Historic England

Building and Landscape Conservation

Ivy on Walls

Prepared for Historic England by Dr Martin Coombes and Prof Heather Viles, Oxford Rock Breakdown Lab (OxRBL), University of Oxford; and Alan Cathersides, Historic England

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This is the final report for the Ivy on Walls project. It has been peer reviewed by three independent reviewers from industry and academia.

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Front cover: Detail of ivy. © Alan Cathersides

FOREWORD

The presence of ivy on buildings, particularly ruins, has long been a subject for debate. 18th-century drawings and paintings depicting the 'picturesque' showed many an ivy-clad 'romantic ruin' full of ancient mystery and interest. Other commentators considered it a sign of neglect and decay, requiring urgent removal to preserve the monument and allow its architecture to be enjoyed. More than any other plant, ivy seems to polarise viewpoints with little or no middle ground. Writing in 1923 Sir Lionel Earle, the Secretary of the Office of Works, probably summed up the 'anti-ivy' viewpoint when writing about proposed works at Windsor Castle: *"I also think that all the ivy on the walls should be cut. I believe the Queen favours such a policy. Ivy is a rank and odious plant"*. Many of those charged with looking after monuments and historic buildings have since echoed these sentiments.

As ever, anecdotal evidence suggests that the real situation is more complicated with examples showing that the plant has either protected vulnerable fabric or has had little harmful impact. This paradox was most evident at Wigmore Castle in Herefordshire where English Heritage* carried out a major consolidation in 1997–99. A dense covering of ivy was removed which revealed significant damage to the structure in some areas, whilst in others well-preserved ashlar stonework was untouched. However, since its exposure, some of this mudstone is now visibly decaying so the ivy clearly performed the protective role of the original render. These observations at Wigmore prompted the Conservation Department to commission the Oxford University School of Geography and the Environment to look more closely and scientifically at the protective and damaging potential of ivy.

This report is the outcome of this work. It looks at how ivy can directly and indirectly affect the monuments upon which it grows and shows how it can be both protective and destructive and examines in detail how this occurs. Examples of practical issues on site are discussed, using case studies dealt with during the project. Although deliberate planting of ivy against historic walls is only likely to be an exceptional recommendation, this research shows that careful thought should be given to its partial or complete removal. If it is to be kept, then it is essential that the plant and walls are regularly inspected, maintained and treated. Finally the conclusions summarise the findings and offer practical guidance for the management of ivy-covered monuments.

Chris Wood
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* In April 2015 English Heritage split into two new organisations. The English Heritage Trust is a charitable body charged with the responsibility for managing the 400+ sites owned by the government or in its guardianship. Historic England became the Non-Departmental Public Body which advises the government on the historic environment. Conservation Department became part of the Planning Group within Historic England. Historic England is used throughout the report to avoid confusion, but readers should be aware that prior to April 2015 the work was carried out under the English Heritage name.

SUMMARY

It is very common for ivy to grow on historic walls and there is much speculation about the damage it may or may not be causing. This is especially important to understand for assets that are culturally valued, including listed monuments and ruins, which need to be managed and conserved. It is undeniable that damage can occur in association with ivy growth but the causal links have, so far, largely been based on anecdotal evidence. Scientific evidence generated from observation and experimentation is notably lacking. Such evidence is needed to inform management decisions and best practice, and to guide the allocation of resources.

This report describes research commissioned by English Heritage (now Historic England) to address these knowledge gaps, undertaken by the School of Geography and the Environment, University of Oxford. The core research focussed on English ivy (*Hedera helix* L.) and was undertaken in two phases: Phase I (2006–2010) and Phase II (2011–2015). Desk-based research, field monitoring, laboratory simulation, test wall observation, microscopy, case studies, and discussion with asset managers have all been used. This has generated a significant amount of information to help better understand the direct and indirect influences of *H. helix* on walls and the deterioration processes that affect them.

Key factors considered in the research were: the interaction between ivy and masonry (and any structural defects) as the plant clings and grows, and the ways in which it does and does not cause physical damage; the influences of ivy on microclimate (temperature and moisture) at the wall surface including frost damage; relative differences and changes in surface and subsurface moisture content; stone soiling and discolouration; and changes in the condition of stone over time both with and without a cover of ivy. A range of observations and experiments is discussed in the report alongside an analysis and interpretation of the data collected. Key findings of the study are:

- Physical damage by ivy growth: the potential for ivy to cause damage to historic walls is primarily controlled by the condition and physical characteristics of the underlying structure. Ivy cannot actively ‘bore’ its way into walls but it can cause serious problems where it grows into existing defects such as holes, cracks and crevices. Where defects do exist ivy stems can grow into them, but this is relatively uncommon – most stems grow over/across defects in order to continue upwards growth. The potential for damage can be minimised through appropriate management, including regular pruning to prevent growth onto roofs and over guttering, and removing excessive arboreal growth.
- Rooting-in: the greatest damage often occurs when ivy ‘roots-in’ to walls. This is not common, but can be stimulated when shoots come into contact with darkness, moisture and weathered material (protosoil) within already deteriorating walls. The common practice of killing ivy by cutting it at its base can also stimulate rooting-in and this is no longer recommended where the plant is already growing into existing cavities.

- **Surface attachment**: juvenile ivy stems attach and climb up walls via aerial rootlets. Attachment is remarkably strong (via physical and chemical means) but is entirely superficial – aerial rootlets do not penetrate into the materials they are attached to and they do not extract moisture or nutrients (the same is true for ivy growing on tree trunks). Forceful removal of stems can cause physical damage to the substrate underneath, and it will inevitably leave marks that may be an aesthetic issue for some assets.
- **Microclimate buffering and weathering**: ivy is very effective at reducing extremes of temperature and relative humidity, and the frequency and range of variations that can otherwise contribute to deterioration over time. Ivy also reduces the frequency, severity and duration of frost events that cause damage to vulnerable masonry materials. Monitoring of test walls shows no evidence that weathering is increased under a cover of ivy over a period of several years.
- **Surface soiling and pollution filtering**: ivy foliage is an effective trap of fine airborne particulates. It reduces the amount of pollution reaching the surface of walls that contributes to soiling and chemical degradation. The influence of ivy on biological soiling (by green algae for example) is probably less important than seasonal changes in moisture, but ivy cover can limit greening of stone via shading effects.
- **Moisture**: the influence of ivy on the moisture content of walls is complicated and there is no simple answer as to whether it increases or decreases damp. Its relative importance varies between different construction materials and locations, and between different wall heights and aspects. A thick cover of ivy certainly shields walls from rain, but it may reduce evaporation of ground-level moisture where there is an existing damp problem. Long-term monitoring of test walls shows that any influence of ivy on near-surface damp is well within the typical range of moisture variations naturally caused by seasonal weather. There is no evidence that ivy influences deeper-seated moisture in walls.

The scientific evidence gathered has been used to inform management best-practice, presented in the final chapter of this report. Crucially, in all cases, decisions about whether to remove ivy from vulnerable historic structures requires careful consideration of factors relevant to that particular asset. It cannot be assumed that ivy is always doing damage and that it should be removed – in some cases it can aid conservation of the asset and its removal may do more harm than good. Different management options should be considered: complete removal, partial removal, management, or no action. Where the decision is made to remove ivy from walls, this report concludes with some practical tips on how best to go about it.

This is the final report for the Ivy on Walls project. It has been peer reviewed by three independent reviewers from industry and academia.

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We also thank the many people who gave access to case study sites and contributed to our studies at these sites, including the members of Horsham Green Gym, Simon Bagnall, Head Gardener at Worcester College, Oxford, Andy Turner and Roy Porter at the English Heritage Trust and Dan Bashford, Jon Breckon, David Kenny, Caron Newman, Chris Welch, Liz Whitbourn, Amanda White and Andy White at Historic England.

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1 INTRODUCTION AND BACKGROUND

1.1 Ivies

Ivies are evergreen, woody, climbing or creeping plants belonging to the genus *Hedera* of the Araliaceae family. All species of ivy display distinct 'juvenile' and 'adult' (arborescent) growth phases. The juvenile phase is characterised by creeping or climbing flexible stems capable of attaching to surfaces via aerial rootlets (Figure 1-1a, b). The arborescent growth phase produces woodier, self-supporting stems that do not produce aerial rootlets. The foliage of the two growth phases is distinct (juvenile leaves are palmately lobed whilst adult leaves are unlobed and cordate) and arborescent stems display annual flowers in autumn turning to black berries over winter (Figure 1-1c, d). The exact number of ivy species varies according to taxonomic judgement but is in the order of 5 to 11, being distributed throughout Europe, Asia and North Africa. Only two species are native to Britain: *Hedera helix* (Common or English Ivy) and *H. hibernica* (Atlantic or Irish Ivy). McAllister and Rutherford (1990) provide an overview of both species within the British isles, while a more detailed review of *H. helix* ecology is provided by Metcalf (2005). Other hardy species of ivy are commonly found in gardens and occasionally as garden escapes – particularly *H. colchica* (Persian or Colchis Ivy) and *H. canariensis* (Canary Islands Ivy). Marshall et al (2017) discuss hybridization in the genus *Hedera*. There are hundreds of horticultural varieties available, with a wide range of leaf sizes, shapes and colours. As the most commonly encountered species in Britain, all work described in this report is specifically focussed on *H. helix*. Nevertheless, the basic growth characteristics of all ivies are considered to be similar and the conclusions drawn may be applicable to other species more generally.

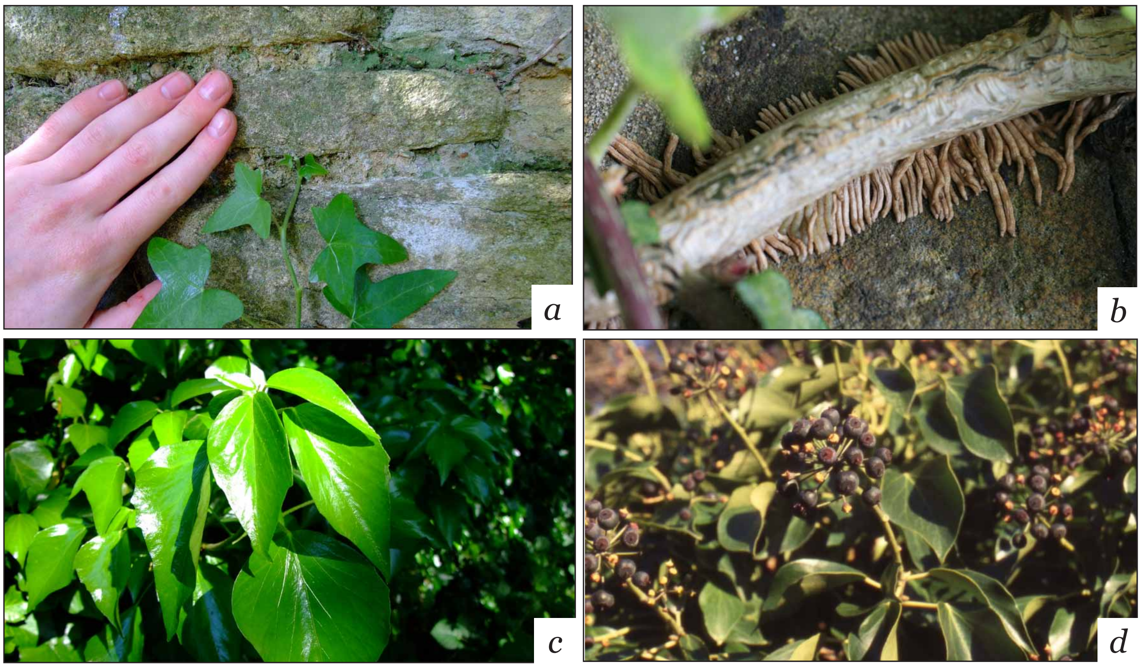


Figure 1-1. Growth characteristics of ivy (Hedera helix): (a) climbing juvenile stem with characteristic palmately lobed leaves; (b) stem attachment via aerial rootlets; (c) typically lush green, unlobed cordate adult phase leaves; (d) arborescent (flowering) ivy with distinctive berries (b,c,d ©Alan Cathersides).

The discussions here do not include climbers from other genera and families, and so care should be taken in using results and conclusions to formulate management policies for these. There are very few other self-clinging climbers hardy in Britain and the most commonly encountered in gardens (although rarely outside of these) are the various species of Virginia Creeper or Boston Ivy (*Parthenocissus* spp.). These plants are deciduous and their means of attachment to surfaces is distinct from ivy, via adhesive pads on the ends of tendrils (modified leaves) rather than adhesive aerial rootlets.

1.2 Ivy as a management issue on historic walls

Opinion varies as to whether ivy growing on buildings, monuments and ruins is good or bad (Table 1-1) but the view that it is generally destructive and should be removed is common. Whether true or not, much opinion about ivy is based on anecdotal evidence of the damage the plant can undoubtedly cause when allowed to 'run rampant'. This is particularly true for historic assets where structures may be built from vulnerable materials and, in some instances, may be in a poor state of repair before ivy takes hold. The growth of ivy also raises broader concerns about the presentation of historic sites (see Ashbee 2010 for a full discussion). Managing ivy on historic structures is therefore an important practical problem that needs to be addressed. Managers are tasked with making decision about maintenance needs and necessary activities for heritage conservation; at a time of ever restricted budgets, evidence of risk informed by robust science is essential.

Table 1-1. Perceived benefits and problems of ivy on buildings based on discussions with clerks of works/maintenance managers and gardeners during the scoping phase of this project

Perceived benefits	Perceived problems
Keeps old walls sound	Roots damage stone, mortars, pointing
Provides a security barrier	Triggers security lights
Can help with weather-proofing (shields walls from driving rain)	Can cause damp/ maintains moisture on wall surface
Can give colour and texture to a building	Rootlets leave marks on the stonework
Easy to grow	Can grow onto other people's properties
Can cover an unsightly building	Lifts copings and slates
Can enhance the appearance of buildings	Grows into glass windows
Good habitat for birds and insects	Can encourage insect infestations
	Can grow up gutters and hoppers and get into drainpipes
	Rootlets remove moisture and 'suck cement out of mortar'

From 'Ivy on Walls' scoping project, Carter and Viles 2006

The capacity of ivy to cause structural damage by growing into defects in masonry, and rooting into and under walls, is undeniable. The nature of these impacts and the circumstances under which they occur have, however, remained virtually untested. Much of our existing understanding is based on anecdotal evidence and assumed knowledge. The impacts of ivy attachment (via aerial rootlets) and the influence of a permanent (evergreen) cover of foliage on concurrent agents of deterioration (such as damp and frost) have also been largely assumed rather than observed scientifically. Improved understanding of the level of threat that ivy poses to historic structures is therefore very important for the heritage sector: When is ivy likely to be a problem and when should it be removed? When is ivy largely benign, or even protective, and can be left? How does ivy accelerate or retard other deteriorative processes, such as weathering? How can ivy be appropriately managed to minimise damage and aid the conservation of historic structures?

1.3 'Ivy on Walls' Project

To address some of the questions surrounding the impact of ivy, the 'Ivy on Walls' project was commissioned by English Heritage (now Historic England) in 2006 under the National Heritage Protection Plan (NHPP) Action 2C3 (Attritional Environmental Threats). The research has been carried out by Professor Heather Viles and colleagues at the Oxford Rock Breakdown Laboratory (OxRBL), School of Geography and the Environment, University of Oxford. The project has largely focussed on ruined masonry structures, although some additional work in other settings has also been carried out, on brick and non-ruined structures. The project has been undertaken in two phases.

Phase I (2006–2010)

Phase I involved a range of historic sites across England, and focussed on observing:

- the condition of stonework under well-established ivy
- the influence of ivy foliage on stone surface microclimates, in reference to weathering processes
- the influence of ivy on the delivery of particulate pollutants to the face of walls

Initial observations of aerial rootlet attachment, damage by shoots penetrating into walls, and influences on stone moisture were also made. Results from this first phase of work (summarised in Table 1-2) have been published as academic papers (Sternberg et al. 2010, 2011; Viles et al. 2011) and a seminar report (2010) available online: http://www.geog.ox.ac.uk/research/landscape/rubble/ivy/.

Phase II (2011–2015)

Phase II focussed on intensive monitoring of ivy growth and stone condition at purpose-built test walls (see Section 1.4) with additional laboratory experiments. Research activities undertaken during the second phase of the project, and how they built on Phase I, are also summarised in Table 1-2. This report discusses findings from both phases of the 'Ivy on Walls' project, with reference to previously published sources where appropriate.

Table 1-2. Key findings from the 'Ivy on Walls' project (Phase I) and associated Phase II research activities described in detail in this report

Key finding (Phase I)	Associated research questions	Phase II research activities
Stone weathering		
Ivy moderates microclimatic fluctuations at the surface of walls. Buffered extremes of temperature (maxima and minima), and reduced frequency of fluctuations in temperature and relative humidity.	*Does microclimatic buffering slow stone deterioration?* Certain mechanical weathering processes (i.e., thermal stress, freeze-thaw, and frequency of salt crystallisation) may be reduced under ivy, which may slow down deterioration relative to bare stone.	• Continued microclimatic monitoring of test walls. • Infrared thermal imaging of test walls. • Stone condition/deterioration monitoring of test walls (stone hardness and microscopy). • Accelerated laboratory weathering simulations.
Damp		
Relative humidity is higher under ivy. Higher near-surface humidity under ivy canopies relative to bare walls. *Ivy may shield walls from driving rain.* Observational evidence of ivy foliage shielding wall faces from rain.	*Does a cover of ivy affect the moisture content of walls?* Higher relative humidity at the face of ivy covered walls may be indicative of damp by limiting evaporation rates; whereas shielding effects may limit deep-seated moisture in walls.	• Monitoring near-surface moisture in test walls using surface moisture meters. • Observation of deeper-seated moisture within test wall using Electrical Resistivity Tomography (ERT). • Observation of near-surface moisture in ivy-covered and bare sections of stonework at case study sites.

Table 1-2. Key findings from the 'Ivy on Walls' project (Phase I) and associated Phase II research activities described in detail in this report

Key finding (Phase I)	Associated research questions	Phase II research activities
Surface soiling		
Ivy foliage traps air-borne particulates. A cover of ivy reduces the amount of particulate pollution reaching the wall face; ivy acts as a particulate sink.	*Is stone soiling reduced under a cover of ivy?* Soiling (discolouration) of stone may be reduced under ivy, as well as weathering associated with particulate pollution.	• Long-term colorimetric monitoring of test walls using a spectrophotometer. • Microscopic observations of stone and mortar using light and semi-quantitative electron microscopy.
Attachment and structural damage		
No damage to stone by aerial rootlets. Visual observations indicated that rootlets caused minimal damage to underlying stone.	*How do rootlets affect vulnerable building materials?* Aerial rootlet attachment and their impacts on stone are minimal, but likely vary between material types.	• Assessment of aerial rootlet attachment to 'mini walls' made from a range of vulnerable materials. • Observation of rootlet attachment using microscopy.
Ivy stems and roots can exploit structural defects in walls and can cause considerable damage. Ivy growing into wall defects can cause damage when stems thicken; damage can be caused when true roots develop from stems growing into and under walls.	*How does ivy respond to wall defects as it grows, and under what circumstances does it cause damage?* Ivy can exploit existing defects and cause considerable damage, but little is known about its growth habit in response to defects (before damage occurs) or whether the type of defect affects rooting-in behaviour.	• Observation and monitoring of ivy growth in response to test wall defects, and poor-condition walls at case study sites. • Observations of ivy growth, interaction with wall structures, and condition of building materials at case study sites where removal is being undertaken.

