvinata*

While most empirical work in this project focuses on the species *B. rutabulum*, some work has also focused on the species *Grimmia pulvinata*. In particular, some of the moisture analyses in Chapter 5 such as the Karsten tube tests, have focused on this species of acrocarpous moss because the round growth pattern enabled testing without removing moss colonisation from the substrate. *G. pulvinata* is another species of moss that is very common in Europe and is commonly found in both urban and rural environments. The species distribution map of *G. pulvinata* roughly mirrors the GBIF distribution map of *B. rutabulum*, in that it is a ubiquitous species that covers the entirety of the United Kingdom. Also known as grey-cushioned grimmia or pulvinate dry rock moss, this species is easily identified due to its silver hair-points. This species is extremely tolerant of airborne pollution and has consequently been studied as an accumulation biomonitor species within urban cemeteries in Paris (Natali et al. 2016).

2.4 How do we define 'impact'?

Due to the lack of moss-specific research in cultural heritage, there does not appear to be a consensus of the typology of moss impacts in literature. In Table 2.1 below,

several possible impacts of moss growth have been compiled using findings from previous research on lichens and greening of cultural heritage. Although these are theorized impacts of moss growth that have been shaped by observations from previous research, these may be impacts we can expect to see from the findings of this research project. Creation of a broad 'typology of moss impacts' is helpful to determine which factors should be analyzed or prioritized when forming the methodology of this research project.

Table 2.1: Typology of moss impacts

Physical	Chemical	Aesthetic
Moisture relations	Encrustation and patina (surface)	Colonisation
Thermal blanketing	Rhizoid penetration and Chelation	Staining
Surface weathering		
Rhizoid penetration		

Physical Impact – These changes caused by organisms can be broadly defined as the types of damage identified by ICOMOS-ISCS in their Illustrated Glossary on Stone Deterioration Patterns (ICOMOS, 2001). They may be directly or indirectly caused by the presence of biological growth. Indirect causes of physical damage do not initiate the degradation, however they accelerate the processes caused by climate and other environmental factors. Some broad indicators of physical damage are defined by ICOMOS-ISCS into 4 categories: Crack and deformation, detachment, features induced by mineral loss, and discolouration and deposit (ICOMOS, 2001). The physical impacts of biological growth on cultural heritage are further explored in the introductions to chapters 4 and 5.

Chemical Impact – These changes are directly caused by the metabolic processes within the growth cycle of organisms. Certain impacts such as encrustation and surface deposition have been identified as active bioprotective processes defined as 'bioconstruction' (Carter and Viles 2005). Others, such as the deposition of oxalic acids have been characterized as biodeteriorative (Herrera et al. 2009). The

chemical impacts of biological growth on cultural heritage are further explored in the introductions to chapters 4 and 5.

Aesthetic Impact – These changes to not affect the structural stability of the stone, nor do they cause a decrease in lifespan of the material. In most cases, the negative aesthetic impact of mosses is the obscuring nature of the biological growth on intricate facades, mosaics, or works where the nature of the surface material is detailed or intricate (Douglas-Jones et al. 2015). On a positive note, the benefit of the aesthetic impact of moss growth is that it can bequeath a structure with a sense of age, charm, or destination authenticity (Lee et al. 2015). Destination authenticity is identified as a key basis for deriving consumer value in the context of heritage tourism, and has been "argued to be a prominent driving force for the modern tourist to travel" (Lee et al. 2015, pp. 984). The aesthetic impact of biological growth on cultural heritage is further explored in the introductions to chapters 3 and 4.

2.5 Stakeholders

This project is aimed to address gaps between heritage science and conservation practice, and thus has a variety of targeted audiences and stakeholders. The primary target audiences for the project outcomes include conservation practitioners and heritage bodies such as Historic England, the National Trust, and Historic Scotland. It is hoped that through the findings of this project, some clarity and practical management strategies can be put in place regarding the management of mosses on historic buildings in England. Additional audiences would be heritage scientists and biogeomorphologists working in the field of lower plants on substrates, in particular these outcomes may interest lichenologists and heritage scientists working on specific sites in England or elsewhere.

2.6 Sites

This research project evaluated several sites in Oxfordshire, England. These sites ranged from a UNESCO World Heritage site, to a local listed building previously

owned by the Arts and Crafts artist William Morris. These sites served as places for non-destructive tests to examine moisture regimes when comparing areas with and without mosses, microclimate environmental monitoring sites, and sites to deploy the visitor survey examining perceptions surrounding mosses on built heritage. Further information on the sites can be found in the introductory sections of chapters 3 and 5.

2.6.1 Wytham Woods, Oxfordshire



Figure 2.3: OxRBL test site at Wytham Woods. At left, collage showing test walls and gravestones. At right, showing weathered sample blocks used for this project. Photo credit: Hong Zhang, Dr Julie Eklund

Wytham Woods is a semi-natural woodland site used for research and testing in North Oxford. Owned and maintained by Oxford University since 1942, it spans over 400 ha and contains a semi-natural woodland, secondary woodland, limestone grasslands, and natural plantations. The Oxford Resilient Buildings and Landscapes Laboratory (OxRBL) has a test site in Wytham Woods in which a range of heritage stone materials are exposed in the form of blocks and test walls, Fig 2.3. While not specifically used as part of this research for analyses or as a case study site, this is nonetheless an important site to mention. This research project uses a set of weathered limestone blocks from a previous research project (Eklund, no date). In 2010 16 Portland limestone blocks were placed on a geotextile surface in a grassland area and were appropriated for this research project in 2017 after 7 years of natural weathering.

At this site there appeared to be a relative dominance of the species *Brachythecium rutabulum*. This is to be expected because the site presents an ideal situation

for this species to flourish. *B. rutabulum* prefers calcareous substrates (of which there were limestone test blocks and walls) and areas of shaded lawns which are extensive at this site as seen in Fig 2.3.

2.6.2 Blenheim Palace, Oxfordshire



Figure 2.4: Blenheim Palace, Oxfordshire exterior. Source: Wikimedia Commons

Blenheim Palace itself is Grade I listed, as are the grounds including the park, woodland and formal gardens, Fig 2.4. Blenheim Palace is also a designated UNESCO World Heritage site, and was inscribed in 1987 due to its outstanding universal value arising from the relationship between the Baroque Palace and the Park created by the famous landscape gardener 'Capability' Brown. The site ranges over 800 ha and is enclosed by an 18th century dry-stone wall.

Blenheim Palace still remains privately owned, with a portion of the palace occupied and inaccessible to visitors. Built between 1702-1722, the squared ashlar facade mainly consists of cream-coloured oolitic freestone (Arkell 1948). As described by David Green, "For except in the kitchen court, where thanks to Sarah Duchess of Marlborough's insistence on economy Vanbrugh introduced cheap stone from Heythrop, now crumbling, only the best limestone from the Strongs' quarries at

Taynton, and from equally dependable places like Cornbury and Barrington, was used"(Green, 1958, p. 1401). To this date, the layout of the principal buildings remain unaltered since their construction and are described in the UNESCO listing to have a high degree of authenticity and integrity.



Figure 2.5: Blenheim Palace boundary walls, Oxfordshire. Credit: Roger Templeman 2006

There are very few mosses visible on the main buildings of Blenheim Palace since the buildings undergo regular cleaning and maintenance. However, the structures separate from the main buildings, such as the boundary walls and bridge have sparse colonies of acrocarpous mosses, identified as *Grimmia pulvinata* and *Orthotrichum anomalum*.

2.6.3 Kelmscott Manor, Oxfordshire

Currently owned by the Society of Antiquaries of London (acquired 1962), the main house at Kelmscott Manor was built c. 1570 for Richard Turner, with later additions c. 1670, 1871, and 1896 (Historic England listing 1199373). The main building is built from uncoursed limestone rubble walls, and the boundary walls consist of coursed, roughly hewn limestone with cementitious mortar capping, Fig 2.6. Similar to Blenheim Palace, Kelmscott Manor remains unaltered since William Morris' death, and even retains interior furniture and fixtures from the time of his ownership. In comparison to Blenheim Palace however, the property is only 28 ha in total and comprises the main buildings, a small orchard, and a meadow.

Mosses grow luxuriantly at this site including at the base of north-facing walls (*Brachythecium rutabulum*), and on the tops of mortar- capped boundary walls



Figure 2.6: Kelmscott Manor, Oxfordshire exterior. Source: Wikimedia Commons

(*Grimmia pulvinata*). Additionally, there is extensive pleurocarpous and acrocarpous moss growth on the roof tiles on all buildings at the site, identified as *Hypnum tectorum, Grimmia pulvinata,* and possibly *Schistidium acrocarpum.* Although *Hypnum tectorum* can appear similar to other *Hypnum* species and in particular *Hypnum andoi*, they can be distinguished in this context due to the prevalence on roof structures. *Hypnum tectorum* is also known as Roof Plait-Moss due to its common sight on roof structures. There has been no regular cleaning or removal of mosses at this site because William Morris described Kelmscott as existing symbiotically with nature, and his philosophy for the buildings emphasized Kelmscott organically intertwining with nature over time.

2.6.4 Oxford Botanic Gardens, Oxfordshire

Oxford Botanic Gardens were established in 1621 with the main boundary walls built during the 1620s, and the main Grade I listed Danby gateway built between

1632-33 using Headington Freestone. The botanic gardens are owned and maintained by the University of Oxford, and consist of the main walled garden, glasshouses, and the lower garden, Fig 2.7. The imposing boundary walls are built from Headington freestone, and stand 5m high, 100m long, with stone coping (Historic England listing 1000464).

At this site the main instances of moss growth were found on the boundary walls. The primary species identified were *Brachythecium rutabulum*, *Grimmia pulvinata*, and *Hypnum jutlandicum*.

2.6.5 Chipping Norton, Oxfordshire

Chipping Norton is a small market town and civil parish located in northwest Oxfordshire, with a population of a round 6,500 people. The test area at this site was a small area of dry-stone walling adjacent to the Grade I listed church,



Figure 2.7: Oxford Botanic Gardens, Oxfordshire interior. Source: Wikimedia Commons



Figure 2.8: St. Mary's Church, Chipping Norton, Oxfordshire. Source: Wikimedia Commons

St. Mary the Virgin, located in the North-West area of Chipping Norton, Fig 2.8. The dry-stone walling comprised of local limestone, medium-grained and ooidal in nature (Chipping Norton Limestone).

This area had a dominance of *Brachythecium rutabulum* with only a few instances of acrocarpous mosses, *Grimmia pulvinata* on the tops of the dry-stone walling.

2.6.6 Choice of sites

The range of sites used in this project was specifically chosen to exemplify the diversity of built cultural heritage in the United Kingdom, and to demonstrate a wide variety of building and boundary walls. This project includes a rich variety of structures, from examples of vernacular architecture (local dry-stone walling at St. Mary the Virgin Church in Chipping Norton), to an example of building walls at a UNESCO World Heritage site at Blenheim Palace. The inclusion of vernacular

architecture in the form of dry-stone walls was intentional, as these walls are often overlooked and under-studied in conservation research. The range of sites also shows a range from local, national, to international importance, which may also play a role in how conservation decisions are made at each site.

2.6.7 Methodology

The suite of methods used in this project have been chosen to reflect the interdisciplinary nature of heritage science and combine both natural and social science methods. Chapter 3 uses social science methods through surveys and survey analysis to determine common perceptions of mosses on built heritage. The results from Chapter 3 link to Chapters 4 and 5 which use natural science methods and analyses to determine the impacts of mosses on limestone and cementitious mortar. Certain methods chosen for this project, such as Scanning Electron Microscopy (SEM), Optical Light Microscopy (OLM) of petrological thin sections, environmental monitoring with iButtons, Karsten tube tests, and condition surveys, have been widely used within the field of heritage science to determine the impact of biological growth on substrates. This project also proposes using the Keyence 3D microscope as a novel addition to the combination of methods commonly used to visualize the lithobiontic interface of cultural heritage.

In the heated idleness of youth we were all rather inclined to quarrel with the implication of that proverb which says that a rolling stone gathers no moss. We were inclined to ask, "Who wants to gather moss, except silly old ladies?" But for all that we begin to perceive that the proverb is right. The rolling stone rolls echoing from rock to rock; but the rolling stone is dead. The moss is silent because the moss is alive.

— G.K. Chesterton, Heretics

3 Perceptions

Contents

3.1 Perceptions of moss growth on historic buildings: Similarities and differences in opinion between public and experts and the implications for heritage conservation 28
3.2 Abstract . . . 28
3.3 Introduction . . . 28
3.4 Background . . . 31
3.5 Sites and People . . . 33
3.5.1 Visitor Survey . . . 33
3.5.2 Expert Opinion Survey . . . 35
3.6 Methods . . . 36
3.6.1 Questionnaire Format and Scope . . . 36
3.6.2 Data Analysis . . . 37
3.7 Results . . . 38
3.7.1 Participants' expertise in built heritage . . . 38
3.7.2 Participants as heritage visitors . . . 39
3.7.3 Participants' knowledge of moss . . . 40
3.7.4 Aesthetics of moss growth . . . 42
3.7.5 Perceptions of damage . . . 43
3.8 Discussion . . . 45
3.8.1 Further Questions . . . 46
3.9 Conclusions . . . 46
3.9.1 Key findings . . . 47
3.9.2 Implications for conservation . . . 47

3.1 Perceptions of moss growth on historic buildings: Similarities and differences in opinion between public and experts and the implications for heritage conservation

Authors: Jang, K. and Viles, H. This work has been submitted to the *Journal of Heritage Tourism* with minor changes to the text and formatting, and is currently under review.

Keywords: Bryophyte, moss, cultural heritage, survey

3.2 Abstract

Bryophyte (moss) growth on built cultural heritage is an under-researched factor in heritage management strategies. Moss is commonly identified as a biodeteriogen that should be removed, because it is thought to negatively harm both the aesthetic and physical values of the built heritage asset. This paper examines survey results from heritage professionals and visitors to challenge these perceptions. Through survey results from both sample groups, it was determined that visitors and heritage professionals alike believe that moss growth should only be removed from buildings if it is definitively causing damage to the built structure. The survey also reveals that moss growth on heritage buildings has several positive associations, such as reinforcing 'authenticity' and 'historic' values. Results from these surveys could be used to inform future conservation management strategies for cultural heritage sites.

3.3 Introduction

This paper analyses the perceptions of bryophyte growth on historic buildings comparing those of built heritage experts with those of visitors to historic buildings

using a survey method. The survey aims to evaluate the level of knowledge about bryophytes possessed by both built heritage experts and members of the public and explore their opinions on the roles of bryophytes in the deterioration and aesthetic characteristics of historic building materials. When examining the prevalence of biological growths on historic buildings, mosses are often cited as one of the most common growth types, and as seen in modeling species distributions from heterogeneous data of European bryophyte flora we can simply observe that, "mosses best fit the pattern 'everything is everywhere'" (Mateo et al. 2013, p 2). Despite the widespread nature of moss growth, and the depth of research on other types of biological growths such as lichens and algae on heritage, mosses are comparatively understudied and overlooked.

Biological growth on buildings is one of the factors which should be considered in cultural heritage management strategies. There is debate about how to determine the point of intervention, level of cleaning, and whether or not preventative measures should be taken to prevent biological growth occurring in the first instance. When discussing the removal of biological growth, black biological patinas in particular have shown adaptation to microclimate conditions and resistance to biocides, moreover the 'ecotoxicity of commercial biocides increasingly discourages their use in outdoor environments' (Gazzano et al. 2013, p. 300). A more natural "pesticide" of lichen secondary metabolites (LSM) has been suggested as a potential natural herbicide, due to the allelopathic effects of LSM on vascular plants and bryophytes (Gazzano et al. 2019, p. 301). As the 'Ethics of doing nothing' has been discussed as a valid strategy for heritage management, there are also considerations to allow biological growth continue unchecked or simply monitor the growth without intervention (Ashley-Smith 2018).

In this paper, we differentiate bryophytes from other common forms of biological growth on historic buildings, such as lichens, cyanobacteria, fungi, and algae. Together, these forms of biological growth contribute to a patina, defined by Gazzano et al. as pigmentation changes caused by "biochemical and structural characteristics" from rock-inhabiting fungi, cyanobacteria, and green algae (Gazzano

et al. 2013, p. 300). Moreover, the term 'mosses' will be used as an all-encompassing term to describe all bryophyte species in general (defined as true bryophyta, as compared to liverworts or hornworts).

As biological growth and patinas can change the viewer's perception and experience of a cultural heritage site, it is important to determine how the presence of mosses will affect values such as aesthetics, authenticity, and perceived damage as defined in the original Burra Charter (Australia, ICOMOS 1979), and more recent heritage-based values typologies (Fredheim and Khalaf 2016). In certain cases, the presence of mosses may positively impact the aesthetic value of a site by contributing to its historic or authentic values. As examined in previous research, the greening of historic sites can add important contextual information regarding the age of the site. For example, in the case study of Dryburgh Abbey, Scotland, biological growth on the ruined abbey is seen as intrinsic to the beauty and 'romantic' aesthetic of the site (Douglas-Jones et al. 2016). Established c. 1150 by the Premonstratensians, Dryburgh Abbey was a Cistercian monastery destroyed during the Scottish Reformation in 1544. Today the site is designated as a scheduled monument in the care of Historic Scotland (HS). The surviving ruins are typically medieval gothic, constructed of local sandstone faced with coursed ashlar. While this study does not specifically mention mosses, the presence of algae and lichens in the subterranean Chapter House has been noted as a cause for concern due to the building having "national significance as the largest area of medieval polychromatic wall decoration in Scotland" (Douglas-Jones et al. 2016, pp. 4). However when visitors were asked directly about the removal or cleaning of biological growth many visitors expressed an appreciation for the biological growth. One visitor expressed the desire for the abbey to have "death in beauty," while another visitor noted that the abbey should "be able to decay slowly, without us preventing it" (Douglas-Jones et al. 2016, pp. 827).

The main objective of this paper is to determine if visitors at a range of sites, and heritage professionals online confirm previous research about the aesthetics of biological growth on buildings. Perhaps in the case of sites like Dryburgh Abbey,

where the natural values and context of the site are intrinsically intertwined, the impact of cleaning biological growth needs to be carefully evaluated. This can justify the value reasoning behind the expert and visitor surveys used in this paper. If both built heritage experts and visitors value the presence of biological growth (and indeed mosses) on built heritage, then perhaps cultural heritage management strategies need to be modified to align with these insights.

The paper aims to understand the perceptions of mosses on historical buildings, and whether there are any significant differences between opinions from built heritage visitors and professionals. Specific research questions that this paper sets out to answer include, 'how do people believe mosses affect built heritage, is this in an overall positive or negative way?' and 'does the level of experience held in built heritage conservation or management influence these answers?' Finally, it will ask, 'what questions about mosses on historic buildings are people most interested in having answered?' and if there are any commonalities between both visitors and experts.

3.4 Background

The presence of biological growth on cultural heritage is well documented, with primarily negative consequences for both the physical and chemical deterioration of built heritage materials often outlined, as well as effects on the visual aesthetics (Bartoli 2014). The term biodeterioration describes the "physical or chemical damage caused by biological agents on structural materials and occurs through the formation of biofilms" and can refer to multiple types of biological growths including vascular plants, lichens, fungi, bryophytes, algae, and cyanobacteria (Herrera et al. 2009, p. 75). In particular, moisture uptake and surface saturation are concerns when discussing moss colonisation (Garcia-Rowe & Saiz-Jiminez 1991). However, recent research has uncovered possible benefits from biological colonisation such as protection from mechanical weathering (Chen et al. 2000, p. 139) and has defined these under the umbrella term of 'bioprotection' (Carter and Viles 2005).

The ICOMOS-ISCS Illustrated Glossary on Stone Deterioration Patterns defines biological colonisation as one of the five main features of stone deterioration, and breaks it down into six primary coloniser categories with moss as a single category (ICOMOS-ISCS 2008). Despite this, relatively few studies have analysed perceptions of biological growth, and in particular mosses, from the standpoint of both visitors and experts on built heritage. Despite research findings showing the possible benefits of biological growths on built heritage, it is a commonly held belief that biological growth on cultural heritage negatively impacts visual aesthetics, or is a visual indicator of underlying problems such as excess moisture (Garcia-Rowe & Saiz-Jiminez 1991).

Public bodies such as Historic England and Historic Environment Scotland have similar advice when it comes to the management and removal of mosses on historic buildings. Historic England notes that while biological growths contribute to an appealing aged patina of masonry, mosses "[indicate high moisture levels which can damage masonry" (Historic England 2019, p. 33) and go on to say that cleaning may not always be the right choice, as frequent treatments can erode the underlying material and cause further damage (Historic England 2019, pp. 33). In Historic Environment Scotland's Advisory Standards of Conservation and Repair for the Historic Building Environment in Scotland, they recommend that "where damp conditions have caused moss and algal growth on masonry, the area is to be scraped clean with wooden spatulas and cleaned down to remove all organic debris and soil prior to re-pointing. The source of moisture encouraging such growth must be addressed in order to prevent re-growth. Seek specialist advice on biological growths such as algae, fungi, and lichens where the effect to the masonry may not be benign but removal could cause masonry damage. It should be recognised, that biocide is unlikely to have a long-lasting effect and may damage the masonry. Consequently, the use of biocide should not form part of a regular maintenance regime" (Historic Environment Scotland 2014, p. 6). Biocides and other mitigation strategies such as UV light treatments for biological greening (including but not limited to moss growth) have been well-studied, and are recommended as part of

short-term conservation management strategies for cultural heritage, but may have negative long-term effects on the substrate and environment (Silva et al. 2017).

The East Ayrshire Council Conservation Area Maintenance Guide, published with guidance from Historic Scotland and the Scottish Lime Centre, describe physical and chemical problems caused by moss growth on roofs, such as blocked gutters, pitting, water retention, and chemical deterioration caused by water runoff on slate roofs (Austin-Smith: Lord LLP, 2007, p. 19). Finally, the Edinburgh World Heritage Historic Home Guide for Roofs recommends brushing moss off of clay roof tiles as they hold moisture which causes the tiles to deteriorate more quickly and cause frost damage (Mayhew, 2018, p. 7), which is also corroborated with the Historic Environment Scotland Inform Guide on Biological Growth on Masonry, which states that "moss retains water extremely well, and this can keep a masonry surface in a persistently wet state, which exacerbates stone decay" (Eklund and Young, 2013, p. 5).

As we can see from the advice from public bodies that inform heritage management strategies, they almost universally describe mosses as a biodeteriogen and advocate cleaning measures for built heritage. However, strict cleaning schedules and the portrayal of pristine heritage sites oppose the aesthetic values appreciated by heritage visitors as seen in previous case studies (Douglas-Jones et al. 2016). Exploration of the values perceived by biological greening on cultural heritage as well as the advice from heritage organizations regarding cleaning and management regimes helped to shape and inform the questions provided in the survey.

3.5 Sites and People

3.5.1 Visitor Survey

Three heritage case study sites in Oxfordshire were chosen to target different segments of built heritage visitors. Firstly, UNESCO world heritage site Blenheim Palace was chosen due to the wide range of visitor demographics and high volume of visitors. According to the Blenheim Palace Economic Impact Report 2017/2018, they received 910,423 international and domestic visitors that year (p. 9.) As

evidenced by the survey results, the age range from this heritage site was the widest, and many visitors were only casually interested in cultural heritage. Blenheim Palace itself is Grade I listed, as are the grounds including the park, woodland and formal gardens. Blenheim Palace still remains privately owned, with a portion of the palace occupied and inaccessible to visitors. Built between 1702-1722, the squared ashlar façade mainly consists of cream-coloured oolitic limestone freestone called Clypeus stone (Arkell 1948).

Secondly, Oxford Botanic Gardens was chosen to target heritage visitors who were likely more familiar with or interested in plant growth and heritage sites. Established in 1621 with the main boundary walls built during the 1620s, the main Grade I listed Danby Arch was built between 1632-33 using Headington Freestone (a locally quarried Jurassic limestone) The botanic gardens are owned and maintained by the University of Oxford, and consist of the main walled garden, glasshouses, and the lower garden. The imposing boundary walls are built from Headington Freestone, and stand 5 m high, 100 m long, with stone coping (Historic England listing 1000464). This site had 144,000 visitors in 2017 according to an Oxford University online news article (published 19 March 2018), and visitors at this site were likely to be more interested in the gardens and botanical features than the heritage aspects of the site.

Lastly, Kelmscott Manor was chosen due to the association with 'rural' and 'countryside' characteristics. The manor was prominent Arts and Crafts artist William Morris' summer country house and is located in rural Lechlade-on-Thames, Gloucestershire. William Morris also founded The Society for the Protection of Ancient Buildings (SPAB) in 1877 as a reaction to Victorian restoration philosophies, which he deemed overly enthusiastic and invasive (SPAB website, 2017). Currently Kelmscott Manor is owned by the Society of Antiquaries of London (acquired 1962). The main house was built c. 1570 for Richard Turner, with later additions c. 1670, 1871, and 1896 (Historic England listing 1199373). The main building is built from uncoursed limestone rubble walls, and the boundary walls consist of coursed, roughly hewn limestone with cementitious mortar capping.

Although the main house is Grade I listed, both the front boundary wall and summerhouse are Grade II listed. Morris and the Society for the Protection of Ancient Buildings viewed Kelmscott Manor as 'living history' and saw the Manor and gardens as inseparable, allowing the Manor's biological patina to grow over time (Cooper, 2005). Due to this philosophy, Kelmscott Manor has flourishing colonies of mosses present on the boundary walls, roofs, and even the exterior cladding of the main manor. Additionally, due to the remote nature of the Manor, accessible only by private car and not public transport, visitors to the site are likely keen to be regular visitors to heritage sites. The Kelmscott Manor website states that the site has 20,000 visitors a year, many fewer than the other two sites.

The combination of the three heritage sites gives the visitor survey a realistic profile of visitors to heritage sites; from those who are regular and avid visitors to heritage sites, to those who are interested in aspects of the site that are aligned with but not intertwined with the heritage value. The presence of landscaped grounds in all three settings is also significant, as the close relationship between built heritage and the natural environment is noteworthy at these three particular sites. Additionally, all three heritage sites are accessed via paid entry, which will affect the visitor profiles.

3.5.2 Expert Opinion Survey

The Expert Opinion Survey (EOS) was disseminated online via a custom Google Forms questionnaire, and the groups targeted for the survey were chosen to get a broad view of built heritage professional opinions at a regional, national, and international scale. At a regional or local scale, several groups within Oxford were chosen to participate due to their experience with local built heritage restoration and conservation projects. These groups were the Oxford University Estates conservation department, the Oxford Rock Breakdown Laboratory, the Oxford Preservation Trust, and Purcell (Oxford). At a national level, groups were chosen that have had demonstrable experience with conservation projects across the United Kingdom. These groups were Cliveden Conservation and the Institute of Sustainable

Heritage (UCL). The international CoOl Conservation Dist List (American Institute for Conservation of Historic & Artistic Works) was chosen because the members have experience with conservation projects around the world, in particular in the United States, but they also have members who specialize in other areas of conservation which would give a broader spectrum of professional opinions.

3.6 Methods

3.6.1 Questionnaire Format and Scope

Collection of the Visitor Opinion Survey (VOS) was undertaken primarily in person from August-September 2018, on site at Kelmscott Manor, Blenheim Palace, and Oxford Botanic Gardens, with express permission from management and relevant departments. Visitors were asked to fill out a paper copy of the survey, which were then transcribed. In some cases, the survey was conducted in the form of a semi-structured interview where any anomalous answers were discussed with the participant after the paper survey had been filled out. An online version of the VOS was also distributed online via the British Bryological Society and to postgraduate students in the Oxford Faculties of History and Classics. We recorded the majority of responses to the VOS at the three heritage sites: Blenheim Palace (45), Kelmscott Manor (12), and Oxford Botanic Gardens (8), online VOS (29) and from the online EOS (49), giving 143 completed surveys to the VOS and EOS in total. Although the total sample size is not large, it is comparable to other recent surveys in heritage research with a single recorder (Summerby-Murray, 2015).

The scope of the questionnaire covered demographics, perceptions of moss growth, and gave the opportunity for other comments via an open question at the end (see Appendix B for questionnaire). The questions focused on the participants' level of background knowledge regarding moss growth, then delved more specifically into their perceptions of the effects of moss growth on built heritage. As the participants in the VOS were assumed not to have any specific background knowledge on built heritage or restoration, the results between the VOS and EOS were expected to differ based on the levels of knowledge, first-hand experience, and preconceptions.

The format of the questionnaire comprised 13 questions including multiple choice questions (Yes/No/Other), Likert scale questions (1-5), and two open-ended questions. Part I of the questionnaire established the respondent's background and level of built heritage experience. Part II examined the respondent's level of knowledge about mosses and their overall perceptions of the effects of mosses on buildings.

Part I:

- Do you consider yourself a built heritage professional? (Yes, No, Other)
- What is your job title? (Optional and open-ended)
- Have you been involved with the restoration/conservation of a listed building or scheduled monument? (Yes, No Other)
- How often do you visit historic buildings for leisure? (Never, Rarely, Often, Very Often)

Part II

- My level of knowledge about mosses is: (Likert scale 1-5)
- In the image above, which number(s) show(s) moss? (Multiple choice)
- In your opinion, how do mosses affect buildings? (Multiple choice)
- In your opinion, how do mosses specifically affect buildings? (Check all that apply, multiple choice)
- Should mosses be removed from historic buildings and monuments? (Multiple choice)
- How do mosses affect the aesthetics of historic buildings? (Check all that apply, multiple choice)
- "I enjoy the look of mosses on historic buildings" (Likert scale 1-5)

3.6.2 Data Analysis

Data for Q1,2-4,7-12 was simply graphed based on the frequency of the answers from the multiple-choice question sets. Q5 asked participants to self-identify their level of moss knowledge using a 5-point Likert scale. The Likert scale ranged from 1 = Very low – "I do not know what moss is," to 5 = Very high – "I can differentiate between moss, lichen and algae." Q6 asked the respondents to

visually identify moss from 4 images of biological growth. Pearson's correlation coefficient was applied to determine whether there was an association between the level of self-identified moss knowledge and the likelihood of a correct visual identification. The Likert scale questions (Q5 and Q11) were analysed using a 2-sample t-Test to determine if there were any statistically significant differences in responses between the visitors and experts.