1.4 Overview of the research approach

A range of research activities have been undertaken during the 'Ivy on Walls' project. This includes qualitative observations and monitoring at a range of field sites alongside quantitative measurements of ivy's direct and indirect impacts using established scientific techniques. The specific methods used are described in detail in the following chapters, but the general approach taken involved three types of observation.

1.4.1 Field sites

Observation and monitoring has been undertaken at several sites in England, summarised in Table 1-3. The particular structures examined, their construction, materials, aspect, state of repair and extent of ivy cover varied (see Viles, 2010a and Sternberg et al., 2010 for further details), allowing for observations under a range of different settings. Further details and findings from these sites are described in the following relevant sections; detailed observations relating to particular management issues (including removal of ivy) at these and other sites are described in Chapter 4 as a series of case studies.

Key questions addressed at field sites were: (1) What evidence is there that ivy stems, roots and aerial rootlets damage walls? (2) What evidence is there that a cover of ivy protects walls and masonry? (3) What influence does ivy have on wall surface microclimates (temperature and moisture) and the potential for weathering? (4) What is the influence of ivy on airborne particulate pollutants reaching the face of walls?

1.4.2 Laboratory experiments and microscopy

Experiments in the laboratory and microscope observations (light-based and Scanning Electron Microscopy) were used to address the following questions:
(1) Does ivy protect stone from damaging frosts? (Section 3.3.3)
(2) Does attachment by aerial rootlets damage stonework? (Section 2.5)

Table 1-3: Site Summary

Site	Structure details/nature of ivy growth	Qualitiative observation		Semi-quantitative observation/ measurement			Quantitative data collection/ measurement			
		Ivy regrowth/ interaction with masonry	Ivy removal and/ or management	Measurement of ivy stems, growth rates etc	Thermal imaging	Microscopy	Microclimate (temp/relative humidity)	Moisture (surface/ near-surface)	Surface hardness	Soiling/ discolouration
Wytham Woods test wall site	Purpose-built test wall. Limestone (Elm Park) and lime mortar construction. Carefully controlled ivy growth; complete cover on half of four aspects to thickness of around 20 cm	×	×	×	×	×	×	×	×	×
Holywell Cemetery, central Oxford	Poor condition limestone (unknown type) and lime mortar perimeter walls, mid-19th century. Mix of juvenile and adult ivy cover, patchy thickness.	×	×	×				×	×	
Godstow Abbey, Wolvercote, Oxford	12th-century abbey ruin. Scheduled Monument. Primarily limestone block/mortar construction. Patchy ivy growth on most of the walls.	×	×							
Abbey Inn, Byland, North Yorkshire	Local sandy-limestone construction 19th-century inn, ivy cover up to around 20 cm thick, east-facing wall.	×					×			
St. Thomas a Becket churchyard, Ramsey, Cambridgeshire	Ivy growing on a range of headstone materials. Monitoring on a south-facing 2.5 m limestone perimeter wall with patchy ivy cover (around 24-cm thickness).	×					×			
Elms Colliery, Nailsea, Somerset	Early 19th-century colliery. Scheduled Monument. Monitoring on a west-facing limestone wall roughly 10m high, relatively thin ivy cover (< 10 cm).	×					×			
Drop Redoubt, Western Heights, Dover, Kent	Early/mid-19th-century fort. Scheduled Monument. East-facing, 7m high brick wall with extensive ivy cover (up to 95 cm thickness).	×					×			
Various sites, Oxford City Centre	Observations at Rewley Abbey (east-facing), Rhodes House (east-facing), Trinity College (west-facing), Old City wall (north-facing), Pembroke College (south-facing). Monitoring at London Road and Walton Street and hanging ivy cover to a thickness of about 30 cm.	×	×			×		×		
Garden wall at Warnham, East Sussex	Freestanding brick masonry wall (1.5 to 2.5 m high) of a private garden. Original structure dated c.1890. Extensive arboreal ivy growth requiring removal.	×	×	×				×	×	

Table 1-3: Site Summary		Qualitiative observation		Semi-quantitative observation/ measurement			Quantitative data collection/ measurement			
Site	**Structure details/nature of ivy growth**	Ivy regrowth/ interaction with masonry	Ivy removal and/ or management	Measurement of ivy stems, growth rates etc	Thermal imaging	Microscopy	Microclimate (temp/relative humidity)	Moisture (surface/ near-surface)	Surface hardness	Soiling/ discolouration
Worcester College, Oxford	South-facing limestone garden wall, around 2.5 m high with patchy ivy growth up to 45 cm thickness.	×					×			
Walton Street Cottage, Worcester College, Oxford	Limestone construction cottage with slate roof, dating to the 1700s. Ivy has grown across much of the outer wall and onto the roof. Subsequently removed during multiple phases of management	×	×	×				×	×	
St Mary's Church, Derbyshire	Grade I-listed 13th-century church. Stone block/mortar construction. Management of extensive ivy growth on and within the walls and roof space.	×	×							
Hampstead Cemetery, London	Grade II-listed cemetery site dating from the 1870s to present. Headstone of a range of stone types and varying conditions. Ivy is managed at the site but many headstones have ivy growth.	×								
Garden walls, Gillingham, Dorset	Stone masonry boundary wall with tile capping of unknown age. Extensive ivy growth over/into the structure.	×								
Gleaston Castle, Cumbria	14th-century ruined site. Limestone block construction walls with evidence of extensive ivy penetration into wall fabric.	×	×							
Maxstoke Priory, Warwickshire	Originally 14th-century Scheduled Monument. Extensive ivy growth over and into walls; clear evidence of structural damage from ivy growth including lifting of capping stones.	×	×							
Littlehampton Fort, West Sussex	Mid-19th-century fortification. Observations of brick and mortar walls. Extensive ivy growth over and into walls associated with deteriorating pointing.	×	×							
Thornton Abbey, North Lincolnshire	12th-century ruined site. Observations of stone block and mortar walls. Evidence of deeply penetrating and thick ivy stems in wall fabric.	×	×							

1.4.3 Test walls

A purpose-built test wall was constructed in 2007 at Wytham Woods near Oxford. This consists of a single structure with four faces (north, east, south and west facing) around a central core built from blocks of Elm Park limestone (23–24 cm thick) and lime mortar (Figure 1-2a). Each face is 1.2 m wide and 2 m high. Defects were purposefully built into each face (holes, crevices and recessed mortar joints) and ivy was encouraged to grow up one side of each face. Colonisation was initially very slow, until 2009 when the ivy took hold and began to colonise rapidly. This has allowed detailed observation of growth behaviour in response to the defects under controlled conditions. After the ivy had become fully established (having completely covered one-half of each face by 2012), long-term monitoring of 'bare' and 'ivy-covered' sections have been carried out (Figure 1-2b). The plants were trimmed back regularly to maintain the bare/covered sides of each face.

Research questions being addressed using the test wall were: (1) How does ivy respond to masonry defects and do these encourage stems to penetrate into walls?; (2) Under what circumstances does ivy produce the 'true' roots that are known to cause considerable damage?; (3) How does a cover of ivy affect wall surface microclimate, stone soiling and damp – how do these effects vary with wall aspect and height?; (4) Is there any evidence that stone deteriorates faster or slower with a cover of ivy?

Figure 1-2. Ivy test wall, Wytham Woods: (a) in 2009 ©Heather Viles, (b) in August 2015.

2 THE DIRECT INFLUENCES OF IVY ON WALLS AND THEIR DETERIORATION

Observations and monitoring at the purpose-built test walls (Section 2.1) and field sites (Section 2.2) were used to gather evidence of the ways in which ivy interacts with masonry materials and the potential for it to cause structural damage. Given the challenges of measuring plant growth in a controlled way, observations were largely qualitative and semi-quantitative. The test walls did, however, allow comparison of growth behaviour on different wall aspects (north, east, south and west facing walls) and in response to different types of defects over a precisely-known period of time, and whilst controlling for location and material type. Observations at field sites focussed on well-established ivy plants of largely unknown age (attempts were made to establish age where possible), and were important in providing evidence of growth behaviour and impacts over much longer periods than were possible at the test walls.

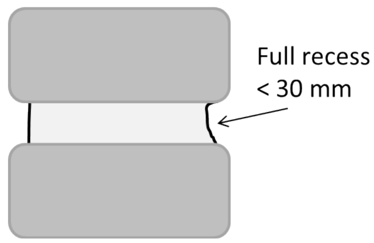
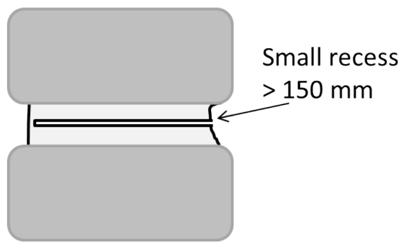
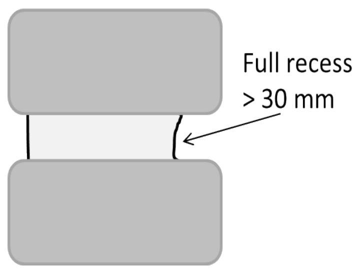
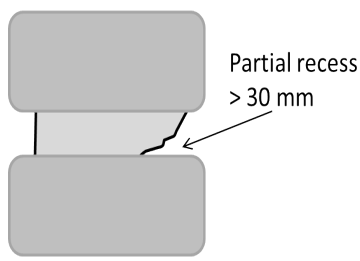
Findings from all of these observations are discussed in relation to existing understanding of climbing plant growth behaviour in Section 2.3, in order to better understand and explain the nature of ivy growth in response to different types of masonry defects. The importance of rooting into walls for causing structural damage is further considered in Section 2.4 and an assessment of the impact of aerial rootlet attachment to stonework is given in Section 2.5.

2.1 How does ivy respond to wall defects? Test wall observations

2.1.1 Baseline survey

The Wytham Woods test wall was initially mapped using a system of numbered block rows (courses) and joints (horizontal bed joints and perpendicular joints). To aid subsequent observations of stem interactions the locations of all (intentional) defects were recorded and categorised into four broad groups (holes, recesses, crevices and normal mortar, see Table 2-1). The dimensions (width and depth) of all defects were measured.

Table 2-1. Defect classification for the ivy test wall at Wytham Woods, Oxford

Defect group	Description	Schematic
Normal mortar (control)	A typical mortar joint set-back slightly from the stonework. Dimensions: less than 30 mm recess across the full width of the joint, relative to the stone face.	
Hole North = 6 East = 5 South = 9 West = 3	Small circular hole within a mortar joint. Dimensions: *c.*10 mm in width penetrating 150 mm or more into the joint (some holes are blind-ended, some penetrate the entire width of the wall). On monuments, holes may be caused by removal or decay of fixings or possibly unfilled drill holes into mortar joints as part of past investigation work. Fine cracks would be a similar defect.	
Recess North = 8 East = 13 South = 11 West = 11	A recessed mortar joint (distinctive from normal mortar by depth of recess). Dimensions: greater than 30 mm recess across the full width of the joint, relative to the stone face. On monuments, recesses may be caused by the loss of infill stones such as gallets and pinning stones, the loss of small stones from the wallface, or mortar joint decay.	
Crevice North = 3 East = 5 South = 2 West = 5	A partial, 'wedge-shaped' recess in mortar. Dimensions: a partial, tapered recess into the joint. Depth is greater than 30 mm at its deepest point relative to the stone face. On monuments, crevices may be caused by mortar joint decay and/or erosion and cavernous decay of brick, stone or render.	

2.1.2 Stem occupation and penetration into joints and defects

The colonised sides of the test wall were surveyed in July 2013 and August 2014, when the presence and size (width/penetrating depth) of occupying ivy stems were measured wherever possible (Figure 2-1). Where more than one stem had grown into a defect the number of stems was noted and the largest of these measured. Whether stems growing into a defect were 'exiting' or not was also noted (exiting stems were those that had grown into and back out of a defect, continuing to grow up the wall rather than growing further into the masonry structure).

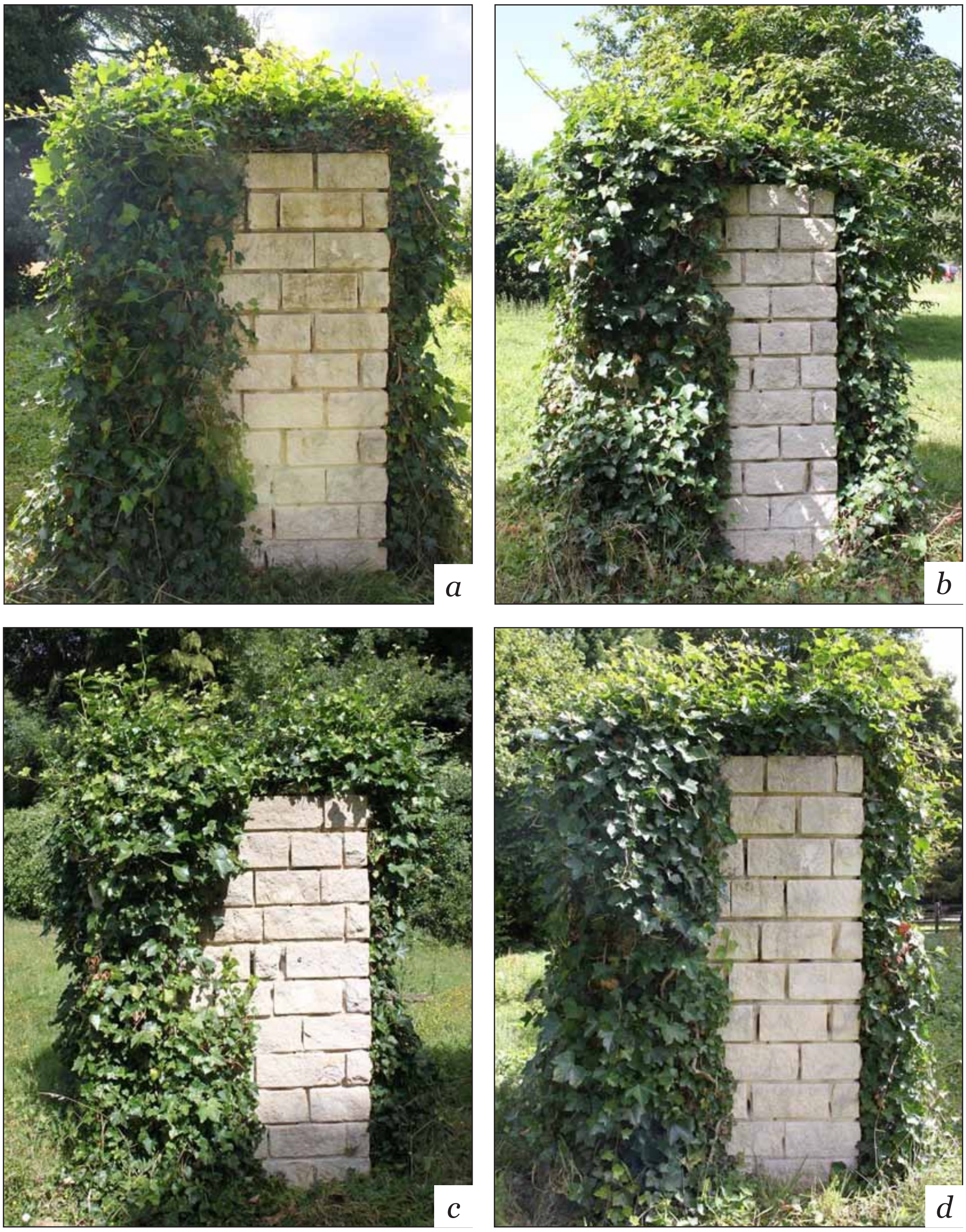


Figure 2-1. Ivy foliage and canopies on each face of the Wytham ivy wall (a: north wall, b: east wall, c: south wall, d: west wall) August 2014.

The numbers of defects with occupying ivy stems (for each type of defect and wall aspect) are shown in Table 2-2, with the number of stems that were exiting shown in brackets. These data are shown graphically in Figure 2-2a and Figure 2-2b as 'percent stem occupancy', representing the proportion of the available defects that had occupying ivy stems on the four wall aspects. The proportion of stems that had entered a defect, but which had subsequently exited to continue growing up the wall face, are shown in Figure 2-2c and Figure 2-2d. These data do not account for the probability of stems encountering a defect (e.g., stems are less likely to encounter a small hole than normal mortar joint) but allow relative comparisons by defect type and between aspects.

Table 2-2. Number of mortar defects with occupying stems (number of exiting stems)

Number of mortar joints and defects on each aspect of the Wytham ivy wall with occupying ivy stems. The number of stems that are exiting[1] is shown in brackets. Wall originally planted with ivy in 2007.

Defect type	July 2013					August 2014				
	North	*East*	*South*	*West*	Total	*North*	*East*	*South*	*West*	Total
Normal	9(9)	14(14)	8(8)	8(8)	39(39)	8(8)	14(14)	8(8)	9(9)	39(39)
Holes	0(0)	1(0)	3(0)	1(0)	5(0)	0(0)	0(0)	3(0)	1(0)	4(0)
Recesses	6(6)	9(8)	9(8)	10(8)	34(30)	6(6)	8(8)	9(8)	9(8)	32(30)
Crevices	2(2)	4(2)	1(1)	5(5)	12(10)	3(3)	4(2)	2(2)	7(6)	16(13)

[1]Stems that had grown into and back out of a defect to continue growth up the wall were classified as 'exiting'.
[2]See Table 2-1 for details of mortar defect types

A higher proportion of available 'normal' (control) mortar joints were occupied by stems on north (90%) and east (93%) facing aspects in 2013 compared to the south (57%) and west (62%) aspects (Figure 2-2a). This difference was less distinct by 2014 (Figure 2-2b). This reflects a faster rate of colonisation on the north and east compared to south and west aspects. Aspect likely affected the health and vigour of the plants, with cooler and wetter north and east aspects offering less stressful conditions than warmer and drier west- and south-facing sides. Growth on the south-facing side was indeed less dense and lush compared to the other aspects (see Figure 2-1c). A healthy, vigorously climbing plant is likely to have more clinging stems, more interaction with the wall face, and a higher propensity to occupy any available joints and defects. It is noteworthy that for all four aspects, 100% of the stems that had grown into normal mortar joints were exiting and had not penetrated deeper into the wall nor had they produced 'true' roots (Figure 2-2c-d).