3.7 Results

3.7.1 Participants' expertise in built heritage

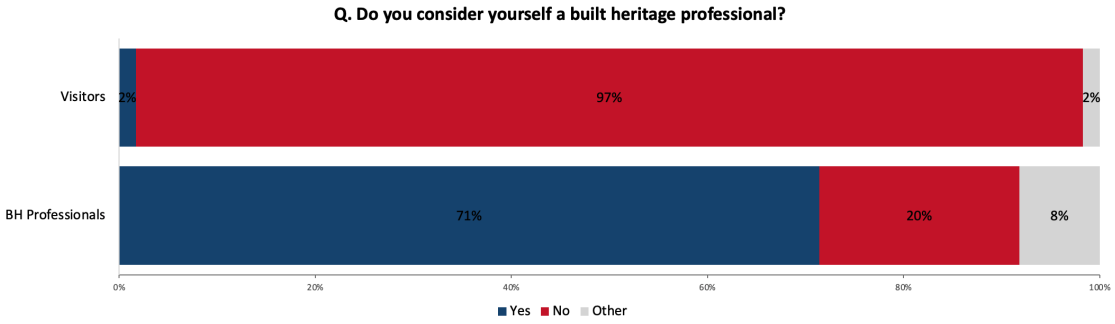


Figure 3.1: Survey participants' self-reported built heritage experience

Part I of the survey established the participants' background and level of built heritage experience, beginning with their occupation. The participants in each survey were asked whether or not they self-identified as built heritage professionals (Q1), Fig 3.1. In the expert survey (71%, n=36) agreed, (20%, n=10) disagreed, and (8%, n=3) identified as 'other' . In comparison, in the visitor survey (2%, n=1) agreed, (97%, n=88) disagreed, and (2%, n=1) identified as 'other' .

The EOS also asked for participants to list their job title voluntarily (Q2). All (20%, n=10) participants who disagreed with the self-identification of 'built heritage professional' identified as experts or professionals working in another aspect of conservation, for instance paper, furniture, or materials conservation.

To determine the accuracy of these self-identified answers, both sets were then asked whether or not they had been involved with the restoration or conservation of a listed building or scheduled monument (Q3). In the expert survey (82%,

n=40) agreed and (18%, n=9) disagreed, while in the visitor survey (8%, n=7) agreed while (92%, n=83) disagreed.

As expected, only a small number of visitor survey participants had been involved with the conservation of a listed building or scheduled monument compared to the built heritage experts. After speaking with these participants, we noted that several participants owned Grade II listed houses and had been involved with personally restoring their homes, while another visitor was the church warden of a Grade I listed church and had overseen the restoration of several aspects of the church.

3.7.2 Participants as heritage visitors

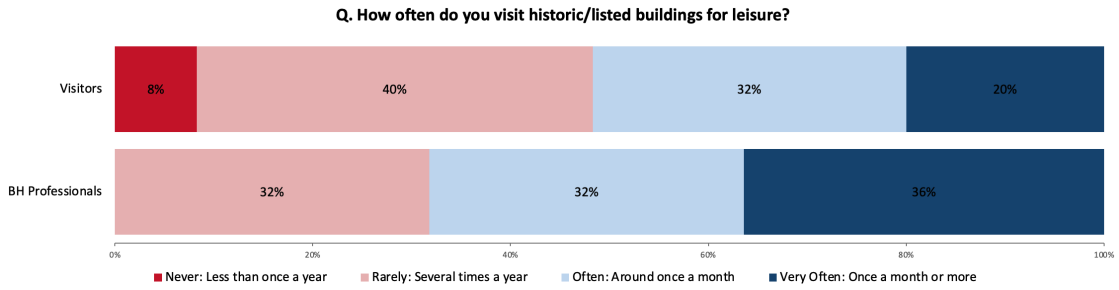


Figure 3.2: How often do survey participants visit historic buildings for leisure?

Participants from both surveys were asked to identify how often they visited historic buildings for leisure (Q4), Fig 3.2. They were asked to choose one answer from a modified Likert scale: (Never - Less than once a year, Rarely - Several times a year, Often - Around once a month, and Very Often - More than once a month).

When asked how often the respondent visited historic buildings for leisure, EOS respondents were the most likely to visit 'Very Often: Once a month or more' (36%) compared to VOS respondents, who were most likely to visit 'Rarely: Several times a year' (40%). Additionally, 8% of VOS respondents agreed that they 'Never: Less than once a year' visited historic buildings for leisure, while none (0%) of the EOS respondents agreed with that statement.

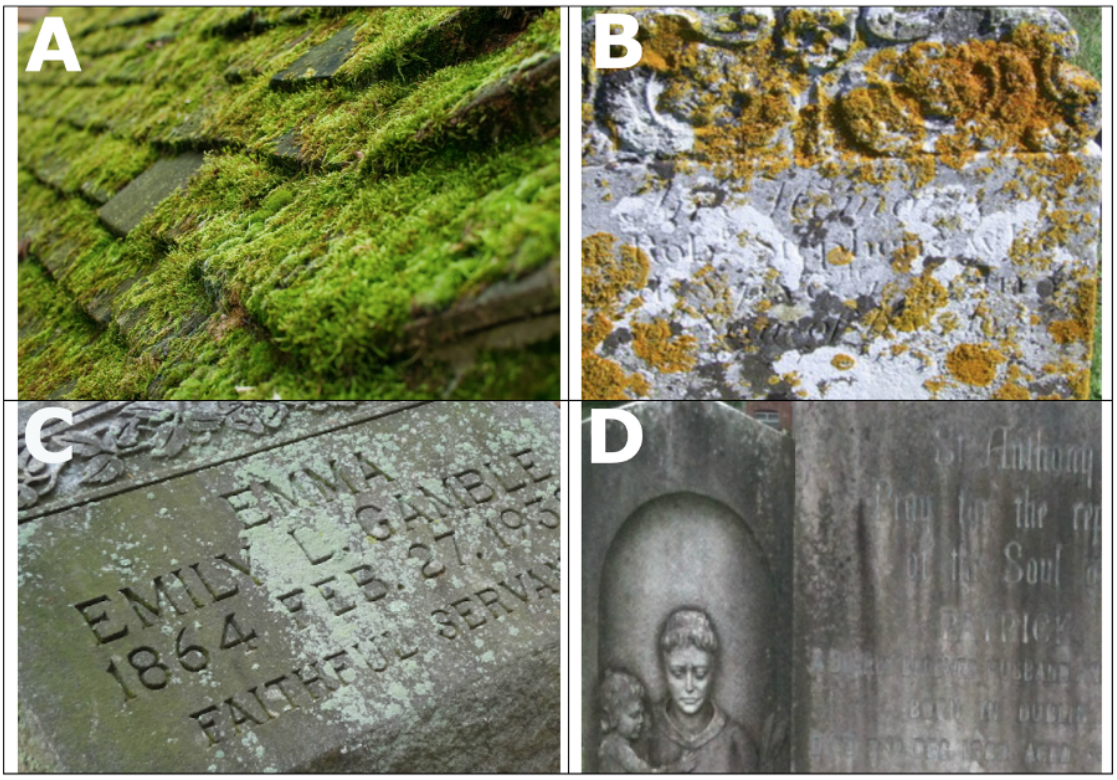


Figure 3.3: Identification of biological growth question, showing: A - Mosses, B and C - Lichens, and D - Cyanobacteria

3.7.3 Participants' knowledge of moss

Part II of the survey delved further into the respondent's level of knowledge about mosses and their perceptions of the effects of mosses on buildings, starting with their self-identified level of knowledge about mosses. Q5 simply asked respondents to state their level of knowledge about mosses from 1-5. When comparing visitors and experts, experts are more confident in their ability to identify mosses than visitors. The around half of the experts (51% of EOS respondents) indicated that their level of moss knowledge was good or high, compared to only 27% from the visitor survey. Results from an unpaired t-test gives a p-value of < 0.0001 which is statistically significant. We can see here that there is a demonstrable difference in the self-stated level of moss knowledge between visitors and experts.

Q6 used the image in Fig 3.3 without the identifying caption and asked the participants to identify which image(s) in the collage showed moss growth. This question determined the participants' baseline level of moss knowledge, and whether

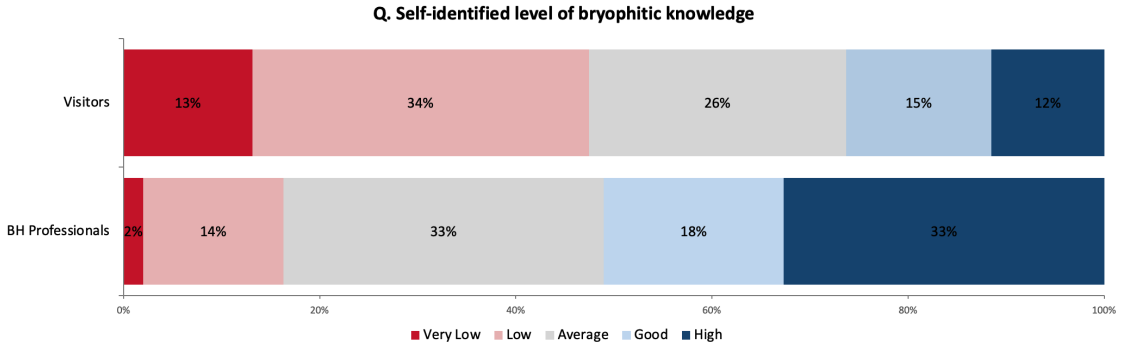


Figure 3.4: Survey participants' self-identified level of moss knowledge

there were any significant differences between experts and visitors. Since the question was multiple choice, and marked 'check all that apply,' it was also used to examine whether moss growth is commonly confused with other types of biological growths commonly found on built heritage (for instance, lichens, algae, and cyanobacteria). Overall, 86% of experts and 33% of visitors correctly identified moss growth from the image provided. We can see that there is a large gap in knowledge between experts and visitors when it comes to identifying moss correctly.

Additionally, the survey analysed whether respondents may be overconfident in their level of moss knowledge. We analysed participants' responses using a 2-sample t-Test to determine if there was a relationship between them indicating a high level of moss knowledge (Q5) and correctly identifying moss growth from Fig 3.3. Indeed, our findings indicate a moderately positive significant relationship (r=0.368) between the level of self-identified moss knowledge and correctly visually identifying moss growth from a collage of different types of biological growths.

If a respondent misidentified mosses from the grouped images in Fig 3.3, the results and answers in the following questions still remain significant. A relatively high number of respondents misidentifying mosses is relevant because this means that treatments, management strategies, and cleaning of buildings could be undertaken on the basis of misinformation. It shows that even self-identified built heritage professionals are still unsure of identifying moss growth, and that special care should be taken to consult professionals trained in biological growth.

3.7.4 Aesthetics of moss growth

Q11 looked at whether visitors and experts enjoyed the look of mosses on historic buildings, and whether they thought that the presence of mosses added any value to the look of a historic building using a 5-point Likert scale. For both visitor and expert surveys, the majority of respondents felt positive about the look of moss growth. Overall, experts are more likely to enjoy the look of mosses on historic buildings than visitors, with 90% of respondents marking 3/5 or higher when asked if they agree with the statement 'I enjoy the look of mosses on historic buildings' compared to visitors, with 77% of respondents marking 3/5 or higher. Results from the Pearson Correlation Coefficient gives a p-value of < 0.1164, at $p = 0.05$, the result is not statistically significant. The results suggest that both visitors and experts mildly enjoy the appearance of mosses on historic buildings.

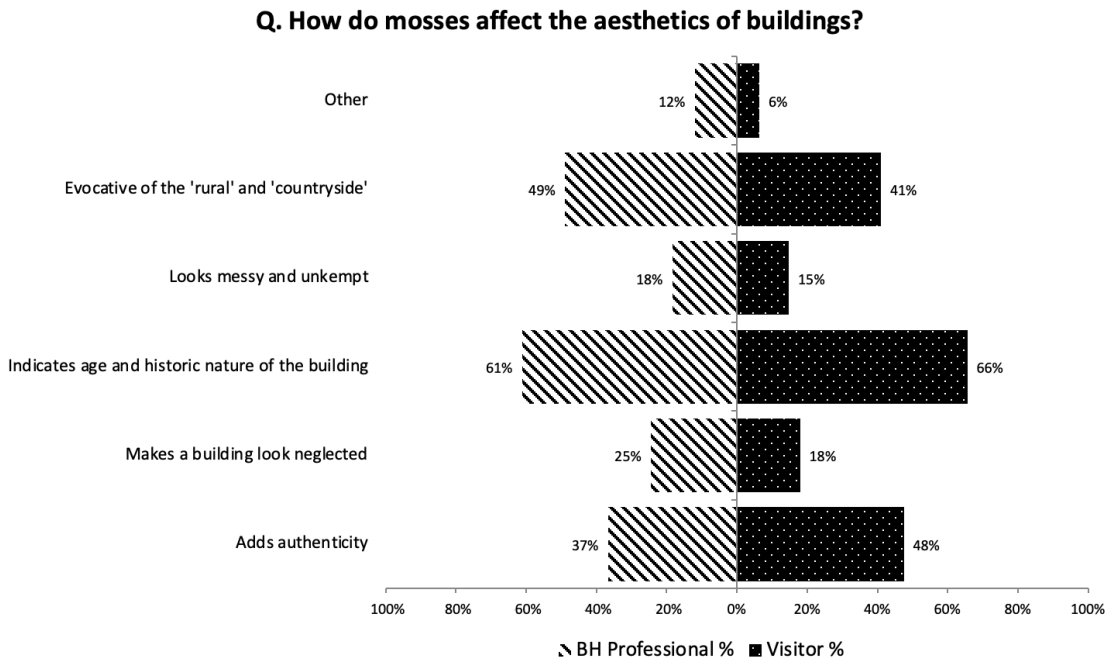


Figure 3.5: Comparison between visitors and BH professionals, 'How do mosses affect the aesthetics of buildings?'

When asked in Q10, 'How specifically do mosses affect the aesthetics of buildings?' both experts and visitors agreed that they strongly indicate the age and historic nature of buildings, are evocative of the 'rural' and 'countryside' and add authenticity

Fig 3.5. These findings correspond with previous research on biological patinas found on historic buildings, where many interviewees "expressed positive values associated with ageing, weathering and decay. For most visitors to the case study sites, marks of age, weathering and decay played an important role in establishing the authenticity, significance and aesthetic appeal of buildings and monuments, as identified by Riegl and Ruskin over a century ago" (Douglas-Jones 2016, p 825). Additional research supports the idea that the perception of 'authenticity' of cultural heritage sites in urban environments is complex and multilayered, since it relies on both physical and intangible aspects, and is "more than to the exact restoration of urban details" (Martokusumo 2011, p 187). Some small differences in perceptions appear when examining the language surrounding the description of mosses, with visitors agreeing more with negative descriptors such as "looking messy and unkempt" or "neglected" and experts agreeing more with positive descriptors such as "authenticity" Fig 3.5.

3.7.5 Perceptions of damage

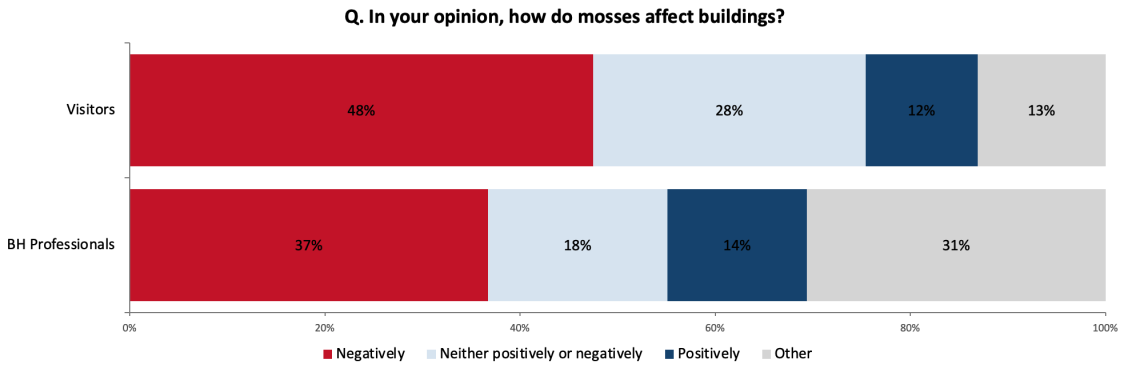


Figure 3.6: Comparison between visitors and BH professionals, whether mosses positively or negatively affect buildings.

Both sample sets were asked how, in their opinion, mosses affected historic buildings (Q7), and were given the choices: 'Positively: They protect the surface from damage', 'Negatively: They shorten the lifespan of buildings', 'I do not believe they positively or negatively affect the building in any way' and 'Other' Fig 3.6. In this case, 'Other' may indicate that the respondent is unsure and did not wish to speculate, or they may believe that the impact of moss growth may increase

depending on the quantity and spread of the colonisation. Both the EOS and VOS results showed a common opinion that mosses negatively affect buildings by shortening the lifespan (37% of EOS respondents and 48% of VOS respondents). When comparing the results from this question, overall the visitors hold a slightly more negative view of moss growth on buildings compared to experts, and experts are more reluctant to give a definite opinion on their effect either way.

More specifically, respondents were then asked in their opinion how mosses interacted with the built heritage substrate (Q8). In a question marked 'check all that apply,' they were given 8 options plus the ability to give their own response if they had another idea not already listed Fig 3.7.

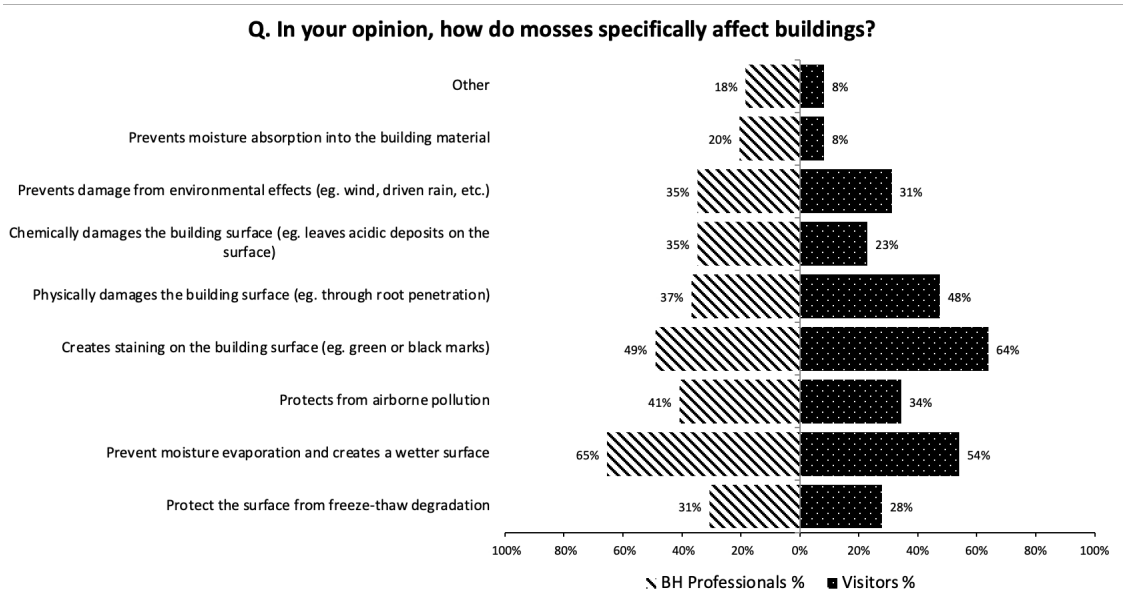


Figure 3.7: Comparison between visitors and BH professionals, how mosses specifically affect buildings.

This question showed a marked difference between the experts and visitors Fig 3.7. When ranking the answers by the percentage of respondents agreeing with the statement, the EOS' first choice was, 'Prevent moisture evaporation and creates a wetter surface' (65% of respondents), while the VOS' first choice was, 'Creates staining on the building surface' (64%). However, overall it appears as if respondents to both the EOS and VOS have slightly more negative views of moss growth's effect on built heritage substrates, and think that moss causes harm

physically and chemically. Around 1/3 of respondents from both the EOS and VOS believe that mosses have protective qualities, agreeing that mosses protect the surface from freeze-thaw degradation and airborne pollutants.

Finally, when asked specifically whether mosses should be removed from historic buildings (Q9), an overwhelming percentage agreed that they should only be removed in certain cases (71% both EOS and VOS). Both sample sets agreed that moss growth should only be removed if mosses are certain to have caused damage (or will cause damage) to the substrate and would negatively affect the lifespan of the heritage asset.

3.8 Discussion

As seen in the results, experts are both more experienced and knowledgeable regarding built heritage, and they also have a higher level of familiarity and knowledge with identifying moss growth than visitors. This is to be expected due to their involvement with built heritage conservation and restoration projects, as seen from the results of Q3. The level of confidence in moss knowledge for both experts and visitors also seems to correspond with the likelihood of correct moss identification, with experts indicating a higher level of baseline knowledge and correct identification (Q5 and Q6).

From the survey results, while experts tend to enjoy the look of mosses on heritage buildings more than visitors, they are also more likely to acknowledge that they may cause damage to the physical structure of the building by preventing moisture evaporation and increasing surface wetness. Both visitors and experts have a nuanced view of moss growth, agreeing that the presence of moss is likely beneficial in some way to the structure by protecting it from freeze-thaw damage and airborne pollutants. However, when asked whether mosses should be removed from heritage buildings both the EOS and VOS are in agreement - mosses should only be removed in very specific cases.

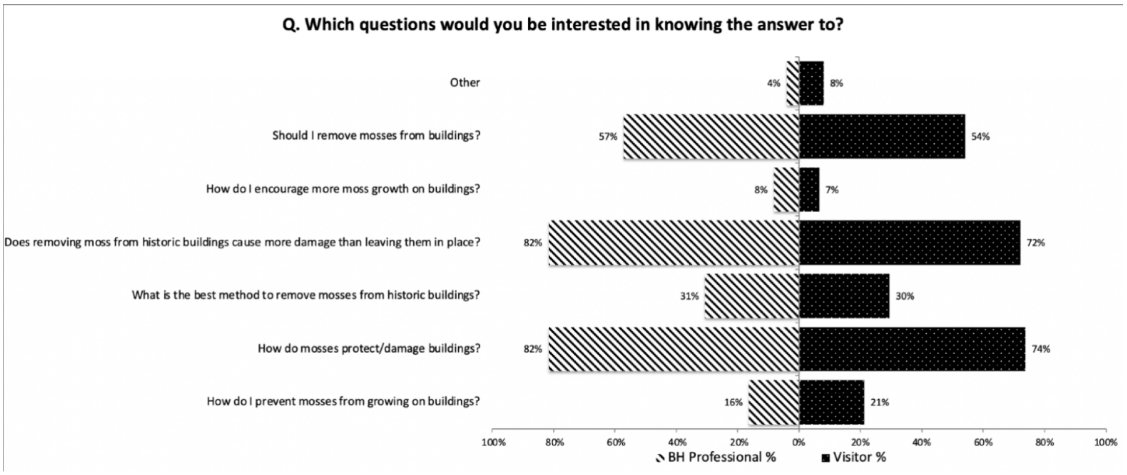


Figure 3.8: Identifying further research questions.

3.8.1 Further Questions

Fig. 3.8 identified gaps in knowledge about moss growth and the interaction with built heritage, indicated by both experts and visitors. The three questions clearly identified as most in need of answering from both surveys are:

1. How do mosses protect/damage buildings?

2. Does removing mosses from historic buildings cause more damage than leaving them in place?

3. Should I remove moss from buildings?

3.9 Conclusions

Both experts and visitors to historic buildings have a nuanced view of moss growth on historic buildings, acknowledging that while there are likely negative effects of the biological patina, that there may be protective qualities provided by its presence as well. The main objective of this paper was to determine if findings from heritage professionals and visitors to a range of heritage sites confirmed previous research about the aesthetics of biological growth on buildings. Our survey found that both visitors and experts enjoyed the look of mosses on buildings, and also ascribed similar values and characteristics to building with mosses as previous

research. These findings indicate that mosses are commonly associated with positive values such as 'authenticity' and 'history.' The responses from the survey indicate that mosses on historic buildings are not only expected, but welcomed, especially in the cases of rural heritage.

3.9.1 Key findings

- Experts are more likely to have a higher level of moss knowledge and are more likely to correctly identify images of moss growth. There is also a significant relationship between self-identified level of moss knowledge and incorrectly visually identifying moss.

- Both experts (71%)(n=35) and visitors (71%)(n=67) strongly believe that moss growth should only be removed from historic buildings on a case-by-case basis.

- There are 3 primary questions to focus on for future research into moss growth on historic buildings (as outlined in 3.8):

- Both experts and visitors agree that moss growth on historic buildings is a strong indication of age, authenticity, and the 'countryside'.

- Visitors have a more negative view of moss growth than heritage professionals - both in terms of the aesthetic qualities and in terms of how they affect the building lifespan and deterioration.

3.9.2 Implications for conservation

One of the key findings in this paper determined that both experts and visitors do not view moss growth on historic buildings as detrimental to the aesthetic experience, and strongly support only removing moss growth when or if they cause problems to the underlying substrate. Again, this aligns with previous research supporting the idea that biological growth and the greening of heritage sites, especially rural heritage sites, contributes to the aesthetic appreciation and context of the site.

The survey results give some support to the idea that conservation site managers can employ a less aggressive management strategy on biofilms when it concerns moss growth. In terms of management strategies, perhaps the 'Ethics of doing nothing' approach has merit when it comes to moss growth on historic buildings, with an emphasis on long-term monitoring strategies (Ashley-Smith 2018). Since moss is a relatively slow-growing organism in comparison to higher plants, these findings may help shape long-term conservation management plans. The added benefit that the presence of mosses can add value to the heritage site through 'authenticity', 'age', and the idea that the biological patinas are an indication of the passage of time.

More research is needed to understand the biochemical and biomechanical impacts of mosses on built heritage materials. Although the results from this survey suggest a more relaxed approach to cleaning mosses from heritage sites, there is relatively less known about the specific impacts that mosses can have on their underlying substrates. To truly understand whole impact that mosses have on built heritage, these impacts should be investigated in combination with the aesthetic and contextual impact on built heritage structures.

Moss is a plant, that the wisest of kings thought neither unworthy his speculation, nor his pen, and though amongst plants it be in bulk one of the smallest, yet it is not the least considerable: For, as to its shape, it may compare for the beauty of it with any plant that grows...

— Robert Hooke, Micrographia, 1665

4

Visualization & Workflow

Contents

4.1 Visualization workflow for analyzing moss impacts at the lithobiontic interface on limestone built heritage . 50
4.2 Abstract 50
4.3 Introduction 51
4.4 Materials and Methods 57
4.4.1 Workflow 57
4.4.2 Step 1 - Visual Assessment 58
4.4.3 Step 2 - 3D Microscopy 59
4.4.4 Step 3 - Optical Light Microscopy (OLM) 60
4.4.5 Step 4 - Scanning Electron Microscopy (SEM) 60
4.5 Results 61
4.5.1 Step 1 Findings: Visual analysis/Condition assessment of sample blocks 61
4.5.2 Step 2 Findings: Keyence 3D microscopy and profilometry . . . 63
4.5.3 Step 3 Findings: Optical light microscopy from polished thin sections of weathered sample limestone 65
4.5.4 Step 4 Findings: SEM of cross-sections of weathered limestone 66
4.5.5 Evaluation of the proposed 4-Step workflow 71
4.6 Discussion 72
4.7 Conclusions 73

4.1 Visualization workflow for analyzing moss impacts at the lithobiontic interface on limestone built heritage

Authors: Jang, K. and Viles, H. This work has been submitted to the *International Biodeterioration and Biodegradation* with minor changes to the text and formatting.

Keywords: Bioprotection, biodeterioration, bryophyte, moss, cultural heritage, workflow

4.2 Abstract

Lithobiontic (rock-dwelling) organisms (such as bacteria, algae, lichens and mosses) commonly grow on stone-built cultural heritage, and have been recorded to enhance stone deterioration at the interface between organism and stone (here called the lithobiontic interface). The lithobiontic interface has been well-researched for lichens, however much less is known about moss-dominated lithobiontic interfaces. This paper outlines a workflow involving the staged use of a number of complementary techniques to visualise and analyse the lithobiontic interface, and applies it to a set of weathered limestone blocks with known moss colonisation histories. The workflow is used in this paper on a limited sample set to characterize the impacts of a single moss species, but has the potential to enhance the visualization of many other lithobiontic interfaces. The workflow deploys visual analysis, optical light microscopy (OLM) of petrological thin-sections, 3D microscopy, and scanning electron microscopy (SEM). Findings indicate that *Brachythecium rutabulum* growth on limestone blocks is associated with rougher surfaces compared to freshly cut surfaces, and those covered in lichen and algae when exposed for the same amount of time. Evidence was also found of the nature of mosses as secondary colonisers, through observations of the presence of moss growth in lichen perithecial pits. Analysis of the cross-section through weathered limestone substrates found that the moss-rock interface extended 0.1-3.0 mm below the rock surface – similar to that under lichens on the same limestones. Additionally, moss rhizoids within

the rock substrate were commonly found to be associated with calcium carbonate crystal formation. The findings support previous research describing mosses as agents of biodeterioration through increased biogeochemical and biogeomechanical weathering. The workflow and complementary methods proposed here provide a template for future research on the roles mosses play in the biodeterioration and bioprotection of stone-built cultural heritage.

4.3 Introduction

Mosses (bryophytes) are common components of the flora growing on rocks and building materials, occupying what is often called the lithobiontic ecological niche or lithobiontic interface. The lithobiontic ecological niche or interface has been widely characterized as the zone in which organisms interact with the underlying substrate (Golubic et al. 1981; Makhalanyane and Cowan 2014). Unlike many other lithobiontic organisms, relatively little is known about the impacts that mosses have on their underlying substrates. In general terms, such impacts can be defined as being either biodeteriorative or bioprotective in nature (Carter and Viles 2005; Favero-Longo and Viles 2020; Zhang et al. 2019). Establishing the balance between biodeteriorative and bioprotective impacts of specific mosses is very important in order to understand the dominant roles that they may play on rocks and building materials. In turn, this knowledge can inform management strategies for mosses growing on built cultural heritage. In order to explore the impact of mosses it is necessary to investigate the interactions between mosses and the underlying substrate within this lithobiontic interface.