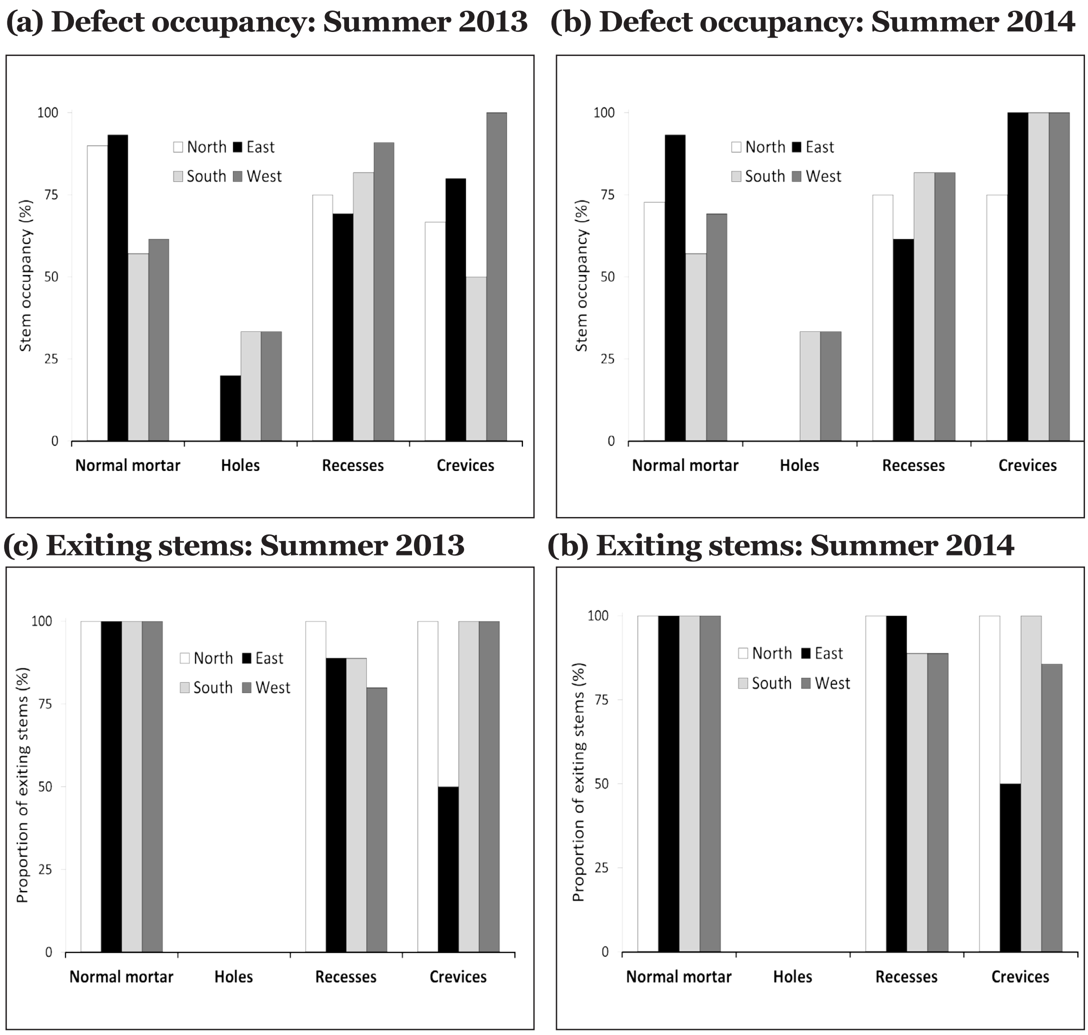


Figure 2-2. Stem occupancy (%) of available mortar defects in the Wytham test wall in (a) 2013 and (b) 2014 and the proportion (%) of these that were exiting in (c) 2013 and (d) 2014.

More than 50% of the available mortar recesses and crevices were occupied by stems in 2013 (Figure 2-2b). By 2014, 100% of the available crevices on three of the wall aspects had occupying stems (Figure 2-2b). As with the normal joints, a high proportion of stems entering recesses and crevices were exiting and did not penetrate deeper into the wall structure (Figure 2-2c-d). In contrast, few of the available smaller holes were occupied by ivy stems in 2013 and 2014 (Figure 2-2a-b). This likely reflects the fact that stems were less likely to encounter these compared to the larger defects. Where stems did encounter a hole, there were some instances where stems had grown across without entering. Nevertheless, it is important to note that where stems had encountered and grown into holes, none of them were found to be exiting (Figure 2-2c-d). This is likely due to the stems being unable to 'turn' and exit from very small defects, discussed in more detail in Section 2.3.

Does ivy always exploit defects to their full extent, and does the type of defect make a difference?

On average, 64% of all the available joints and defects contained ivy stems in 2013, 6 years after initial planting. These stems occupied around 60% of available defect depth. By 2014, 65% of joints and defects contained stems, occupying 59% of their available depth. The relationship between defect depth and stem penetration depth was, however, very variable between the defect types. Broadly speaking, for deeper defects such as recesses and crevices the proportion (in terms of depth) that an occupying stem had penetrated tended to be lower (Figure 2-3). That is to say, the depth to which stems penetrated deeper defects was, proportionally, less than for the shallow defects; stems rarely exploited the full depth of the defects available to them. This reflects the tendency for most stems to exit a defect in order to continue growing up the wall face, rather than penetrating further into the structure even where it was possible to do so (see Figure 2-2c-d). Figure 2-3 indicates that shallower features (i.e., normal mortar set-back from the stone) were often fully occupied by stems (in terms of the available depth) whereas deeper crevices and recesses were occupied to relatively shallow depths. This trend was fairly consistent between 2013 (Figure 2-3a) and 2014 (Figure 2-3b).

What are the implications of these observations?

The assumption that ivy will always exploit defects to their full extent is incorrect. In the majority of cases climbing (juvenile) stems that entered a joint subsequently exited and continued growing upwards, even where it was possible to penetrate deeper into the structure. This could be a function of time (i.e., that the ivy will penetrate deeper as it grows) but this is unlikely given that most stems had already exited in order to continue growing up the wall face. Furthermore, the relative depth of stems occupying defects actually decreased between monitoring years (also see Section 2.1.3). Observations on older walls with well-established ivy (Section 2.2) further suggest that stems exploiting the full depth of available defects are relatively rare. It is, however, these deep penetrating stems (even if comparatively rare) that present the great cause for concern with respect to structural damage.

At the test wall it was generally the case that deepest penetration of stems occurred within the smaller holes (the red squares in Figure 2-3) and there are undoubtedly many cases elsewhere where ivy has penetrated deep into walls where pre-existing cavities exist (See Fig. 2-9). Whilst it is not clear under what circumstances this happens, there are probably several contributing factors including whether defects are blind-ended (and thus whether a light stimulus is present) and, perhaps more importantly, the influence of defect size and shape on the ability of stems to turn and exit, or grow up into internal cavity space (see Section 2.2 for further discussion).

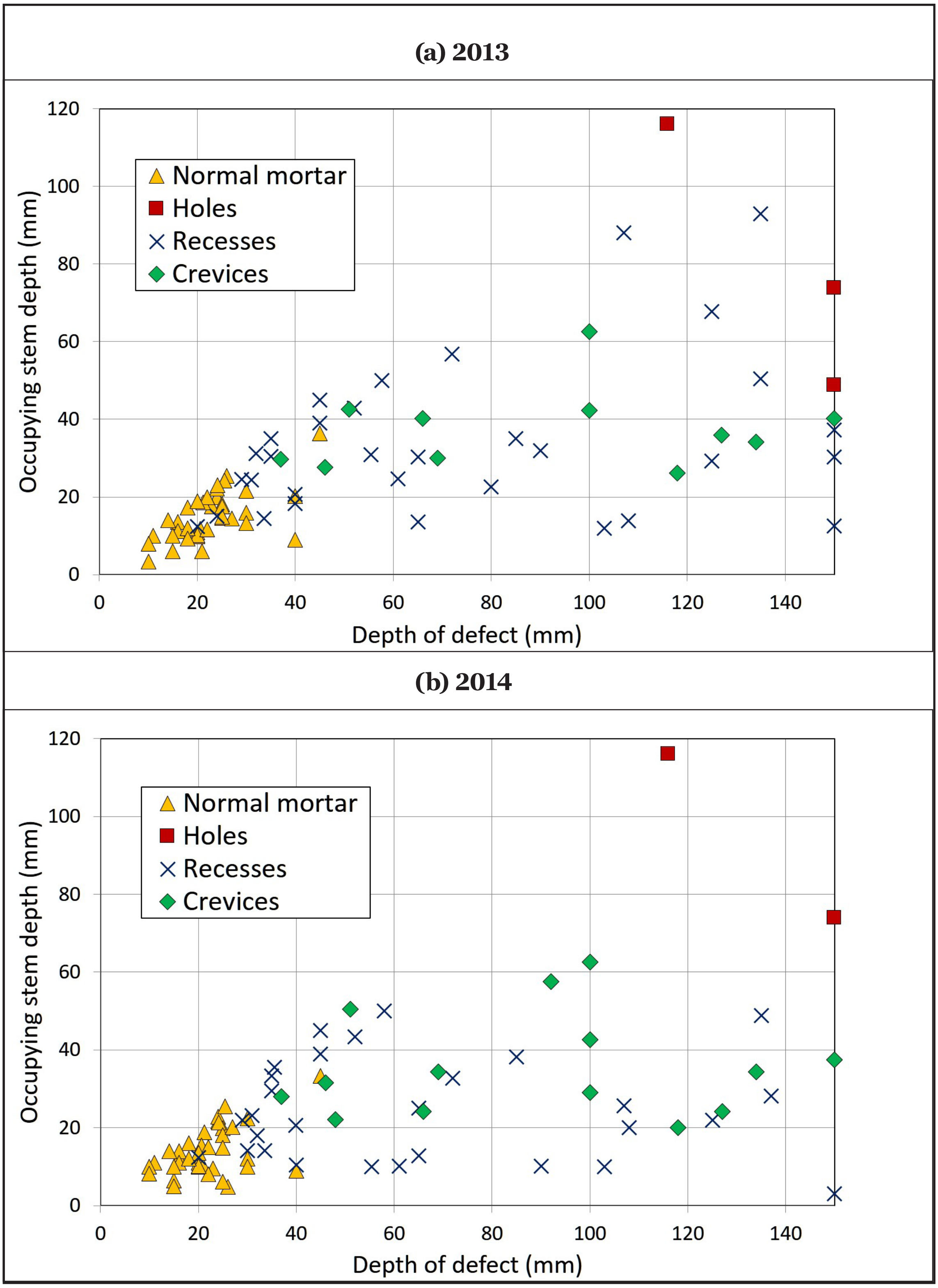


Figure 2-3. Relationship between available defect depth and the depth of occupying ivy stems at the Wytham test wall in (a) 2013 and (b) 2014 (all measured depths are minimums).

2.1.3 Do the number and thickness of stems increase over time?

The progressive thickening of ivy stems over time is thought to exert pressures within joints/defects that can cause structural damage, especially where more than one stem occupies a joint. At the test wall the average number of stems occupying defects at the test wall in 2013 and 2014 are shown in Figure 2-4a. There was no great change between one year and the next, but an increasing trend was consistent between the four wall aspects; more stems were growing in individual defects in 2014 than in 2013 reflecting continued growth of the plant. The width of the stems in joints and defects also increased from an average of 6.9 mm in 2013 to 7.6 mm in 2014 (Figure 2-4b). In contrast, the depth to which occupying stems were penetrating decreased slightly between 2013 and 2014 (Figure 2-4c). This may reflect a 'loosening' of stems away from walls as the plant ages. This has been noted in other locations, particularly towards the base of walls where stems become woodier and thicker, and where the aerial rootlets often become less effective at clinging to the wall surface (see Section 2.5).

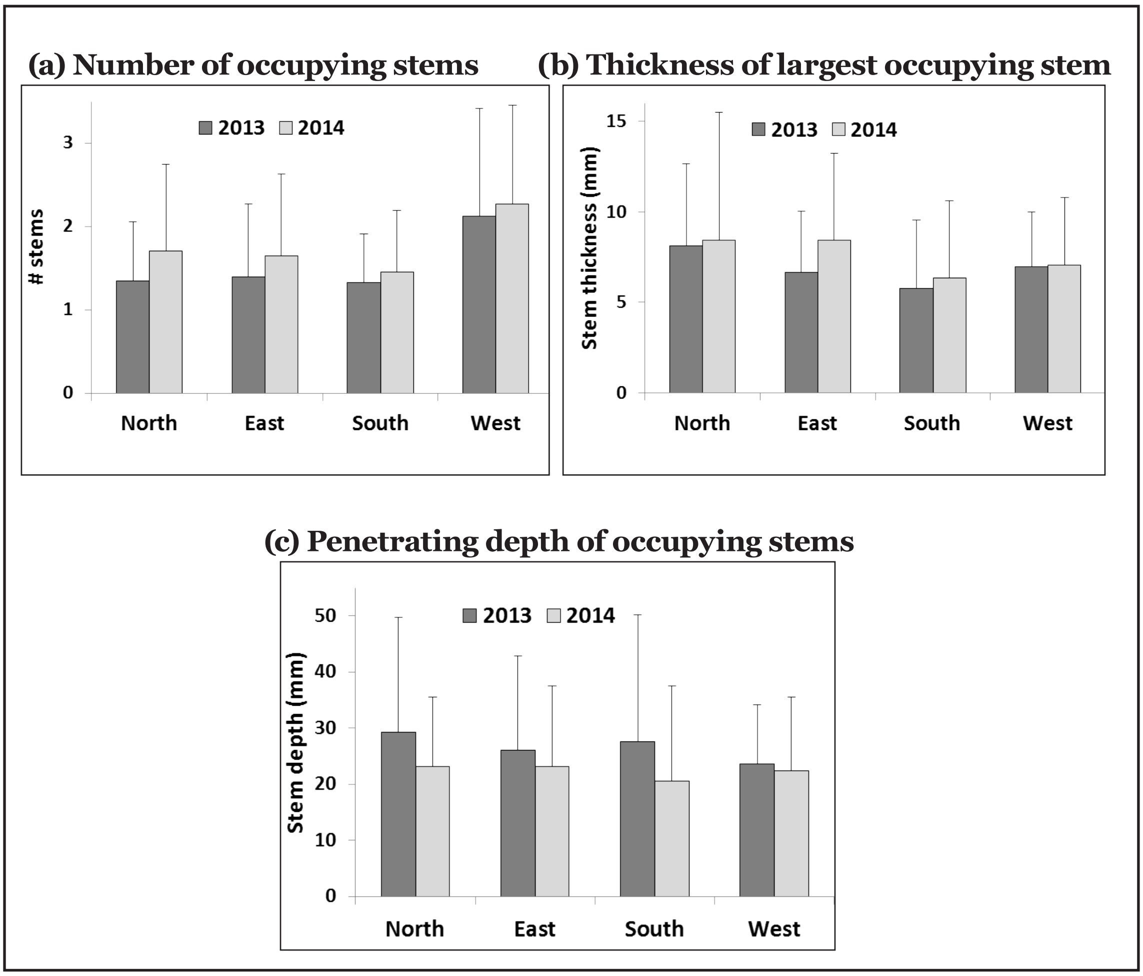


Figure 2-4. Stem occupancy in all defect types in mortar joints at the Wytham test wall in 2013 and 2014: (a) number of stems; (b) thickness of largest stem; (c) penetrating depth of largest stem (averages +SD).

The majority of ivy stems growing on the test wall in 2013 and 2014 were thinner than the joints they occupied. This means that after the 3 to 5 year period during which growth was well-established on these walls, there was no evidence that joint widening had occurring due the thickening of occupying ivy stems. There were, however, examples of stems tightly packed into some mortar joints (Figure 2-5). Monitoring over a longer period of time is necessary to help determine whether thickening stems are able to exert sufficient force to dislodge and/or crack the masonry.

Figure 2-5. Examples of ivy stems packed into mortar joints at the Wytham test wall, 2014 survey: (a) a confined stem that has thickened (growing wider than the occupied joint) after it has exited; (b) a young, exiting stem occupying a relatively thin joint; (c) several stems tightly packed into a joint.

2.1.4 Conclusions from observations at the test wall

Based on the observations at the test wall, the following general conclusions can be made:

- Young and healthy ivy plants growing up walls can occupy a very high proportion of mortar joints and defects after only a few years of growth. This is not unexpected given that a close physical association with the climbing support (in order to achieve secure attachment) is the key growth strategy of climbing stems. The tenacity of stems may be much less for older (arborescent) plants, where there is evidence that stems tend to come away from walls, especially towards their base.

- Without exception, ivy did not penetrate into the wall by its own means. Stems only exploited existing joints and defects in the test wall.

- Aspect influences the rate of ivy growth by affecting environmental conditions (light, temperature and moisture) and thus plant health and vigour. In this way, the nature of interactions between ivy and a wall surface (whether positive, negative or benign) may vary between aspects, at least during initial stages of colonisation. This requires further investigation.

- Where ivy stems had grown into masonry joints and defects, the majority grew back out in order to continue growing up the wall face. In doing so, stems rarely exploited the full available depth of defects. This demonstrates that ivy does not actively 'seek out' and exploit deeper cavities in walls even where such an opportunity exists. Deeper penetration into defects is more a matter of chance encounter.

- Where ivy stems exit from the defects they grow into, subsequent thickening as the plant ages can cause damage by exerting pressure. However there was no evidence of this process at the test wall after a period of 3-5 years of well-established growth.

- Ivy stems that grew deeper into the test wall entered exclusively via small holes in the mortar. The ability of stems to exit shallower joints and cavities, or alternatively penetrate deeper where such void space already exists, is influenced by defect size and shape (discussed further in Section 2.3).

2.2 How does ivy respond to wall defects? Field observations

Additional observations of ivy stem growth, behaviour in response to masonry defects, and evidence of damage were made at a number of field sites. These supplemented research at the test wall by focussing on much older growth in a greater variety of growing conditions.

2.2.1 Stem growth in the field

Observations made on older walls support those made at the test wall; in the majority of cases stems encountering a defect did not exploit it to its full extent. Indeed, it was not uncommon for stems to 'ignore' available entry points altogether, especially where they are small (see Figure 2-6). Rather, most stems that had grown into a cavity exit it by performing a 'U-turn' (where possible to do so) in order to continue growing up the wall face (Figure 2-8). This behaviour was shown quantitatively by measuring the depths of deteriorating mortar joints and their occupying stems in a limestone masonry wall at Holywell Cemetery, central Oxford (Figure 2-7). The relationship was found to be generally negative, indicating that ivy cannot be assumed to fully exploit defects even when stems have entered them. This supports observations made at the test wall (e.g. Figure 2-3).


Figure 2-6. Examples of juvenile stems growing over rather than into defects, Holywell Cemetery, Oxford.

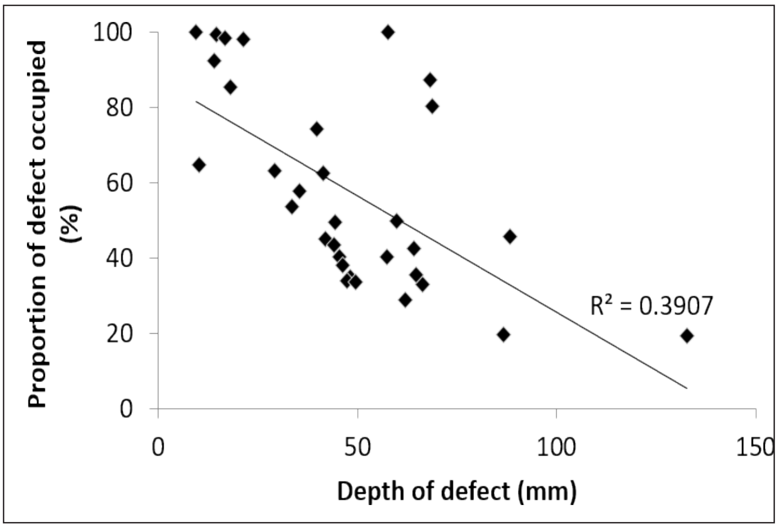


Figure 2-7. Depths of wall defects at Holywell Cemetery, Oxford, and their occupying stems (2014 data). R^2 indicates the strength of the relationship (values closer to 1 indicate a stronger relationship).