Lithobiontic organisms have multiple impacts on the surface of built cultural heritage. They are known to contribute to both physical and chemical weathering, under the umbrella term of biodeterioration (Carter and Viles 2005). Chemical biodeterioration due to lithobionts, also known as biogeochemical weathering, is defined as a naturally occurring phenomenon as a result of digestive processes and byproducts of the growth of lithobiontic organisms (Adamo and Violante 2000). This can include deposition of oxalic acids or chelating agents on the substrate, leading

to chemical dissolution of the underlying material, nutrient uptake by rhizoids or hyphae, or neoformation at the surface leading to biocrusts and crystal formation within the stone matrix itself (Carter and Viles 2005; Favero-Longo and Viles 2020). Furthermore, mechanical disintegration and disaggregation of mineral grains may occur as a result of growth processes and/or stresses generated by wetting and drying of lithobiontic organisms (Smith et al. 2008). These biochemical and biomechanical impacts can, in combination, lead to the production of microscale features such as hyphal pitting, biotroughs, and etching (de la Rosa et al. 2012) and enhance surface roughness which can encourage further deterioration. Surface roughness is an important indicator on stone-built cultural heritage with roughness measurements used to assess surface age, level of deterioration, and suitability for cleaning methods (Vazquez-Calvo et al. 2012). Thus surface roughness is an important factor when considering long and short-term management strategies (Pinheiro et al. 2019). Furthermore, from previous research we know that biological remnants and moss fragments have been found on the surface of cultural heritage even after cleaning has taken place, meaning that the evidence of moss growth is very difficult to remove once established (Savković et al. 2016).

However, the presence of a lithobiontic layer is not always necessarily negative and a strict cause of biodeterioration, indeed in some cases closely-bound biological growth has been found to have a protective effect on substrates by protecting them from environmental effects and surface deposition, as in the case of Roman pavements in Cadiz, Spain colonised by lichens (Ariño et al. 1995) by acting as both active and passive mechanisms of bioprotection (Carter and Viles 2005). As the role of lithobionts is complex and multilayered, and many species can have both positive and negative impacts on the underlying substrate, a considered approach is needed when researching the lithobiontic interface of understudied organisms such as mosses growing on built cultural heritage (Caneva et al. 2020; Owczarek-Kościelniak et al. 2020).

Much of what is known about the lithobiont interface in cultural heritage research is derived from research on lichens, and many findings from lichens have

simply been translated to the moss-rock interface (Matteucchi et al. 2019; Tonon et al. 2019). However, the physiology and morphology of most common bryophyte species are vastly different to those of most lichen species, and therefore moss effects on the rock surface should not be assumed to be the same as those of lichens. Lithobiontic lichens can broadly be separated into two growth forms, i.e. endolithic and epilithic. Endolithic lichens have reproductive structures embedded within the substrate whilst epilithic lichens have reproductive structures covering the surface of the substrate (Morando et al. 2017). Through microscopic and spectroscopic analyses, the hyphal penetration of several species of crustose (both endolithic and epilithic) lichens was observed between 1-3 mm below the surface of Portland and Botticino limestone (Morando et al. 2017). In comparison, although bryophytes like lichens are non-vascular plants, they have very different morphologies and primarily absorb water and nutrients through leaf-like structures called phyllids and attach to the substrate through small structures called rhizoids (Coe et al. 2014; Hanson and Rice 2014). Through the microscopic analyses in this project, we expect to find some intrusion into the rock matrix or attachment mechanisms based on knowledge of moss physiology and morphological structures (Morando et al. 2017). Based on previous research about the chemical weathering processes of mosses, we also expect to find some evidence of oxalate crystals or other chemical deposition near the rhizoid terminus.

The nature of the lithobiontic interface (in terms of depth and surface coverage) varies depending on the organisms involved. From research on lichens on limestone, the interface zone (defined as extending from the rock surface downwards to the extent of clear traces of lithobiontic growth, such as fungal hyphae, moss rhizoids, etc.) has been found to be up to 3 mm deep (Morando et al. 2017). For mixed microbial biofilms the lithobiontic interface is likely to be much less deep (Giustetto et al. 2018; Lybrand et al. 2019; Prieto et al. 2020). The depth of the moss lithobiontic interface is largely unknown, however, as found by previous research on endolithic and epilithic lichen growth forms, the affected depth of the lithobiontic zone is likely to vary depending on the species of moss studied (Morando et al. 2017).

In one study on the deterioration of Angkor temples (Cambodia), moss rhizoid penetration attributed to the *Fissidens* genus on sandstone appeared to measure 2.46 mm in depth (Bartoli et al. 2014). The spatial extent of the lithobiontic interface across the surface is also likely to vary hugely between different organisms and substrates. When we consider the growth rate of lichens and mosses, most species of lichens grow less than one millimeter per year (Büdel and Scheidegger 1996) whereas some common species of mosses have been measured to grow more than one millimeter over two days (Asada et al. 2003). These results indicate that the spatial coverage of lichens is relatively stable, whereas the spatial coverage of mosses could vary hugely from year to year (Pfendler et al. 2020).

When addressing the spatial extent of moss, it is also important to recognize its two major growth forms; pleurocarpous and acrocarpous. In comparison to lichen thalli, which grow primarily in circular patches and eventually coalesce, and microbial biofilms, which often form extensive and uniform patches of 'greening,' bryophytes have two distinct growth forms (Gallenmüller et al. 2018). Pleurocarpous bryophytes are often described as 'carpeting,' growing relatively quickly with a form growing as a creeping, lateral mat with amorphous edges. Their flat profiles are tightly bound to the underlying substrate even in their desiccated form. On the other hand, acrocarpous mosses form circular cushions and are slower growing than pleurocarpous bryophytes. They have a higher profile and are more loosely bound to the substrate, and in more immature cases can easily be knocked off by high winds in their desiccated form. Recognizing these two different growth forms of bryophytes, it is likely that their associated lithobiontic interface would vary both laterally and vertically.

This paper proposes a workflow for sampling, visualizing and analyzing the lithobiontic interface on built cultural heritage with a particular focus on mosses. The use of specific workflows is common within other areas of cultural heritage research, such as within 3D modelling of cultural heritage objects to optimize the efficiency of model creation and create high resolution images of large-scale objects (D'Annibale et al. 2013). This paper follows the suggestion of D'Annibale et al.

(2013) to apply optimized visualization methods and workflow to other areas of heritage science. The purpose of the workflow in this case is to increase efficiency and to provide a protocol for sampling to create the best visualizations. Furthermore, within heritage science, we are often constrained by the number of samples available when sampling approaches favour non- or low-destructive methods to limit the amount and scope of damage to the cultural heritage setting (BS EN 16085:2012). Therefore, it is important to maximize the surface area of precious samples available for analyses, and to avoid premature damage to samples for later analyses in the workflow. Moreover, interdisciplinary research such as heritage science often relies on shared workspaces and equipment, so having a workflow maximizes time efficiency within these shared spaces. This paper introduces four complementary techniques to visualise the lithobiontic interface of moss growing on cultural heritage. When used in combination visual analysis, optical light microscopy of polished thin sections, 3D microscopy, and SEM work together well to characterize the surface and near-surface relationship between moss and the stone substrate. To show how this workflow might be useful in a realistic cultural heritage environment where there may be limited samples for analyses, this paper demonstrates this workflow by using it to visualize the moss-rock interface on weathered limestone samples.

This study focuses on the moss species *Brachythecium rutubulum* (Rough-stalked feather moss), which is widespread worldwide, especially in the northern hemisphere (Urmi and Schnyder 2007). Defined as a tenacious species of moss with a relatively rapid growth rate, *B. rutabulum* also has the capacity to co-exist and compete with vascular plants (Furness and Grime 1982). When grown in the laboratory, *B. rutabulum* maintained exponential growth over a 30-day period and "attained a relative growth rate of 0.071 mm/day – a value exceeding the reported maxima for seedlings of ten vascular plant species" (Furness and Grime 1982, p. 513). *B. rutabulum* is one of the most commonly found species of mosses in the United Kingdom, as found by a survey of bryophytes in arable land in Britain and Ireland (Preston et al. 2010). In a detailed survey of King's Lynn, Norfolk UK, *B. rutabulum* was cited as one of the most common species of bryophytes surveyed, indicating

that they survive and thrive in urban environments in the UK as well as rural (Stevenson and Hill 2008). This survey found that *B. rutabulum* was one of the three most common pleurocarpous mosses found in arable fields, along with *Kindbergia praelonga* and *Oxyrrhynchium hians*.

Studying this species in light of its rapid growth, widespread nature and biogeography is also important in the context of cultural heritage. Due to the characteristics of this species of moss, it is likely that many heritage sites in the United Kingdom and elsewhere that have moss growth will also have some presence of *B. rutabulum*. As seen in a survey of species richness of biological growth at medieval castles in Central Europe, *B. rutabulum* is one of the noted species recorded and is found particularly on calcareous wall surfaces (Steinbauer et al 2013).

Most methods chosen for this workflow study are already widely used within lithobiontic interface studies. Visual condition assessments are used to assess and characterize weathering features, quantify and identify common species of biological growth, and when combined with photography can be used to track decay over time (Scrivano et al. 2017). Multiple forms of microscopy have been used to investigate the surface and near-surface lithobiontic interface, both to identify the biological species colonizing the substrate, and to quantify the depth of the affected zone (Ljaljević Grbić et al. 2000; Morando et al. 2017; Alfieri et al. 2020; Beata 2020). In addition to these well-established analyses, this workflow proposes additionally using multifocal 3D microscopic imaging techniques (depth-from-defocus) to understand the topographical surface and interaction between biological growth and the underlying substrate. The use of multifocal 3D digital light microscopes to visualize surface topography, surface roughness, and colour change in cultural heritage contexts is a relatively novel tool and offers the ability to relate surface colour and biological coverage with surface roughness (Ashkenazi and Cvikel 2020).

This paper proposes a workflow to characterize and quantify the effects of moss on the lithobiontic interface on built cultural heritage. In addition, the paper uses that workflow on a set of limestone blocks exposed for 7 years in a temperate

grassland environment to test the hypothesis posed by previous researchers that moss rhizoids disintegrate and disaggregate the underlying substrate (Garcia-Rowe and Saiz-Jimenez, 1991; Herrera et al. 2004, 2009).

4.4 Materials and Methods

This project utilizes a set of 15 x 15 x 15 cm cubes of Portland limestone left out in a temperate grassland in 2010 at Wytham Woods, Oxford as part of an unpublished research project (Eklund, 2010). The cubes were cut from two types of Portland limestone - fine-grained Jordan Basebed (JB) and coarse grained, fossil encrusted Bowers Roach (BR). In total, 12 JB and 4 BR blocks were weathered at the Wytham Woods field site. In 2010 the cubes were placed with bedding planes horizontal on a geotextile in an open field setting (51°46'12.7"N 1°19'58.8"W). The cubes were left on site to weather naturally and collected in autumn 2017, after 7 years of exposure. For the purposes of this project, 6 JB and 2 BR blocks were recovered along with the 1 JB and 1 BR control blocks which had been stored in a controlled environment lab facility in Oxford.

Wytham Woods is a semi-natural woodland site used for research and testing near the village of Wytham, just north of Oxford (latitude 51.776, longitude -1.317). Owned and maintained by Oxford University since 1942, it spans over 400 ha and contains a semi-natural woodland, secondary woodland, limestone grasslands, and natural plantations. The Oxford Resilient Buildings and Landscapes Laboratory (OxRBL) has a test site in Wytham Woods in which a range of heritage stone materials are exposed in the form of blocks and test walls.

4.4.1 Workflow

Fig 4.1 explains the workflow and sampling method which was developed to minimize the amount of stone material required and to enable repeat measurements of the same area with different techniques. The proposed workflow provides a step-by-step process for visualizing the lithobiontic interface.

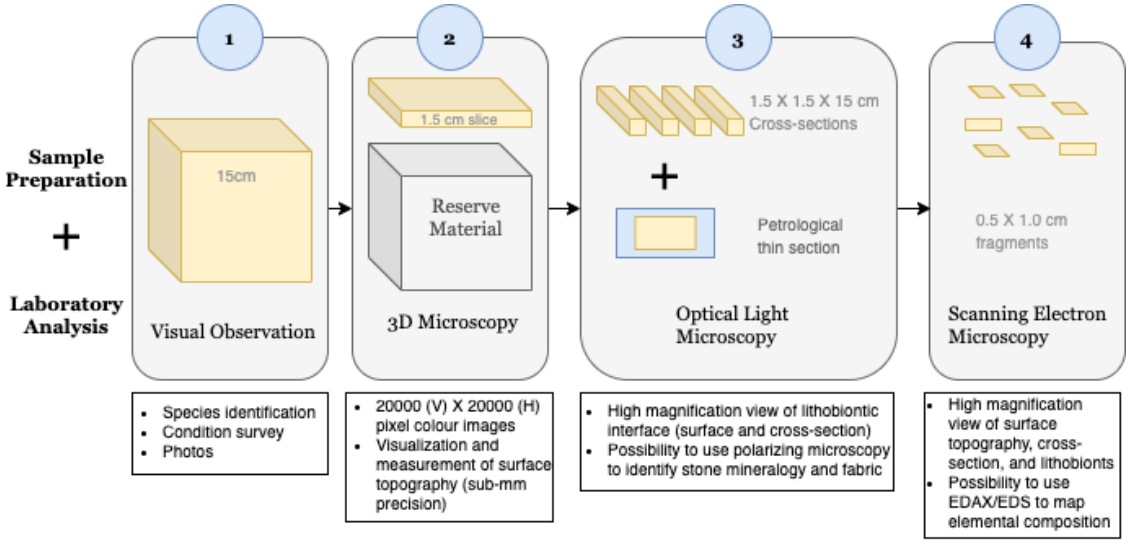


Figure 4.1: Diagram showing block sampling technique and steps 1-4 of the workflow

4.4.2 Step 1 - Visual Assessment

Step 1 assesses the weathered sample and categorizes any visible signs of deterioration before and after biological material is removed. The amount of biological coverage is noted, along with any visual signs of weathering as defined by the ICOMOS-ISCS Illustrated Glossary on Stone Deterioration Patterns. Photographs should be taken of the samples before and after biological growth is removed (Morillas et al. 2018). Loose biological material is removed from the surface of the samples to view the underlying substrates. Removal protocols may differ depending on the type of biological growth, and care should be taken to preserve attachment mechanisms for visualization in later steps (Mascalchi et al. 2020).

In this case study, 11 15 cm weathered cubes of Portland limestone were assessed visually to characterize the biological growth, identify obvious biogeomechanical weathering features, and to indicate areas of interest to sample for later analyses. An initial visual condition inspection was also undertaken at this point. The weathered blocks were photographed (using a Sony ARII camera with 50mm 1.2 lens) and visually mapped for biological growth coverage. This included species identification and percentage cover. Special care was taken to preserve the attachment mechanisms of the rhizoids to the substrate. A sharp scalpel was used to carefully slice away the

loose material, including stalks, leaves and seta, while leaving the rhizoids intact (Mascalchi et al. 2020). This was done to preserve the rhizoid attachment mechanism and any penetration into the stone substrate that may have occurred. Building on previous studies, we should see visual evidence of neoformation, disaggregation, and oxalic acid on the moss-rock interface at the surface or near-surface level.

4.4.3 Step 2 - 3D Microscopy

Step 2 assesses a smaller portion of the chosen weathered sample for surface roughness using the Keyence VHX-6000 3D microscope. As described in Fig 4.1 a 1.5 cm slice is removed from the weathered blocks, providing a weathered surface and freshly cut surface for imaging and analysis in this step. Using the VHX XYZ-stage, colour 3D images can be photo-stitched up to 20000 (V) x 20000 (H) pixels. Ideally the sample analyzed during this portion of the workflow should have one weathered surface and one freshly cut surface. This would allow direct comparison using the profilometry capabilities of the Keyence microscope.

In the case study example, a 1.5 cm thick slice was removed from the surface of the weathered block. This produced a large, flat area ideal for imaging using depth-from-defocus software. The slice had two flat 15 x 15 cm surfaces; one which had been exposed during the exposure trial, and the other which had been freshly cut and acted as a control. The bulk of the sample was then set aside and reserved either for future sampling, or to resample in case of errors. Using the 1.5 cm slice (see Fig.4.1), images were taken with the Keyence 3D microscope VHX-6000 series and then photo-stitched to show larger areas of both the weathered surfaces and freshly-cut surfaces. Using the profilometry capabilities of the Keyence 3D microscope, 6 x 3 cm lengths across areas with and without moss growth were measured to determine their mean and maximum Δ depth, Table 4.2. The mean value from these measurements was determined for both weathered and unweathered surfaces, to indicate whether moss had an impact on the surface roughness and texture of a weathered surface.

4.4.4 Step 3 - Optical Light Microscopy (OLM)

Step 3 analyzes cross-sections of the weathered material to determine if there is evidence of lithobiontic growth within the stone matrix. Rectangular cross-sections of the samples are cut from the slice used in Step two and are analyzed using OLM. Additionally, standard petrological thin-sections are prepared using cross-sections of the weathered material. The weathered material is shaved to 30 microns thick, impregnated in resin and placed on a glass slide for viewing.

In the case study example, a Leica Stereomicroscope MZ10F was used to analyze four petrological thin sections of cross-sections through the weathered material. This stage allowed us to view the affected lithobiontic interface, and how far it might extend below the surface. Following the modified methodology of previous lichen-rock interface research (Gazzano et al. 2009), microphotographs were taken using petrological thin-sections of colonised limestone. In comparison to the Gazzano methodology, the thin sections were not dyed to view organic matter, since the bryophyte rhizoids were visible with the naked eye.

4.4.5 Step 4 - Scanning Electron Microscopy (SEM)

Step 4 uses a Hitachi scanning electron microscope (SEM) S-4300 to view direct and oblique angles of the top surface and cross-sections through the weathered material. These pieces are carbon coated and affixed to the stub mounts using carbon tape. Both 45° angle and flat stub mounts are used, in order to directly image the surface of the stone, and so that we can see a direct and oblique view of the surface to highlight the attachment mechanisms and to quantify the depth penetration into the matrix of the stone.

In the case study, the remaining portion of the slice from Step 2 was used to quantify the affected lithobiontic interface. A thin, 0.5 cm portion of the weathered surface was isolated using a hand saw, and then snapped by hand into pieces roughly 1.0 cm wide for stub mounting. During this step, 11 pieces from four representative blocks were used to give a representative overview of the blocks with and without moss cover.

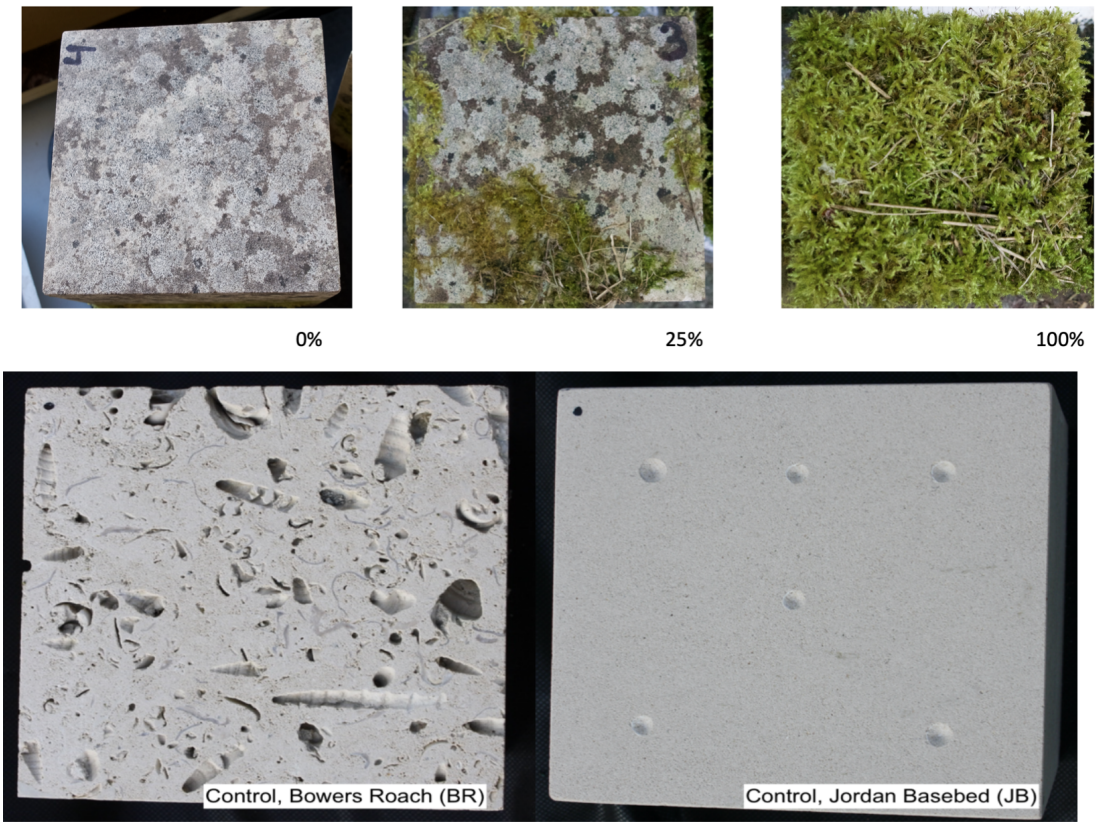


Figure 4.2: Surface photographs of weathered blocks shown before surface clearing, at different percentages of moss coverage. Block 2, showing 100% cover in the image is completely obscured

4.5 Results

4.5.1 Step 1 Findings: Visual analysis/Condition assessment of sample blocks

At the time of collection for this current project, the cubes at Wytham had accumulated several different types of biological growth, including moss, lichens, and algae, Fig. 4.2 and were taken to an indoor laboratory environment for recording and preparation. The control blocks had 0% biological growth coverage and showed 0 signs of weathering Fig. 4.2. The species *Brachythecium rutubulum* (Rough-stalked feather moss), commonly found on calcareous rocks was identified as the primary coloniser of the weathered samples, as seen in Fig. 4.2. In addition, some evidence of immature lichen perithecia and algal greening were identified on the weathered sample, however they were not formally identified to species level.

These growths were later visually examined using the 3D microscopy and SEM imaging techniques. At the time of collection, the Bowers Roach sample blocks had more visible moss colonisation than the Jordan Basebed sample blocks. As seen in Fig 4.2, Bowers Roach limestone is coarsely-grained, and comprises visible fossils and discontinuities whereas Jordan Basebed limestone is finely-grained without visible fossils or discontinuities. This difference in surface roughness, porosity, and material texture can explain the variability in capacity for primary bioreceptivity between these two materials and why the Bowers Roach limestone was colonised more easily during the same timespan.

After the initial visual inspection, the loose moss material was removed as described in the method above. Then, a final visual inspection was undertaken before slicing the sections for thin section cross-sections. The typical visual inspection results are noted in Table 4.1.

Table 4.1: Initial visual inspection results of moss coverage, biological growth (*B. rutabulum* (*B. rut*), black crustose lichen (BCL), green algae (GA)), and observed weathering on Jordan Basebed (JB) and Bowers Roach (BR) limestone

Block No.	**JB/BR**	**%Moss Coverage**	**Bio Growth**	**Weathering**
Control JB	JB	0	None	None
Control BR	BR	0	None	None
1 Initial	BR	75	*B. rut*, BCL, GA	Obscured
1 Cleared	BR	0	BCL, GA	Powdering
2 Initial	BR	100	*B. rut*	Obscured
2 Cleared	BR	0	BCL	Powdering Flaking
3 Initial	JB	25	*B. rut*, BCL	None
3 Cleared	JB	0	BCL	
4 Initial	JB	0	BCL	None
4 Cleared	JB	0	BCL	
5 Initial	JB	15	*B. rut*, BCL	None
5 Cleared	JB	0	BCL	
6 Initial	JB	15	*B. rut*, BCL, GA	None
6 Cleared	JB	0	BCL, GA	
7 Cleared	JB	15	*B. rut*, BCL, GA	None
7 Cleared	JB	0	BCL, GA	
8 Cleared	JB	15	*B. rut*, BCL	None
8 Cleared	JB	0	BCL	

As we can see in Table 4.1, the presence of loose material from the moss growth can obscure some signs of weathering and deterioration. This may be an issue when trying to complete condition surveys at cultural heritage sites, where thick mats of moss growth cover walls and roof structures.

4.5.2 Step 2 Findings: Keyence 3D microscopy and profilometry

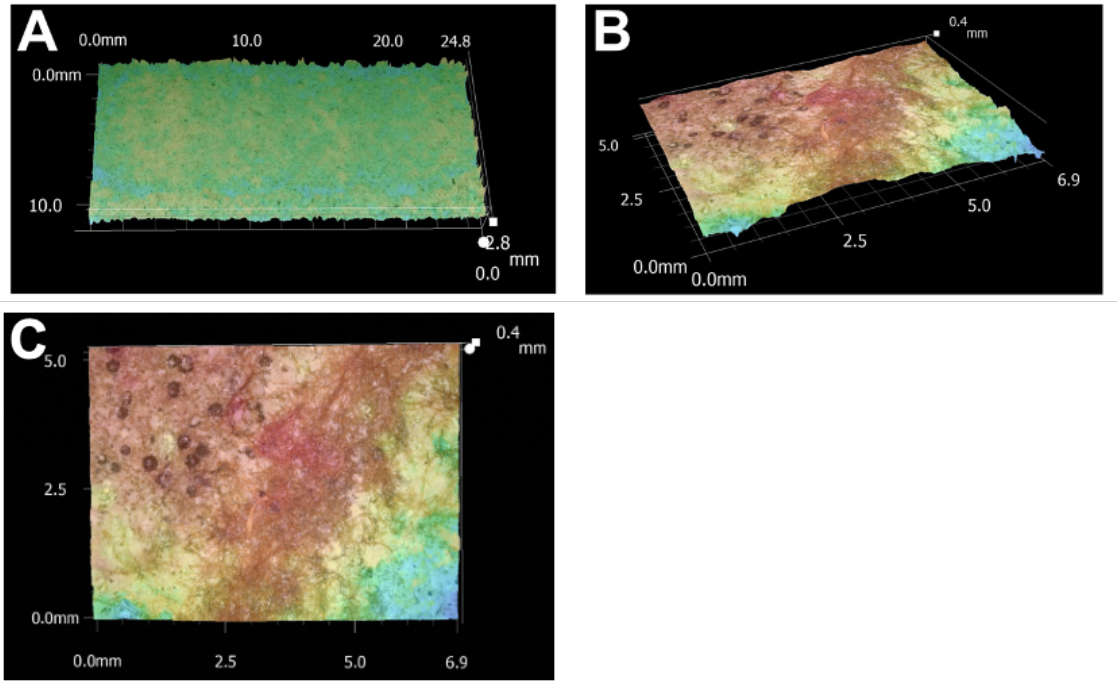


Figure 4.3: Keyence 3D Microscope surface roughness imaging A - Surface topography mapping of freshly cut limestone surface, scale 0 - 2 mm height, B - Surface topography mapping of weathered limestone surface showing remnants of moss growth and lichen perithecia, scale 0 - 2 mm height, C - Top-down view showing remnants of moss growth and lichen perithecia

Using 3D microscopy allows us to visually compare the freshly cut and weathered surfaces of the limestone. It also gives us the tools to measure surface roughness using optical profilometry, and create large photo-stitched images of the topographical surface. The Keyence 3D imaging microscope uses depth-from-defocus (DFD) software to calculate three-dimensional depth imaging based on the amount of defocusing from stacked two-dimensional images. It also gives us the ability to hand-select lengths across surfaces, which is very helpful on samples which are

colonised by multiple different types of biological growths, which is often the case. In this particular example using these samples, we can select areas which only contain mosses on the weathered samples, to exclude areas which contain lichens or algae.

Fig. 4.3 illustrates the difference in surface roughness between the freshly cut side of the limestone surface (Fig. 4.3A) and the weathered limestone surface (Fig. 4.3B). As we can see, there is a marked difference between the two surfaces, both in terms of the raised aspects where biological growth has accumulated on the surface, and the worn areas where environmental or biological processes had taken place and removed some of the superficial layer of stone. This image is typical and representative of the entire surface of the weathered stone blocks.

After measuring six 3.0 cm randomly chosen lengths across each stone surface using the profilometry tool, the average surface roughness was calculated and compared between the freshly cut and the weathered surfaces. Mean measurements for the freshly cut side were Δ 0.45 mm, and Δ 0.9 mm for the moss covered surfaces, Table 4.2. From the measured surfaces it is clear that the weathered areas are notably rougher than the freshly cut areas, as expected. We also compared moss covered surfaces to lichen covered surfaces to determine if there were any measurable differences in surface roughness. Lichen covered areas were slightly less rough (mean Δ 0.7 mm) than moss covered areas (mean Δ 0.9 mm). Results from an unpaired t-test gives a p-value of 0.0216 when comparing lichen covered and moss covered areas, meaning that there is a statistically significant difference between the two areas.

When looking at the images however, it appears as if the difference in roughness may be due to the bryophyte stems and leaves covering the substrate and creating a raised area. Even after removing as much of the loose material in sample preparation, it was impossible to remove all of this material without damaging the underlying substrate or pulling out the rhizoids completely from the matrix of the stone.

Given its tenacity, there is a possibility that this close-covering embedded remnant material could act as a potential biocrust or bioprotective layer preventing further surface erosion and acting as a sacrificial crust from environmental effects. As seen in previous conservation treatment evaluations, moss ‘fragments’ can be

Table 4.2: Keyence profilometry segment measurements, (Moss Weathered = MW, Lichen Weathered = LW, Lichen and Moss Weathered = LMW, Unweathered = U) where Δ Depth measures the difference between the lowest and highest points within 3.0 cm lengths across the surface

Block/Sample	**MW/LW/LMW/U**	**Δ Depth (mm)**	**Δ Depth (mm)**	**Δ Depth (mm)**
B1, S1	U	0.45	0.5	0.6
B1, S2	U	0.3	0.4	0.55
B1, S3	U	0.3	0.6	0.4
B1, S4	MW	0.9	1.0	0.7
B1, S5	LW	0.85	0.7	0.75
B1, S6	MW	0.5	1.5	1.0
B2, S1	U	0.4	0.45	0.45
B2, S2	U	0.6	0.3	0.45
B2, S3	U	0.3	0.55	0.45
B2, S4	MLW	1.1	0.5	0.6
B2, S5	LW	0.8	0.65	0.8
B2, S6	MW	0.95	0.75	1.0
B3, S1	U	0.5	0.6	0.3
B3, S2	U	0.45	0.35	0.55
B3, S3	U	0.45	0.3	0.6
B3, S4	MW	0.85	0.9	0.9
B3, S5	LW	1.0	0.55	0.55
B3, S6	LW	0.65	0.4	0.8
Δ U Mean =	0.45			
Δ W Mean =	0.8			

found embedded within the stone even after treatment (Savković et al. 2016). Indeed other types of closely-bound biological growth has been found to have a protective effect on substrates by protecting them from environmental effects and surface deposition, as in the case of Roman pavements in Cadiz, Spain colonised by lichens (Ariño et al. 1995) by acting as both active and passive mechanisms of bioprotection (Carter and Viles 2005).