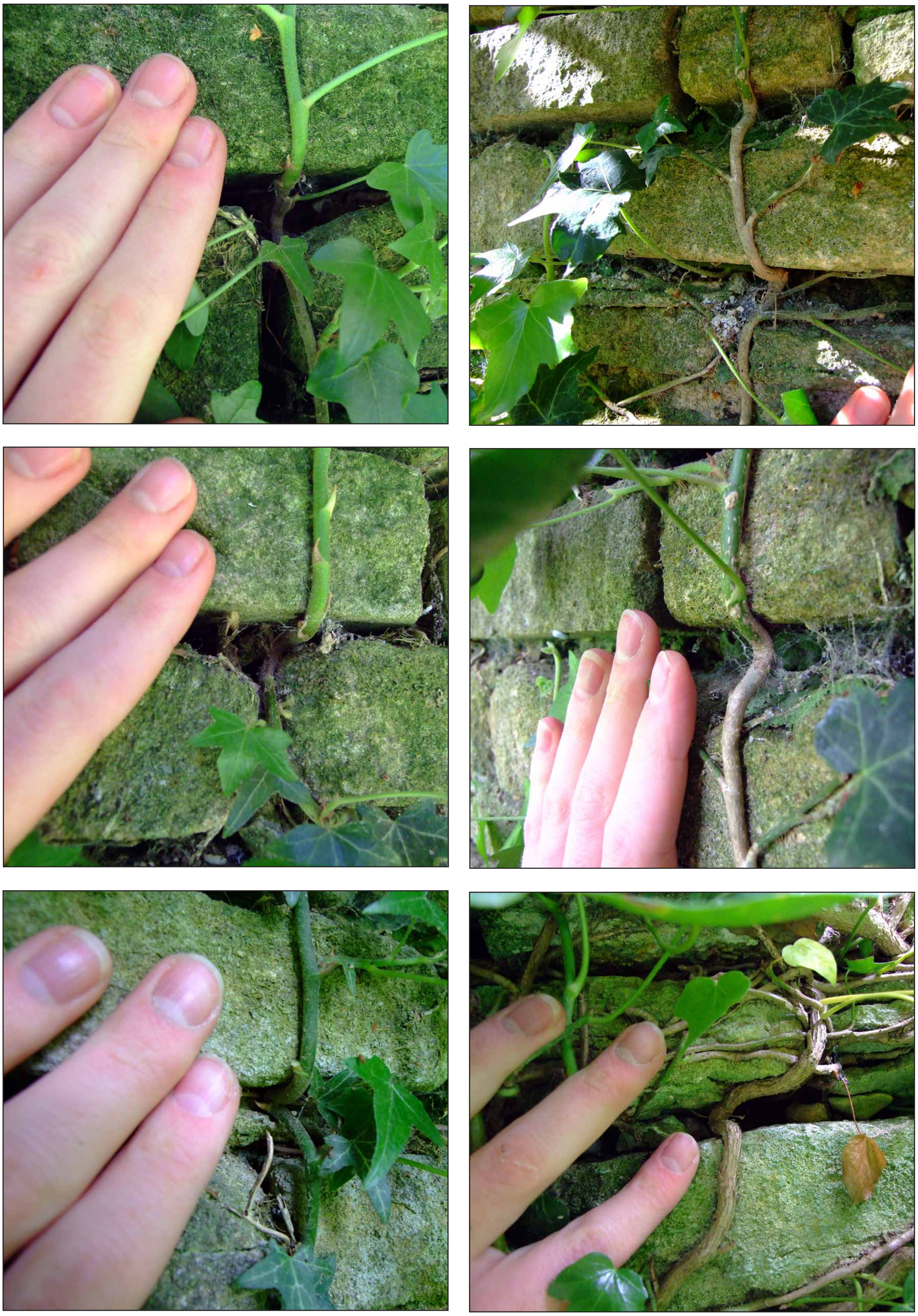


Figure 2-8. Typical 'U-turn' exiting behaviour of juvenile ivy stems encountering potential entry points in a wall with poor condition mortar joints, Holywell Cemetery, Oxford.

2.2.2 Stem damage in the field

Whilst most climbing juvenile stems were either found to grow over mortar defects altogether, or grow in a short distance before exiting, it is undeniable that ivy does penetrate deeper into walls and can cause damage. Firstly, all the evidence suggests that this can only occur where defects and entry points already exist, such as where decaying mortar joints and/or cracks between mortar the adjacent stone are present. Where stems do grow deeper into walls, their subsequent thickening (reaching upwards of 25 cm diameter in exceptional circumstances) can lead to significant structural damage. Types of damage can take many forms depending on the condition of the structure the ivy is growing up/into and the nature of defects (i.e., size, shape and connectivity) available to climbing stems (see Section 2.3). For example, stem thickening in joints that can cause weakening and loosening of blocks, and may induce stress cracking of stone and brick (Figure 2-9a). Whole masonry blocks may be 'punched out' of walls and coping stones lifted where stems grow and thicken under them (Figure 2-9b). The most damage seems to occur when stems grow through the entire width of a wall, and continue growing up the opposite face (Figure 2-9c-e). Where this is extensive (either as a dense mass of individual stems within cavities or fewer, but very thick older stems) the entire wall may be destabilised. Crucially, growth into and through walls can only occur when possible entry points and internal void spaces exist, whether a result of prior deterioration or structural design. Other structural issues can arise where ivy adds substantial weight to the wall head, usually when arboreal growth forms large and spreading canopies (Figure 29-f). Further issues not associated with masonry deterioration arise when growth remains unchecked, such as ivy growing into guttering and under roof tiles.

Figure 2-9. Ivy growth in association with structural deterioration of masonry: (a) thickening and re-sprouting of cut ivy stems in mortar joints, Holywell Cemetery, Oxford; (b) punched out bricks by thick re-sprouting ivy stems, Hampstead Cemetery, London; (c) stems growing into poorly repaired pointing mortar, Littlehampton Fort, West Sussex; (d) thick stems growing through a stone masonry wall, Thornton Abbey, North Lincolnshire; (e) woody stems growing through a historic wall in poor condition, Chudleigh, Devon; (f) Spreading arboreal canopy contributing to bulging of the wall head, Holywell Cemetery, Oxford (c,d,e ©Alan Cathersides).

2.3 Controls on ivy growth habit and potential for damage

The growth habit of ivy in response to wall features is best explained by considering how the plant responds to external stimuli (Trewavas, 2009). Plant growth behaviours are the result of several interacting 'tropisms' (directional responses to stimuli) involving the release of plant hormones such as auxins (Hart, 1990; Esmon et al., 2005). Considering tropisms is therefore important in order to understand growth behaviour of ivy stems colonising walls. Indeed, whereas ivy stems have no capacity to 'seek out' cavities and defects they may follow wall contours and enter defects in response to touch, light and other stimuli.

There is generally very little experimental research on the tropisms of ivy and other climbers in a context of building conservation. However, for most climbers like ivy four key tropisms dominate growth behaviour: (i) **phototropism** - response to light, (ii) **gravitropism** - response to gravity, (iii) **thigmotropism** - response to touch, and (iv) **hydrotropism** - response to water. The relevance of each of these stimuli for ivy on historic walls is considered in Table 2-3. It is important to note that these different stimuli are interacting, and it may be the case that no single tropism dominates ivy's growth behaviour and/or that different stimuli are more or less important during different growth phases.

Although beyond the scope of this research it should be noted that as for all plants, overall growth patterns for ivy will be influenced by both the macro- and micro-climate of where they are growing. For example, a macro-climate such as the generally wetter west of the country will produce more growth than the drier east and warmer lowland; and southern sites will see more growth than colder, northern sites where the growing season is shorter. Micro-climate influences such as moist soils near rivers, sheltered areas or frost pockets will also influence growth patterns.

Table 2-3. Summary of key plant tropisms and their associated relevance to understanding ivy on walls			
Tropism	**Stimuli**	***Hedera* spp. characteristics**	**Relevance for ivy on historic walls**
Phototropism	Light	Juvenile stems are negatively phototropic Adult phase is positively phototropic	▪ Ground-creeping vines grow towards shade cast by vertical structures (e.g., trees, walls, headstones). ▪ Climbing juvenile stems grow away from light, forcing stems to follow the contours of walls closely as they grow for secure attachment. ▪ Clinging aerial rootlet development is partly associated with light, produced on the opposite side of stems exposed to full sunlight. ▪ Development of true roots is associated with darkness in most plants. ▪ Phase change to woodier, self-supporting adult growth is partly controlled by exposure to light.
Gravitropism (geotropism)	Gravity	Juvenile stems are negatively gravitropic Adult growth less/ non responsive to gravity	▪ The climbing habit of juvenile ivy stems is driven by the plant's response to gravity. ▪ If ivy stems have penetrated into a wall (driven more by other tropisms and external factors) then gravitropism encourages growth up into internal wall cavities, where these exist. ▪ Growth habit switches from clinging and climbing in juvenile stems to spreading and canopy-forming arborescent growth (such phase change usually only occurs once a height >2 m has been reached, but not always).
Thigmotropism	Touch	Juvenile stems are positively thigmotropic Adult growth is negatively thigmotrophic	▪ A positive response to touch stimulates intimate contact between stems and the wall face. ▪ Climbing stems typically follow the contours of a wall (including recesses and cavities) very closely as is grows up in response to touch (and possibly light) stimuli. This is associated with aerial rootlet development from stems in contact with a surface. ▪ The spreading arborescent growth phase of ivy is non-clinging. ▪ Adult growth grows towards light (see above) and does not respond to touch.
Hydrotropism	Moisture	For most plants primary roots are positively hydrotropic	▪ Initiation of true root development may be partly associated with contact with moisture in wall joints and defects (in association with darkness and presence of fine weathered material) and/or water stress in cut stems, see Section 2.4. ▪ True roots can form where ground-spreading stems become covered in weathered debris/ rubble as a wall above deteriorates.
Key sources of information include: Hart 1990; Häder and Lebert 2001; Metcalf 2005 as well as field observations made during this study.			

Juvenile ivy growth

Juvenile stems respond negatively to gravity and positively to touch, having the tendency to grow upwards once an obstacle is reached, and to closely follow the contours of the surface on which they are growing. Light and touch cues are also thought to be important for initiating the formation of clinging aerial rootlets on juvenile stems, which form on their shaded sides (also see Section 2.5). The propensity of juvenile stems to grow upwards (negative gravitropism) and 'inwards' by following the contours of its support (positive thigmotropism) explains much of the growth behaviour that has been observed on walls (Section 2.2 and Section 2.3) and, importantly, the damage that this may ultimately cause.

Arborescent ivy growth

In contrast to juvenile stems, adult arborescent ivy growth (which usually develops once the plant reaches more than 2 m in height or the top of its support) is adapted for flowering and pollination rather than climbing – it has self-supporting woody stems that spread outwards to form a canopy, having lost sensitivity to gravity and touch, and no longer needing to cling and climb.

Typical growth behaviours in response to wall features are illustrated schematically in Figure 2-10 and are summarised in the following sections.

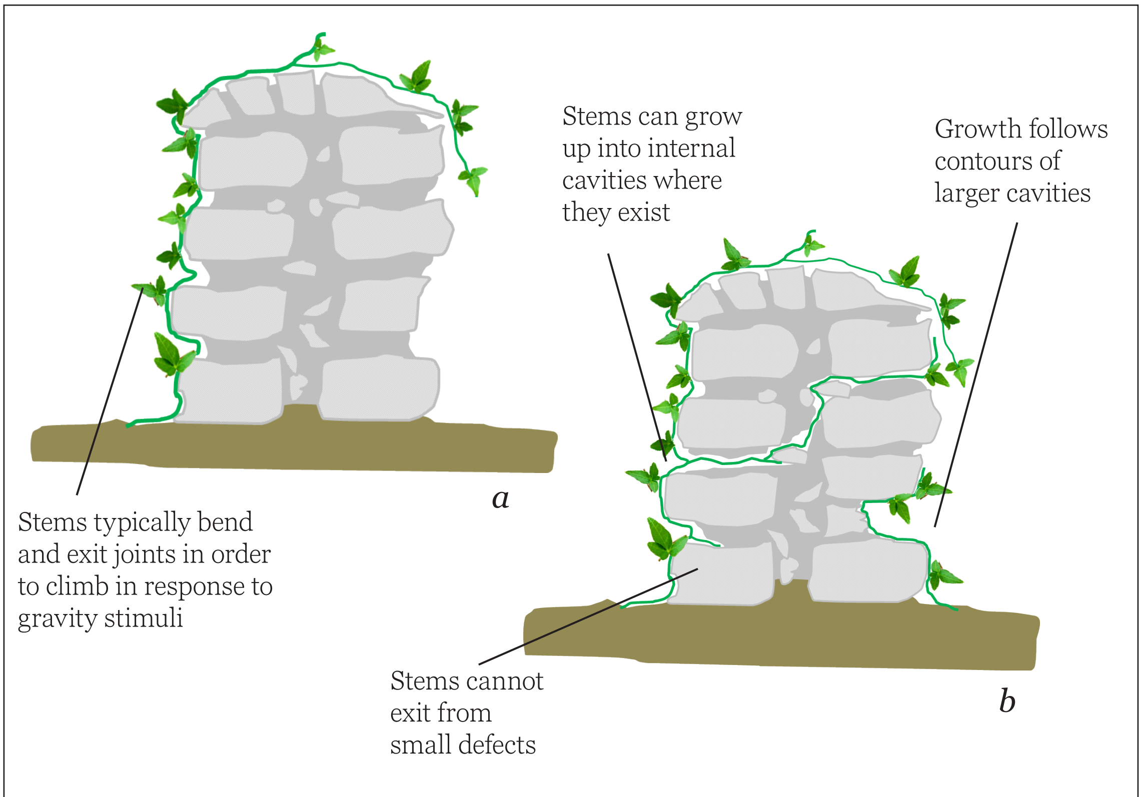


Figure 2-10. Schematic of typical ivy growth on masonry walls (in cross-section): (a) wall with recessed but otherwise good condition mortar and pointing; (b) deteriorating wall with internal cavities.

2.3.3 Growth and damage in association with recessed mortar joints

Stems encountering typical mortar joints in historic masonry walls (i.e. those a few centimetres in width and depth) usually begin to enter in response to touch, following the curve of the top lip of the stone block it is climbing up. If the joint is relatively shallow, the entering stem can grow around and back out whilst remaining in contact with the surface at all times. This occurs via rootlet attachment and stem bending (tropism) in response to touch and other stimuli (e.g. Figure 2-11a). Where stems encounter a joint that is recessed further back, a typical response is for stems to enter a short distance before turning and 'jumping' the gap to the stone above. This allows stems to exit and to continue upwards growth in response to gravity and light (Figure 2-10a and examples in Figure 2-8).

Due to the importance of touch stimuli, climbing juvenile stems often follow the contours of horizontal mortar joints ('bed joints'). Once a stem has begun to grow in a bed joint, particularly if recessed relative to the masonry blocks (this may be the case either by design or as a result of mortar deterioration), growth may follow that joint for quite some distance until upwards growth can resume, which is usually the next perpendicular joint. Growing along recessed areas such as joints is a particularly effective strategy for climbers to ensure secure attachment to their support. In exposed conditions stems may also follow recessed mortar joints because these provide shelter from the drying effects of wind and sun. These responses mean that ivy stems can occupy a very high proportion of mortar joints and can make them particularly difficult to remove (e.g. Figure 2-11b). Growth in joints may exert destructive pressures once stems thicken (e.g., Figure 2-11c). Conversely, growth of stems along joints may act as a support to unstable walls owing to their rigidity. Attempts to remove stems growing in joints may exacerbate the loss of mortar leaving them exposed to moisture ingress and further decay.

Figure 2-11. Examples of typical growth responses of juvenile ivy stems to different kinds of wall features: (a) stems closely follow the contours of shallow mortar joints; (b) thickened stems in joints are difficult to remove completely; (c) stem thickening within joints may cause stress cracking of adjacent masonry blocks; (d) stems entering small holes can grow into internal void space (where this already exists) as they cannot turn and exit; (e) stems growing in and around surface deterioration can aid detachment of loose pieces of stone; (f) stems growing through walls (from one side to another) and around masonry blocks can cause considerable damage, but may also support poor condition walls. (f ©Alan Cathersides)

2.3.4 Growth and damage in association with small holes, cracks and crevices (< 1 cm)

Observations at a range of sites and at the test wall show that when smaller holes are present (such as cracks between mortar and masonry blocks) stems often grow over them altogether (see Figure 2-6). More rarely, if a stem does enter a small hole then the typical exiting behaviour described above cannot occur as there is insufficient room for the stem to turn (e.g. Figure 2-11d). Alternatively, stems may not exit a hole if it is connected to internal void space. In these cases stems can continue to grow upwards (in darkness) in response to gravity (see Section 2.3.6). In the case of small, blind-ended holes and crevices, entering stems will either die or stop growing completely (Figure 2-10b) or, conceivably, may sprout true roots if the right conditions exist (see Section 2.4).

2.3.5 Growth and damage in association with loose and deteriorating masonry

In instances where material has become loosened from the main wall structure, such as a fractured block (Figure 2-11e), poorly repaired pointing (Figure 2-12a), or crumbing and blistering stone (Figure 2-12b), stems can grow behind these and continue to climb up the main structure. The disturbance of deteriorating parts of walls by upward growing ivy stems will worsen the damage, particularly when these thicken. In this respect ivy may exacerbate other modes of deterioration, such as surface scaling (Figure 2-12c) and fracturing of rock resulting from previous frost damage for example (Figure 2-12d).

2.3.6 Growth and damage in association with large voids and internal cavities

For larger defects, such as missing blocks or cavernous weathering forms, the typical growth response is for stems to follow the contours of the void in an upward direction (Figure 2-10b). For example, in situations when a void is present between two blocks — and which is too large for stems to turn and exit — growth will follow the contours of the cavity in response to touch stimuli (e.g. Figure 2-12e). If such a cavity is blind-ended, the stem will continue to grow around and back out (continuing up the wall) so that subsequent thickening of the stem is unlikely to cause any damage. However, if a cavity (or any other smaller entry point) is connected to larger internal void space, stems can grow into the wall and, if connected to the opposite side, back out and up the opposite face (Figure 2-10b, Figure 2-11f). Considerable damage can occur when stems penetrate into and back out of walls (Figure 2-12f). Greatest damage occurs from the combination of juvenile stems growing up and into wall void spaces and subsequent phase change to the adult arborescent form, once it reaches the top of the support, which triggers thickening of woody stems inside the wall structure.

Figure 2-12. Ivy stems interacting with exiting deterioration features: (a) growth under loosened pointing repairs (Holywell Cemetery, Oxford); (b) penetration into badly deteriorating and friable limestone (Holywell Cemetery, Oxford); (c) aerial rootlet attachment to spalling limestone (Wytham Woods test walls); (d) shoots growing between a fractured limestone block (present before colonisation and possibly caused by frost damage, Wytham Woods test walls); (e) stem growth into, around, and out of larger voids; (f) stems growing into, thorough and out of walls can cause serious damage to walls (Maxstoke Priory, Warwickshire). (f ©Alan Cathersides)

2.4 Ivy roots: rooting into and under walls

In addition to the damage caused by thickening and penetration of stems deeper into existing wall cavities, 'rooting-in' behaviour can be particularly destructive. This involves the formation of longer 'true' or primary roots that obtain moisture and nutrients for the plant (which aerial rootlets do not). As well as forming in soil, true roots can sprout from creeping and climbing (juvenile phase) stems and penetrate into the fabric of walls, and these true roots can become very thick (e.g. Figure 2-13). Growth of primary roots at ground level can also cause problems for historic walls, especially for very old plants that can develop remarkably thick roots and ground-level stems, and for ruined and deteriorating masonry structures that are vulnerable to ground disturbance.