4.5.3 Step 3 Findings: Optical light microscopy from polished thin sections of weathered sample limestone

As seen in Fig 4.4A, the freshly cut JB limestone surface has no evidence of biological growth or encrustation from environmental deposition. In comparison, the weathered surfaces Fig 4.4B and C show evidence of black deposits and small instances of



Figure 4.4: Light microscope images of petrological thin sections of weathered Jordan Basebed limestone samples at 40X magnification. A - Freshly cut edge without biological growth, B - Black deposit shown on surface of weathered stone. C - Rhizoid penetration of moss growth on weathered stone.

rhizoid penetration from *B. rutabulum growth*. The black deposits seen in these thin sections could be due to atmospheric pollution deposition or may be remnants of biological matter. Additionally, in terms of surface roughness the weathered surface appears uniformly rougher than the freshly cut surface. No evidence of lichen growth was observed in the weathered surface despite being observed in Step 1. However, this could be due to the area selected for creating the thin section lacking lichen growth or disruption of the lichen fruiting bodies during thin section creation.

4.5.4 Step 4 Findings: SEM of cross-sections of weathered limestone

Moving on from the Keyence and OLM cross-section techniques, the next stage of analysis used SEM imaging to determine how far the rhizoids penetrated into the substrate, and if rhizoid penetration could be associated with any signs of biogeochemical deterioration.

Filamentous algae can be difficult to distinguish from bryophyte rhizoids on the stone surface, however the algal strands are striated horizontally whereas bryophyte rhizoids are composed of a single, hollow, continuous cell membrane Fig. 4.5A. The morphology of bryophyte leaves is more easily identifiable, being a single-cell thick layer of striated cells Fig. 4.5B.

Using SEM we can also see evidence that bryophytes are secondary colonisers. As seen in Fig. 4.5C-F we can see the progression from embedded lichen perithecia, to the shrunken lichen perithecia or perithecial pits, and finally the colonisation of

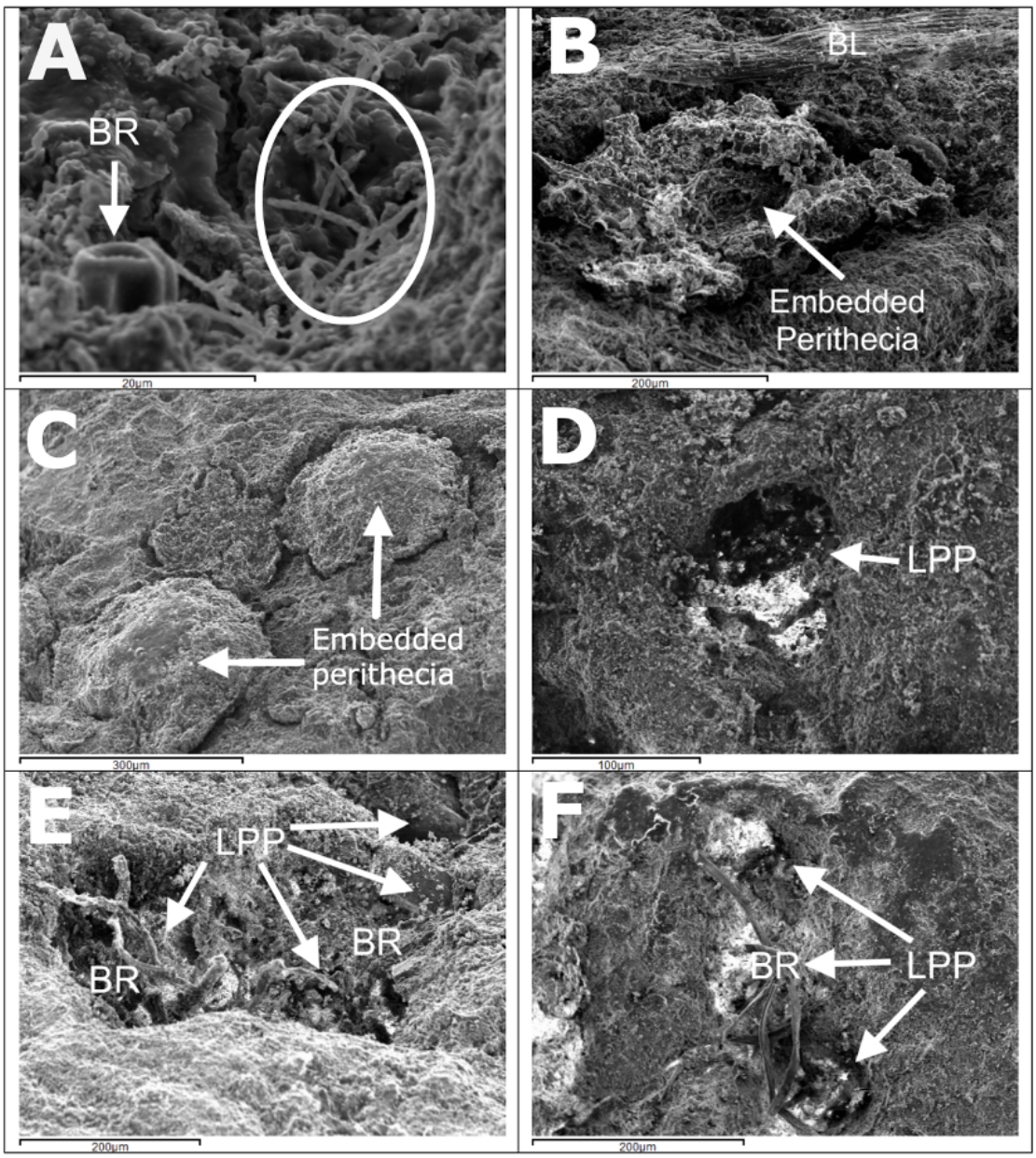


Figure 4.5: SEM images of the top surface of weathered limestone, at direct and oblique angles A - Bryophyte rhizoids (BR) and filamentous algae (circled) on the surface of stone substrate, B - Bryophyte leaf (BL) and embedded desiccated lichen perithecia on the surface of stone substrate, C - Lichen perithecia embedded in the surface of substrate angled stub mount, D - Empty lichen perithecia pit (LPP) on surface of substrate, E and F - Bryophyte rhizoids (BR) within empty lichen perithecia pits (LPP) on surface of substrate angled and flat stub mounts

bryophyte rhizoids within established perithecial pits. During SEM observation, lichen perithecial pits were commonly observed with perithecia, shrunken perithecia, or surrounding bryophyte remnants, however, bryophyte remnants were not com-

monly observed on surfaces without lichen pits. The absence of bryophyte remnants on other surfaces suggests that bryophytes prefer establishing themselves within lichen pits and implicates bryophytes as secondary colonisers.

This growth pattern is also described in surveys of biological growth in medieval castle walls in Central Europe, where the authors recognize that the first colonisers on monumental walls are lichens, with mosses following after (Steinbauer et al 2013, pp. 224). This secondary colonisation of mosses within perithecial pits will, at least in the early stages of growth, have a strong influence on the spatial location of moss impacts on deterioration.

Table 4.3: Average affected zonal depth findings for organic matter, data from SEM analysis

Bio Growth	**Affected Zone**	**Associated Features**
Filamentous algae	0 mm (surface)	N/A
Lichen perithecia	0 - 0.05 mm	Bryophytes within perithecial pits
Bryophyte webbing	0.3 - 0.5 mm	Calcium oxalate crystals
Bryophyte rhizoids	0.1 - 3.0 mm	Calcium oxalate crystals

Additionally, through SEM cross-section analysis we were able to confirm that the rhizoids bore through the stone substrate, in comparison to utilizing existing stone voids (Fig. 4.7. There is visual evidence of displacement and disaggregation of the stone matrix beside the entry and exit points of bryophyte rhizoids through the stone substrate. The voids where bryophyte rhizoids were commonly found were also only slightly wider than the rhizoid itself, suggesting that the rhizoid bored through the stone rather than finding an existing pore or void in the stone, which may have been wider than the rhizoid or more variable in diameter.

As we can see in Fig. 4.6 A-D through the cross-section of stone, we commonly saw bryophyte penetration between 0.1mm-3.0mm depth beneath the stone surface. Additionally, we observed a complex network of rhizoids beneath the surface from 0.3 mm - 0.5 mm depth, Table 4.3. This type of growth beneath the surface of the stone supports the idea that bryophytes within the growth stage of its life cycle contribute to biomechanical weathering. Since they are commonly described

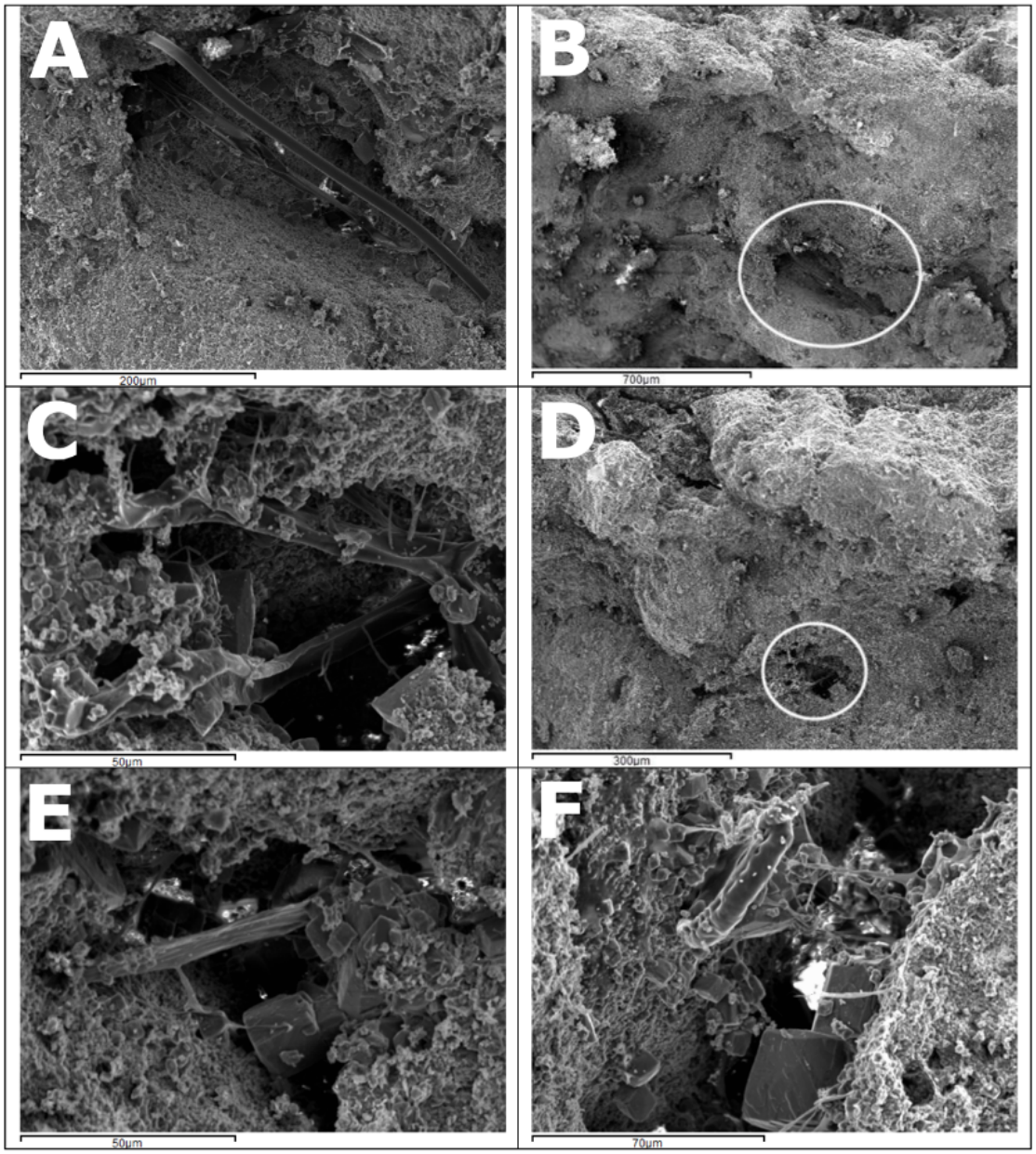


Figure 4.6: SEM images of cross-sections through weathered limestone samples:
A - Close-up of B,
B - Cross-section through stone substrate, showing bryophyte rhizoid penetration to 0.7 mm depth,
C - Close-up of D,
D - Cross-section of stone showing *B. rutabulum* rhizoid penetration to 0.4 mm depth,
E - *B. rutabulum* rhizoid penetration at 0.6 mm depth and oxalate crystal encrustation
F - Complex rhizoid webbing and oxalate crystal formation at 0.3 mm depth

as hygroscopic organisms by nature, the presence of their rhizoids beneath the stone surface supports the idea that through the fluctuations in water absorption

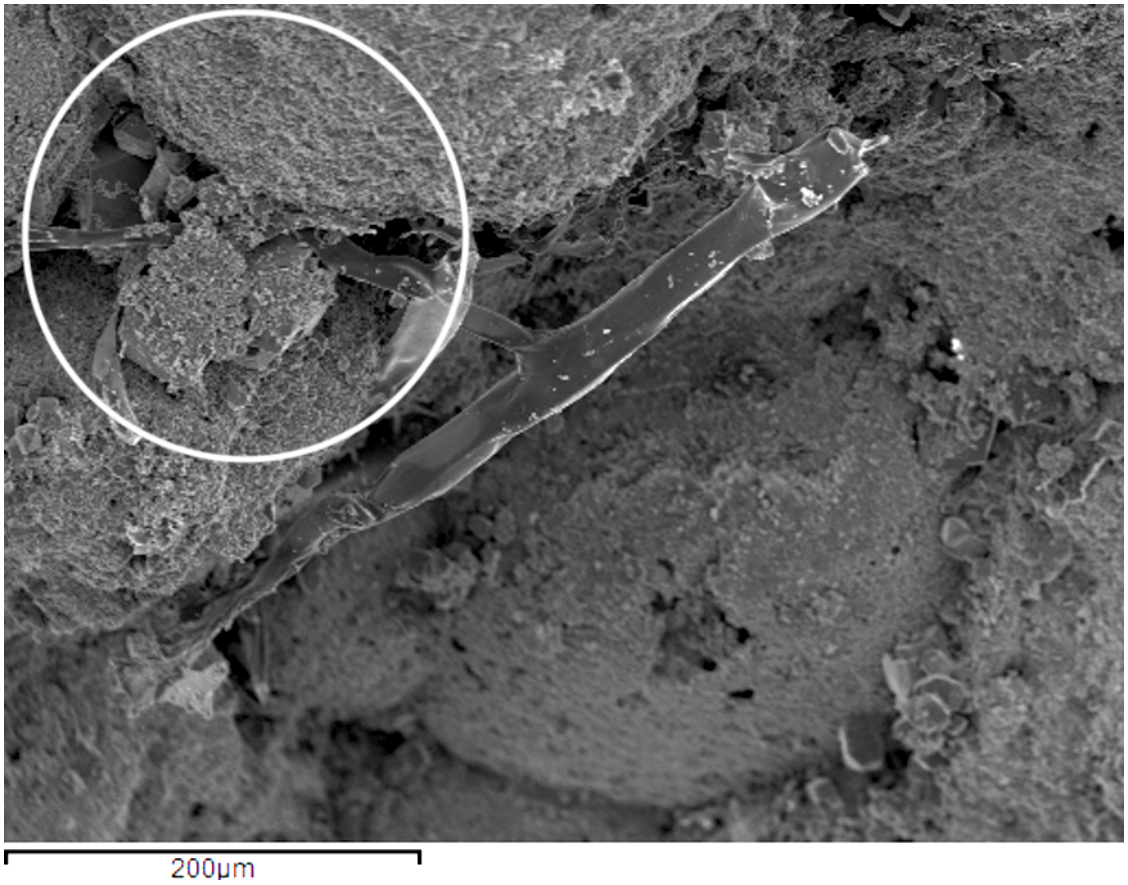


Figure 4.7: SEM image showing rhizoid disaggregation within stone matrix, at 2.0 mm depth

they create microfractures at a sub-surface level.

A key finding observed calcium oxalate crystal formation from 0.1 - 3 mm depth (5 mm atypical) beneath stone surface, and that it was strongly associated with bryophyte penetration as compared to lichen and algal growth. As we see in Fig. 4.6 E-F we can view the presence of bryophyte rhizoids with the oxalate crystals precipitated in stone voids.

Imaging found evidence of biological growth from 0.1 - 3 mm depth (5 mm atypical) beneath the stone surface. These findings align with previous research done on lichen bioweathering and biodeterioration, which have found that the affected zone of sandstone reached several millimeters in depth (Slavík et al. 2016). Epilithic lichens reached 1 mm depth, and endolithic lichens reached 2 -3 mm depth on Portland and Botticino limestones (Morando et al. 2017). These findings also

support previous research observations noting moss rhizoid penetration to 2.46 mm depth on weathered sandstone (Bartoli et al. 2014).

Both mechanisms behind bioweathering, biomechanical and biochemical, have been found to be visually present in the biologically-affected zone from the SEM imaging techniques. Biomechanical weathering is mediated by the moss rhizoids penetrating through the stone, and additional damage occurs during swelling and contraction of the rhizoids due to the change in moisture content (Lisci et al. 2003). Biochemical weathering is due to the deposition of organic acids such as oxalic acid and metal-complexing compounds or chelators (Slavík et al. 2016, p. 299).

4.5.5 Evaluation of the proposed 4-Step workflow

The results from the proposed workflow show that using these complementary analyses provides visualization of surfaces at different scales and quantitative comparisons between freshly cut surfaces and weathered surfaces. Some benefits of following this proposed workflow enables resampling of materials, colour and grayscale images of the top and cross-section through weathered materials, and a mixture of qualitative (condition assessment) and quantitative (surface roughness and hyphal depth) results.

In this case study, the methodology flow from using the 3D microscope imaging technique to SEM aided in species identification and targeting areas for SEM imaging. The 3D microscope images provide a level of detail and texture that traditional OLM does not provide and was useful for differentiating and identifying the different morphological structures on samples containing multiple different biological species. After seeing these structures in colour via the 3D microscope images, these structures were much easier to quickly identify in grayscale during SEM imaging.

Note that it would be impossible to change the workflow from using SEM first to 3D microscope imaging after, because the samples must be coated (carbon, graphite, gold, etc.) and broken into small pieces for SEM imaging, making the samples useless for Keyence imaging which requires large and ideally flat pieces for creating photo-stitched images and profilometry.

4.6 Discussion

The observations from this project have implications for the contributions of *B. rutabulum* on biodeterioration of limestone as well as possible impacts for removing bryophytes from stone in cultural heritage. Observations from this project have implications on *B. rutabulum's* effect on the weathering of limestone in natural and cultural settings. From results of visual analysis, we observed that physical weathering impacts, such as surface powdering and flaking may be obscured by the moss colonisation cover. As discussed in the introduction, the two primary growth forms of mosses are acrocarpous and pleurocarpous. The sprawling, amorphous, and fast-growing pleurocarpous form, such as *B. rutabulum*, may have more of an obscuring effect on these physical weathering features. This may be a consideration when assessing the condition and state of weathering on natural and cultural built heritage. This project also observed statistically significant evidence of increased surface roughness on areas of weathered limestone with *B. rutabulum* in comparison to other types of biological growth. This could suggest that the presence of *B. rutabulum* contributes to and may accelerate processes of biogeomechanical weathering.

Some of the observations from this project have implications for the cleaning and removal regimes for stonework in cultural heritage projects. As found previously and observed in this project, despite cleaning and removing bryophyte stems and leaves from the surface of stonework, biological remnants and fragments remain embedded in the surface (Savković et al. 2016). Here we observed that moss fragments mainly presented within lichen perithecial pits, a consequence of a factor described as secondary bioreceptivity (Guillitte, 1995). Lichens as pioneer colonisers disrupt the stone surface, altering the material properties of the stone. This concept suggests that the underlying factors caused by pioneer colonisers may affect the recolonisation of stonework in cultural heritage, which persist despite cleaning regimes. *B. rutabulum* rhizoid termini were also found to reach below the surface of the stone (0.1 – 3 mm depth). Again, this suggests that simple removal of biological material from the surface of stonework may not completely eliminate

these biological remnants, if this is the goal of the conservation treatment. These findings may suggest a need for careful evaluation of cleaning and removal processes for cultural heritage with bryophytes to prevent accelerating deterioration, protect existing stonework, and to prevent recolonisation.

4.7 Conclusions

- The 4-step workflow described in this paper effectively utilizes limited samples from cultural heritage to visualize the lithobiontic interface at a range of scales and including extensive coverage of the surface and cross-sectional views.
- *B. rutabulum* growth is associated with rougher surfaces compared to freshly cut surfaces, and even in comparison to surfaces covered in other types of observed biological growth such as lichen and algae when exposed for the same amount of time. (Step 3 – 3D Microscopy)
- The impacts of *B. rutabulum* as a secondary coloniser are often located within existing lichen impacts, such as perithecial pits. (Step 4 – SEM)
- *B. rutabulum* growth commonly observed between 0.1 – 3 mm depth beneath the stone surface, and is strongly associated with calcium oxalate crystal formation showing evidence that bryophytes may contribute to biomechanical and biochemical weathering. (Step 4 – SEM)

Give me the man who will surrender the whole world for a moss or a caterpillar, and impracticable visions for a simple human delight.

— Bruce Frederick Cummings, The Journal of a Disappointed Man, 1919

5 Moisture Regimes

Contents

5.1 Moisture interactions between mosses and their underlying stone substrates 76
5.2 Abstract 76
5.3 Introduction 77
5.4 Aims and Objectives 81
5.5 Materials, Sites, and Methods 81
5.5.1 Materials 81
5.5.2 Sites 82
5.5.3 Methods 83
5.6 Results 86
5.6.1 How does aspect and microclimate influence moss growth: Kelmscott Manor temperature and relative humidity data 86
5.6.2 How does moss growth influence microclimate fluctuations: Chipping Norton relative humidity and temperature data 89
5.6.3 How does moss growth influence water uptake and evaporation rates: Mass data 92
5.6.4 Does moss growth influence water uptake at surface level: Protimeter data 93
5.6.5 Does moss growth influence water uptake at subsurface level: Karsten test data 94
5.7 Discussion 97
5.7.1 Limitations and scope of the project 97
5.7.2 Recommendations for further research 98
5.7.3 Relevance to built heritage management strategies . . . 98
5.8 Conclusions 100

5.1 Moisture interactions between mosses and their underlying stone substrates

Authors: Jang, K. and Viles, H. This work is currently under review with the journal *Studies in Conservation* with minor changes to the text and formatting.

Keywords: Non-destructive testing, moisture regimes, water absorption, moss, cultural heritage, Karsten tube, microclimate, conservation

5.2 Abstract

Mosses are a common type of organism found colonising stone in both the natural and built environment. People responsible for managing and conserving historic buildings often worry that mosses can cause biodeterioration, but there is very little research to date on what controls moss growth and the nature and magnitude of their impact. To help fill this knowledge gap, research has been carried out on limestone walls at Kelmscott Manor, the churchyard at Chipping Norton and in the laboratory on limestone test blocks, to examine the impact of microclimate variations on both the initial colonisation and spread of mosses, and the impact of moss colonisation on temperature, relative humidity and moisture conditions. The research used a combination of non-destructive and invasive tests to determine the impact of mosses on moisture relations through direct impacts on surface moisture, water absorption capacity and open porosity. From the results presented, we can infer that mosses have an impact on water uptake and retention on mortar and limestone at both the surface and subsurface level, and that they may play a role in 'shielding' the underlying substrate from light rainfall events. The experimental data also suggests that in certain cases, removing mosses may have more of an impact on moisture regimes than leaving them in-situ.

5.3 Introduction

Mosses are one common form of organisms which grow at the lithobiontic interface. Previous studies have investigated and characterized the impact of a range of organisms growing on cultural heritage and have defined the lithobiontic interface as the zone of interaction between organisms and their underlying substrates (McIlroy de la Rosa et al. 2012). Research on organisms such as lichens, algae and bacteria growing at the lithobiontic interface has revealed a range of biodeteriorative and bioprotective impacts (Slavík et al. 2016; Morando et al. 2017). The relationship between these organisms and their substrates may be complex and multilayered, and the influence may not be entirely bioprotective or biodeteriorative, but rather the true impact may lie somewhere on a spectrum between these two end points. The importance of understanding the lithobiontic interface for conserving and managing built cultural heritage has been previously explored, identifying the impact of the growth of organisms on stone-built cultural heritage to the weathering, durability and lifespan of built heritage (Smith et al. 2008). Mechanisms of biodeterioration at the lithobiontic interface have been characterized primarily for lichens, with an understanding that they can have both direct and indirect chemical and physical impacts (Fontaine, et al. 2015). Specific impacts include direct impacts which contribute to biodeterioration such as pitting, erosion, and the deposition of acidic byproducts from metabolic processes, while some indirect impacts of colonisation have been reported to have bioprotective effects, such as reducing temperature fluctuations at the stone surface and freeze-thaw effects as well as providing a physical barrier for airborne pollutants (McIlroy de la Rosa et al. 2012; McIlroy de la Rosa et al. 2013). According to previous research on epilithic and endolithic lichens on Portland and Botticino limestones, lichen hyphae have been seen to extend 2.0-3.0 mm beneath the surface and thus the lithobiontic interface includes not only on surface, but also subsurface interactions (Morando et al. 2017). Findings from lichens may also have relevance to mosses as these subsurface penetration and anchoring mechanisms are also present in moss morphology and could potentially be a reason why moss fragments are seen within

the stone substrate even after cleaning (Slavik et al. 2016). While mosses are evidenced to have wide impacts on their underlying substrates, including but not limited to biochemical decomposition and accelerated physical degradation, this paper focuses on the direct impacts of moisture and saturation.

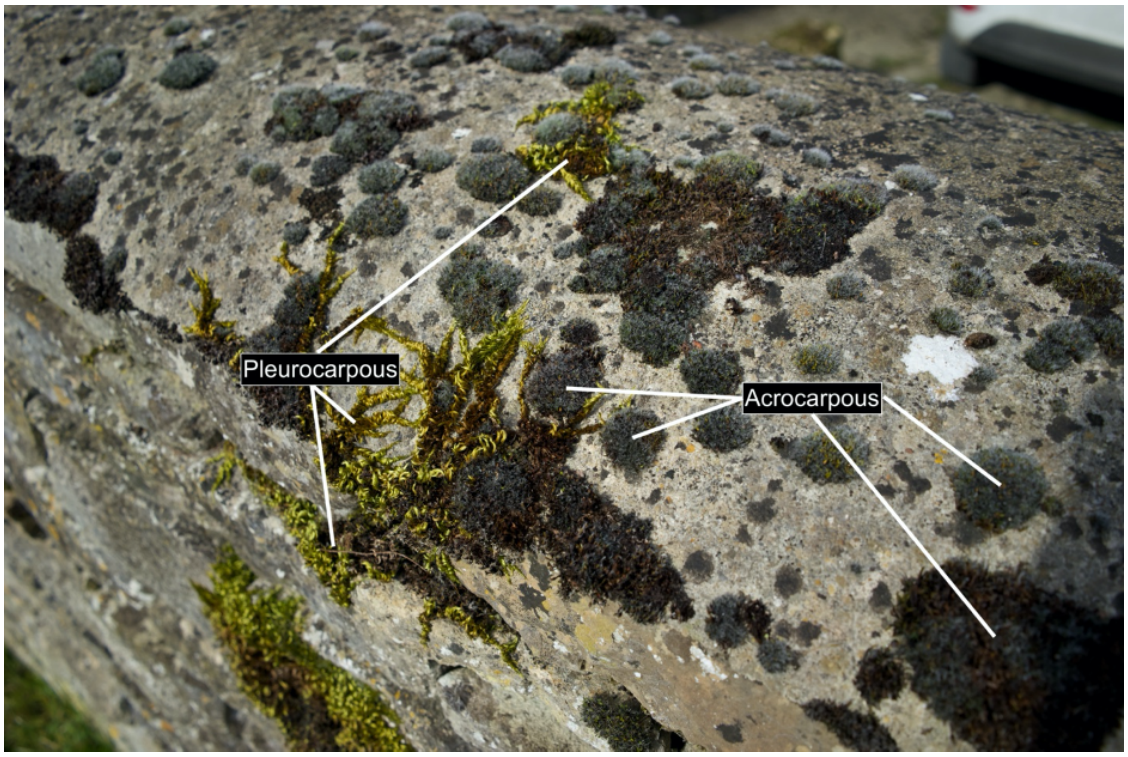


Figure 5.1: Acrocarpous and pleurocarpous moss morphology on a cementitious mortar capped wall at Kelmscott Manor, Lechlade UK. Photo taken by author

The spatial extent of the lithobiontic interface is of particular interest when discussing the impacts of moisture interactions for mosses, due to the nature of their growth patterns and morphology. Moss growth patterns fall broadly within two major categories with distinct characteristics (Fig. 5.1): Pleurocarpous mosses are freely branched and amorphous, with prostrate habit and lateral growth. They are often described as 'carpeting' and are more firmly attached to the substrate. Acrocarpous mosses are unbranched and have an ascending habit, with a circular form. They are often described as 'cushions' and are more loosely attached to the underlying substrate. All forms of mosses are attached to the substrate by small structures known as rhizoids. This project primarily analyses the impact of the species *Brachythecium rutabulum*, which is described by the British Bryological

Society as one of the commonest mosses (in the United Kingdom and worldwide) and is found in a wide range of habitats including natural and urban environments although is especially common on wood and stone (BBS Field Guide 2010, p. 747). This species of moss has a pervasive biogeographical spread and is a common species of moss widely found in temperate and subpolar climatic zones.

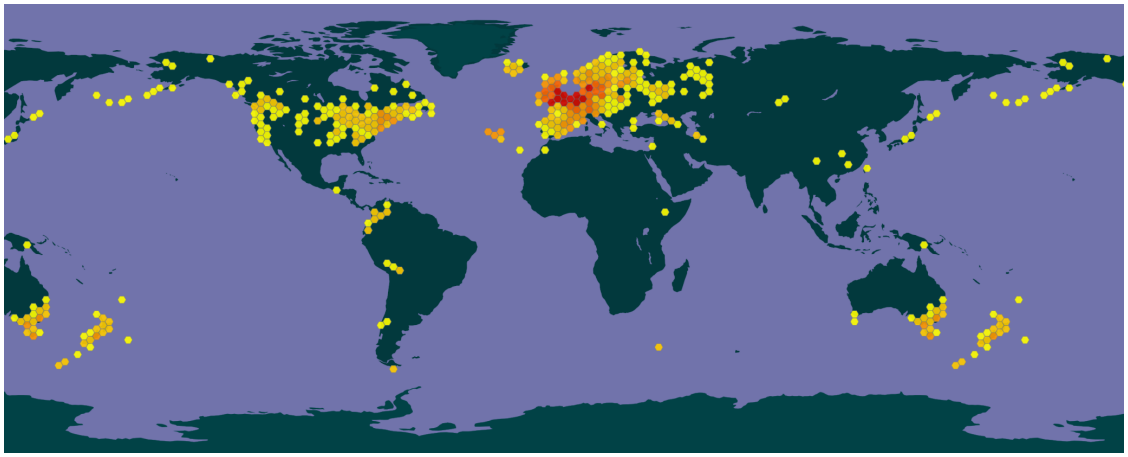


Figure 5.2: Known world distribution of Brachythecium rutabulum. Source: Global Biodiversity Information Facility

While this project primarily analyses the impact of the species *Brachythecium rutabulum*, mosses share certain similarities in morphology and habit which means that at least some of the identified impacts are likely to be applicable to mosses in general. When observing the impacts of moss morphology on moisture and the built environment, the adaptations for surviving drought and routine desiccation are particularly significant. Mosses differ from vascular plants in the nature of their water uptake and circulation, as they lack the tissue structures which transport water and other nutrients. According to previous research, most dryland mosses have evolved to require desiccation and during desiccated periods, "shoot tissues lose virtually all liquid water and can dry to 5-10% of dry mass and water potentials of -100 MPa" (Coe and Sparks 2014, p. 294). Not only can mosses tolerate periods of extreme drought, but some species of mosses have evolved to retain moisture during brief rainfall events. The use of the species Sphagnum mosses is documented throughout World War One for absorptive properties and ability to retain "16-20 times its own weight in liquid, as compared to 4-6 times of cotton" (Rotherham

and Griffiths 2013, p. 202). This species of moss gained widespread use as a field dressing and was harvested for its absorptive properties.

Although there has been relatively little scientific research on the impact of mosses on built cultural heritage, the advice and management strategies from built heritage bodies and local councils (UK) broadly agree on the treatment of mosses on built heritage structures. Advice from local heritage bodies and councils broadly addresses two key issues with mosses. The first is that moss should be treated as general debris, with adverse effects primarily on roof structures, guttering, and drainage. Their treatment as general debris can be extended to areas where they may not be aesthetically pleasing to viewers, such as walls, decorative assemblages, and external structures such as gates (Historic Environment Scotland Advisory Standards 2005; Eklund 2013; Edinburgh World Heritage Historic Home Guide 2019). Of course, the removal of mosses can have a dramatic effect on the aesthetics and presentation of a cultural heritage asset and may be a consideration in the treatment and management strategy of the structure. Past management strategies of rural heritage have indicated that the presence of mosses is beneficial to the aesthetic presentation of a site, and their presence at the abandoned monastery of Dryburgh Abbey particularly conveyed values such as 'age' and 'authenticity' (Douglas-Jones, et al. 2016). In this case, the removal of mosses would be detrimental to the presentation and overall impact of the heritage site. In these rural heritage sites, the relationship between organisms and the underlying structures are seen as inseparable. The second piece of advice from local councils and heritage bodies is relevant to the relationship between moisture and mosses. They often describe mosses as 'retaining moisture' and 'causing moisture,' which accelerates the deterioration of the underlying substrate and recommend removal. These two terms are often used interchangeably, but when examined more closely have very different meanings. The description of mosses 'retaining moisture' is linked to the original use of Sphagnum mosses and their uptake of moisture from external sources. When describing this effect on built heritage, it may be tied to micro and macro-environmental fluctuations, such as relative humidity or rainfall. However, the description of

mosses as 'causing moisture,' on the other hand, has a very different meaning. The use of this description may be misleading because it implies that through the growth and colonisation of mosses they create inherently moist and wet environments when as described above they regularly undergo desiccation.

5.4 Aims and Objectives

The primary objective of this project is to determine if the presence of mosses impacts moisture regimes on their underlying substrates in any way. Non-destructive and non-invasive tests in the field and lab have been chosen to examine the following research questions:

1. How does moss growth influence microclimate fluctuations, and similarly, how do microclimate fluctuations and aspect influence moss growth?

2. How does moss growth influence evaporation rates and water uptake at surface and subsurface levels?

5.5 Materials, Sites, and Methods

5.5.1 Materials

This project used a mixture of laboratory and on-site analyses to investigate the role of mosses on moisture relations on limestone and cementitious mortar. The laboratory portion of this research project uses a set of weathered limestone blocks from a previous research project (Eklund, no date). In 2010 16 Portland limestone blocks were exposed as part of a project on bioreceptivity in a grassland area at Wytham Woods, near Oxford (516'12.7"N 19'58.8"W) and were appropriated for this research project in 2017. The cubes (15 x 15 x 15 cm) were cut from two types of Portland limestone - fine-grained Jordan Basebed (JB) and coarse grained, fossil encrusted Bowers Roach (BR). In total, 12 JB and 4 BR blocks were exposed with bedding planes horizontal on a geotextile in an open field setting. The cubes were left on site to weather naturally and collected in autumn 2017,

after 7 years of exposure. For the purposes of this project, 6 JB and 2 BR blocks were recovered along with the original 1 JB and 1 BR control blocks which were stored over the same period in a controlled environment lab facility in Oxford. The field investigations included cementitious mortar capping on limestone walls at Kelmscott Manor, Lechlade UK, microclimate monitoring of structural walls at Kelmscott Manor, and local ooidal limestone from Chipping Norton.

5.5.2 Sites

The laboratory analyses were carried out at the Oxford Resilient Buildings and Landscapes Laboratory (OxRBL) in the School of Geography and the Environment, University of Oxford. This laboratory allowed for a temperature and relative humidity stable environment for testing, as well as storage for the control blocks in the stone storage facility. The field analyses took place at Kelmscott Manor, Lechlade UK and Chipping Norton UK. Currently owned by the Society of Antiquaries of London (acquired 1962), the main house at Kelmscott Manor was built c. 1570 for Richard Turner, with later additions c. 1670, 1871, and 1896 (Historic England listing 1199373). The main building is built from uncoursed limestone rubble walls, and the boundary walls consist of coursed, roughly hewn limestone with cementitious mortar capping. Mosses grow luxuriantly at this site including at the base of north-facing walls (pleurocarpous), and on the tops of mortar-capped boundary walls (acrocarpous). Additionally, there is extensive pleurocarpous and acrocarpous moss growth on the roof tiles on all buildings at the site. There has been no regular cleaning or removal of mosses at this site because William Morris described Kelmscott as existing symbiotically with nature, and his philosophy for the buildings emphasized Kelmscott organically intertwining with nature over time. Kelmscott Manor was chosen as a research site due to the association with 'rural' and 'countryside' characteristics, as it was William Morris' summer country house, and for William Morris' own philosophy for the manor itself. The test area at the Chipping Norton site was a small area of dry-stone walling adjacent to the Grade I listed church, St. Mary the Virgin, located in the North-West area of Chipping

Norton. The dry-stone walling provided a flat surface for testing, and also had small colonies of acrocarpous mosses. Again, the test area comprised of local limestone, medium-grained and ooidal in nature (Chipping Norton Limestone).

5.5.3 Methods

Table 5.1: List of analyses, equipment and sites: How does moss growth influence moisture regimes?

Methodology	Equipment	No. tests/sites	Materials
Microclimate monitoring (T/RH) under moss 'cushions' and on adjacent surfaces	IButton DS1923 Hygrochron Temperature/Humidity Data Logger	2 under moss 2 bare	Horizontal wall top, dry stone limestone wall, Chipping Norton
Monitoring of surface moisture under moss cushions vs bare surfaces	GE Protimeter Surveymaster dual-function moisture meter Model: BLD5360	4 moss cushions, 4 adjacent areas, 5 measurements in each position	Horizontal wall top, dry stone limestone wall, Chipping Norton
Monitoring surface moisture on moss-covered vs bare surfaces after experimental wetting	GE Protimeter Surveymaster dual-function moisture meter Model: BLD5360	2 control blocks, 4 moss covered blocks, 2 bare blocks. 5 measurements in each position repeated until dry	Portland Limestone blocks, Laboratory
Monitoring water uptake and drying using modified BS EN 1936:2006	Balance (precision +/- 0.000 kg)	2 bare blocks, 2 moss covered blocks	Portland limestone blocks, Laboratory
Monitoring moisture absorption capacity on moss-covered and bare surfaces	TQC brand vertical and horizontal Karsten tubes, Plastic-fermit sealing compound	82 tests total*	Cementitious mortar capping; Kelmscott Manor, Limestone; Chipping Norton, Portland limestone blocks; Laboratory

(*Unweathered no moss = 16, Weathered no moss = 18, Weathered moss present = 16, Weathered moss present but removed = 16, Weathered moss present contact sponge method = 16)

Due to the historic nature of the sample sites, non-invasive and non-destructive test methods used in previous cultural heritage research have been adapted for this project (Viles et al. 2011; Eklund et al. 2013; Wilhelm et al. 2016).

This project uses a mixture of monitoring and direct analyses of moisture uptake and saturation to explore the controls on moss growth and their impacts on moisture relations. Microclimate monitoring took place at Kelmscott Manor, UK and Chipping Norton in summer 2019, using 4 iButton (DS1923 Hygrochron Temperature/Humidity Data Logger) devices to monitor the microclimate differences between areas with and without moss cover (Tonon et al. 2019). At Kelmscott Manor, the devices were placed on South and North facing walls. Areas were chosen at High (1 m from base) and Low (0.5 m from base) wall positions on the same wall, with the Low wall devices placed directly next to moss colonisation. The aim of this monitoring experiment was to determine the impact of aspect, relative humidity, and temperature on the colonisation of mosses, and to determine if microclimatic conditions impacted the bioreceptivity of certain surfaces. It was theorized that cooler areas with higher relative humidity would be more receptive to moss growth than hotter areas with lower relative humidity.

Microclimate monitoring at Chipping Norton, UK took place over summer 2019 using a modified methodology to investigate the impacts of mosses on surface microclimates. 4 iButtons were placed on a horizontal surface with 2 of the iButtons covered with *B. rutabulum* growth and 2 of the devices were left bare. The aim of this monitoring experiment was to mimic the natural state of a moss-covered wall, and to determine if the presence of mosses impacted the temperature fluctuations and relative humidity of the underlying substrate in any way.

Field experiments were also devised to examine the surface moisture of areas covered with mosses compared to bare stone. In Chipping Norton, the handheld Protimeter (GE Protimeter Surveymaster dual-function moisture meter Model: BLD5360) device was used in resistance mode to simply measure the %Wood Moisture Equivalent (%WME) of areas of bare stone directly next to areas with moss colonisation. The moss-colonised areas beside the bare stone simply had the

prongs pushed into the center of each growth with the prongs perpendicular to the substrate. Five repeat measurements were taken on each measured area, and average values calculated. In the laboratory environment, bare or moss covered surfaces of sample blocks were measured with the Protimeter to determine the baseline 'dry' measurement. The surface of each sample was then flooded with 15 mL of water. The handheld Protimeter device was then used at periodic intervals of 5 minutes, with the surface measured 5 times in the same spot and using the same bedding direction (following the protocol of Eklund et al. 2013.) The measurements were repeated until the initial 'dry' measurement was reached or 3 hours had elapsed.

Karsten Tube tests were used to compare the water absorption characteristics of areas covered with mosses, weathered stone without moss, and bare/unweathered stone (BS EN 16302:2013.) This is a well-established experiment within the field of cultural heritage used as a proxy measurement for water absorption (Blaeuer et al. 2012; Hendrickx 2013; Vandevoorde et al. 2013; Scatigno et al. 2016; Ruiz et al. 2019). The measurements took place on-site at Kelmscott Manor using the cementitious mortar capped wall shown in Fig. 5.1, at Chipping Norton using the top of the drystone walling constructed from local ooidal limestone, and in the laboratory environment using the limestone test blocks. This experiment measured the impact of both pleurocarpous and acrocarpous mosses. The Karsten Tube tests used the standard method to measure water absorption, but also used a modified version of the implemented Contact Sponge Method (i-CSM) method as described by Scrivano and Gaggero (2017). In contrast to the i-CSM method, which uses a known weighted device to press a wetted sponge onto stone which is then weighed, the method used in this project used a wetted sponge with a known amount of water (3 mL) applied to a dry cushion of acrocarpous moss. A Karsten Tube was then fitted over the wetted cushion of acrocarpous moss and then the test was conducted according to the standard. This method was used to measure the difference in Karsten Tube results from areas which had moss colonisation (dry) and moss colonisation (wet).

This project analysed a large sample set of Karsten Tube tests (total of N=82 tests.) The aim of using such a large sample set of tests was to determine the relative reliability and variance of Karsten Tube tests on a variety of different substrates (weathered and unweathered limestone and cementitious mortar), and to investigate the possibility of using the i-CSM methodology on moss growth. The Karsten Tube tests were applied to 5 different treatments of substrates (Unweathered no moss, Weathered no moss, Weathered moss present but removed, Weathered moss present, Weathered moss present contact sponge method) to determine if there were any statistically significant differences in the volume of water absorbed.

Open porosity of sample blocks with and without moss growth was measured using the standard BS EN 1936:2006 in the laboratory. This test was modified from the standard as the sample blocks were not dried in the oven prior to the analyses, they were only left to acclimate to the lab environment for a period of 1 month before testing. This change was made because the live moss growing on the sample blocks would not have survived the oven drying period, and live moss was required for subsequent testing on the sample blocks.

Statistical analysis was undertaken to determine if there were significant differences between the covered and uncovered monitoring groups in Chipping Norton and with the substrate treatments during Karsten Tube tests.

5.6 Results

5.6.1 How does aspect and microclimate influence moss growth: Kelmscott Manor temperature and relative humidity data

At Kelmscott Manor, mosses were observed to grow primarily on roof structures, boundary walls, and at the base of structural walls. Shaded areas were more likely to have prevalent moss growths, as were North-facing walls and roof structures. Both acrocarpous and pleurocarpous mosses were observed to colonise Kelmscott Manor, with *Brachythecium rutabulum* at the base of structural walls, and *Grimmia pulvinata* on the tops of mortar-capped boundary walls. *Grimmia pulvinata, Hypnum*

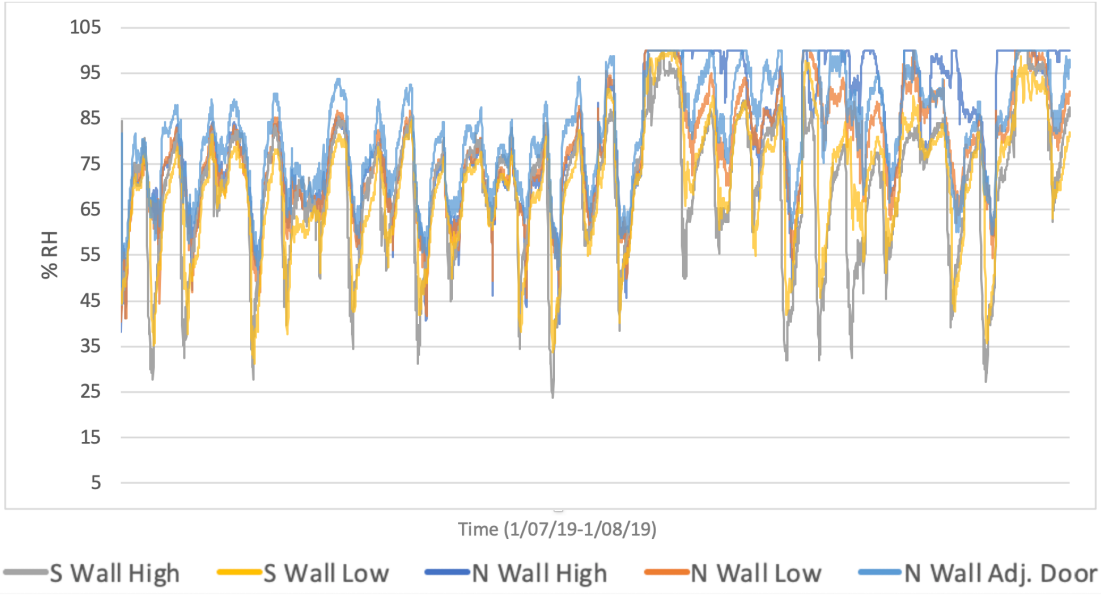


Figure 5.3: Kelmscott Manor relative humidity microclimate monitoring (Jul7-August 2019), influence of aspect and wall height on daily relative humidity fluctuations.

tectorum, and possibly *Schistitium acrocarpum* were also observed on the roof tiles of all buildings at the site.

Table 5.2: Average daily range %RH Kelmscott Manor

N Wall Low	29.48
N Wall High	29.14
S Wall High	39.18
S Wall Low	33.60
N Wall Adj. Door	29.10

There appears to be a moderate effect of aspect and wall height on relative humidity fluctuations at Kelmscott Manor. As we can see in Fig. 5.3 and from the daily fluctuations in relative humidity at this site, the relative humidity on the North-facing walls is relatively higher than that of the South-facing walls. We would expect to see wetter conditions on North-facing walls as they are exposed to fewer sunlight hours per day. Additionally, the North-facing walls are observed to have relatively more stable relative humidity than South-facing walls. These wetter and more stable conditions may encourage mosses to grow on North-facing walls. This typical growth pattern was observed at Kelmscott Manor, where the

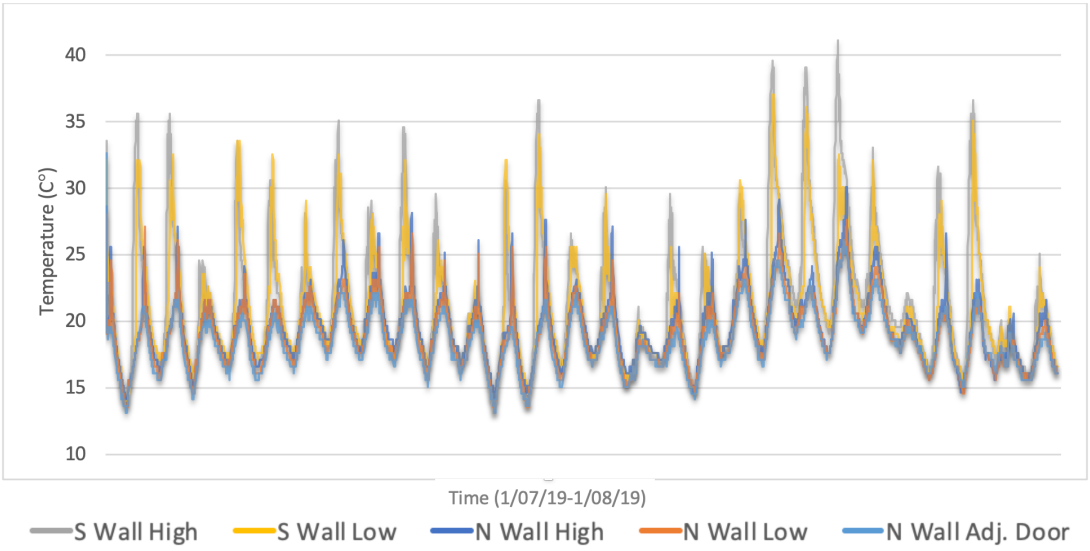


Figure 5.4: Kelmscott Manor temperature microclimate monitoring (July-August 2019), influence of aspect and wall height on daily temperature fluctuations.

mosses primarily grew on North-facing walls and roof structures and were especially prevalent along the base of North-facing walls.

Table 5.3: Average daily temperature (°C) max, min, and range at Kelmscott Manor

	Avg. Daily Max	**Avg. Daily Min**	**Avg. Daily Range**
N Wall Low	30.12	14.11	8.31
N Wall High	28.09	13.08	7.22
S Wall High	41.08	13.08	13.53
S Wall Low	37.07	14.07	12.03
N Wall Adj. Door	32.60	13.09	5.67

As expected, the influence of aspect on microclimate at Kelmscott Manor Fig. 5.4 shows the South-facing walls reaching higher temperatures than the North-facing walls. The absolute readings for the daily maximum reach much higher on the South- facing walls than the North-facing walls, and they also have much higher daily ranges. The S Wall High iButton data in particular reached very high temperatures, much higher than commensurate readings of air temperature at the nearby Cirencester Met Office weather station (Location: 51.078, -1.994) at the same time and date. Microclimate monitoring was undertaken at Kelmscott Manor, Gloucestershire (July-August 2019), and Chipping Norton, Oxfordshire

(July-August 2019). Relative humidity drift is a common problem with iButton Hygrochrons, especially in areas with higher relative humidity readings. In cases where values above 100% RH were recorded, they have simply been treated as 100% RH Figs. 5.3, 5.5, and 5.6.

There appears to be a moderate effect of aspect and wall height on relative humidity fluctuations at Kelmscott Manor. As we can see in Fig. 5.3 and from the daily fluctuations in relative humidity at this site, the relative humidity on the North-facing walls is relatively higher than that of the South-facing walls. We would expect to see wetter conditions on North-facing walls as they are exposed to fewer sunlight hours per day. Additionally, the North-facing walls are observed to have relatively more stable relative humidity than South-facing walls. These wetter and more stable conditions may encourage mosses to grow on North-facing walls. This typical growth pattern was observed at Kelmscott Manor, where the mosses primarily grew on North-facing walls and roof structures and were especially prevalent along the base of North-facing walls.

These findings may explain why mosses prefer to inhabit certain areas of Kelmscott Manor and not others. Other factors which would regularly affect bioreceptivity, such as substrate acidity and texture, amount of rainfall and airborne pollutants are fairly similar in all areas at Kelmscott Manor. Both the relative humidity and temperature data at Kelmscott Manor appear to suggest more favorable microclimates at the base of North-facing walls.

5.6.2 How does moss growth influence microclimate fluctuations: Chipping Norton relative humidity and temperature data

A separate monitoring experiment explored the effect of moss coverage on the underlying substrate in Chipping Norton (June-August 2019) by comparing iButton data on bare stone surfaces and directly adjacent areas with live moss growth placed on top of the iButtons.

As with the previous microclimate monitoring exercise, RH data >100% were transformed to 100% to remove any drift/ oversaturation values when the RH sensors

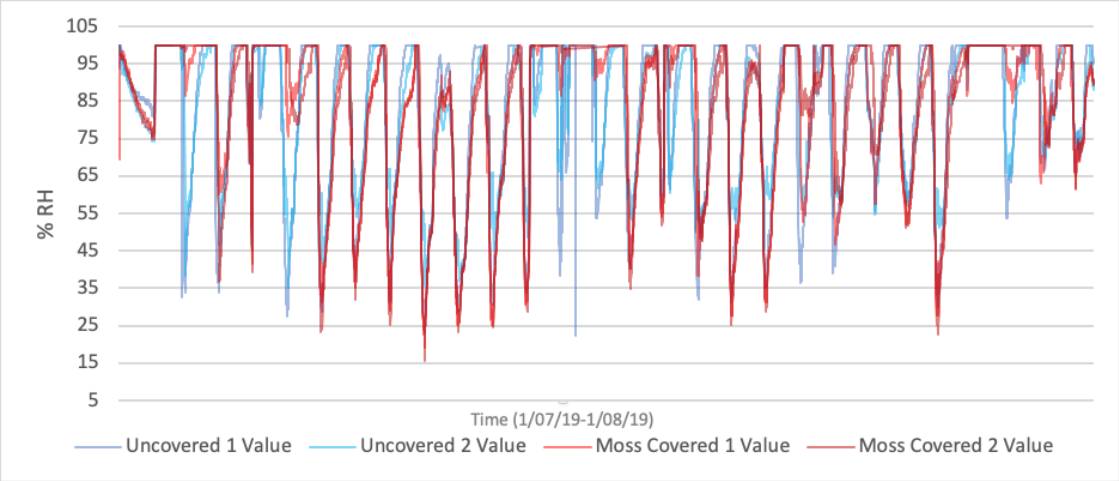


Figure 5.5: Chipping Norton relative humidity microclimate monitoring (July-August 2019), influence of biological cover on relative humidity fluctuations.

become affected by liquid water. Fig. 5.5 illustrates that both the Uncovered and moss Covered areas were routinely saturated during rainfall events. Additionally, they appeared to reach higher relative humidity than recorded at Kelmscott Manor over the same period (Fig. 5.3), most likely due to the positioning of the iButtons. Whereas at Kelmscott Manor the iButtons were fixed to vertical walls, the iButtons at Chipping Norton were placed on flat horizontal limestone surfaces. The higher relative humidity readings at Chipping Norton may be due to the small iButton aperture being flooded with water during rainfall events. There was a statistically significant difference between groups (Uncovered 1, Uncovered 2, Covered 1, and Covered 2) as determined by one-way ANOVA ($p = 0.000995$, which is significant at $p < 0.05$). Here we see significant differences in the mean daily ranges in relative humidity between the four treatments over the monitoring period June-August 2019. Results from the Tukey post hoc test tell us that the Uncovered 1 treatment was significantly different from the other 3 treatments.

Table 5.4: Average daily range %RH comparing covered and uncovered iButtons

Uncovered 1	Uncovered 2	Covered 1	Covered 2
67.84	48.59	51.0	50.13

Fig. 5.6 visualizes the relative humidity data from Chipping Norton using conditional formatting in order to illustrate the time lag in response between

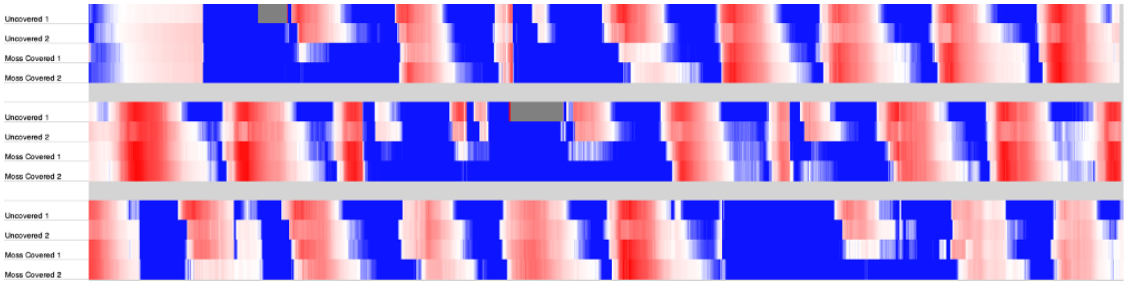


Figure 5.6: Chipping Norton relative humidity microclimate monitoring (June-August 2019), influence of biological cover on relative humidity fluctuations. Conditional formatting to indicate dry conditions (red) <80% RH and wet conditions (blue) >80%RH. Grey indicates invalid data. Each horizontal bar representing 1 month of data.

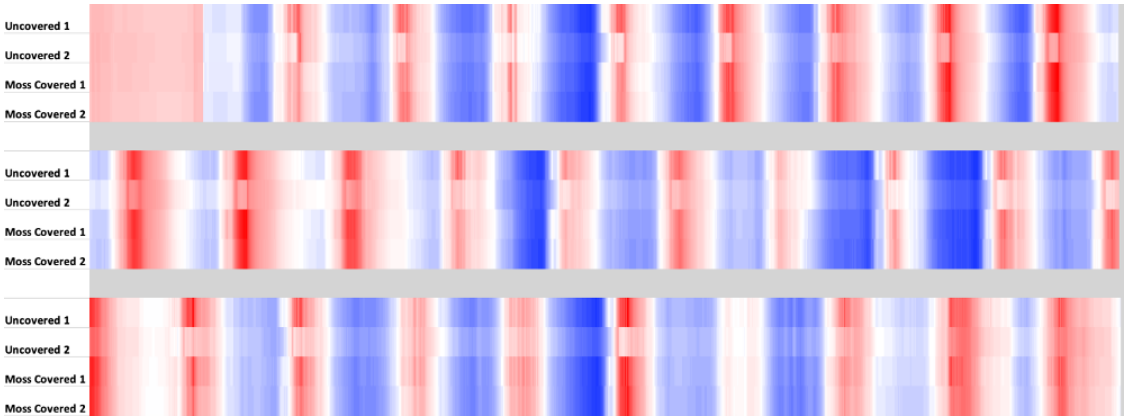


Figure 5.7: Chipping Norton temperature microclimate monitoring (June-August 2019), influence of biological cover on temperature. Conditional formatting to indicate cooler (blue) <25°C and warmer (red) >25°C conditions. Each horizontal bar representing 1 month of data.

Table 5.5: Average daily temperature (°C) max, min, and range at Chipping Norton, Covered vs Uncovered

	Avg. Daily Max	**Avg. Daily Min**	**Avg. Daily Range**
Uncovered 1	30.38	10.33	20.05
Uncovered 2	25.19	11.30	13.89
Covered 1	29.61	10.65	18.96
Covered 2	28.60	10.43	18.17

covered and uncovered areas. Each horizontal bar represents a single month of data from June-August 2019, with red areas representing low RH% (<80% RH) and blue areas indicating high RH% (>80% RH). Here we can see a significant difference in the Covered and Uncovered iButtons in the time that it takes for moisture to reach the iButton aperture, as well as the amount of time that it takes for each iButton to

reach 'dry' measurements. Since the Uncovered iButtons have no surface covering they sense an increase in RH% very quickly. The Covered iButtons on the other hand, lag behind the Uncovered iButtons. This is likely due to the moss covering the aperture on the iButton and shielding it from the effects of light rain, dew, or mist. This shielding effect is particularly evident in the last few weeks in June 2019, where we can see that there were some periods of light rain. The Uncovered iButtons have a longer duration of high RH% values, and the Covered iButtons have a delayed and much shorter timespan in the high RH% range. Conversely, the shielding effect of mosses on their substrates also appears to increase the duration of high RH% readings in periods of heavy rainfall. This is evident in beginning of June, middle of July and end of August during the monitoring period. We can see that there is a delayed response from the Covered iButtons in initially sensing the increase of RH%, however, once those areas become completely saturated (heavy rainfall events), they take much longer to dry than the Uncovered iButtons.

In comparison to the RH% results from the Uncovered and Covered iButtons, there appears to be no such shielding effect with regards to temperature (Fig. 5.7). Both treatments result in broadly similar results, with the differences in average maximum and minimum temperatures achieving comparable ranges.

Overall the results from this monitoring experiment showed that each iButton showed different RH trends, with no major differences in temperature. The moss-covered iButtons seemed to have lags in both wetting and drying after rainfall periods. The results from this experiment most likely underestimates moss impacts, as there had to be an air gap between the moss cover and the iButton. Improvements in methodology in future experiments could provide further, more representative data.