Triggers of true root formation are not well understood and are particularly difficult to study quantitatively for plants growing into historic fabric. However, existing research and observations made at a range of sites do allow some conclusions to be drawn in relation to ivy growth on masonry walls. Importantly, the cues associated with the development of clinging aerial rootlets and true roots are largely distinct. It is significant that true roots do not respond to gravity and light cues in the same way that juvenile stems do; true roots are sensitive to gravity and respond by growing downwards (positive gravitropism) but both light and soil regulates this response to some degree (Feldman, 1984; Massa and Gilroy, 2003). True roots are also strongly hydrotropic (see Table 2-3).

Figure 2-13. An example of 'rooting-in' by a juvenile ivy stem growing in a recessed mortar joint of a deteriorating limestone wall, Holywell Cemetery, central Oxford (0.5 m above ground level).

2.4.1 Damage by rooting under walls

At ground level, ivy's primary roots function in the same way as most other plants and provide all the water and nutrients the plant needs. They also offer some degree of anchoring, although the main supporting mechanism (as for most climbers) is intimate growth in association with the support (Section 2.3) and via aerial rootlets (Section 2.5). Roots in the ground can potentially cause structural problems for walls, although the root systems of climbers are unlikely to be as extensive as those of trees or large shrubs. The direction and extent of ground root systems are difficult to predict but those of ivy and other plants growing close to walls are likely to spread outwards, away from the wall itself, and may only spread beneath the structure if there are poor or insubstantial foundations, or if moisture and/or nutrients are available.

Under certain conditions (e.g., heavy clay soils) large established ivy plants may cause soils to dry out. This could result in heave and other ground movements, although the moisture requirements of ivy with its waxy, moisture retentive leaves are unlikely to equal those of trees. Other factors influencing the rate and extent of root growth include soil structure (Feldman, 1984) and as such it is reasonable to assume that ivy growing in very compacted, thin soils is less likely to develop the most destructive (extensive) root architecture. This said, ivy can flourish even in very shallow, heavy soils (Metcalfe, 2005) and its ground root system need not be very deep at all. Rather, a relatively shallow network of spreading roots close to the soil surface can be sufficient for healthy growth. It is worth emphasising that ivy need only be rooted into a small patch of earth for it to spread more widely across an area, even where no soil exists at all, taking root wherever it reaches another patch of suitable soil. This can involve re-rooting of trailing stems once the plant has completely overgrown a vertical obstacle, thus engulfing the structure entirely (Darlington, 1981).

Phase change is a very important consideration for ivy rooting behaviour; juvenile climbing stems root very easily whereas the woodier adult stems will rarely form true roots (Fearnley-Whittingstall, 1992). For juvenile stems, true roots can form in as little as 6–10 days when covered with soil, usually at right angles to the main stem and invariably at nodes, while adult phase stems may take 2 to 4 weeks to develop new roots (Girouard, 1967a, b). The relative ease with which juvenile stems can take root is particularly important, as it is the juvenile stems that can grow into wall cavities in response to growth stimuli. Observations during this study do indicate, however, that rooting-in behaviour is relatively rare for ivy and appears only to occur in certain circumstances, as discussed below.

2.4.2 Rooting stimuli

Physiologically, the initiation and development of roots is not fully understood but occurs primarily in response to the release and relative concentrations of plant hormones and other chemicals such as ethylene. These are produced at the shoot growing tip, and their subsequent transport down the stem stimulates root development (Feldman, 1984). Removing the growing tips of stems (by regular pruning for example) may therefore reduce ivy's propensity for rooting – but this remains untested. For stems growing into wall defects, three primary rooting stimuli are important to consider:

- Darkness:
  Root initiation is generally inhibited by exposure to light (Feldman, 1984). Ivy stems growing only superficially up the face of walls are therefore extremely unlikely to take root. On the other hand, stems that enter deeper recesses and cavities (under the conditions described in previous sections of this report) experience darkness that may favour root initiation. It is possible that some relationship exists between the depth that a stem is able to penetrate (as influenced by the condition of the structure and therefore the geometry of available defects) and the likelihood of root initiation, but this requires further research. Whether stems on shaded walls are more likely to take root than those on well-lit aspects is also an interesting question that has not yet been addressed.

- Mechanostimulation
  Contact between growing stems and soil particles is important for plant root initiation (Massa and Gilroy, 2003). This is an example of a thigmotropic process (Table 2-3). This has important implications for stems growing into highly deteriorated walls, as the presence of weathered materials (forming a 'protosoil') is a likely key trigger for true root initiation (see Section 2.4.3 for an example).

- Moisture
  A relationship between moisture and root growth is well known, if little understood. Plant roots typically exhibit positive growth in soils towards areas of higher water potential (Takahashi, 1997) and this, coupled with gravity cues, is a primary driving force behind root extension in soil (usually downwards, but also laterally). Water stress may drive roots to depth towards moisture (Esmon et al., 2005) and this may conceivably encourage ivy rooting under walls in dry and shallow soils if moisture is present at depth, especially on warmer southern aspects.
  The counter argument here is that the growth and vigour of some plants (below as well as above ground) is greatest on the cooler and wetter, shaded sides of walls. For English ivy, it appears that very wet conditions encourage rapid rooting of juvenile stems (Dunham, accessed 2015) but the plant does not do well if sitting in waterlogged soil for any length of time due to a lack of oxygen at the roots (Metcalf, 2005). Ivy's response to moisture is important in a context of climate change (and its future prevalence on walls) given that it is considered drought tolerant and therefore may have a significant competitive advantage over other common plants that may be more sensitive to future climate scenarios (Webster et al., 2017).

Considering these factors, the conditions of darkness (in internal cavities), presence of weathered material such as decayed lime mortar and Roman cement, and moisture (in combination) are all likely to initiate true root growth in juvenile stems that have penetrated into walls. An important implication here is that stems are unlikely to grow into cavities 'in order to' take root, but may well form roots if those stems growing into pre-existing defects are exposed to the right stimuli.

2.4.3 Field observations of rooting

Careful observations made at various sites where ivy was found to be growing into deteriorating walls, including the limestone boundary walls of Holywell Cemetery, Oxford city centre, highlight the importance of specific stimuli for rooting. In most instances, stems penetrating wall defects were not found to be producing true roots at all. Growth of true roots is therefore not an 'automatic' response in all penetrating ivy stems. Where true roots were present, the occupied cavity contained highly-weathered material in the form of small stone fragments and finer mineral grains (Figure 2-14). True root initiation is only observed where penetrating stems had come into contact with such fine weathered material (or 'protosoil'). This, coupled with favourable condition of darkness in wall cavities and the likely retention of moisture by weathered material, appears most conducive to true root initiation.

These qualitative observations support the known ability of ivy to re-root itself when sections of stem are buried or pinned to the ground (a process called 'layering' in horticulture). For example, ivy stems growing naturally across damp woodland floors can produce roots at every node (Figure 2-15). An important consideration here is that the common practice of cutting ivy at the base in order to kill and remove it, will certainly induce severe and sudden water stress; where stems have already penetrated into highly-weathered joints and cavities rooting may be initiated in response to being cut in this way (see Section 2.4.4). Conversely, the likelihood of rooting-in is much reduced where stems are only able to penetrate dry, shallow (so as not to be in complete darkness) and 'clean' (having little or no weathered debris) defects. This reinforces the notion that the condition of a wall (and of its mortar joints) is crucial for ivy rooting-in behaviour and the potential damage this can ultimately cause.

Figure 2-14. 'True' roots sprouting from a juvenile stem growing under a mortar repair, in the presence of darkness, moisture and weathered debris, Holywell Cemetery, Oxford (recently sprouted roots indicated).

Figure 2-15. 'True' roots readily sprout from juvenile ivy stems when in contact with moisture and soil. Here, an example of layering involving roots sprouting from leaf nodes of a stem lifted from a forest floor ©Alan Cathersides.

2.4.4 Does ivy re-sprout and root when cut at the base?

A common approach to dealing with problem ivy is to cut the main stem towards its base and/or manually pull stems away from walls. Whilst cutting will cause the plant to wither and die to some extent, this practice is no longer recommended, at least without careful consideration, as it may encourage rooting-in behaviour especially when stems are already growing into parts of the wall above ground level. Observations clearly show that even when the greatest of care is taken to remove ivy from a wall, it is very difficult to ensure that all plant material is removed – the tenacity of the aerial rootlets is remarkable and stems are often tightly wedged into confined spaces. This can be a problem given that even the smallest remaining stem fragments are able to re-sprout and beginning growing again under the right conditions (Figure 2-16).

Re-sprouting is most likely when the plant is cut at the base and left in place, as the leaves may continue photosynthesising for a period of time after being cut, giving the necessary energy for regrowth and the development of new true roots. Use of chemical killers (e.g. glyphosate) injected into stems before being cut may reduce the likelihood of re-sprouting by weakening the plant, but even then stems remaining attached to the wall may re-sprout above the point of cutting. Attempts to completely remove all stems following cutting will reduce the chance of re-sprouting, but the act of removal itself can cause damage to walls in a very poor state of repair. If a single leaf is missed this can supply sufficient energy for regrowth (e.g. Figure 2-16a, b).

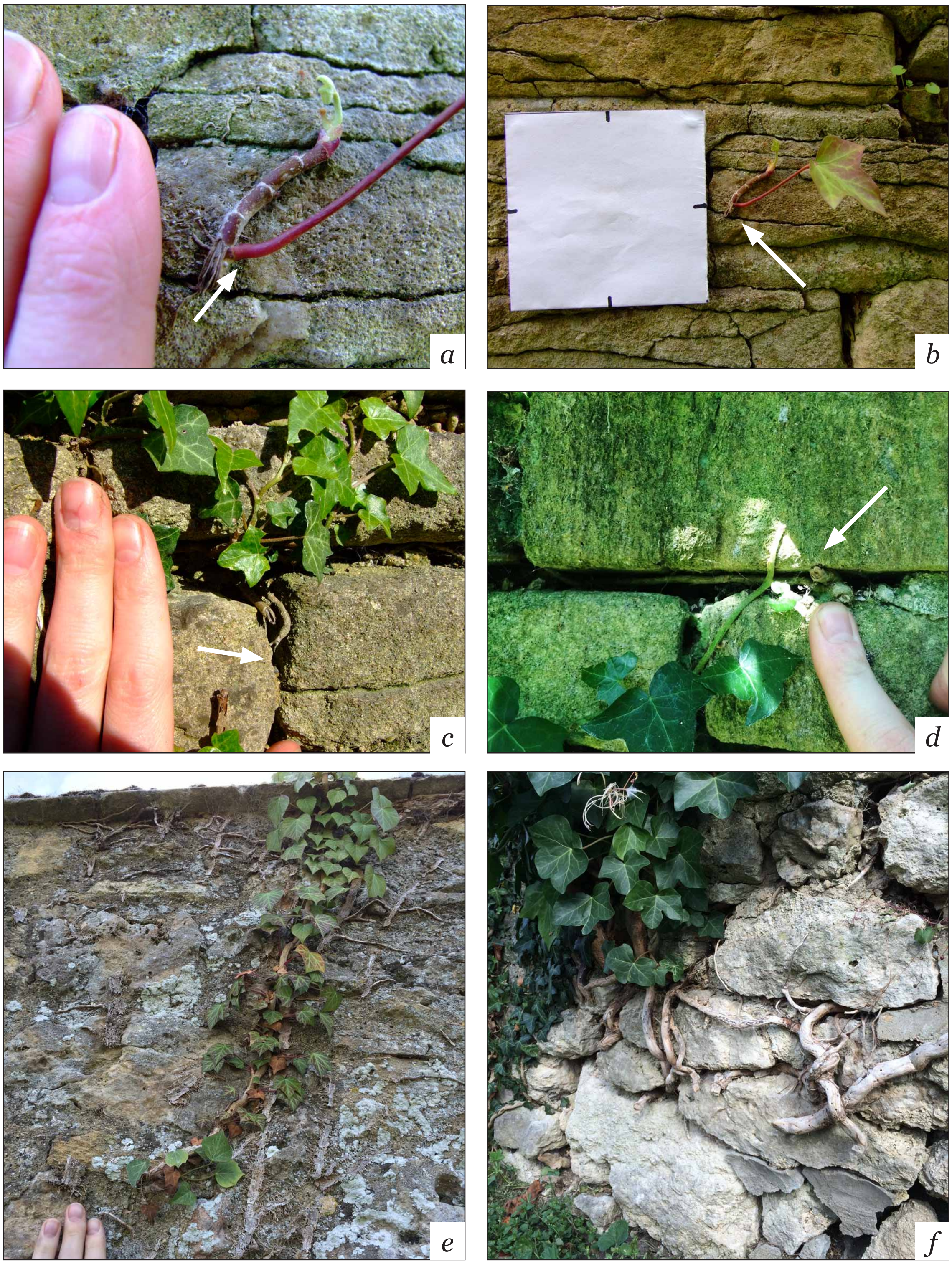


Figure 2-16. Examples of ivy regrowth following cutting/attempted removal from walls (the severed end of the stem is indicated in each case): (a, b) re-sprouting from a small cut stem fragment (Holywell Cemetery, Oxford, white paper = 10cm² for scale); (c, d) re-growth from severed stems growing within mortar joints (Holywell Cemetery, Oxford); (e) vertical re-growth from a severed stem (Godstow Abbey, Wolvercote); (f) re-growth of ivy that has been cut at the base of a deteriorating garden wall (Wytham village, Oxfordshire).

2.5 Attachment of aerial rootlets

The primary clinging mechanism of juvenile ivy stems is their aerial rootlets. Produced from the sides of stems that are in contact with the surface, often in groups or clusters, aerial rootlets can attach to a range of masonry materials with remarkably tenacity. Until now the extent to which aerial rootlets damage masonry has not been immediately clear, with some believing that rootlets cause deterioration by penetrating into materials and/or degrading the surface via extraction of moisture and nutrients. Scientific research does not support this view, however. Existing research of ivy stems grown on cork (Melzer et al. 2010; 2012) provides useful insights into the way that ivy aerial rootlets attach themselves, which is largely superficial in nature. Rootlets are, in fact, covered in tiny 'root hairs' about 10 µm in width that cannot be seen without a microscope. These hairs play a key role the attachment processes, summarised as four-phases (based on Melzer et al., 2010):

- Phase 1: initial contact between the substrate and the attachment structures (aerial rootlets). The tropisms discussed in Section 2.2 are the main drivers of this initial contact between juvenile stems and walls.

- Phase 2: enhancement of contact with the substrate, via morphological changes in aerial rootlet and microscopic root-hair structures. This is associated with increased stiffening ('lignification') of the structures in response to the initial contact. This increases the diameter of the hairs and thus increases the contact area with the substrate. This also increases mechanical 'interlocking' of growth within existing surface topographic features (pits, grooves, and other surface textural forms).

- Phase 3: secretion of a chemical adhesive glue from root-hair excrescences. This substance contains proteinaceous nanoparticles (arabinogalactan proteins, AGPs) about 70–100 nm in diameter (Lenaghan et al., 2013; Huang et al. 2016) that are able to occupy even the smallest textural features of the substrate. Release of the glue is probably triggered by initial contact (in Phase 1 and Phase 2) and attachment is in-part via an electrical mechanism creating millions/billions of hydrogen bonds with the substrate (Zhang et al., 2008). Much work is currently being undertaken on the chemical and mechanical properties of this substance, largely for potential commercial and medical uses (e.g., Huang et al. 2016).

- Phase 4: deformation of the microscopic root-hairs (associated with their drying out) in a way that increases the mechanical adhesion to the substrate. This process is illustrated in Figure 2-17 (reproduced from Melzer et al., 2010); the root-hairs are surrounded by oriented cellulose microfibrils that deform/twist and change shape as they dry out. Two kinds of deformation take place, each more or less relevant for attachment to different substrates. Hairs develop a spoon-shaped end (flattened and raised at the edges) that braces the hairs against smooth surfaces at the glued spots (Figure 2-17a–c). At the same time, twisting and shortening of the root-hairs can achieve firm attachment to rougher surfaces (such as stone and mortar), by anchoring the rootlets and stems tightly against the surface (Figure 2-17d–f). This all occurs at an extremely small scale many thousand times smaller than a millimetre.

Building on this understanding, further observations of ivy attachment to masonry materials were undertaken at various field sites and using microscopy. The purpose of these observations was primarily to determine whether the superficial attachment mechanisms outlined above (which were based on ivy growing on cork) apply to stone and mortar. In doing so the potential for damage by aerial rootlet attachment was assessed and the implications for managing ivy growth on vulnerable walls was considered.

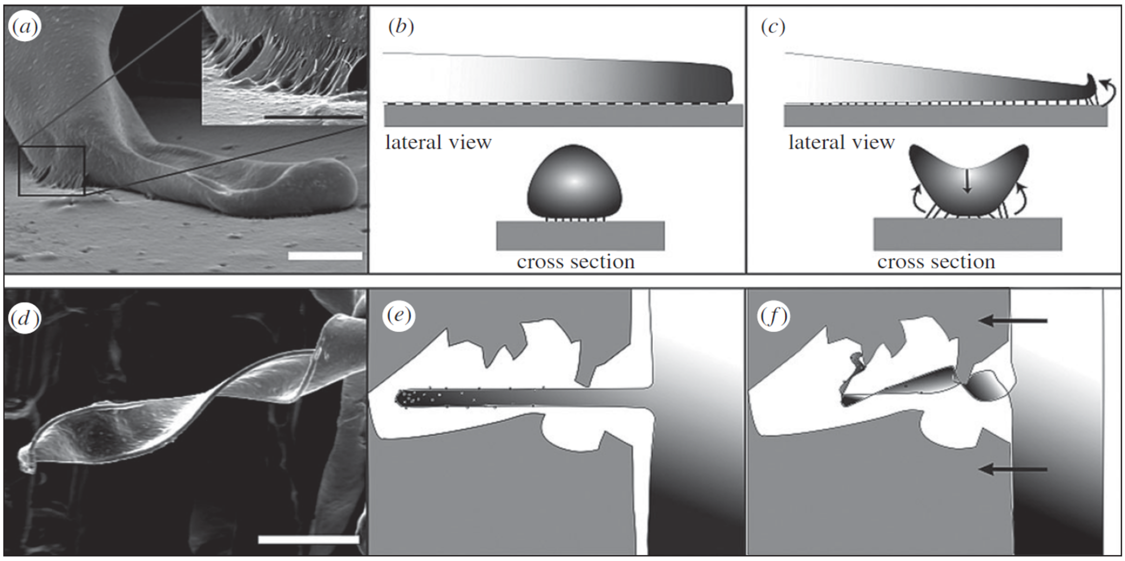


Figure 2-17. Proposed mechanisms of chemical (organic glue, a-c) and mechanical (deformation of root hairs, d-f) attachment by ivy aerial rootlets [scale bar in (a) and (f) = 10 µm]. © Plant Biomechanics Group, University of Freiburg. Reproduced from Melzer et al., 2010 with kind permission from the Plant Biomechanics Group, University of Freiburg.