5.6.3 How does moss growth influence water uptake and evaporation rates: Mass data

This experiment compared the impact of moss growth on water retention and the evaporation rate on the weathered 15 cm Portland limestone cubes. By repeatedly weighing each cube or block over a 24-hour period, the amount of water retained

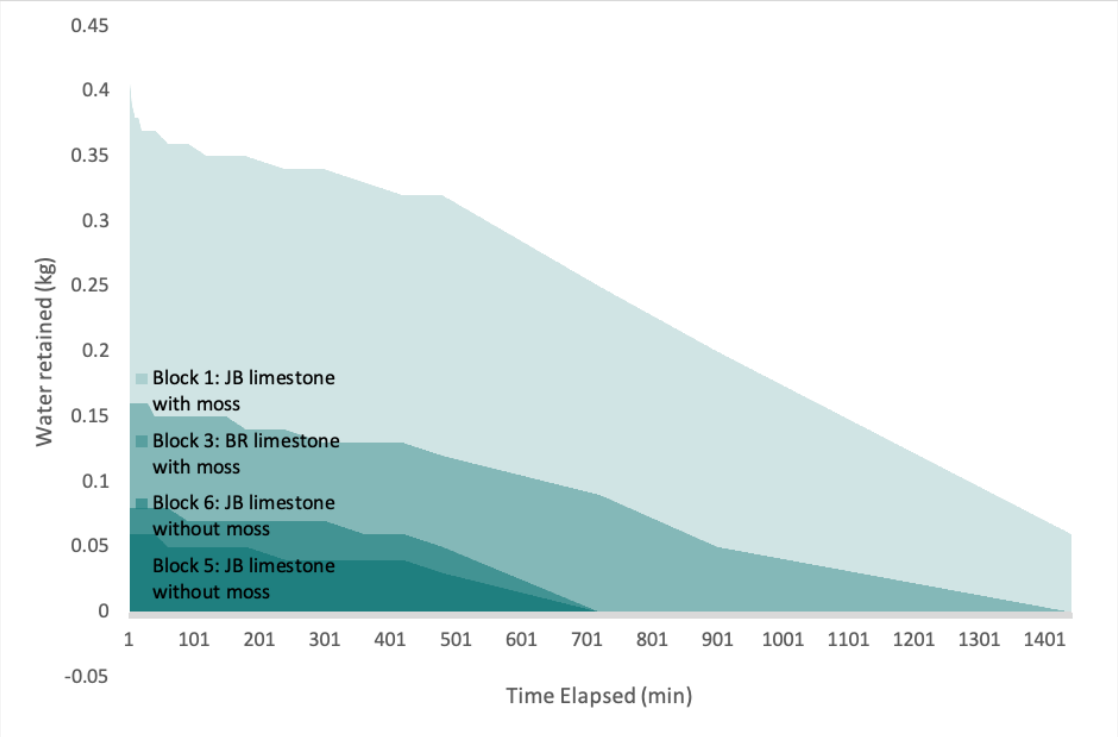


Figure 5.8: Comparison of 4 test blocks with and without moss and their capacity to carry water.

by the block at different time periods was obtained by subtracting the initial dry weight. All blocks used in this experiment with the exception of Block 5 had been weathered in a natural environment. Although the sample size is small, the results show that the blocks with moss growth retain more water than the blocks without moss growth Fig. 5.8. The blocks with moss growth initially absorb much more water, and also retain the water for a longer period of time, with Block 1 only reaching its initial dry weight after drying in the lab environment for 24 hours.

5.6.4 Does moss growth influence water uptake at surface level: Protimeter data

These experiments investigated the influence of water uptake at the surface using the 15 cm cubes of weathered Portland stone. Fig. 5.9 plots median values of surface moisture measurements taken in the laboratory environment before and after flooding the surface of blocks to determine the drying time for blocks with and without moss coverage. Standard errors were used to determine the whisker

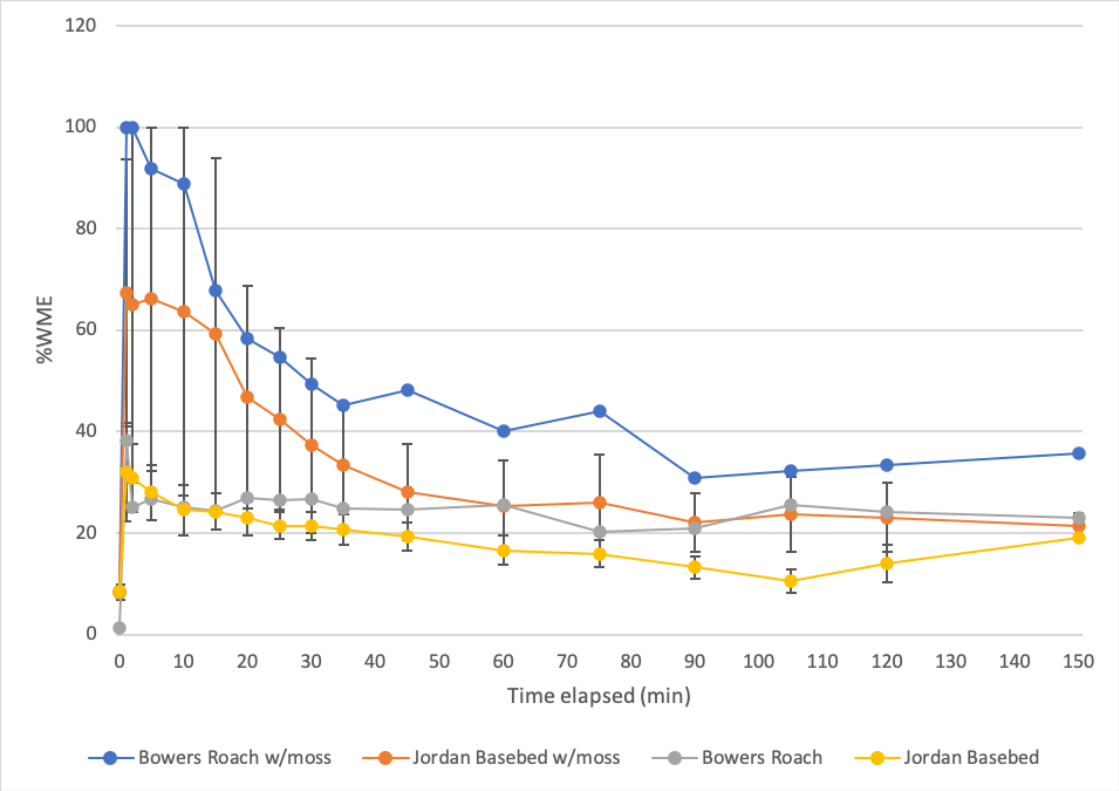


Figure 5.9: Surface moisture measurements using capacitance (handheld Protimeter) in %Wood Moisture Equivalent comparing Bowers Roach and Jordan Basebed limestone blocks with and without moss growth (N=8).

length. Jordan Basebed blocks covered with moss had high standard errors as each of the four blocks had varying degrees of biological growth coverage. Although blocks were chosen with similar amounts of moss coverage, they were not identical which may have led to a difference in the surface moisture levels.

Fig. 5.9 depicts a large difference in the amount of water initially taken up by both the Bowers Roach and Jordan Basebed blocks with moss growth and those without moss growth. Surface moisture levels peak and then drop quickly until around 30 minutes, when the measurements appear to stabilize somewhat, reaching their initial dry measurements 2.5 hours after the initial surface flooding.

5.6.5 Does moss growth influence water uptake at subsurface level: Karsten test data

Fig. 5.10 plots median values from all 82 Karsten tube tests, with standard errors used as the whisker values. These results were obtained in the lab environment

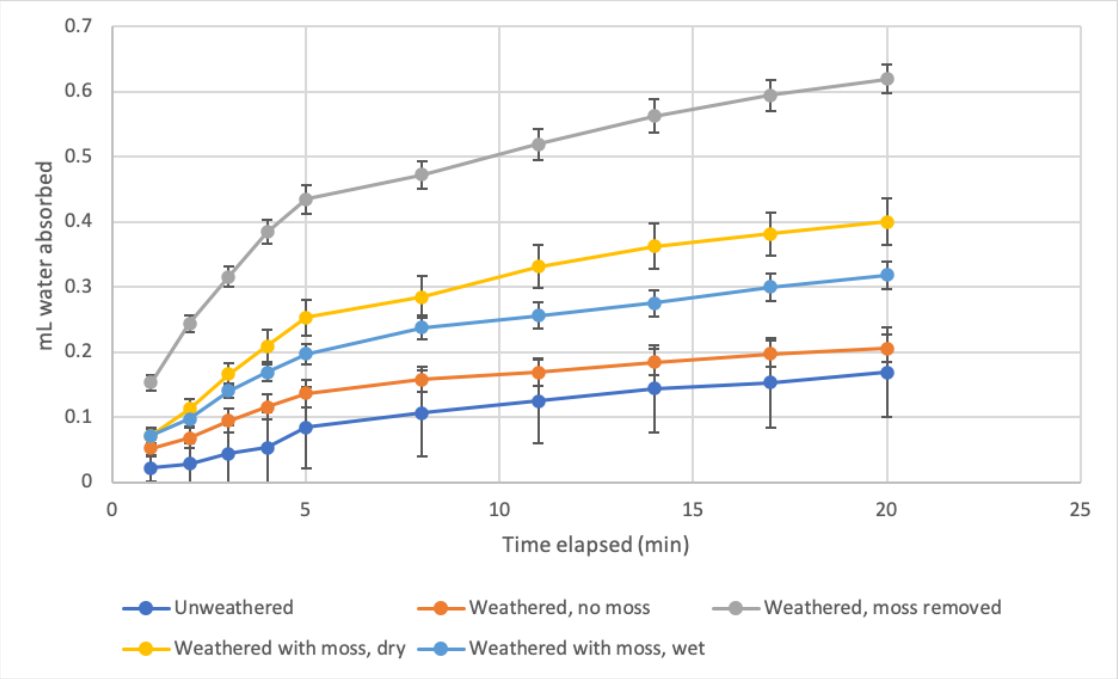


Figure 5.10: Karsten tube tests from field and lab (N= 82), showing water uptake from different substrate conditions. Grouped results from Jordan Basebed, Bowers Roach and Chipping Norton Limestone, and cementitious mortar.

using weathered samples (N= 23), and in the field at Kelmscott Manor (N = 3) and Chipping Norton (N= 56). The weathered Portland limestone samples in the laboratory environment absorbed the least amount of water during the tests. The substrates that absorbed by far the most water were the areas that had moss growth which had been manually removed before testing. Areas with moss (removed or otherwise) absorbed more water than areas without moss. Note that in Fig 5.10 the results from all substrates have been grouped together. Here initial evidence suggests that removing mosses causes the most water to be absorbed, regardless of substrate type.

Additionally, one-way ANOVA using Karsten tube median values (5 treatments: Unweathered no moss, Weathered no moss, Weathered moss present but removed, Weathered moss present, Weathered moss present contact sponge method) gives a significant result at $p < 0.05$, with a p-value of <0.00001. We can see that there are significant differences in the 5 Karsten tube treatments. Results from the Tukey post hoc test tell us that the 'Weathered moss removed' treatment was

significantly different from the other 4 treatments.

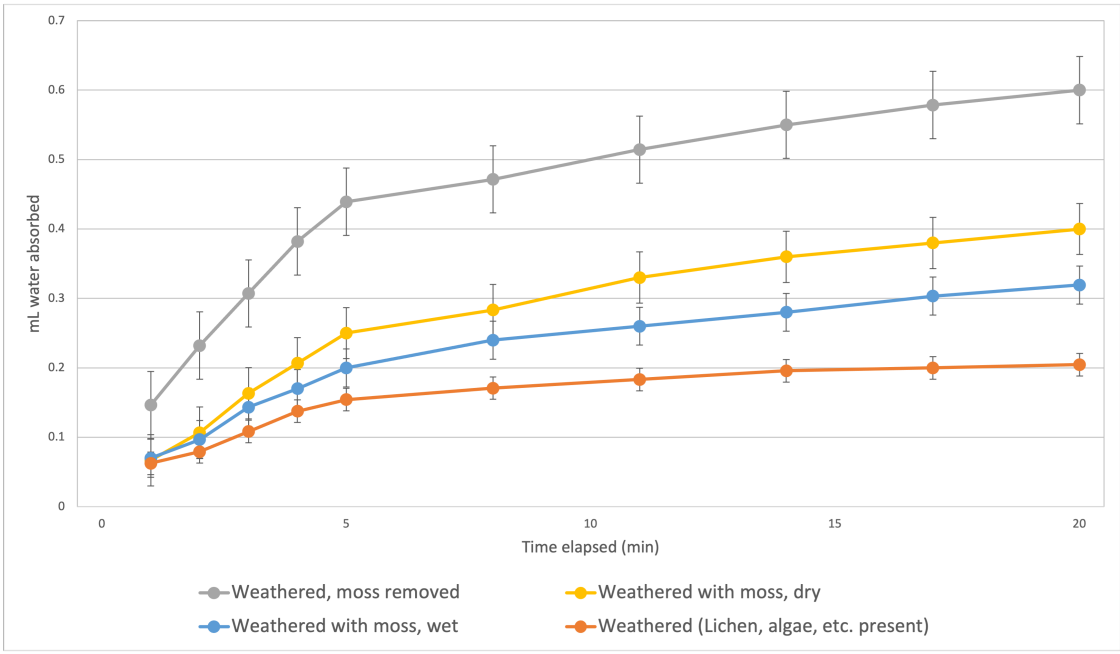


Figure 5.11: Repeated Karsten tube tests (N= 56), showing water uptake from different substrate conditions on Chipping Norton limestone.

The results from repeated sampling in Chipping Norton on the same areas with moss and moss removed show that mosses increase water absorption independent of material type. Fig 5.11 shows the results from Karsten tube tests over moss growth and then repeated Karsten tube tests in the same areas with the moss removed. The results appear to echo the results from Fig 5.10, where all results from different materials and substrates were grouped together, suggesting that moss growth increases water absorption regardless of the underlying substrate.

In Fig 5.12 we can see the effect of material type on absorption rates. There appears to be a minor effect of substrate type on water absorption in comparison to the results shown above due to the influence of moss growth. While the amount of water absorbed overall is much lower than seen in the tests with the mosses removed, the variance and standard error between tests is also much lower suggesting that you may expect more reliable results from water absorption tests within substrate types.

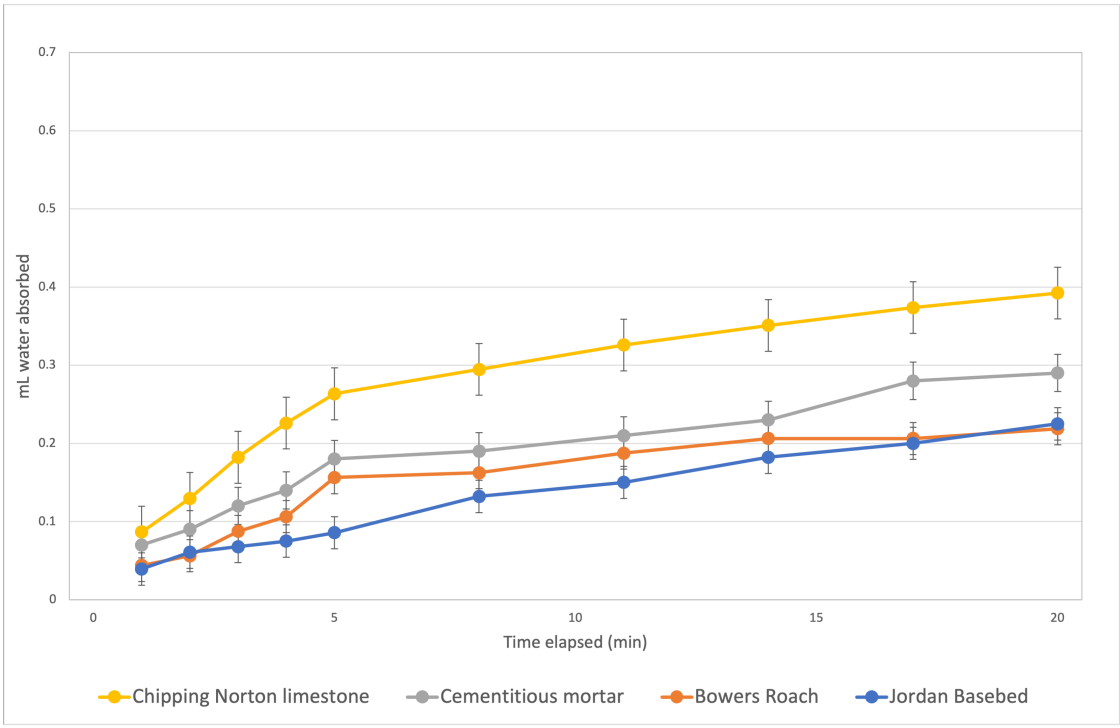


Figure 5.12: Karsten tube tests from field and lab (N= 82), showing water uptake separated by material type

5.7 Discussion

5.7.1 Limitations and scope of the project

The microclimate monitoring for this project was limited to a small area in England and done for a short period of time. For more robust findings, these experiments could be repeated and monitored for a longer period of time. This project focuses on limestone and cementitious mortar, and future research should investigate other material types such as slate and bricks. While the results show significant findings when regarding the moisture regimes of mosses and moisture regimes, more testing should be done to increase the confidence level. However, the benefit of the methodology and analyses used in this project illustrates the suitability of non-destructive tests in the lab and field. Such tests are simple, easy to deploy, and can be tailored to different substrates. They are also suitable for many different environments and can be undertaken without disturbing the aesthetics of cultural heritage sites (for instance, long-term monitoring using iButtons is

relatively discreet).

5.7.2 Recommendations for further research

This project showed some significant initial findings that could be explored further in future research. In particular, the differences between covered and uncovered areas and the impact on moisture beneath biological growths has potential to be explored in future projects. The relationship between mosses and moisture, while appearing straightforward, may be more complex than initially imagined. Further research particularly on the impacts of moss removal, moisture, and built heritage has the potential to be explored.

There is additional scope to evaluate the differences in moisture regimes when comparing the two distinct growth forms of mosses. This research project mostly examined the pleurocarpous growth type, defined as carpeting, with amorphous edges, and in particular the species *B. rutabulum*. This project also investigated the impact of acrocarpous mosses on water absorption through the Karsten tube tests, and future projects could further explore the impact of acrocarpous mosses and their circular, cushion-like forms. These two growth types are visually distinct from one another, and also have demonstrated differences in growth rates and patterns - therefore one might surmise the effect on substrates may be different. The influence of upright cushions and the absorption capabilities of water as compared to the flatter growth type is another question to be explored in future research.

5.7.3 Relevance to built heritage management strategies

Previous research and advice given to built heritage caretakers has suggested that mosses simply create wet environments, and that they also prefer wetter climates to flourish and grow. From the data presented in this paper, we can confirm that mosses prefer to inhabit wetter and darker environments, (differences in moss cover on N vs S walls at high and low levels at Kelmscott Manor). However, to say that mosses simply create wet environments, saturate their substrates, and cause moisture to linger on substrates may be overstating a more complex relationship.

From the microclimate data at Chipping Norton which compared the results from bare stone and moss-covered stone, we can see that mosses may in fact shield the substrate from lighter periods of rain and moisture. Not only did the presence of moss delay the impact of relative humidity spikes, but in light rainfall events the presence of moss shortened the impact of moisture on the underlying substrate creating a drier underlying substrate than the bare surfaces.

When we further explored the impact of mosses on surface and subsurface water retention and uptake using a range of other methods, they fell broadly in line with previous research. Results from the water uptake and absorption tests (Karsten tube and modified BS EN 1936:2006), as well as surface moisture retention (Protimeter experiment) showed that in all cases the presence of moss increased the overall amount of water absorbed and lengthened the amount of time for each sample to return to baseline moisture measurements. Whether by the mechanisms of their growth, such as their rhizoids or deposition of acidic metabolic by-products, or their overall morphology above the substrate surface, mosses appear to have an impact on the uptake and evaporation of water.

The results presented here have relevance for recommendations for moss management strategies and removal. For built heritage located in drier climates, the removal of mosses may not be necessary for the overall health and preservation of the site. Keeping in mind the results from the covered and uncovered microclimate monitoring experiment with iButtons at Chipping Norton, we could see a buffering effect that may be beneficial to buildings located in drier climates. Moreover, the growths appeared to have a negligible effect on surface temperature fluctuation and absolute temperature measurements, so fears regarding physical deterioration regarding temperature fluctuations may be allayed.

For built heritage located in wetter climates and for those with dramatic and invasive growths, the traditional advice may still apply. Despite this advice, the management strategy at Kelmscott Manor has conventionally followed William Morris' conservation philosophy, which allowed the Manor to coexist symbiotically with the natural environment. Mosses and other species of lower plants have been

allowed to colonise the roof structures, walls, and other structures at Kelmscott Manor and yet there do not appear to be any great deterioration or damp problems present in these areas.

The findings from this project showed evidence that the presence of mosses can prolong the effects of intense rainfall on their underlying surfaces Fig. 5.6 as well as increase overall water uptake Figs. 5.8, 5.9, and 5.10. In these cases the presence of mosses may be detrimental to the underlying substrates, and may accelerate processes of deterioration. Areas with delicate decorations and any substrates that are sensitive to water, such as frescoes or wall paintings, should take particular care to prevent moss growth from occurring. However, it is important to keep in mind that moss growth will not occur unless the underlying environmental conditions are suitable. In most cases, controlling and monitoring the environmental conditions in the interior of built heritage will prevent mosses and other undesirable biological growths from growing. Results from the water uptake (Karsten tube) experiments also suggest that prevention of moss growth may be the best method to prevent further deterioration of the substrate through water absorption, since the findings indicate that the substrate with the highest amount of water absorption were the areas that previously had moss growth which had been manually removed. Once moss is established it may cause more harm than good to remove it.

5.8 Conclusions

Key findings:

- As suggested by previous research and literature, mosses prefer to inhabit areas that have higher RH% values, and smaller fluctuations in RH% and temperature.
- Mosses may play a role in 'shielding' the underlying substrate from light rainfall events, while prolonging surface wetness in more intense rainfall events
- Mosses have an impact on water uptake and retention at both the surface and subsurface level

The findings from this project suggest that the relationship between mosses and moisture is more complex than usually portrayed. From previous research, most sources suggested that the presence of mosses indicated that the underlying substrate was likely to be wetter than those substrates without mosses. The results gained from the experiments presented in this paper show that this may not be the case, and that in certain cases substrates covered with mosses may shelter underlying surfaces from brief rainfall events.

Additional tests (e.g. Karsten tube tests) illustrated that the impact of removing mosses may be more inherently damaging than leaving them in-situ. These initial findings suggest that more research should be undertaken to fully understand the moisture regimes surrounding mosses and cultural heritage.

The liveliness in me just loves to feel the liveness in growing things, in grass and rain and leaves and flowers and sun and feathers and furs and earth and sand and moss.

— Emily Carr, the Book of Small, 1942

6 Discussion

Contents

6.1 Structure of Discussion 103
6.2 How do built heritage experts and visitors view the presence of moss growth on historic buildings? 105
6.2.1 The three questions clearly identified as most in need of answering from both surveys are: 105
6.3 How can we visually characterize the deterioration and weathering processes of moss growth on limited samples of historic stone? 107
6.4 How does moss growth affect moisture relations on stone substrates? 108
6.5 Typology of moss impacts 109
6.6 Can we characterize the impacts of moss growth on stone masonry: Bioprotection vs. Biodeterioration . . 112
6.7 Practical guidelines for treating moss 113
6.7.1 Ethics of doing nothing 115

6.1 Structure of Discussion

The Discussion chapter of this thesis is structured to reflect the original objectives and research questions posed by this project. It will begin by addressing the initial objectives as stated in Chapter 1:

1. How do built heritage experts and visitors view the presence of moss growth

on historic buildings?

- To examine the perceptions of moss growth on built heritage, identify the aesthetic impacts of moss growth, and identify gaps in knowledge, and examine how these opinions might inform future conservation policy and conservation management plans.

2. How can we visually characterize the deterioration and weathering processes of moss growth on limited samples of historic stone?

   - To provide a workflow with complementary visual analyses which characterizes the physical impacts of moss growth.

3. How does moss growth affect moisture relations on stone substrates?

   - To examine the difference in surface moisture, water absorption, and humidity fluctuations on areas with and without mosses.

The discussion will then address the typology of moss impacts as suggested in Chapter 1. Due to knowledge gained about moss growth on substrates during this thesis, is this initial typology of moss impacts still suitable or should it be revised?

Bringing together the research findings from this project, it will then address the original aim of this project, which was to characterize the impacts of moss growth on stone masonry, and to determine if their presence on built structures can be categorized as having either an overall bioprotective or biodeteriorative effect on built structures. The discussion will evaluate the overall impact of moss growth on limestone and cementitious materials by linking the findings from chapters 3, 4, and 5. Tying together evidence from the three paper-based chapters, it will provide a comparison between lichen vs. moss impacts on built heritage. Finally, it will revisit practical guidelines for managing moss growths on historic buildings, and conclude with a proposal on the 'Ethics of doing nothing'.

6.2 How do built heritage experts and visitors view the presence of moss growth on historic buildings?

As we could see from the survey findings examining perceptions of moss growth on cultural heritage, both visitors and built heritage experts have complex views surrounding mosses and the role they play in aesthetics and deterioration. The appearance of mosses is likely to be embraced in rural environments, or in cases where the heritage asset is a ruin or scheduled monument, however, they are less likely to be viewed positively in urban environments. These findings correspond with previous research on biological patinas found on historic buildings, where many interviewees "expressed positive values associated with ageing, weathering and decay. For most visitors to the case study sites, marks of age, weathering and decay played an important role in establishing the authenticity, significance and aesthetic appeal of buildings and monuments, as identified by Riegl and Ruskin over a century ago" (Douglas-Jones 2016, p 825). Both visitors and experts widely agree on the treatment of mosses, saying that they should only be removed in cases where they are obviously causing damage.

6.2.1 The three questions clearly identified as most in need of answering from both surveys are:

1. How do mosses protect/damage buildings?

    - From the findings of this research project, we can see that there are a range of impacts from moss growth on built heritage. Many of the findings appear to contribute to the biodeterioration of stone through biomechanical and biochemical weathering. As seen in Chapter 4, moss appears to contribute to biomechanical weathering through increasing surface roughness and hyphal intrusion, and in Chapter 5 through an increase in moisture uptake at both the surface and subsurface level. There may be some contribution to biochemical weathering through the

deposition of oxalic acid, as seen in Chapter 4. However, mosses may also contribute to bioprotection through sheltering the surface from low-level rainfall events as seen in Chapter 5.

2. Does removing mosses from historic buildings cause more damage than leaving them in place?

    - There was evidence that removing mosses from limestone and cementitious mortar may dramatically increase the amount of water uptake as in Karsten Tube tests from Chapter 5. In Chapter 5 Karsten Tube tests were conducted before and after acrocarpous and pleurocarpous growth forms were removed from limestone and cementitious mortar-capped boundary walls at heritage sites (Kelmscott Manor and Chipping Norton). We could see evidence that removing mosses contributed to increased water absorption, Fig. 5.10. This means that removing mosses may contribute to localized increases in moisture uptake, and in turn increase the likelihood of physical deterioration through excess moisture. Future research could be done to see if similar results can be obtained from different substrates.

3. Should I remove moss from buildings?

    - The findings from this research project suggest that each site should be evaluated individually. As suggested by the choices of wall diversity and structures, local vernacular architecture may have different conservation decisions and outcomes than sites with international significance. With relation to the sites studied in this project, the answer may be different for boundary walls, such in the cases at Kelmscott Manor and Chipping Norton, which have lower heritage designation than for Blenheim Palace, which is a UNESCO World Heritage site. Outcomes may differ depending on the values expressed by each individual heritage site as defined by heritage-based values typologies such as the Burra Charter (Australia,

ICOMOS 1979) and Friedheim and Khalaf 2016. For heritage sites valued for 'authenticity,' 'age' and naturalistic aesthetics as in the case of Kelmscott Manor, moss growth may even be encouraged. Additionally, the scale of moss colonisation should be evaluated at each site since the overall aesthetic impact of mosses was determined to be relatively positive as seen in Chapter 3.

6.3 How can we visually characterize the deterioration and weathering processes of moss growth on limited samples of historic stone?

From the research done in this project, we can see evidence that mosses contribute to processes of biodeterioration and decay of their underlying substrates. These impacts can be categorized as active and passive, and can be attributed to the growth of mosses rather than other forms of bio-colonisation such as lichens, cyanobacteria, and algae on the same substrate. One initial concern of this research project indicated that it may be difficult to separate the effects of moss growth from other types of biological growth, since the project used naturally weathered stone which had multiple species on the same surfaces, at some times overlapping one another. The workflow approach described in Chapter 4 describes how it is possible to separate these types of growths even while working with a small sample size with overlapping growths.

The research findings indicate that mosses influence deterioration when it comes to surface weathering and roughness, rhizoid penetration, and disaggregation of the stone matrix. While the impact of mosses when it comes to biodeterioration cannot be quantified, there appears to be a difference between the impact of mosses and other types of biological growths such as lichens or algae, Fig. 4.3 and Table 4.2. Mosses appear to have more of an impact on surface roughness than lichens even when comparing identical exposure and weathering duration, Fig. 4.3. Mosses appear to be a factor in accelerating the rate of biodeterioration when it comes to physical weathering, whereby the processes and metabolic byproducts of growth (rhizoid

penetration, chelation) affect the integrity of the underlying substrates by increasing surface roughness and patination, and contributing to further disaggregation of the stone matrix through rhizoid penetration, Figs. 4.5 and 4.6.

Importantly, findings from this project indicated that some impacts of moss growth may be accelerated by the removal of mosses from the substrate. In particular, the Karsten tube analysis indicated that moisture uptake from surfaces is dramatically increased in surfaces that were previously colonised by mosses but had the mosses removed, Fig. 5.10. This may indicate that in certain cases, removal of mosses may in fact cause more damage than leaving them in-situ.