2.5.1 Field observations

Observations of stone from which ivy stems had been removed indicate that aerial rootlet attachment was always superficial – there was no evidence that aerial rootlets penetrate beyond the immediate surface or 'dissolve' their way into the stone or mortar (Viles, 2010b; Viles et al., 2011). In fact, it was often the case that stone was 'cleaner' and less discoloured immediately beneath stems compared to surrounding areas of stone that are exposed to weathering agents such as pollution and rain (see Ramsey churchyard case study in 4.2 and White, 2010). Rootlets are, nevertheless, an aesthetic problem where attempts have been made to remove stems by pulling them away from walls. This often leaves fragments of stem and rootlets that remain strongly attached to the surface (Figure 2-18). This can be a particular problem for historic monuments, ruins and buildings that need to be managed sensitively from an aesthetic point of view (Bartoli et al., 2016).

Figure 2-18. Examples of aesthetic 'damage' following the removal of clinging ivy stems: (a) stem remnants and 'staining' of a headstone (Hampstead Cemetery, London); (b) stem remnants on a limestone masonry wall (Holywell Cemetery, Oxford, scale = 10 cm²).

2.5.2 Microscope observations

Observations of rootlets clinging to a range of materials (limestone, brick, mortar, sandstone and chalk) using a light microscope further indicated that attachment is superficial, with no evidence of penetration into the surface (Sternberg, 2010). Mineral debris can be pulled from deteriorating stonework along with clinging stems, however, unless extra care is taken. This is illustrated by observations of aerial rootlets pulled from a limestone wall at Holywell Cemetery, central Oxford (Figure 2-19).

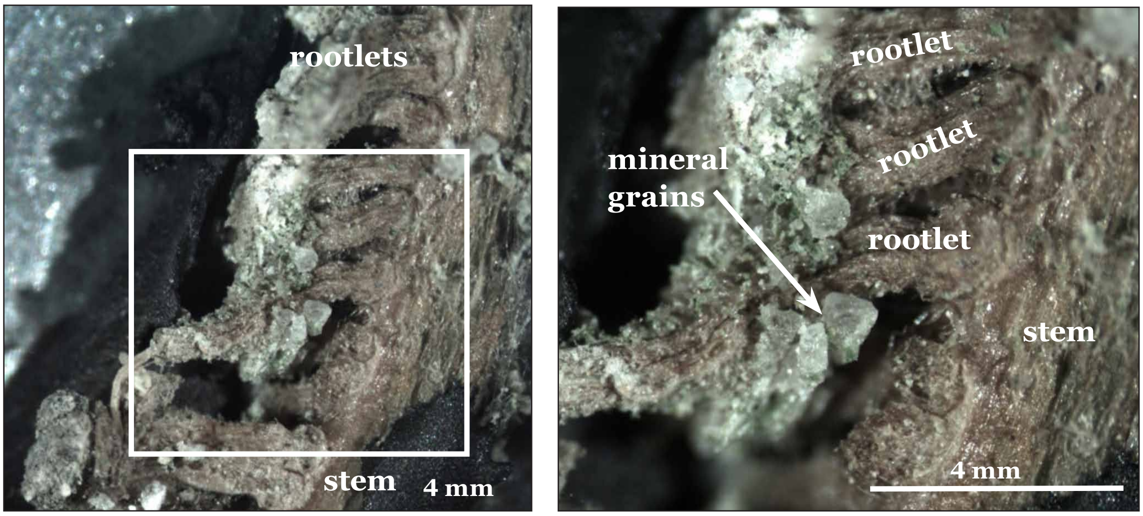


Figure 2-19. Mineral grain removal resulting from ivy being pulled away from a limestone wall in Holywell Cemetery, Oxford (viewed under a light microscope, box indicates enlarged area).

To see whether the superficial attachment mechanisms of rootlets observed on cork (Melzer et al., 2010) are similar for masonry, further observations of samples from the test wall at Wytham Woods were made using a high-powered electron microscope. Scanning Electron Microscopy (SEM, Model JEOL JSM-5900) was used to observe the rootlet/mineral interface at x1000 magnification and above. Rather than images produced by the reflectance of light from a sample, as in the case for light microscopes, SEM produces images by focussing beams of electrons onto a sample. As the electrons interact with the surface (at the atomic scale) they produce signals that can be detected and visualised. In order to reduce electrical 'noise' this techniques involves coating samples with a thin layer of conductive carbon or gold.

Using samples of ivy stems clinging to the test wall stone (Elm Park limestone), at magnifications of around x50 the general structures of the stems were clearly seen, showing multiple aerial rootlets in contact with the substrate (Figure 2-20a). At magnifications of around x200 microscopic 'hairs' that cover the aerial rootlets, and which provide the contact points between the rootlet and the stone, were visible (Figure 2-20b).

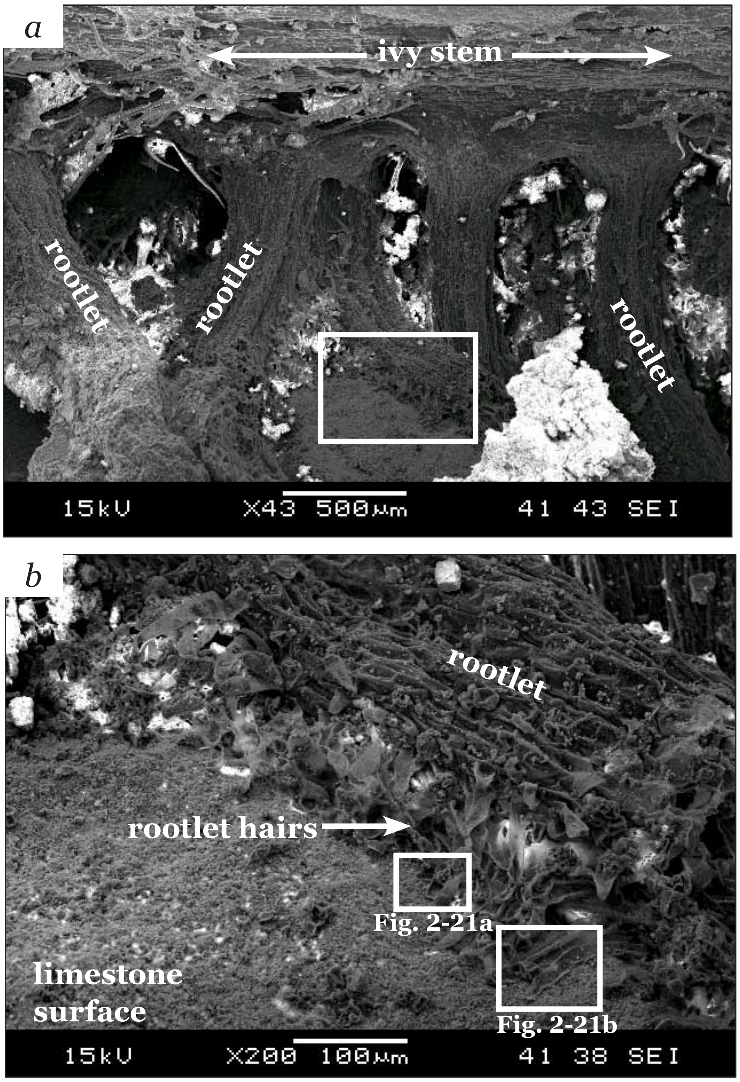


Figure 2-20. SEM images showing superficial attachment of microscopic aerial rootlet hairs to a limestone surface (magnification and scale as shown).

Enlargements of these areas (at magnifications above x1000) showed the attachment between hairs and the stone surface in great detail (Figure 2-21). These observations on stone show very clearly that ivy aerial rootlet hairs have only superficial contact; the 'spoon-shaped' and twisting deformation mechanisms as described by Melzer et al. (2010) (see Figure 2-17) was clearly evident. These observations show that ivy aerial rootlets, and more specifically the microscopic hairs that cover them, do not penetrate into the surface of masonry materials, and certainly do not extract moisture or nutrients from the surfaces they cling to.

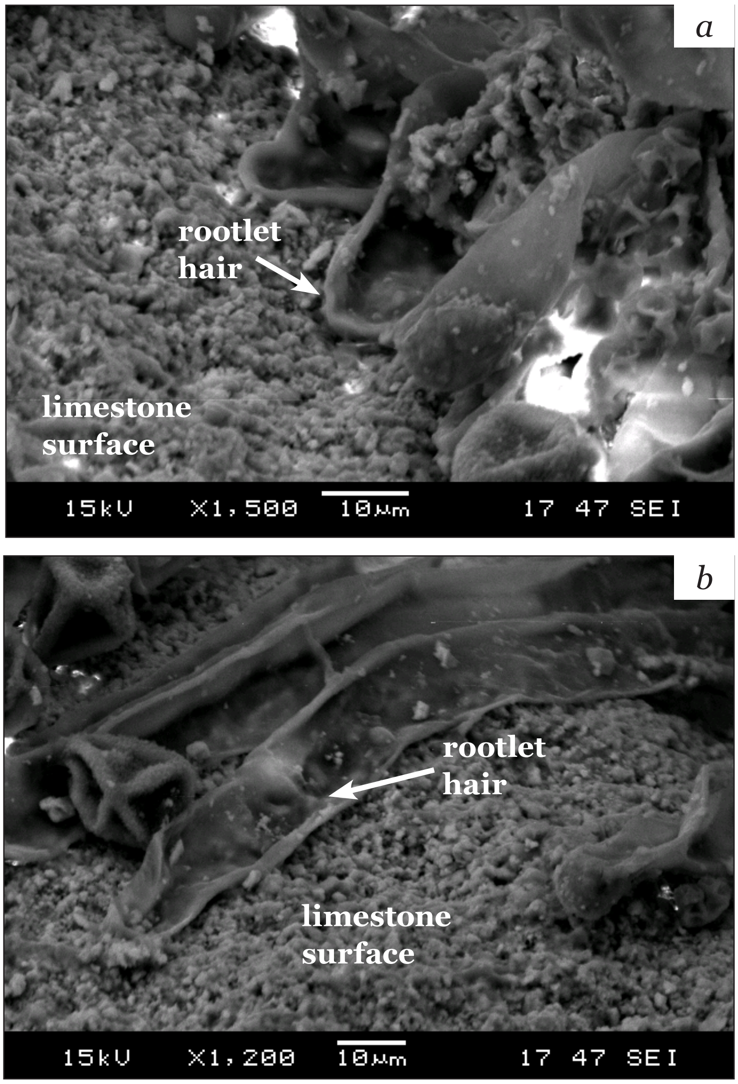


Figure 2-21. SEM images showing superficial attachment of microscopic aerial rootlet hairs to a limestone surface (magnification and scale as shown).

2.5.3 Implications for the removal of ivy stems and aerial rootlets

Adhesion by aerial rootlets (and root-hairs) seems entirely superficial and does not involve ‘active’ penetration into the surface beyond the irregularities/textural features that are already present. The attachment process operates at a scale of nanometres. The issue of rootlets damaging stonework is therefore a wholly aesthetic issue.

There are, however, clearly instances when ivy is to be removed from a wall or building either for conservation reasons or aesthetic preference. In such cases the strength of attachment to the substrate is a key issue. The relative importance of chemical (glue) or mechanical (root-hair deformation) attachment likely depends on the micro-roughness of the surface, and this may have implications for the force required to remove stems. For example, the ability of aerial rootlets to attach to very smooth materials like glass and metal is very much reduced because the mechanical bracing, in particular by twisting root-hairs (Figure 22d-f) cannot occur effectively.

Furthermore, observations have shown that the force required to pull ivy stems off of different materials can vary considerably, depending on the relatively abilities of the attachment mechanisms described above. The tensile strength of ivy aerial rootlets is remarkably high (about 38 megapascals, equivalent to a force of one 380 kg per m^2), which is much greater than that of mortar and stonework. This means that if pulled away from masonry with force and without care, the substrate is much more likely to fail before the rootlets give way (e.g. Melzer et al. 2011).

Attempt to remove ivy from masonry by pulling it away without due care is therefore very likely to cause surficial damage, by removing grains and possibly larger fragments along with the stems themselves. Using herbicides to kill ivy before removal in the hope of loosening its attachment may be counterproductive, as trials by the National Trust have shown that ivy killed in this fashion is in fact more difficult to remove that live stems (Turner, 2010).

3 THE INDIRECT INFLUENCES OF IVY ON WALLS AND THEIR DETERIORATION

3.1 Stone weathering and the importance of environmental variables

Many different processes contribute to the weathering of stone, which act in combination and at varying rates depending on the nature of the environment in which it is exposed. Patterns of temperature and moisture (microclimate), and the delivery of atmospheric pollutants and salts are particularly important (Table 3-1). Vegetation growing on walls has the potential to alter all of these variables to some extent, acting as a 'buffer' between the wall and the surrounding environment. In this way the presence of ivy can, indirectly, alter the occurrence and relative importance of particular deterioration processes. This section describes research undertaken to improve understanding of these influences, focussing on the influence of ivy on wall surface microclimates including frost (Section 3.3), stone soiling and discolouration (Section 3.4), moisture and damp (Section 3.5), and stone hardness (Section 3.6).

Table 3-1. Important stone weathering processes and associated environmental variables

Stone weathering process	Key environmental variables	Examples of associated masonry deterioration
Physical		
Heating and cooling Wetting and drying Freeze-thaw Salt crystallisation, hydration and thermal expansion	▪ Microclimate (temperature and relative humidity) ▪ Moisture (supply and chemistry) ▪ Sources and types of salt	▪ Granular disintegration ▪ Cracking and weakening ▪ Loss of angular fragments ▪ Salt efflorescences
Chemical		
Dissolution and carbonation (of soluble minerals such as calcite) Sulphation (of calcite in reaction with sulphuric acid) Hydrolysis (of silicate minerals)	▪ Material type (lithology and chemistry) ▪ Moisture (supply and chemistry) ▪ Atmospheric pollution (amount and delivery) ▪ Microclimate (temperature and relative humidity)	▪ Material loss in solution (smoothing of stone and loss of architectural detail) ▪ Crusting (e.g., gypsum) ▪ Blistering and spalling ▪ Soiling and discolouration
Biological		
Biophysical deterioration (e.g., growth in voids and cavities, see Section 2) Biochemical deterioration (e.g., dissolution by organic acids)	▪ Type and abundance of biological activity ▪ Microclimate (temperature and relative humidity) ▪ Light availability ▪ Atmospheric pollution	▪ Cracking and loss of stone and mortar ▪ Contributions to crusts and spalling ▪ Soiling and discolouration

3.2 Experimental approach

Quantitative observations at historic sites in England and at test walls at Wytham Woods (see Section 1.4) were used to examine how ivy influences different factors relevant to stone weathering summarised in Table 3-1. A range of techniques was employed, each outlined in the following sections and summarised in Table 3-2.

For microclimate, iButton™ data loggers (hygrochrons®, Maxim Integrated Products) were attached in pairs (with ivy and without ivy cover) to the walls of interest. The loggers were pre-programmed to record near-surface temperature and relative humidity continuously, at hourly intervals. A year-long study of wall surface microclimates was carried out at five historic sites across England (Byland, Ramsey, Oxford, Dover and Nailsea) described in detail by Sternberg et al. 2011 and Viles et al. 2011. Microclimate was also studied in this way on test walls at Wytham Woods. In addition to observations at various field sites, stone colour, moisture and hardness were also measured on the same test walls. For this, measurement points were established at the top, middle and base of the test walls in adjacent ivy-covered and bare sections, and on four different aspects (north, east, south and west). At each measurement point an area of stone roughly 3 cm x 3 cm was smoothed using an abrasive disk in order to establish a comparable baseline, from which all future change was assessed. Baseline colour, hardness and moisture measurements were made in these locations in April 2013 and were re-measured periodically up until spring 2015.

This experimental approach has allowed direct comparisons of differences and changes in stone surface properties relevant to masonry deterioration in adjacent areas with and without a cover of ivy, over a period of a few years. The test walls have also allowed consideration of whether the influences of ivy are affected by factors such as aspect (wall orientation) and height on walls. Observations at field sites where walls were already colonised by ivy have been invaluable, but in these situations it is very difficult to control for factors such as construction/material type and time of exposure. By using test walls we have been able to monitor the influence of ivy in a scientifically controlled way.

Statistical testing

Various tests have been used to determine whether any differences found at field sites and test walls are statistically significant. This follows standard scientific procedure to assess whether differences within data that can be seen visually (in graphs and tables) can be confirmed mathematically or not. In essence, statistical tests help determine the likelihood that a difference in experimental data occurred through chance, and thus whether trends and relationships found are likely to be 'true' or 'noise'. These tests are important as they place a level of confidence in the research findings.

A range of tests is available, the selection of which depends on the types of data and the comparisons that are being made. The most powerful tests have assumptions that need to be met in order to be statistically valid (termed 'parametric tests'). Where these assumption cannot be met (including when variability within a dataset is too great or when data are skewed) alternative tests can used (termed 'non-parametric tests'). The decision of which tests to apply to data collected during this research has followed these general principles. Where differences were found to be statistically significant, post-hoc tests were used to help identify which variables were significantly different from each other. This included comparisons between bare and ivy-covered sections of wall, between wall aspects, and between different heights on the walls where appropriate.

The result of a statistical test is expressed as a probability or 'p' value. Following standard practice, a p-value of 0.05 or less is used to indicate that the difference between samples is significant (having only a 5% probability of occurring by chance). A p-value of 0.01 or less indicates a highly-significant difference (having only a 1% probability of occurring by chance).

Table 3-2. Summary of monitoring undertaken and equipment used to assess the influence of ivy on factors relevant to the deterioration of walls

Variable	Relevance to stone deterioration	Equipment used for measurement	Data collected
Microclimate (temperature and relative humidity)	Repeated and rapid changes in temperature and moisture contribute to breakdown via expansion and contraction (e.g., thermal weathering and wetting and drying). Freezing of stone can cause frost cracking.	iButton™ Thermochron® and Hygrochron® data loggers (Maxim Integrated Products)	Hourly stone surface temperature and relative humidity measurements at five historic sites in England and on test walls with differing ivy cover and aspect (N, E, S, W).
		Thermal imaging camera (VarioCam HR)	Imaging of test walls during hot summer conditions in July 2014, for areas with/without ivy cover.
		Environmental cabinet (Sanyo-FE 300H/MP/R20)	Laboratory simulation to test the ability of frost protection by ivy to reduce rates of stone deterioration.
Stone soiling & discolouration	In addition to colour change from natural weathering processes, soiling leads to unsightly marks, blackening and greening of stonework that is often undesirable for historic structures. Airborne pollutants from fuel combustion are also involved in chemical degradation of natural stone.	Scanning Electron Microscope (Cambridge S90B)	Density of particulate pollutants on ivy leaves covering walls in areas of varying traffic flow, at three sites in Oxford.
		Spectrophotometer (CM-700d)	Repeat measurement of stone surface colour every 3 to 4 months on test walls with differing ivy cover, aspect and height on the wall.

Table 3-2. Summary of monitoring undertaken and equipment used to assess the influence of ivy on factors relevant to the deterioration of walls

Variable	Relevance to stone deterioration	Equipment used for measurement	Data collected
Moisture and damp	Damp is associated with a range of problems in masonry structures. Continuously wet stone is susceptible to chemical degradation, whilst repeated fluctuations in moisture can cause damage via interactions with salts.	Handheld moisture meters (GE Surveymaster Protimeter and CEM DT-128)	Monthly measurements of surface moisture (up to a few centimetres deep) on tests walls with differing ivy cover, aspect and height on the wall. Spot-measurements at various field sites.
		Electrical Resistivity Tomography (GeoTom ERT)	Profiles of sub-surface moisture (up to 20 cm) in test walls with four orientations. 2D visualisations of stone moisture.
Stone surface hardness	Useful as a direct indicator of stone condition and breakdown over time. As materials weather hardness will change – usually getting softer, but this is not always the case.	Equotip 3 Surface Hardness Tester (Type D impact body)	Hardness measurements every 2 to 4 months on test walls with differing ivy cover, aspect and height on the wall over a period of a two years. Spot-measurements at various field sites.

3.3 Ivy influence on wall surface microclimate

3.3.1 Field site observations

Observations of the influence of ivy on wall surface microclimates at different historic sites across England are described in the 'Ivy on Walls Phase I Seminar Report' (see Chapter 4) and by Sternberg et al. 2011. In summary, at all sites extremes in temperature and relative humidity were reduced under ivy relative to areas with no ivy. On exposed walls (no ivy cover) daily maximum temperatures were on average 36% higher and daily minimum temperatures 15% lower compared to adjacent covered areas. The significance of these findings for conservation is that daily and seasonal variations in temperature and relative humidity are reduced under ivy, meaning the potential for damaging expansion and contraction of construction materials is lessened. In addition, minimum temperatures during winter months were buffered under ivy at all the sites, indicating a possible protective role with respect to frost damage. The protective role of ivy against frost was also examined experimentally, described in Section 3.3.3 below.

Importantly, observations of ivy-covered walls at historic sites showed that the extent of 'protection' that plant may afford (with respect to microclimatic buffering) depends on many factors, including the thickness of the ivy cover and the direction that the wall is facing. It is sensible to assume, for example, that a thicker growth will have the greatest buffering influence on wall microclimates. The importance of aspect (wall orientation) on microclimate was not assessed directly at the field sites but this was possible using purpose-built test walls.

3.3.2 Test wall observations

Microclimate data collected at the Wytham Woods test wall build on those described above. As well as providing further evidence of microclimate buffering over different timescales, ivy's influence on damaging frost events was also assessed in greater detail, and by controlling materials and ivy cover, at the test wall.

Wall surface temperatures

Temperature records for each aspect (N, E, S, W) are shown in Figure 3-1 for the first year of monitoring at the test wall (April 2013 to April 2014). The general moderating effect of ivy is clear for all aspects, with lower thermal peaks during summer months and higher thermal minima during winter months. There are, however, interesting differences between aspects. Summertime thermal buffering was notably greatest for the south- and west-facing walls but was less for the east wall, and considerably less for the north-facing wall. In comparison, the buffering effect of ivy on wintertime minimum temperatures was relatively consistent between the four aspects (see Section 3.3.3).

Temperature differences between ivy-covered and bare sections of wall are summarised in Figure 3-2 and Table 3-3. In summer, averaged daily wall surface temperatures varied little between aspects ($p = 0.238$) and between ivy-covered and bare sections of wall (Figure 32a). Aspect also had little influence on daily maximum temperatures ($p = 0.643$), but ivy was highly significant in buffering maximum temperatures relative to bare sections of wall ($p < 0.001$, Figure 3-2b). This effect was greatest on south- and west-facing walls (where thermal peaks were reduced by around 20%) compared to north- and east-facing walls (where thermal peaks were reduced by around 10%, Table 3-3). In winter, averaged daily temperatures were no different between the four wall aspects ($p = 0.476$), nor were average daily minimum temperatures any different ($p = 0.958$). The influence of ivy on winter temperatures was marked, however. Average winter temperatures were significantly lower on bare (no ivy) sections of the north ($p = 0.05$), east ($p = 0.01$) and south ($p = 0.05$) facing walls (Figure 3-2c). This trend was also measured on the west facing wall but was not statistically significant. Daily minimum temperatures were significantly lower without ivy in winter, on all four aspects (Figure 3-2d, $p < 0.001$). On average, minimum temperatures measured at the surface of ivy-covered stone were about 40% higher than the adjacent areas of bare stone (Table 3-3).

Ivy also had a noticeable effect on temperature differences between day and night, measured as the diurnal temperature range (the difference between daytime maxima and night-time minima). Diurnal variations reflect the extent of heating and cooling (and associated expansion and contraction) of masonry over the course of a day. For the first year of monitoring, the average diurnal temperature range was significantly reduced under ivy ($p < 0.001$) (Figure 3-3). This buffering effect was greatest on the south and west walls (a diurnal range reduction of about 50%) compared to the east (43% reduction) and north (30% reduction) walls (Table 3-3).

These observations show very clearly that a cover of ivy reduces the variability and range of temperatures experienced at the wall face, over diurnal, seasonal and annual timetables. By keeping temperatures relatively constant, and by buffering more extreme temperature changes, ivy foliage can limit the repeated heating-cooling and expansion-contention of masonry materials (relative to bare stonework) that contributes to progressive deterioration (Sternberg et al. 2011; Viles et al. 2011). Observations at the test wall and at different historic sites in England show that the overall buffering influence of ivy on temperature is consistent, but that the size of this effect varies somewhat between different aspects (Table 3-3). This is explained by the proportion of time walls are warmed by direct insolation and cooled via radiative cooling when in shade. With respect to temperature, ivy had the greatest buffering effect on south- and west-facing walls, by shading those surfaces that receive prolonged direct sunshine.

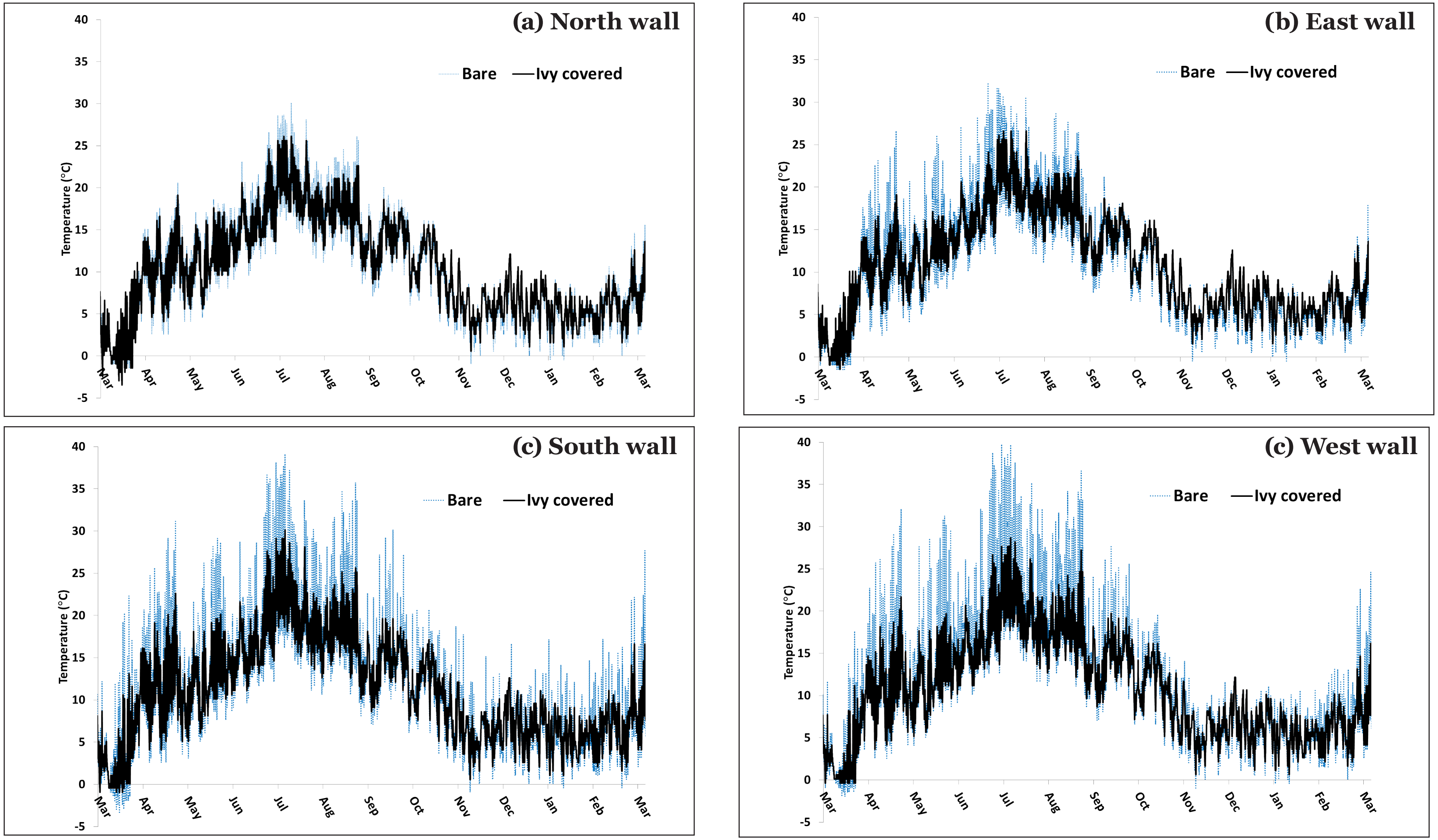


Figure 3-1. Wall surface temperatures for the Wytham Woods test walls, April 2013–April 2014 (black line= ivy-covered stone, dashed blue line = bare stone).

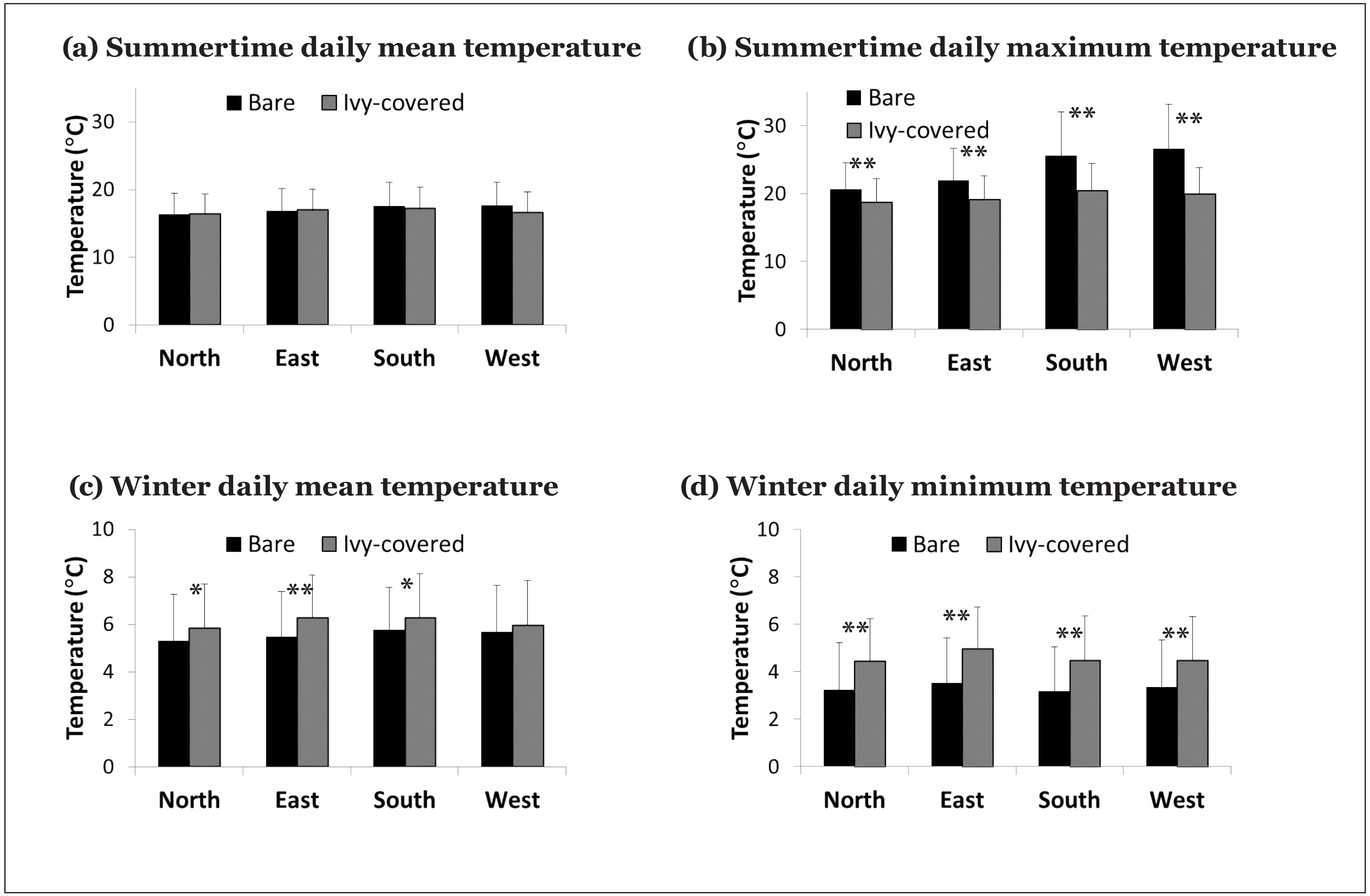


*Figure 3-2. The influence of ivy cover and aspect on thermal properties at the surface of the Wytham test walls (summer values calculated as the mean + SD of 122 days of Jun–Sep 2013, winter values calculated as the mean + SD of 120 days of Nov–Feb 2013/14). Significant differences (post-hoc SNK) as indicated, where * indicates p = 0.05 and ** indicates p = 0.01.*

Table 3-3. The effect of a cover of ivy on wall-surface thermal properties for different aspects at the Wytham test site				
Values are percentages relative to adjacent areas of bare stone, 2013-2014 data.				
	North	East	South	West
Summer mean daily temperature[1]	0%	-1%	-2%	-6%
Summer daily maximum[1]	-9%	-13%	-20%	-25%
Winter mean daily temperature[2]	9%	15%	9%	5%
Winter daily minimum[2]	38%	43%	45%	36%
Annual mean diurnal range[3]	-30%	-43%	-50%	-52%

[1]Summer: 1st June 2013 to 1st October 2013

[2]Winter: 1st November 2013 to 1st March 2014

[3]Diurnal range calculated as daily maxima – daily minima for every day from 12th April 2013 to 12th April 2014

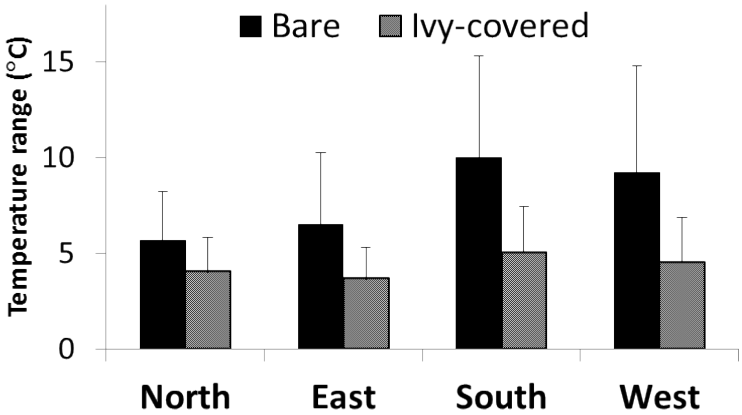


Figure 3-3. Wall-surface diurnal temperature range, April 2013 to April 2014 (n = 365, mean + SD).

Thermal imaging

Additional observations of the effect of ivy cover on wall-surface microclimate were made using a thermal-imaging camera (VarioCam HR) on a hot day in July 2014 when ambient temperature peaked at around 24°C. Photographs of each wall were taken in the late afternoon under clear skies. The camera was angled in order to visualise temperatures of bare stone and adjacent ivy foliage, and of the stone underneath by gently lifting the foliage away from the walls where possible.

The shading influence of ivy in hot weather is clearly shown (Figure 3-4). Stone shielded by ivy was much cooler than adjacent bare stone during the hottest part of the day, by as much as 10°C or more. This supports measurements collected using data loggers, which recorded lower thermal peaks under ivy (see Table 3-3). A combination of direct shielding from solar radiation and localised cooling via evapotranspiration explains these differences. As well as reducing the variability and range of temperatures experienced over the course of a day and across the year, thermal buffering by ivy during summer may reduce the likelihood of damaging salts crystallising within masonry materials, by limiting the extent and frequency of drying.

The thermal images also show that faces of exposed stone blocks heat-up to a greater degree than the slightly-recessed mortar joints that surround them, which remain relatively cool. This difference in temperature between stone and mortar was clearly reduced under a cover of ivy (which kept all materials generally cool). This may afford some protection to the wall given that stresses generated by differential heating/expansion and cooling/contraction will be lessened relative to bare sections of wall.

As well as some protection of wall materials from certain weathering processes, thermal buffering by ivy and other vertical greenery has implications for the energy efficiency of historic (and modern) buildings. These influences have gained increasing attention in the fields of engineering and construction including in a context of climate change and energy use (see Bolton et al. 2014; Stafikhani et al. 2014; Wong et al. 2010 for some further discussions). *Hedera* species may, for example, reduce building energy consumption during extreme weather by up to 50% in the UK (Cameron et al. 2015).

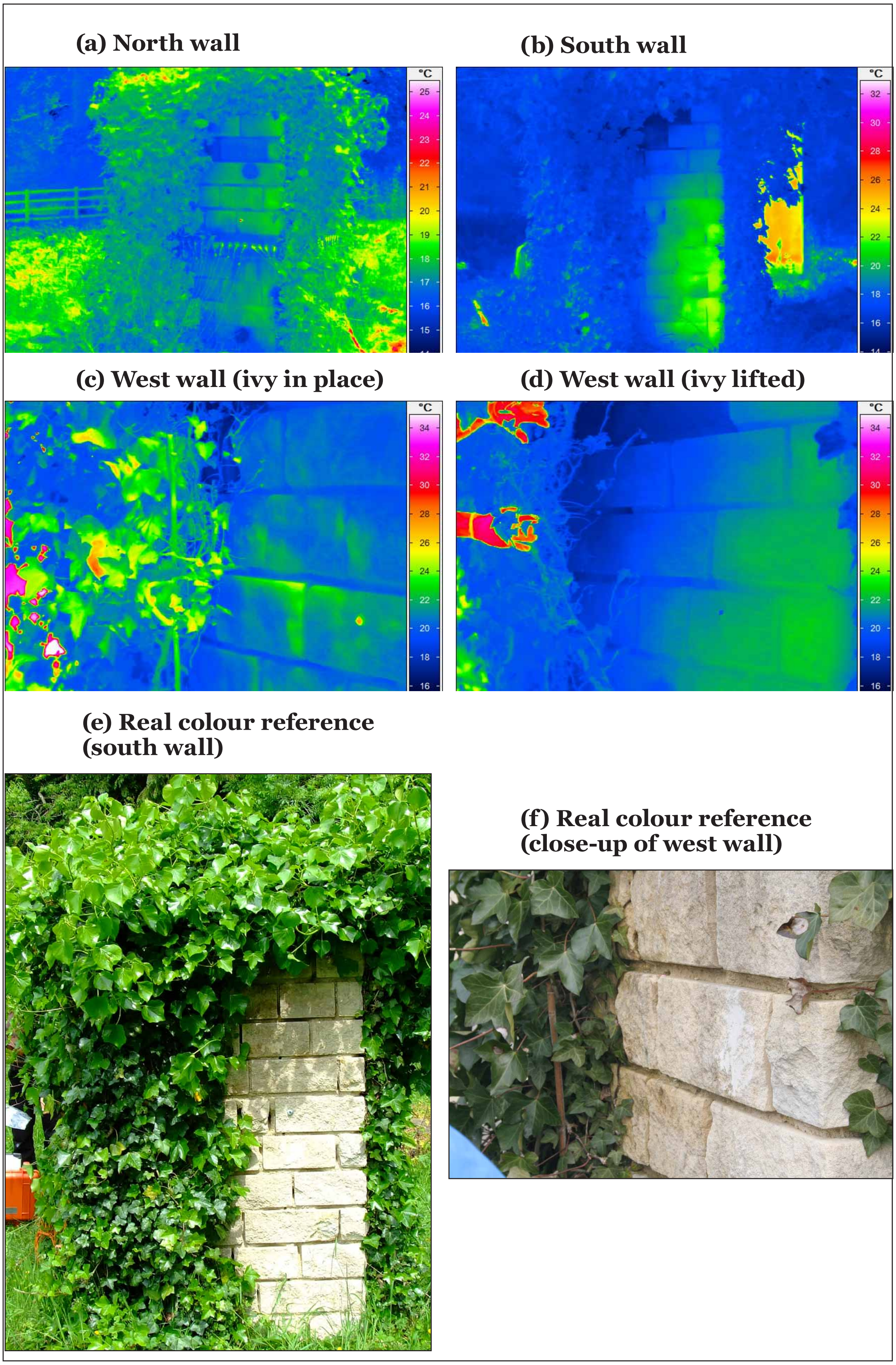


Figure 3-4. Examples of thermal imaging of the Wytham test walls, June 2014.