6.4 How does moss growth affect moisture relations on stone substrates?

There appears to be a significant impact of moss growth on moisture relations on limestone and cementitious mortar, especially when it comes to surface moisture and water absorption at the surface and subsurface depths. There appears to be a significant difference in moisture uptake when comparing surface with mosses, bare surfaces, and surfaces with other types of biological growths such as lichens, Figs. 5.10 and 5.9. The findings indicate that even when controlling for other types of biological growths, mosses have a significant impact on the amount of water uptake and retained by substrates, Fig. 5.8. These findings are supported by previous research projects which indicate that mosses have a capacity to tolerate desiccation and for some species of mosses such as Sphagnum mosses, retain "16-20 times its own weight in liquid, as compared to 4-6 times of cotton" (Rotherham & Griffiths, 2013, p.202).

Additionally, there is evidence that mosses sustain surface and near-surface moisture for a longer duration than bare substrates or lichen-covered substrates. Some previous research suggested that mosses created moist environments simply by their presence and growth, however, the microclimate monitoring done in this project found that the mosses sustained moisture from rainfall events, but did not create moist environments if the conditions did not occur.

Findings indicate that these impacts may occur whether or not mosses are in active growth or dormancy, as investigations in Chapter 5 were undertaken during the summer months when moss growth remains dormant. This is relevant because it indicates that the impacts may continue to persist even if the underlying conditions which caused moss growth initially are removed, and that the impacts continue during seasons in which mosses are usually dormant.

The findings from this project did not find much evidence to suggest moss' capacity to retain moisture as a large factor in increasing freeze-thaw shattering. In most cases, the observed risk from freeze-thaw shattering appears to be relatively minor, as seen in both the relative humidity and temperature fluctuation data from Chapter 5. Considering the impact of climate change, freeze-thaw deterioration may be less likely to be a hazard across the United Kingdom in future. Additionally, although mosses do retain water, removing them may in fact exacerbate water uptake and saturation due to the weakened surface beneath the colonisation which has then been suddenly exposed as seen in Chapter 5. While we can see that there is a significant impact on moisture relations concerning moss growth, it is tempered by the initial findings that removing mosses may also accelerate processes of deterioration and decay. It may be that in cases where there is significant moss coverage, the benefits of removing mosses and accepting the possibility for accelerating surface powdering and flaking outweigh the negatives of increased surface moisture and water uptake.

6.5 Typology of moss impacts

As discussed in Chapter 2, a table of moss impacts had been compiled based on results and findings from previous research on lichen growth and biological greening on cultural heritage.

The research presented in this thesis has not found any new impacts to those in Table 6.1, but has shown that these impacts can be divided into active and passive categories, Table 6.2.

Table 6.1: Typology of moss impacts

Physical	Chemical	Aesthetic
Moisture relations	Encrustation and patina (surface)	Colonisation
Thermal blanketing	Rhizoid penetration and Chelation	Staining
Surface weathering		
Rhizoid penetration		

Table 6.2: Typology of moss impacts, revised

Active	Passive
Rhizoid penetration	Rhizoid remnants
Chelation	Moisture/thermal buffering
Tertiary bioreceptivity	Moisture relations
	Staining and patina

While the initial Table 6.1 is not incorrect in the assessment of different types of moss impacts, perhaps a more meaningful way to organize these impacts is through the distinction between active or passive impacts of moss growth Table 6.2. The distinction here is that the passive impacts of moss growth occur whether or not the organism is in a growth phase of its development. The active impacts of moss growth can directly be attributed to the growth of mosses.

In Table 6.2 we can see that several impacts occur and continue developing in both the active and passive categories. When we consider staining and patina at the surface level, the active process of metabolism and growth contributes to an increase in patination and colour changes on the substrate. These patinas persist while mosses revert to their dormant phase in the growth cycle (most often during the drier seasons), and continue to interact with the underlying substrate even while the mosses themselves lie dormant. The same can be said regarding the impact of moss rhizoid penetration, which creates voids within the stone matrix, and surface weathering. These impacts may be initially started by the growth of mosses on the substrate, but their effects persist and continue while mosses are in their dormancy, Figs. 4.5 and 4.6.

Differences in the active and passive impacts of moss growth occur when we consider factors such as chelation, tertiary bioreceptivity, thermal blanketing and

moisture relations. Chelation and tertiary biodeterioration occur during the active growth cycle of mosses. The deposition of oxalic acids during mosses' growth phase contributes to chelation of the underlying substrate, and as in previous research has noted an uptake in certain minerals and elements (such as Calcium) to sustain natural growth processes, Fig 4.6. These impacts lessen when mosses are no longer in their active growth phase, as the minerals are no longer necessary for survival. Similarly, tertiary bioreceptivity as seen when mosses act as secondary colonisers, only occurs during the growth phase of mosses. Evidence can be seen of this process in Fig 4.5 where bryophytes were commonly found colonizing lichen perithecial pits. Bryophyte growth further contributes to altering the substrate making it more susceptible to future biological colonisation.

Certain impacts have been categorized as 'Passive' impacts because mosses do not need to be in their active growth phases to occur. These impacts have been described as moisture/thermal buffering and moisture relations. As seen in Fig 5.6 there is evidence of relative humidity buffering between moss colonisation and the substrate. From the findings of this project, there was no statistically significant impact on thermal buffering, however, there is scope to investigate this further with more analyses using iButtons. Additionally, moisture relations were categorized in the 'Passive' category because there is evidence that mosses do not need to be in their active growth phases to occur. As seen in the microclimate monitoring experiments which were undertaken during the summer, there were significant differences between substrates with and without moss growth (Kelmscott Manor and Chipping Norton microclimate monitoring experiments, July - August 2019, 5). Ideally, these conditions and experiments would be replicated at the same sites during the winter period to evaluate whether these impacts also occur during other seasons and in the growth period of mosses as well. These impacts have also been designated in the 'Passive' category, because the impacts would not occur if the moss growths were removed. This is in comparison to the impacts which occur in both the 'Active' and 'Passive' categories together.

6.6 Can we characterize the impacts of moss growth on stone masonry: Bioprotection vs. Biodeterioration

This section addresses the overall aim of the thesis, which was to characterize the impacts of mosses and to determine if their presence on built structures can be categorized as having either an overall bioprotective or biodeteriorative effect.

The mechanisms and impacts of moss growth have been discussed in this chapter, and in summation mosses can broadly be confirmed and characterized as biodeteriogens. Findings from Chapters 4 and 5 illustrate that species *B. rutabulum* and *G. pulvinata* impact surface roughness and increase disaggregation of the stone matrix due to rhizoid penetration. Rhizoid termini appeared to correlate with calcium oxalate crystallization at near-surface depths, which is evidence of biochemical interactions and deterioration. Finally, growth of species *B. rutabulum* and *G. pulvinata* appeared to increase water uptake at both surface and near-surface depths on limestone and cementitious mortar substrates. Together these impacts appear to have a negative impact on the fabric and integrity of underlying substrates. The project found some small evidence that moss growths may have additional bioprotective or neutral effects which warrants further investigation. The research findings were inconclusive on the impact of *B. rutabulum* on thermal fluctuations at the stone surface. There were no statistically significant differences in the average daily range in temperature of the iButtons with and without moss coverage, Figs. 5.7. There is some evidence of moss growth contributing to moisture buffering, or protection from small spikes in relative humidity in comparison to bare stone, Fig 5.6. Humidity fluctuations are a concern during colder months when freeze-thaw shattering can contribute to the physical deterioration of stone substrates. This may indicate that a small amount of moss growth can protect against these smaller fluctuations, which in turn may offer a small amount of protection to the underlying substrate.

We can create a comparison between lichen and moss impacts from the findings of this project and literature review in Chapter 2. Due to the lack of research on

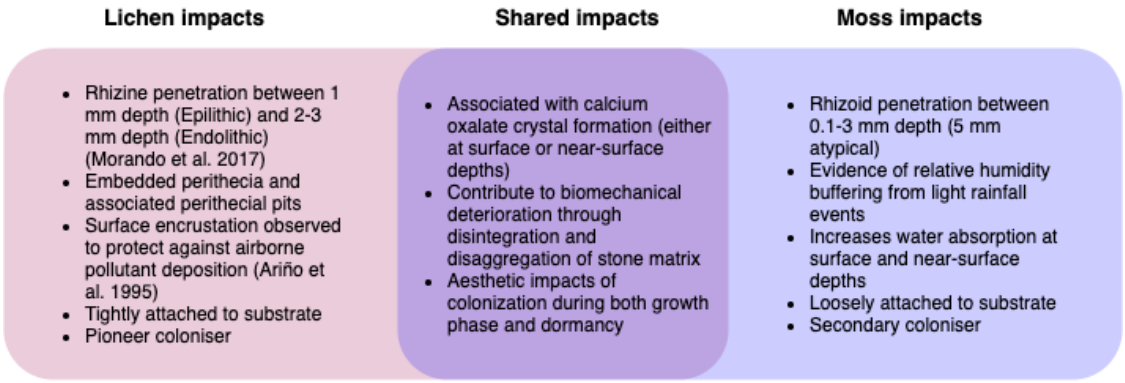


Figure 6.1: Comparison of lichen and moss impacts

moss impacts, the shared impacts column as noted in Fig 6.1 will likely shift in time, as more evidence is uncovered. The presence of both invariably changes the aesthetic presentation of a site, and they both contribute to biomechanical and biochemical deterioration via their attachment structures and through byproducts of growth. Differences occur due to their morphology and relation to moisture regimes. Lichens are more tightly attached to their underlying substrates, forming a 'skin' which is difficult to remove, whereas mosses are more loosely attached. Lichens also produce perithecia, which are spherical fruiting bodies embedded in the surface of substrates. These perithecia shrink and die, leaving perithecial pits which allow mosses to establish themselves as secondary colonisers. A significant difference between the two organisms appears to be in their relation to moisture regimes, with *B. rutabulum* and *G. pulvinata* displaying an increase in water absorption at both surface and near-surface depths.

6.7 Practical guidelines for treating moss

As with most cases surrounding built heritage management, the results from this research project and the advice to the management of cultural heritage, suggest that each site should be evaluated on a case-by-case basis. When reviewing practical guidance from heritage bodies, the Edinburgh World Heritage Historic Home Guide for Roofs recommends brushing moss off of clay roof tiles as they hold moisture which causes the tiles to deteriorate more quickly and cause frost damage (Mayhew,

2018, p. 7), which is also corroborated with the Historic Environment Scotland Inform Guide on Biological Growth on Masonry, which states that "moss retains water extremely well, and this can keep a masonry surface in a persistently wet state, which exacerbates stone decay" (Eklund and Young, 2013, p. 5). The findings from this project broadly agree with this advice, as findings from Chapter 5 reveal that the presence of mosses increased the duration of surface moisture on substrates (Fig. 5.6) and increased the overall volume of water absorbed at both surface (Fig. 5.9) and near-surface levels (Fig. 5.10). The project also provides a useful framework with which to evaluate moss growth on other materials and substrates. Results may vary depending on climate and substrates, as this project deals with limestone and cementitious mortar in the drier climate of central southern England while the Historic Environment Scotland Inform Guide generally deals with sandstone in wetter climate conditions in Scotland.

As discussed in Chapter 2, the presence of endangered species adds complexity to management and removal strategies of mosses on built heritage. In light of the findings form this project, it is recommended that careful observation and identification should take place if significant moss colonisation is present. If possible, bryophyte specialists should be contacted to map and identify moss species before removing significant moss growth from cultural heritage sites. Since endangered and vulnerable species of mosses are more likely to be sensitive to airborne pollutants, mapping and identification may be more necessary at rural than urban sites.

Based on the results from this project, a key message to convey to heritage practitioners is that prevention of moss growth may be a significant portion of conservation management strategies in future since reversing deterioration caused by moss growth is not possible. We can see evidence of increased pitting, surface roughness, and mechanical disaggregation caused by rhizoid growth, and evidence of rhizoid growth and calcium oxalate crystallization at near-surface depths. These impacts cannot be reversed once altered, nor can the near-surface effects be fully removed even after thorough cleaning (Savković et al. 2016). Additionally, we can see evidence that water uptake is increased when mosses are allowed to colonise

a substrate and are then removed (Fig. 5.10). This suggests that preventing moss growth in the first place may be a fundamental management strategy. While the long-term effects of biocides have been debated, alternatives may include the addition of copper or zinc flashings on roof structures.

Secondly, and related to the first message, is that management strategies may include monitoring and treating underlying moisture conditions to prevent micro-climatic conditions required for moss growth. From the microclimate monitoring experiments, there was evidence that mosses prefer areas with higher relative humidity and often darker or north-facing aspects (Chapter 5). Such advice might include pruning overhanging branches near roof structures, to clearing bushes and trees close to wall structures to allow surface moisture to evaporate more easily.

6.7.1 Ethics of doing nothing

Due to the impact of the COVID 19 pandemic, and the uncertain landscape of heritage and conservation in the near future, it may be wise to evaluate the impact of the 'Ethics of doing nothing' as a conservation strategy in itself (Ashley-Smith 2018). The instances of benign neglect may increase in the near future, as funding for heritage and conservation has been impacted by this global pandemic. This strategy may not be detrimental when considering moss growth, as we can see that moss growth contributes to the patina of age on built heritage and visitors "expressed positive values associated with ageing, weathering and decay. For most visitors to the case study sites, marks of age, weathering and decay played an important role in establishing the authenticity, significance and aesthetic appeal of buildings and monuments, as identified by Riegl and Ruskin over a century ago" (Douglas-Jones 2016, p 825). Again, these findings were supported by findings from Chapter 3 which found that both visitors and built heritage experts found the presence of moss on built heritage appealing. Moreover, specific findings from this project suggest that removing mosses may cause increased water uptake and absorption, validating the 'Do nothing' strategy as preventing potential damage on built heritage.

To a naturalist nothing is indifferent; the humble moss that creeps upon the stone is equally interesting as the lofty pine which so beautifully adorns the valley or the mountain.

— James Hutton, Theory of the Earth, 1788

7 Conclusions

Contents

7.1 Key findings 117
7.2 Lessons learned and opportunities for further research 119
7.3 Opportunities for further research 120

7.1 Key findings

The key findings in this section summarise the main conclusions from Chapters 3, 4 and 5:

- Survey respondents who indicate a high level of moss knowledge are more likely to correctly identify images of moss growth from a collage of different types of biological growths, and experts are more likely to correctly identify moss than visitors.
- Both experts (71.4%)(n=35) and visitors (71.3%)(n=67) strongly believe that moss growth should only be removed from historic buildings on a case-by-case basis.
- Both experts and visitors agree that moss growth on historic buildings is a strong indication of age, authenticity, and the 'countryside'.

- Visitors have a more negative view of moss growth than heritage professionals - both in terms of the aesthetic qualities and in terms of how they affect the building lifespan and deterioration.

- The 4-step workflow described in Chapter 4 effectively utilizes limited samples from cultural heritage to visualize the lithobiontic interface at a range of scales and including extensive coverage of the surface and cross-sectional views.

- *B. rutabulum* growth is associated with rougher surfaces compared to freshly cut surfaces, and even in comparison to surfaces covered in other types of observed biological growth such as lichen and algae when exposed for the same amount of time.

- The impacts of *B. rutabulum* as a secondary coloniser are often located within existing lichen impacts, such as perithecial pits.

- *B. rutabulum* growth commonly observed between 0.1 – 3 mm depth beneath the stone surface, and is strongly associated with calcium oxalate crystal formation showing evidence that bryophytes may contribute to biomechanical and biochemical weathering.

- As suggested by previous research and literature, mosses prefer to inhabit areas that have higher RH% values, and smaller fluctuations in RH% and temperature.

- Mosses may play a role in 'shielding' the underlying substrate from light rainfall events, while prolonging surface wetness in more intense rainfall events

- We can see that mosses have an impact on water uptake and retention at both the surface and subsurface level

7.2 Lessons learned and opportunities for further research

This project used a combination of natural and social science methods to reflect the interdisciplinary nature of heritage science research at a range of heritage sites in England. Sampling a variety of heritage walls and in-situ structures as well as the set of experimental blocks allowed for both destructive and non-destructive testing. The destructive testing methods used in this project (SEM, 3D microscopy, OLM of petrological thin sections, mass data) are more than is normally possible on most heritage sites. It also focused on limestone and cementitious mortar which are important components of the historic environment in Oxfordshire and the United Kingdom. The project also focused on *B. rutabulum* and to a lesser degree, *G. pulvinata*, both of which are very common species of mosses found throughout the United Kingdom and in temperate climates worldwide. The species of moss are examples from both growth forms of mosses, being pleurocarpous and acrocarpous, showing that the set of methods used are appropriate for both cases. Future research should investigate whether other materials and moss species show similar results.

Sample sizes for this project were small, but comparable to other studies in cultural heritage research and visitor surveys in cultural heritage studies. Further research could be done to replicate these experiments with different substrates and heritage case study sites.

Many research projects conducted between 2019 to 2020 have also been impacted by the COVID-19 pandemic and surrounding effects on travel and working conditions. This research project was impacted directly through the limitation of access to laboratory space, equipment, and the closure of case study sites. In these cases, there were additional tests planned to enhance the rigour and depth of field and lab experiments which were unable to be undertaken. In particular, additional microclimate monitoring experiments, analysis using 3D microscopy and SEM, and moisture experiments had been planned but were cancelled due to the closure of all Oxford University laboratories and the closure of Kelmscott Manor to all visitors.

What has been demonstrated by this project is that there is now a set of methods proven useful for investigating the moss-lithobiontic interface, which is a novel addition to research. For visualizing the surface and cross-section of the moss-lithobiontic interface, this project employed visual condition assessments, OLM, SEM, and 3D microscopy. For analyzing moisture regimes, this project used microclimate monitoring, handheld surface moisture meters, mass data, and Karsten tube tests with a modified methodology for moss colonisation. Through using these sets of methods there has also been considerable progress made with visualizing the moss-lithobiontic interface and evaluating the effects of moss growth on moisture regimes. This project also provides a useful typology of impacts for future exploration of the moss-lithobiontic interface (Fig. 6.1), and delivers practical outcomes and guidance for the management of moss on cultural heritage sites.

7.3 Opportunities for further research

One key take-home message from this project is that there still exists a large portion of work that can be done to further understand the impact of mosses on a variety of substrates. Many analyses and experiments undertaken in this project used relatively inexpensive and widely-available equipment, meaning that they could be replicated by heritage institutions and applied to different types of substrates. Although this project primarily evaluated limestone and cementitious mortars, there are additional types of suitable substrates, both natural and man-made. Particularly for the British context, slate and clay tiles would be very suitable. Treated wood and lime-based mortars would be similarly appropriate choices. Additionally, although this project focused on the species *B. rutabulum* with additional work on *G. pulminata*, future research could expand on and evaluate differences between moss species. As described in Chapters 1 and 2, bryophytes are found on all seven continents, so further research could be done in different locales, climates, and seasons.

This research project exists as an indication that there are significant differences between mosses, lichens, and other types of biological growths. It also demonstrates

notable variations between substrates with and without moss growth, in terms of moisture relations and overall deterioration and decay. This thesis confirms that mosses are an overlooked and enigmatic part of both the natural and built environments. Their presence indicates both an authentic patina of age, and illustrates natural decay revealing the passage of time.

8
References

Abe, K., & Murata, T. (2014). A prevention strategy against fungal attack for the conservation of cultural assets using a fungal index. *International Biodeterioration and Biodegradation*, 88, 91-96.

Adamo, P., & Violante, P. (2000). Weathering of rocks and neogenesis of minerals associated with lichen activity. *Applied Clay Science*, 16(5–6), 229–256. https://doi.org/10.1016/S0169-1317(99)00056-3

Ah-Peng, C., Wilding, N., Kluge, J., Descamps-Julien, B., Bardat, J., Chuah-Petiot, M., & Hedderson, T. A. J. (2012). Bryophyte diversity and range size distribution along two altitudinal gradients: Continent vs. Island. *Acta Oecologica*, 42, 58–65. https://doi.org/10.1016/j.actao.2012.04.010

Alfieri, P.V., Alves, D., & Traversa, L.P. (2020). Non-destructive diagnose of the biodeterioration of heritage assets through an optical microscopy. *Journal of Cultural Heritage*, 43, 249-254.

Antonelli, F., Perasso, C. S., Ricci, S., & Petriaggi, B. D. (2015). Impact of the sipunculan Aspidosiphon muelleri diesing, 1851 on calcareous underwater

cultural heritage. *International Biodeterioration and Biodegradation*, 100, 133–139. https://doi.org/10.1016/j.ibiod.2015.02.025

Ariño, X., Ortega-Calvo, J. J., Gomez-Bolea, A., & Saiz-Jimenez, C. (1995). Lichen colonization of the Roman pavement at Baelo Claudia (Cadiz, Spain): biodeterioration vs. bioprotection. *Science of the Total Environment,* 167(1–3), 353–363. https://doi.org/10.1016/0048-9697(95)04595-R

Arkell, A.J., (1948). The building-stones of Blenheim Palace, Cornbury Palace, Glympton Park, and Heythrop House, Oxfordshire. *Oxoniensia*, 8, 49-54.

Asada, T., Warner, B. G., & Banner, A. (2003). Growth of mosses in relation to climate factors in a hypermaritime coastal peatland in British Columbia, Canada.*American Bryological and Lichenological Society*, 106(4), 516–527.

Ashkenazi, D., & Cvikel, D. (2020). A journey into the microstructure: Using a multifocal 3D digital light microscope to study archaeological artefacts retrieved from shipwrecks. *Digital Applications in Archaeology and Cultural Heritage*, 16(June 2019), 1–11. https://doi.org/10.1016/j.daach.2019.e00129

Ashley-Smith, J. (2018). The ethics of doing nothing. *Journal of the Institute of Conservation*, 41(1), 6–15. https://doi.org/10.1080/19455224.2017.1416650

Austin-Smith: Lord LLP (2007). Conservation Area Maintenance Guide. East Ayrshire Council. Retrieved from: east-ayrshire.gov.uk/Resources/PDF/K/KilmarnockConservationAreaMaintenanceGuide.pdf

Bai, F-Y., Chen, X.P., Huang, J.Z., Lu, Y.S., Dong, H.Y., Wu, Y.H., Song, S.L., Yu, J., Bai, S., Chen, Z., Yang, T.Y., & Peng, X.Y. (2021). Microbial biofilms on a giant monolithic statue of Buddha: The symbiosis of microorganisms and mosses and implications for bioweathering. *International Biodeterioration and Biodegradation,* 156, 1-10.

Barthlott, W., & Mutke, J. (2005). Geographic patterns of vascular plant diversity at continental to global scales. *Biol. Skr.*, 55, 521–531.

Bartoli, F., Municchia, A. C., Futagami, Y., Kashiwadani, H., Moon, K. H., & Caneva, G. (2014). Biological colonization patterns on the ruins of Angkor temples (Cambodia) in the biodeterioration vs bioprotection debate. *International Biodeterioration and Biodegradation,* 96, 157–165. https://doi.org/10.1016/j.ibiod.2014.09.015

Bassi, M., & Giacobini, C. (2001). Scanning electron microscopy: A new technique in the study of the microbiology of works of art. *International Biodeterioration and Biodegradation*, 48, 55–66.

Beata, G. (2020). The use of-omics tools for assessing biodeterioration of cultural heritage: A review. *Journal of Cultural Heritage*, In Press. https://doi.org/10.1016/j.culher.2020.03.006

Berndt, R., Buchgraber, G., Havemann, S., Settgast, V., & Fellner, D. W. (2010). A publishing workflow for cultural heritage artifacts from 3D-reconstruction to internet presentation. *Conference: Digital Heritage - Third International Conference, EuroMed 2010, Lemessos, Cyprus*, 166–178. https://doi.org/10.1007/978-3-642-16873-4

Bledsoe, R., & Boopathy, R. (2016). Bioaugmentation of microbes to restore coastal wetland plants to protect land from coastal erosion. *International Biodeterioration and Biodegradation*, 113, 155–160. https://doi.org/10.1016/j.ibiod.2016.02.010

Bonn, M. A., Joseph-Mathews, S. M., Dai, M., Hayes, S., & Cave, J. (2007). Heritage/cultural attraction atmospherics: Creating the right environment for the heritage/cultural visitor. *Journal of Travel Research,* 45(3), 345–354. https://doi.org/10.1177/0047287506295947

British Bryological Society: Mosses and Liverworts of Britain and Ireland, A Field Guide. 2010. Eds. Atherton I., Bosanquet, S., Lawley, M. *British Bryological Society*. Latimer Trend & Co. LTD. Plymouth, UK.

BS EN 1936:2006 Natural Stone Test Methods. Determination of real density and apparent density, and of total and open porosity.

BS EN 16085:2012 Conservation of Cultural Property. Methodology for sampling from materials of cultural property. General rules.

BS EN 16302:2013 Conservation of Cultural Heritage. Test methods. Measurement of water absorption by pipe method.

Blaeuer, C., Vergès-Belmin, V., & Franzen, C. (2012). Simple field tests in stone conservation. *International congress on the deterioration and conservation of stone, New York*, 22–26.

Büdel, B., & Scheidegger, C. (1996). Thallus morphology and anatomy. *Lichen Biology*. pp. 37–64. doi:10.1017/CBO9780511790478.005. ISBN 9780511790478.

Caneva, G., Fidanza, M.R., Tonon, C., & Favero-Longo, S.E. (2020). Biodeterioration patterns and their interpretation of potential applications to stone conservation: A hypothesis from allelopathic inhibitory effects on lichens on the Caestia pyramid (Rome). *Sustainability*, 12(3), 1-15.

Carmen, V.C., Monica Alvarez de, B., Rafael, F., & Maria Jose, V.M. (2012). The measurement of surface roughness to determine the suitability of different methods for stone cleaning. *Journal of Geophysics and Engineering,* 9(4), S108. https://doi.org/10.1088/1742-2132/9/4/S108

Carter, N. E. A., & Viles, H. A. (2005). Bioprotection explored: the story of a little known earth surface process. *Geomorphology*, 67, 273–281. https://doi.org/10.1016/j.geomorph.2004.10.004

Casoli, E., Ricci, S., Antonelli, F., Sacco Perasso, C., Belluscio, A., & Ardizzone, G. (2016). Impact and colonization dynamics of the bivalve Rocellaria dubia on limestone experimental panels in the submerged Roman city of Baiae (Naples, Italy). *International Biodeterioration and Biodegradation*, 108, 9–15. https://doi.org/10.1016/j.ibiod.2015.11.026

Charron, A. J., & Quatrano, R. S. (2009). Between a rock and a dry place: The water-stressed moss. *Molecular Plant,* 2(3), 478–486. https://doi.org/10.1093/mp/ssp018

Chen, J., Blume, H. P., & Beyer, L. (2000). Weathering of rocks induced by lichen colonization - A review. *Catena,* 39(2), 121–146. https://doi.org/10.1016/S0341-8162(99)00085-5

Chen, S., Ferry Slik, J. W., Mao, L., Zhang, J., Sa, R., Zhou, K., & Gao, J. (2015). Spatial patterns and environmental correlates of bryophyte richness: sampling effort matters. *Biodiversity and Conservation*, 24(3), 593–607. https://doi.org/10.1007/s10531-014-0838-8

Coe, K. K., & Sparks, J. P. (2014). Physiological ecology of dryland biocrust mosses. *Photosynthesis in Bryophytes and Early Land Plants, Advances in Photosynthesis and Respiration*, 37, 291–308. https://doi.org/10.1007/978-94-007-6988-5.

Coombes, M.A., Viles, H.A., & Zhang, H. (2018). Thermal blanketing by ivy (Hedera helix L.) can protect building stone from damaging frosts. *Scientific Reports*, 8(1), 1-11.

Cooper, N. (2005). Kelmscott Manor. *Country Life*, 44–49.

Daly, C. (2016). The design of a legacy indicator tool for measuring climate change related impacts on built heritage. *Heritage Science,* 1–12. https://doi.org/10.1186/s40494-016-0088-z

D'Annibale, E., Tassetti, A. N., & Malinverni, E. S. (2013). From panoramic photos to a low-cost photogrammetric workflow for cultural heritage 3D documentation. *International Archives of the Photogrammetry, Remote Sensing, and Spatial Information Sciences*, XL-5/W2, pp. 2–6.

Douglas-Jones, R., Hughes, J. J., Jones, S., & Yarrow, T. (2016). Science, value and material decay in the conservation of historic environments. *Journal of Cultural Heritage*, 21, 823–833. https://doi.org/10.1016/j.culher.2016.03.007

Dungani, R., Aditiwati, P., Nazrul, I., Sri Aprilia, A., Hatarti, S., Sulaeman, A., Sumardi, I., Karliati, T., & Yuniarti, K. (2019). Evaluation of the effects of decay and weathering in cellulose-reinforced fiber composites. *Composites Science and Engineering.* 173-210.

Edinburgh World Heritage: Historic Home Guide (2019). *Edinburgh World Heritage.* Available from: https://ewh.org.uk/wp-content/uploads/2018/02/EWH-Roofs-Guide.pdf

Eklund, J. 2010. Project title: Non-destructive on-site assessment of porosity, surface texture and aspect on the microbial colonization of building stone. John Fell OUP Research Fund. Project Reference: 092/234. University of Oxford.

Eklund, J., & Young, M.E. (2013). Biological Growth on Masonry: Identification and Understanding. Historic Scotland INFORM Guide, *Historic Scotland.* Retrieved from: historic-scotland.gov.uk/conservation

Eklund, J., Zhang, H., Viles, H.A., & Curteis, T. (2013). Using handheld moisture meters on limestone: Factors affecting performance and guidelines for best practice. *International Journal of Architectural Heritage*, 7(2), 207-224, DOI: 10.1080/15583058.2011.626491

Eyssautier-Chuine, S., Vaillant-Gaveau, N., Gommeaux, M., Thomachot-Schneider, C., Pleck, J., & Fronteau, G. (2015). Efficacy of different chemical mixtures against

green algal growth on limestone: A case study with Chlorella vulgaris. *International Biodeterioration and Biodegradation*, 103, 59–68. https://doi.org/10.1016/j.ibiod.2015.02.021

Favero-Longo, S.E., & Viles, H.A. (2020). A review of the nature, role and control of lithobionts on stone cultural heritage; weighing-up and managing biodeterioration and bioprotection. *World Journal of Microbiology and Biotechnology*, 36(7), 1-18.

Fontaine, L., Hendrickx, R., & Clercq, H. De. (2015). Deterioration mechanisms of the compact clay-bearing limestone of Tournai used in the Romanesque portals of the Tournai Cathedral (Belgium). *Environmental Earth Sciences*, 74, 3207–3221. https://doi.org/10.1007/s12665-015-4358-y

Fredheim, L. H., & Khalaf, M. (2016). The significance of values: heritage value typologies re-examined. *International Journal of Heritage Studies*, 7258, 1–17. https://doi.org/10.1080/13527258.2016.1171247

Furness, S. B., & Grime, J. P. (1982). Growth rate and temperature responses in bryophytes: I . An investigation of Brachythecium rutabulum. *Journal of Ecology*, 70(2), 513–523. Retrieved from https://www.jstor.org/stable/2259919

Gallenmüller, F., Langer, M., Poppinga, S., Kassemeyer, H., & Speck, T. (2018). Spore liberation in mosses revisited. *AoB Plants*, 10, 1–15. https://doi.org/10.1093/aobpla/plx075

Garcia-Rowe, J. & Saiz-Jimenez, C. (1991). Lichens and bryophytes as agents of deterioration of building materials in Spanish cathedrals, *International Biodeterioration*, 28, 151-163.

Gazzano, C., Favero-Longo, S. E., Matteucci, E., & Piervittori, R. (2009). Image analysis for measuring lichen colonization on and within stonework. *The Lichenologist*, 41(03), 299–313. https://doi.org/10.1017/S0024282909008366

Gazzano, C., Favero-Longo, S. E., Iacomussi, P., & Piervittori, R. (2013). Biocidal effect of lichen secondary metabolites against rock-dwelling microcolonial fungi, cyanobacteria and green algae. *International Biodeterioration and Biodegradation*, 84, 300–306. https://doi.org/10.1016/j.ibiod.2012.05.033

Giustetto, R., Gonella, D., Bianciotto, V., Lumini, E., Voyron, S., Costa, E., & Diana, E. (2015). Transfiguring biodegradation of frescoes in the Beata Vergine del Pilone Sanctuary (Italy): Microbial analysis and minero-chemical aspects. *International Biodeterioration and Biodegradation*, 98, 6–18. https://doi.org/10.1016/j.ibiod.2014.10.020

Golubic, S., Friedmann, E.I., & Schneider, J. (1981). The lithobiontic ecological niche, with special reference to microorganisms. *Journal of Sedimentary Research*, 51 (2), 475–478. https://doi.org/10.1306/212F7CB6-2B24-11D7-8648000102C1865D

Green, D. (1958). Restoring Blenheim Palace. *Country Life*, 1400–1401.

Grytnes, J. A., Heegaard, E., & Ihlen, P. G. (2006). Species richness of vascular plants, bryophytes, and lichens along an altitudinal gradient in western Norway. *Acta Oecologica*, 29(3), 241–246. https://doi.org/10.1016/j.actao.2005.10.007

Guiamet, P. S., Soto, D. M., & Schultz, M. (2019). Bioreceptivity of archaeological ceramics in an arid region of northern Argentina. *International Biodeterioration and Biodegradation*, 141, 2–9. https://doi.org/10.1016/j.ibiod.2018.10.003

Guillitte, O. (1995). Bioreceptivity: A new concept for building ecology studies. *Science of the Total Environment*, 167(1–3), 215–220. https://doi.org/10.1016/0048-9697(95)04582-L

Gulotta, D., Villa, F., Cappitelli, F., & Toniolo, L. (2018). Biofilm colonization of metamorphic lithotypes of a renaissance cathedral exposed to urban atmosphere. *Science of the Total Environment*, 639, 1480–1490. https://doi.org/10.1016/j.scitotenv.2018.05.277

Hallmann, N., Kirchhoff, M., & Hoppert, C. (2018). Algal and fungal diversity on various dimension stone substrata in the Saale/Unstrut region. *Environmental Earth Sciences*, 77(17), 1–10. https://doi.org/10.1007/s12665-018-7791-x

Hanson, D. T., Renzaglia, K., & Villarreal, J. C. (2013). Diffusion limitation and CO2 concentrating mechanisms in bryophytes. In *Photosynthesis in Bryophytes and Early Land Plants, Advances in Photosynthesis and Respiration* (pp. 95–111). https://doi.org/10.1007/978-94-007-6988-5

Hanson, D. T., & Rice, S. K. (2013). What can we learn from bryophyte photosynthesis? In *Photosynthesis in Bryophytes and Early Land Plants, Advances in Photosynthesis and Respiration* (pp. 1–8). https://doi.org/10.1007/978-94-007-6988-5

Hanson, D.T., and Rice, S.K., (eds.), (2014). *Photosynthesis in Bryophytes and Early Land Plants, Advances in Photosynthesis and Respiration* 37, 95–111, DOI 10.1007/978-94-007-6988-5_6

Hendrickx, R. (2013). Using the Karsten tube to estimate water transport parameters of porous building materials. *Materials and Structures*, 46, 1309–1320. https://doi.org/10.1617/s11527-012-9975-2

Herrera, L. K., Arroyave, C., Guiamet, P., Gomez de Saravia, S. G., & Videla, H. (2004). Biodeterioration of peridotite and other constructional materials in a building of the Colombian cultural heritage. *International Biodeterioration and Biodegradation*, 54(2–3), 135–141. https://doi.org/10.1016/j.ibiod.2004.06.001

Herrera, L. K., Le Borgne, S., & Videla, H. A. (2009). Modern methods for materials characterization and surface analysis to study the effects of biodeterioration and weathering on buildings of cultural heritage. *International Journal of Architectural Heritage*, 3(1), 74–91. https://doi.org/10.1080/15583050802149995

Historic England (1955). Listing entry 1199373, Kelmscott Manor. *Historic England Online Listings*. Retrieved from: historicengland.org.uk/listing/the-list/list-entry/1199373

Historic England (1984). Listing entry 1000464, Oxford Botanic Garden. *Historic England Online Listings*. Retrieved from: historicengland.org.uk/listing/the-list/list-entry/1000464

Historic England (2019). Science Special. *Historic England Research*, Issue 12. Retrieved from: historicengland.org.uk/images-books/publications/historic-england-research-12/he-research-12

Historic Environment Scotland (2014). Advisory Standards of Conservation and Repair for the Historic Building Environment in Scotland. Retrieved from: historicenvironment.scot/media/5118/advisory-standards-repair.pdf

Hodgetts, N. (2011). A revised red list of bryophytes in Britain. *Field Bryology*, 103, 40-49.

ICOMOS-ISCS. (2008). Illustrated Glossary on Stone Deterioration Patterns. *International Council of Monuments and Sites*.

Jones, S. (2010). Experiencing authenticity at heritage sites: Some implications for heritage management and conservation. *Conservation and Management of Archaeological Sites*, 11(2), 133–147.

Jones, S. (2017). Wrestling with the social value of heritage: Problems, dilemmas and opportunities. *Journal of Community Archaeology & Heritage*, 4(1), 20–37. https://doi.org/10.1080/20518196.2016.1193996

Kapusta, P., Stanek, M., Szarek-Łukaszewska, G., & Godzik, B. (2019). Long-term moss monitoring of atmospheric deposition near a large steelworks reveals

the growing importance of local non-industrial sources of pollution. *Chemosphere*, 230, 29–39. https://doi.org/10.1016/j.chemosphere.2019.05.058

Kobetičová, K., & Cerny, R. (2019). Terrestrial eutrophication of building materials and buildings: An emerging topic in environmental studies. *Science of the Total Environment*, 689, 1316–1328. https://doi.org/10.1016/j.scitotenv.2019.06.423

Korkanc, M. (2018). Characterization of building stones from the ancient Tyana aqueducts , Central Anatolia , Turkey: implications on the factors of deterioration processes. *Bull Eng Geol Environ*, 77, 237–252. https://doi.org/10.1007/s10064-016-0930-2

Kuchitsu, N. (2007). Luxuriant growth of bryophytes and weathering of sandstone at Ta Nei Temple. *Science for Conservation in: Study on the Biodeterioration of Stone Monuments in Angkor - Results of the Joint Research Project at Ta Nei Tample.* National Research Institute for Cultural Properties and the APSARA National Authority, Tokyo, 57-64.

Lafuente, A., Berdugo, M., Gozalo, B., & Maestre, F. T. (2018). Simulated climate change affects how biocrusts modulate water gains and desiccation dynamics after rainfall events. *Ecohydrology*, 11, 1–10. https://doi.org/10.1002/eco.1935

Lee, H. C., Jo, Y. H., & Kim, J. (2010). Damage evaluation and conservation treatment of the tenth century Korean rock-carved Buddha statues. *Environmental Earth Sciences*, 64, 1-14.

Lee, M. R., & Parsons, I. (1999). Biomechanical and biochemical weathering of lichen-encrusted granite: Textural controls on organic-mineral interactions and deposition of silica-rich layers. *Chemical Geology*, 161(4), 385–397. https://doi.org/10.1016/S0009-2541(99)00117-5

Lee, S., Phau, I., Hughes, M., Li, Y. F., & Quintal, V. (2015). Heritage tourism in Singapore chinatown: A perceived value approach to authenticity and

satisfaction. *Journal of Travel & Tourism Marketing*, 8408(September), 1–18. https://doi.org/10.1080/10548408.2015.1075459

Lepinay, C., Mihajlovski, A., Seyer, D., Touron, S., Bousta, F., & Di Martino, P. (2017). Biofilm communities survey at the areas of salt crystallization on the walls of a decorated shelter listed at UNESCO World cultural Heritage. *International Biodeterioration and Biodegradation*, 122, 116–127. https://doi.org/10.1016/j.ibiod.2017.05.007

Lisci, M., Monte, M., & Pacini, E. (2003). Lichens and higher plants on stone: A review. *International Biodeterioration and Biodegradation*, 51, 1–17.

Ljaljević Grbić, M., & Vukojević, J. (2009). Role of fungi in biodeterioration process of stone in historic buildings. *Proc. Nat. Sci, Matica*, 116, 245–251. https://doi.org/10.2298/ZMSPN0916245L

Lybrand, R. A., Austin, J. C., Fedenko, J., Gallery, R. E., Rooney, E., Schroeder, P. A., Zaharesco, D. G., & Qafoku, O. (2019). A coupled microscopy approach to assess the nano-landscape of weathering. *Scientific Reports*, 9, 1–14. https://doi.org/10.1038/s41598-019-41357-0

Makhalanyane, T., Pointing, S., & Cowan, D. A. (2014). Lithobionts: Cryptic and refuge niches. In: Cowan, D.A. (ed.) Antarctic Terrestrial Microbiology. Springer-Verlag, Berlin Heidelberg, 164-179. https://doi.org/10.1007/978-3-642-45213-0

Martokusumo, W. (2011). The notion of authenticity revisited a search for urban heritage conservation approach. *Jurnal Tataloka*, 13(3), 181–189. Retrieved from http://indo-planning-journals.com/index.php/tataloka/article/view/9

Mateo, R. G., Vanderpoorten, A., Muñoz, J., Laenen, B., & Désamoré, A. (2013). Modeling species distributions from heterogeneous data for the biogeo-

graphic regionalization of the European bryophyte flora. *PLoS ONE*, 8(2), 1-7. https://doi.org/10.1371/journal.pone.0055648

Matteucci, E., Scarcella, A.V., Croveri, P., Marengo, A., Borghi, A., Benelli, C., Hamdan, O., & Favero-Longo, S.E. (2019). Lichens and other lithobionts on the carbonate rock surfaces of the heritage site of the tomb of Lazarus (Palestinian territories): diversity, biodeterioration, and control issues in a semi-arid environment. *Annals of Microbiology*, 69(10), 1033-1046.

Mayhew, R. (2018). Historic Home Guide: Roofs. *Edinburgh World Heritage*. Retrieved from: ewh.org.uk/wp-content/uploads/2018/02/EWH-Roofs-Guide-1.pdf

Mascalchi, M., Orsini, C., Pinna, D., Salvadori, B., Siano, S., & Riminesi, C. (2020). Assessment of different methods for the removal of biofilms and lichens on gravestones of the English cemetery in Florence. *International Biodeterioration and Biodegradation*, 154, 1-10.

McIlroy de la Rosa, J. P., Rosa, D., Warke, P. A., & Smith, B. J. (2012). Lichen-induced biomodification of calcareous surfaces: Bioprotection versus biodeterioration. *Progress in Physical Geography*, 37(3), 325–351. https://doi.org/10.1177/0309133312467660

McIlroy de la Rosa, J. P., Rosa, D., Warke, P. A., & Smith, B. J. (2012). Microscale biopitting by the endolithic lichen Verrucaria baldensis and its proposed role in mesoscale solution basin development on limestone. *Earth Surface Processes and Landforms*, 37, 374–384. https://doi.org/10.1002/esp.2244

McIlroy de la Rosa, J. P., Casares Porcel, M., & Warke, P. A. (2013). Mapping stone surface temperature fluctuations: Implications for lichen distribution and biomodification on historic stone surfaces. *Journal of Cultural Heritage*, 14(4), 346–353. https://doi.org/10.1016/j.culher.2012.09.006

Morando, M., Wilhelm, K., Matteucci, E., Martire, L., Piervittori, R., Viles, H. A., & Favero-Longo, S. E. (2017). The influence of structural organization of epilithic and endolithic lichens on limestone weathering. *Earth Surface Processes and Landforms*, 42(March), 1666–1679. https://doi.org/10.1002/esp.4118

Morillas, H., Maguregui, M., Gallego-cartagena, E., Huallparimachi, G., Marcaida, I., Salcedo, I., & Astete, F. (2019). Evaluation of the role of biocolonizations in the conservation state of Machu Picchu (Peru): The Sacred Rock. *Science of the Total Environment*, 654, 1379–1388. https://doi.org/10.1016/j.scitotenv.2018.11.299

Motti, R., & Bonanomi, G. (2018). Vascular plant colonisation of four castles in southern Italy: Effects of substrate bioreceptivity, local environment factors and current management. *International Biodeterioration and Biodegradation*, 133(June), 26–33. https://doi.org/10.1016/j.ibiod.2018.06.004

Munzi, S., Varela, Z., & Paoli, L. (2019). Is the length of the drying period critical for photosynthesis reactivation in lichen and moss components of biological soil crusts? *Journal of Arid Environments*, 166, 86–90. https://doi.org/10.1016/j.jaridenv.2019.04.019

Natali, M., Zanella, A., Rankovic, A., Banas, D., Cantaluppi, C., Abbadie, L., & Lata, J.C. (2016). Assessment of trace metal air pollution in Paris using slurry-TXRF analysis on cemetery mosses. *Environmental Science and Pollution Research*, 23, 23496-23510. https://doi.org/10.1007/s11356-016-7445-z

Owczarek-Kościelniak, M., Krzewicka, B., Piątek, J., Kołodziejczyk, Ł.M., & Kapusta, P. (2020). Is there a link between the biological colonization of the gravestone and its deterioration?. *International Biodeterioration and Biodegradation*, 148, 1-11.

Pfendler, S., Einhorn, O., Alaoui-Sossé, L., Bousta, F., Alaoui-Sossé, B., & Aleya, L. (2020). Factors inducing bryophyte growth on prehistoric pigments and effect of UV-C treatment. *Environmental Science and Pollution Research*, 1-8.

Pinheiro, A.C., Mesquita, N., Trovão, J., Soares, F., Tiago, I., Coelho, C., Paiva de Carvalho, H., Gil, F., Catarino, L., Piñar, G. & Portugal, A. (2019). Limestone biodeterioration: A review on the Portuguese cultural heritage scenario. *Journal of Cultural Heritage*, 36, 275-285.

Popović, S., Stupar, M., Unković, N., & Simić, G. S. (2018). Diversity of terrestrial cyanobacteria colonizing selected stone monuments in Serbia. *Studies in Conservation*, 63(5), 292–302. https://doi.org/10.1080/00393630.2018.1438127

Pozo-Antonio, J. S., Pereira, M. F. C., Rocha, C. S. A., Puente, I., & Figueiredo, C. (2016). Comparative study of deterioration forms on nearby granitic bridges from an urban setting in the NW Iberian Peninsula. *Geomorphology*, 274, 11–30. https://doi.org/10.1016/j.geomorph.2016.09.009

Preston, C. D., Hill, M. O., Porley, R. D., & Bosanquet, S. D. S. (2010). Survey of the bryophytes of arable land in Britain and Ireland 1: a classification of arable field assemblages. *Journal of Bryology*, 32(November), 61–79. https://doi.org/10.1179/037366810X12578498135959

Prieto, B., Vázquez-Nion, D., Fuentes, E., & Durán-Román, A.G. (2020). Response of subaerial biofilms growing on stone-built cultural heritage to changing water regime and CO2 conditions. *International Biodeterioration and Biodegradation*, 148, 1-7. https://doi.org/10.1016/j.ibiod.2019.104882

Prieto-Taboada, N., Isca, C., Martinez-Arkarazo, I., Casoli, A., Olazabal, M. A., Arana, G., & Madariaga, J. M. (2014). The problem of sampling on built heritage: a preliminary study of a new non-invasive method. *Environmental Science and Pollution Research*, 21, 12518–12529. https://doi.org/10.1007/s11356-014-3119-x

Rad, P., Nosti, S. Č., & Vrednovanja, P. (2016). Specific characteristics of the tangible cultural heritage valuation process in tourism. *Acta Turistica*, 28, 73-100.

Ricci, S., Antonelli, F., Sacco Perasso, C., Poggi, D., & Casoli, E. (2016). Bioerosion of submerged lapideous artefacts: Role of endolithic rhizoids of Acetabularia acetabulum (Dasycladales, Chlorophyta). *International Biodeterioration and Biodegradation*, 107, 10–16. https://doi.org/10.1016/j.ibiod.2015.10.024

Robinson, S. A., & Waterman, M. J. (2014). Sunsafe bryophytes: Photoprotection from excess and damaging solar radiation. *Advances in Photosynthesis and Respiration*, 37, 113–130. https://doi.org/10.1007/978-94-007-6988-5

Rotherham, I.D. & Griffiths, C., eds. (2013). War and Peat. *Landscape Archaeology and Ecology* (10).

Ruiz, L., Flores, V., & Prieto, E. (2019). In situ assessment of superficial moisture condition in façades of historic buildings using non-destructive techniques. *Case Studies in Construction Materials*, 10, 1–14. https://doi.org/10.1016/j.cscm.2019.e00228

Savković, Ž., Unković, N., Stupar, M., Franković, M., Jovanović, M., Erić, S., Šarić, K., Stanković, S., Dimkić, I., & Vukojević, J. (2016). Diversity and biodeteriorative potential of fungal dwellers on ancient stone stela. *International Biodeterioration and Biodegradation*, 115, 212–223. https://doi.org/10.1016/j.ibiod.2016.08.027

Scatigno, C., Gaudenzi, S., Sammartino, M. P., & Visco, G. (2016). A microclimate study on hypogea environments of ancient roman building. *Science of the Total Environment*, 566–567, 298–305. https://doi.org/10.1016/j.scitotenv.2016.05.050

Scatigno, C., Moricca, C., Tortolini, C., & Favero, G. (2016). The influence of environmental parameters in the biocolonization of the Mithraeum in the roman masonry of casa di Diana (Ostia Antica, Italy). *Environmental Science and Pollution Research*, 23, 13403–13412. https://doi.org/10.1007/s11356-016-6548-x

Schiavon, N., Caro, T. De, Kiros, A., Teresa, A., Isabella, C., Parisi, E., Ettore, G. (2013). A multianalytical approach to investigate stone biodeterioration

at a UNESCO world heritage site: the volcanic rock-hewn churches of Lalibela, Northern Ethiopia. *Applied Physics A: Materials Science & Processing*, 113, 843–854. https://doi.org/10.1007/s00339-013-7757-5

Scrivano, S., & Gaggero, L. (2017). Non-invasive analytical technique to address water uptake on stone surfaces: The implemented Contact Sponge Method (i-CSM). *Journal of Cultural Heritage*, 28, 9–15. https://doi.org/10.1016/j.culher.2017.05.013

Scrivano, S., Gaggero, L., Yus, A., & Gisbert Aguilar., J. (2017). Assessing surface weathering by revision and implementation of the peeling-test: In situ sampling and integrated analyses. *Journal of Cultural Heritage*, 27, 88–96. https://doi.org/10.1016/
j.culher.2017.04.004

Silva, M. Rosado, T. et al. (2017). Green mitigation strategy for cultural heritage: bacterial potential for biocide production. *Environmental Science and Pollution Research*, 24(5), 4871-4881.

Slavík, M., Bruthans, J., Filippi, M., Schweigstillová, J., Falteisek, L., & Řihošek, J. (2016). Biologically-initiated rock crust on sandstone: Mechanical and hydraulic properties and resistance to erosion. *Geomorphology*, 278, 298–313. https://doi.org/10.1016/j.geomorph.2016.09.040

Smith, B. J., Gomez-Heras, M., & Mccabe, S. (2008). Understanding the decay of stone-built cultural heritage, *Progress in Physical Geography*, 32(4), 439–461. https://doi.org/
10.1177/0309133308098119

Smith, R. M., Thompson, K., Warren, P. H., & Gaston, K. J. (2010). Urban domestic gardens (XIII): Composition of the bryophyte and lichen floras, and determinants of species richness. *Biological Conservation*, 143(4), 873–882. https://doi.org/10.1016/j.biocon.2009.12.033

Steinbauer, M. J., Gohlke, A., Mahler, C., Schmiedinger, A., & Beierkuhnlein, C. (2013). Quantification of wall surface heterogeneity and its influence on species diversity at medieval castles - implications for the environmentally friendly preservation of cultural heritage. *Journal of Cultural Heritage*, 14(3), 219–228. https://doi.org/10.1016/j.culher.2012.06.003

Sternberg, T., Viles, H.A., Cathersides, A., & Edwards, M. (2010). Dust particulate absorption by ivy (Hedera helix L.) on historic walls in urban environments. *Science of the Total Environment*, 409(1), 162-168.

Stevenson, R. C., & Hill, M. O. (2008). Urban myths exploded: results of a bryological survey of King's Lynn (Norfolk, UK). *Journal of Bryology*, 30(1), 12–22. https://doi.org/10.1179/174328208X282111

Summerby-Murray, R. (2015). Regenerating cultural identity through industrial heritage tourism: Visitor attitudes, entertainment and the search for authenticity at mills, mines and museums of maritime Canada. *London Journal of Canadian Studies*, 30(1), 64–89. https://doi.org/10.14324/111.444.ljcs.2015v30.005

Tania, R., Silva, M., Galvao, A., Mirao, J., Candeias, A., & Caldeira, A. T. (2016). A first insight on the biodegradation of limestone: the case of the World Heritage Convent of Christ. *Applied Physics A: Materials Science & Processing*, 122, 1–7. https://doi.org/10.1007/s00339-016-0525-6

Tao, Y., & Zhang, Y. M. (2012). Effects of leaf hair points of a desert moss on water retention and dew formation: implications for desiccation tolerance. *J Plant Res*, 351–360. https://doi.org/10.1007/s10265-011-0449-3

The Society for the Protection of Ancient Buildings, website (2017). Retrieved from: spab.org.uk/about-us

Thomas, R. J. (1977). Wall analyses of Lophocolea seta cells (bryophyta) before and after elongation. *Plant Physiology*, 59(3), 337–340.

Tonon, C., Favero-longo, S. E., Matteucci, E., Piervittori, R., Croveri, P., Appolonia, L., Meirano, V., Serino, M., & Elia, D. (2019). Microenvironmental features drive the distribution of lichens in the House of the Ancient Hunt, Pompeii, Italy. *International Biodeterioration and Biodegradation*, 136, 71–81. https://doi.org/10.1016/j.ibiod.2018.10.012

Trovão, J., Soares, F., So, D., Mesquita, N., Coelho, C., Catarina, A., Tiago, I. (2019). Fungal diversity and distribution across distinct biodeterioration phenomena in limestone walls of the old cathedral of Coimbra, UNESCO World Heritage Site. *International Biodeterioration and Biodegradation*, 142, 91–102. https://doi.org/10.1016/j.ibiod.2019.05.008

Unkovi, N., Ljaljevi, M., Stupar, M., Savkovi, Ž., Jeliki, A., Stanojevi, D., & Vukojevi, J. (2016). Fungal-induced deterioration of mural paintings: In situ and mock-model microscopy analyses. *Microscopy and Microanalysis*, 22, 410–421. https://doi.org/10.1017/S1431927616000544

Urmi, E., & Schnyder, N. (2007). Mapping Bryophytes: A Review. *Lindbergia*, 33, 40–54.

Vandevoorde, D., Cnudde, V., Dewanckele, J., Brabant, L., Bouw, D., Meynen, V., & Verhaeven, E. (2013). Validation of in situ applicable measuring techniques for analysis of the water adsorption by stone. *Procedia Chemistry*, 8, 317–327. https://doi.org/10.1016/j.proche.2013.03.039

Vazquez-Calvo, C., Alvarez de Buergo, M., Fort, R., & Aras-Muriel, M.-J. (2012). The measurement of surface roughness to determine the suitability of different methods for stone cleaning. *Journal of Geophysics and Engineering*, 9(4), 108–117. https://doi.org/10.1088/1742-2132/9/4/S108

Viles, H.A. (2019) Biogeomorphology: Past, present and future. *Geomorphology.*

Viles, H.A., Naylor, L.A., Carter, N.E. & Chaput, D. (2008) Biogeomorphological disturbance regimes: progress in linking ecological and geomorphological systems. *Earth Surface Processes and Landforms*, 33(9),1419-1435.

Zhang, G., Gong, C., Gu, J., Katayama, Y., Someya, T., & Gu, J.D. (2019). Biochemical reactions and mechanisms involved in the biodeterioration of stone world cultural heritage under the tropical climate conditions. *International Biodeterioration and Biodegradation*, 143, 1-8.

A rolling stone gathers no moss, but it gains a certain polish.

— Oliver Herford

9 Appendices

9.1 A - Co-authors Statements

This Appendix regroups the statements of the co-authors of each publication (submitted or published) that the bulk of the work presented in the three studies (Chapter 3, 4, 5) has been carried out by the author of this thesis.

As a co-author of the following publications (published and/or submitted) I confirm that the first author Katherine Jang has made a substantive contribution to each of the publications, which includes conceptualisation of the research project, data collection, data analysis, writing and revising the manuscript.

Jang, K. and Viles, H. "Perceptions of moss growth on historic buildings: A survey of visitors and heritage professionals and its implications for heritage conservation", *Journal of Heritage Tourism*, submitted.

Heather Viles, Professor of Biogeomorphology and Heritage Conservation



15/9/2020

As a co-author of the following publications (published and/or submitted) I confirm that the first author Katherine Jang has made a substantive contribution to each of the publications, which includes conceptualisation of the research project, data collection, data analysis, writing and revising the manuscript.

Jang, K. and Viles, H. "Complementary analyses for visualising the moss-rock interface on limestone and built heritage", *International Journal of Heritage Studies*, submitted.

Heather Viles, Professor of Biogeomorphology and Heritage Conservation



15/9/2020

As a co-author of the following publications (published and/or submitted) I confirm that the first author Katherine Jang has made a substantive contribution to each of the publications, which includes conceptualisation of the research project, data collection, data analysis, writing and revising the manuscript.

Jang, K. and Viles, H. "Moisture interactions between mosses and their underlying stone substrates", *International Biodeterioration & Biodegradation*, submitted.

Heather Viles, Professor of Biogeomorphology and Heritage Conservation



15/9/2020

9.2 B - Survey Format

Opinion Survey: Mosses on Historic Buildings

This survey aims to determine attitudes toward mosses on historic buildings, and whether the perception is overall positive or negative. This survey will be included in my DPhil research at the University of Oxford, School of Geography and the Environment as a part of my research topic, 'Moss on Rocks': Evaluating biodeterioration and bioprotection of bryophitic growth on stone masonry.

If you have any other questions or comments you can contact me via: katherine.jang@wolfson.ox.ac.uk

* Required

1. Do you consider yourself a built heritage professional? *

Mark only one oval.

- ◯ Yes
- ◯ No
- ◯ Other: _____

2. Have you been involved with the restoration/conservation of a listed building or scheduled monument? *

Mark only one oval.

- ◯ Yes
- ◯ No

3. Are you interested in visiting historic buildings? *

Mark only one oval.

- ◯ Yes
- ◯ No

4. How often do you visit historic/buildings for leisure? *

Mark only one oval.

- ◯ Never: Less than once year
- ◯ Rarely: Several times a year
- ◯ Often: Around once a month
- ◯ Very often: Once a month or more

5. Age: *

Mark only one oval.

- ◯ 18-25
- ◯ 26-35
- ◯ 36--45
- ◯ 46-55
- ◯ 56-65
- ◯ 65+

6. "My level of knowledge about mosses is:" *

Mark only one oval.

	1	2	3	4	5	
Very Low - I do not know what moss is	◯	◯	◯	◯	◯	High - Can differentiate between moss, lichen and algae

Images of biological growth:









7. In the image above, which number(s) show(s) moss? *

Check all that apply.

- [ ] Image 1
- [ ] Image 2
- [ ] Image 3
- [ ] Image 4
- [ ] Unsure

8. In your opinion, how do mosses affect buildings? *

Mark only one oval.

- ◯ Negatively, they shorten the lifespan of buildings.
- ◯ Positively, they protect the building surface from damage.
- ◯ I do not think they either positively or negatively affect the building in any way.
- ◯ Other: _____

9. In your opinion, how do mosses specifically affect buildings? Check all that apply: *

Check all that apply.

- [ ] Protect the surface from freeze-thaw degradation
- [ ] Prevent moisture evaporation and creates a wetter surface
- [ ] Protects from airborne pollution
- [ ] Creates staining on the building surface (eg. green or black marks)
- [ ] Physically damages the building surface (eg. through root penetration)
- [ ] Chemically damages the building surface (eg. leaves acidic deposits on the surface)
- [ ] Prevents damage from environmental effects (eg. wind, driven rain, etc.)
- [ ] Prevents moisture absorption into the building material

Other: [ ] _____

10. Should mosses be removed from historic buildings and monuments? *

Mark only one oval.

- ◯ Yes, they should be removed in all cases.
- ◯ Yes, they should be removed but only in certain cases.
- ◯ No, they should never be removed.
- ◯ Other: _____

11. How do mosses affect the aesthetics of historic buildings? Check all that apply *

Check all that apply.

- [ ] Adds authenticity
- [ ] Makes a building look neglected
- [ ] Indicates age and historic nature of the building
- [ ] Looks messy and unkempt
- [ ] Evocative of the 'rural' and 'countryside'

Other: [ ] _____

12. "I enjoy the look of mosses on historic buildings" *

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

13. Which questions would you be interested in knowing the answer to? Check all that apply: *

Check all that apply.

- [ ] How do I prevent mosses from growing on buildings?
- [ ] How do mosses protect/damage buildings?
- [ ] What is the best method to remove mosses from historic buildings?
- [ ] Does removing moss from historic buildings cause more damage than leaving them in place?
- [ ] How do I encourage more moss growth on buildings?
- [ ] Should I remove mosses from buildings?

Other: [ ] _____

14. Any other comments:

_____

_____