3.3.3 Ivy influence on frosts

For historic masonry, damage from freeze-thaw is an important issue of concern (Ingham 2005; Ruedrich et al. 2011). Although climate change will reduce the likely occurrence of freezing events in Europe (Grossi et al. 2007) recent modelling indicates that the probability of severe cold winters may actually increase over the next few decades (Mori et al., 2014). It is also true that under future climate scenarios, generally wetter conditions for the UK will increase the likelihood of masonry being wet when freezing events do occur. It is the combination of freezing temperatures and the presence of moisture in building materials that leads to damage through the formation of ice crystals within confined pore spaces. Improving understanding of these risks is crucial for managers of historical assets.

Because freezing is a threshold-driven process (it can only occur when temperatures fall below zero degrees) any factor that has an influence on minimum temperatures experienced by vulnerable materials can be significant. Vegetation covering walls is one such factor. Ivy, despite being intolerant of persistent cold (of –2°C or less), can tolerate very sharp cold snaps down to –25°C (Metcalfe, 2005). This, combined with the plant's abundance on historic walls and buildings, means that understanding how ivy (as well as other forms of vegetation) affects the risk of frost damage is an important issue for the heritage sector.

Microclimate monitoring at various field sites in England (Section 3.3.1) provided some evidence that exposed masonry experiences more instances of potentially damaging freezing conditions than when covered with ivy. Building on this, a more detailed assessment of ivy influences on frost events was undertaken at the Wytham Woods test wall during the winter of 2012/13 and 2013/14. Microclimate data were analysed to identify how a cover of ivy influenced the frequency, duration and severity of freezing events, each discussed in turn below, and thus the likelihood of damaging freeze-thaw weathering. Observations at the test wall also allowed a comparison of these effects between different aspects. Following this analysis, a laboratory experiment is described that sought to test whether the observed buffering role of ivy against frost is protective (with respect to stone deterioration) relative to bare stonework.

Test wall observations of freezing

Temperature records for winter 2013/14 are shown in Figure 3-5. For all four aspects, evidence of ivy buffering against freezing temperatures was found. Instances when bare stone experienced freezing temperatures, but when adjacent ivy-covered stone did not, occurred at least twice on each wall face (indicated by arrows in Figure 3-5).

A more detailed analysis of freezing events was undertaken for 2012/13 and 2013/14 winters. Temperature records were interrogated in order to determine the frequency, duration and severity of all individual freezing events, totalling 132 events across all four wall aspects. These data are summarised in Table 3-4 and in Figure 3-6. Statistical comparisons between ivy-covered and bare sections of wall were made using Chi-square and Student's t-tests where appropriate. Each measure (frequency, duration and severity of freezing) is discussed below.

How did ivy affect the frequency of freezing events?

Freezing was always less frequent under a cover of ivy (Figure 3-6a). Overall, ivy-covered stone experienced 56 freezing events compared to 76 on bare stone, a 26% reduction (p = 0.10). There were marked difference between aspects. Ivy covered stone experienced 45% and 37% fewer freezing events on west- and east-facing walls, respectively, compared to a reduction of 16% on the southern and 6% on the northern aspect.

How did ivy affect the duration of freezing events?

On average the total amount of time when temperatures were below freezing was reduced by more than 50% under a cover of ivy (Figure 3-6b). This effect was greatest on the west-facing wall (71%) and least on the north-facing wall (33%). Freezing events lasting different lengths of time (1–5 hours, 6–10 hours, 11–15 hours and more than 15 hours) were also significantly different between ivy-covered and bare stone (p = 0.05, Figure 3-7c). Ivy cover had the greatest influence on longer-duration freezing events (those lasting 11 hours or more). Influences on shorter duration events were more complicated. For the east and west walls, events lasting 1–5 hours and 6–10 hours were all reduced under ivy. In comparison, and perhaps unexpectedly, the shortest-duration events (1–5 hours) were more frequent under ivy on north- and south-facing walls. Considerably more freezing events lasting 6–10 hours were recorded under ivy on the north wall than on the other aspects (Figure 3-6c).

Table 3-4. Characteristics of freezing events recorded at the Wytham Woods test wall in winter 2012/13 and 2013/14

Bold values are for bare sections of wall (no ivy) and values in brackets are for adjacent ivy-covered sections. The percentage difference (ivy-covered relative to bare sections of wall) are also shown.

	North	East	South	West
Number of freezing events (frequency)	**18**(17)	**19**(16)	**19**(12)	**20**(11)
(minimum number of fluctuations below and above zero degrees)	6%	–16%	–37%	–45%
Average duration of freezing events (hrs)	**11**(8)	**8**(5)	**9**(3)	**6**(3)
(number of hours temperature remained below zero degrees)	–30%	–40%	–33%	–45%
Total number of frozen hours	**202**(135)	**167**(69)	**162**(77)	**127**(37)
(cumulative number of hours temperature remained below zero degrees)	–33%	–59%	–52%	–71%
Average severity (in °C) of individual freezing events	**–1.2**(–1.35)	**–1.5**(–0.6)	**–0.9**(–0.7)	**–1.0**(–0.4)
(minimum temperature of individual freezing events)	+17%	–63%	–21%	–61%

Some of the differences between aspects are difficult to explain, but may be the result of thermal buffering by ivy raising the general wall temperature closer to the 0°C boundary during cold snaps. In this way, even small fluctuations in temperature are more likely to cross zero degrees, if only for a short period of time. In comparison, the same, small temperature fluctuations would not cross the freezing boundary on bare sections of wall if the general temperature falls and remains below freezing. Differences between aspects may also reflect variations in the extent/thickness of ivy growth, which was somewhat less on walls that experienced a greater range temperatures across the year and thus which offered more stressful growing conditions (i.e., northern and southern aspects, see Figure 2-1). Nevertheless, the duration of individual freezing events was significantly reduced overall under a cover of ivy (p = 0.004), by an average of 32% relative to bare stone (a reduction from 8.5 hours to 5.8 hours per freezing event).

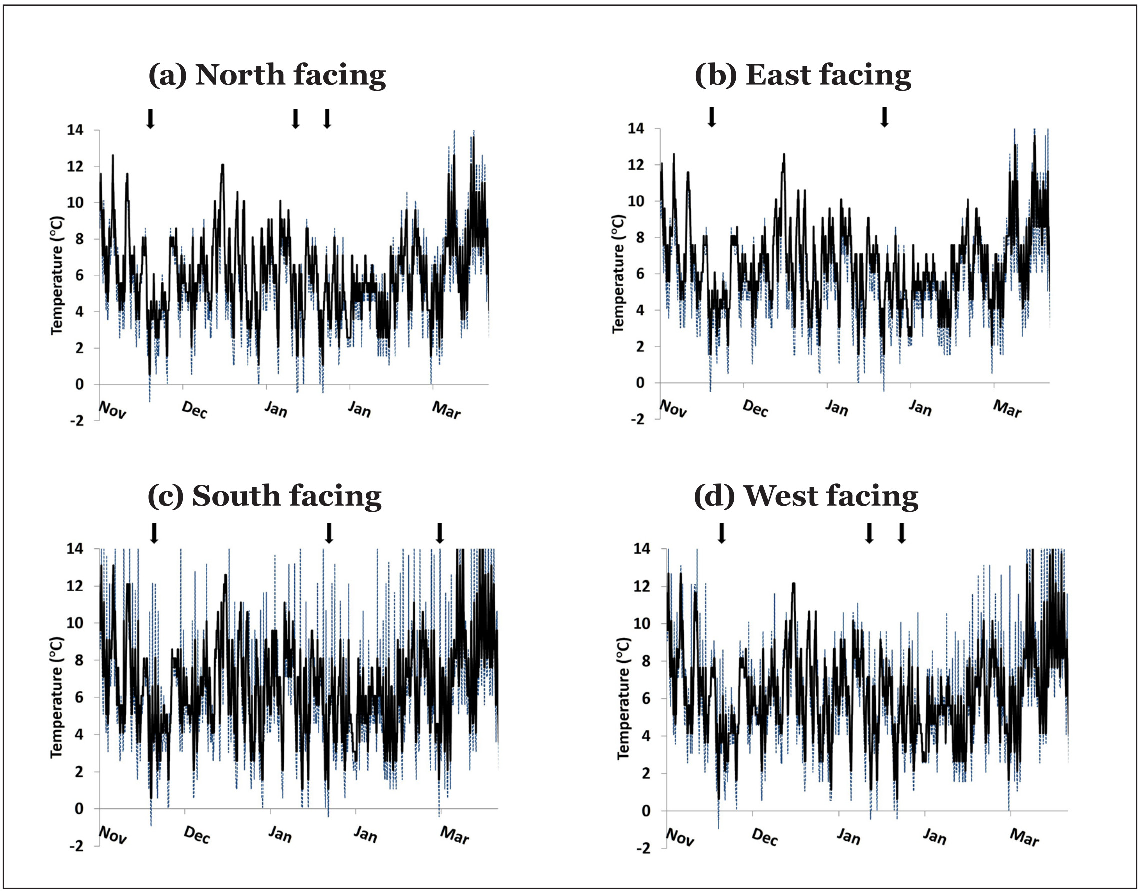


Figure 3-5. Stone surface temperatures at the Wytham Woods test wall in winter 2013/14. Black solid line = ivy-covered stone; dashed blue line = bare stone. Arrows indicate instances where ivy buffered against freezing events.

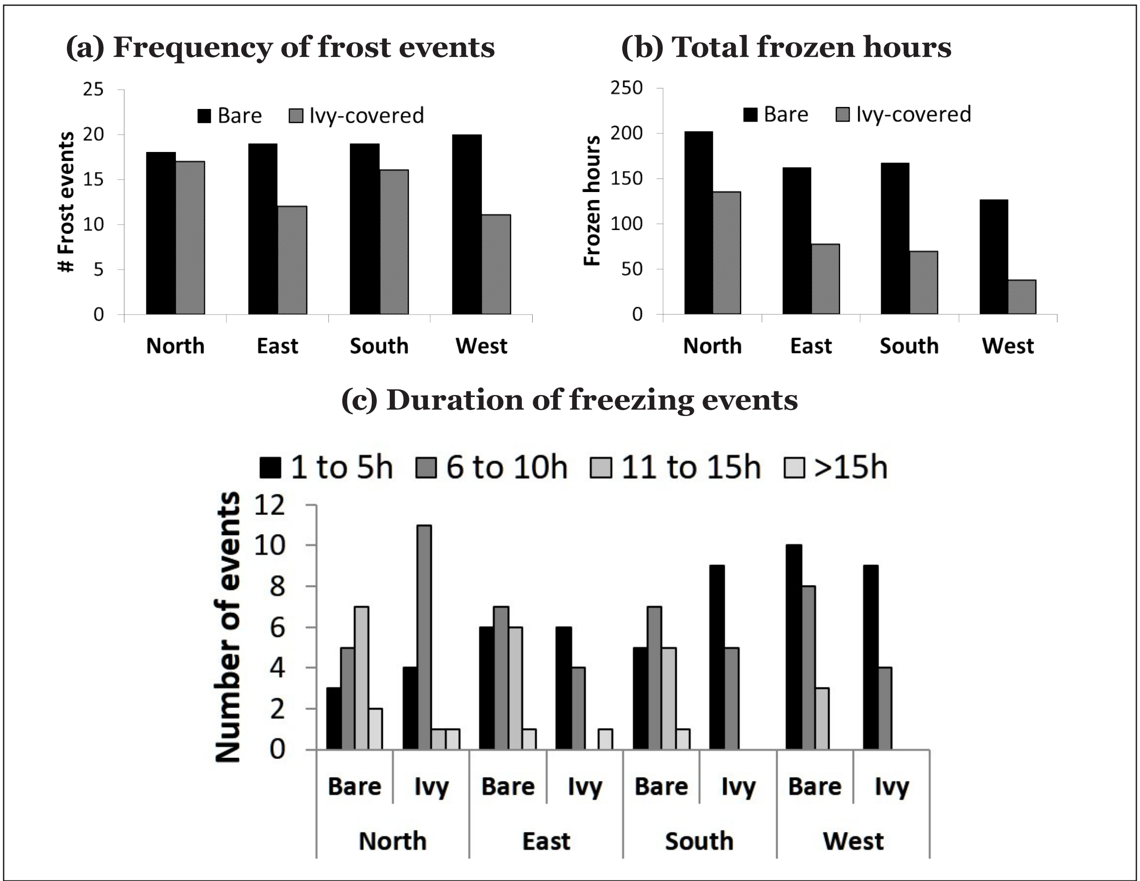


Figure 3-6. The influence of ivy cover and wall aspect on freezing events recorded at the Wytham Woods test wall in winter 2012/13 and 2013/14: (a) number of individual frost events (fluctuations above and below 0°C); (b) total number of hours of freezing temperatures (also see Figure 3-7b); (c) frequency of individual freezing events of different duration (in hours).

How did ivy affect the severity of freezing events?

Freezing events were further categorised based on severity, i.e., those when minimum recorded temperatures fell 0 to –1°C, –1 to –2°C, and less than –2°C, summarised in Figure 3-7a. Ivy cover had a significant effect on the relative occurrence of these different events ($p = 0.05$). The total number of less severe frost events (down to –1°C) was similar between ivy-covered and bare stone, but more severe frosts (below –1°C) were reduced by over half under a cover of ivy (Figure 3-7b). These patterns may be explained by the fact that, by buffering all freezing events to some extent, a cover of ivy results in an overall shift from higher-severity to lower-severity events. In other words, less severe frosts may be completely buffered by ivy (and are therefore not recorded as frost events) whereas more severe frosts are only partially buffered, with temperatures still falling below zero but to a lesser degree. This would result in some 'shifting' between the categories used to assess frost severity in this study. Accepting such complications in the data, actual recorded values at the test wall show that the average temperature of individual freezing events was lower on exposed stone (–1.2°C) compared to ivy-covered stone (–0.8°C), and this difference (a 33% reduction in frost severity) was statistically significant ($p = 0.05$).

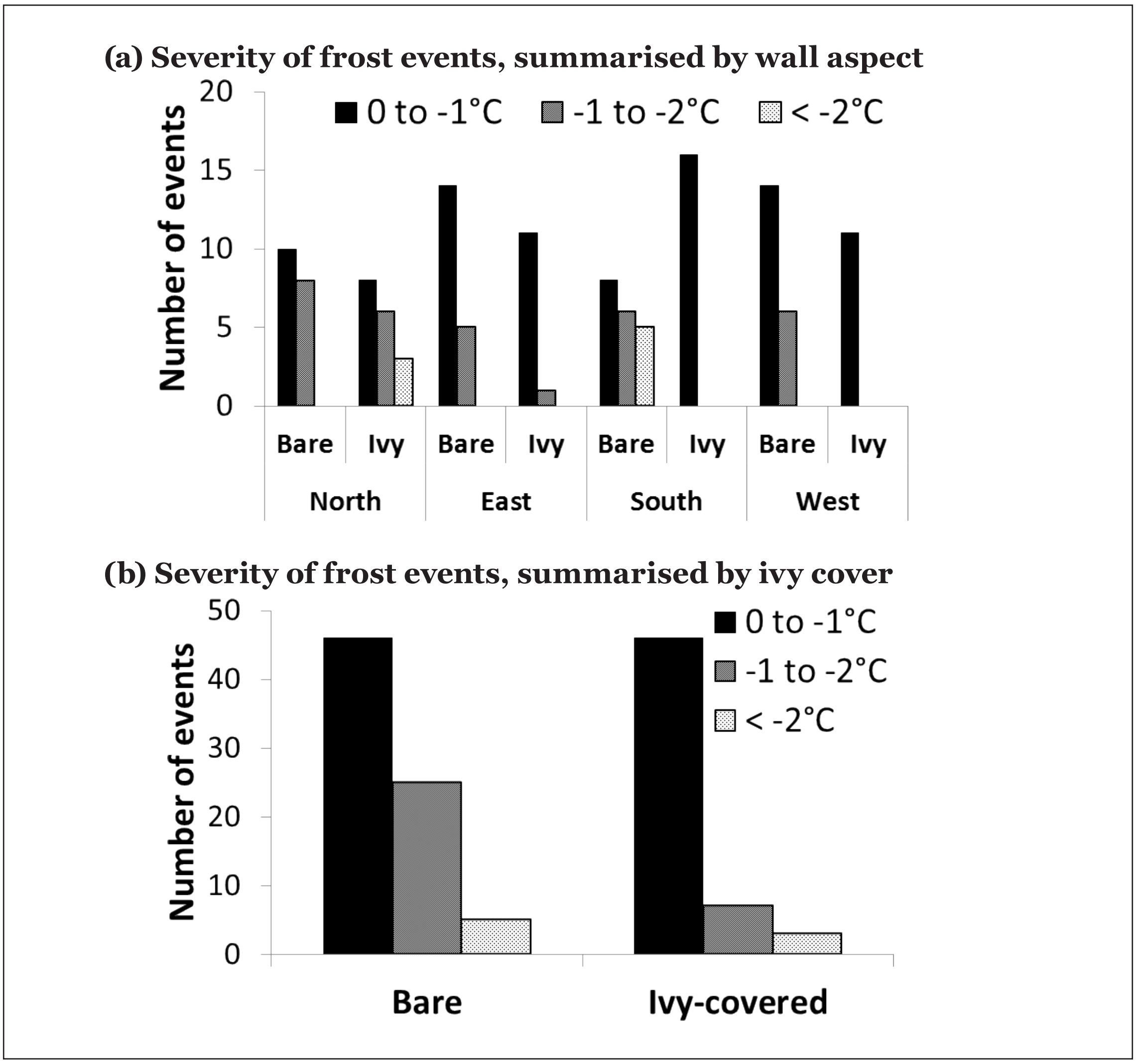


Figure 3-7. Number of frost events of differing severity recorded at the Wytham Woods test wall in winter 2012/13 and 2013/14 summarised by: (a) wall aspect and (b) ivy cover.

3.3.4 Laboratory frost simulation

Microclimate monitoring at the test wall and a range of field sites has demonstrated that ivy is effective at buffering freezing temperatures on masonry walls. As we might expect, there is some variation in this effect with wall aspect and during different freezing conditions, but the overall influence is consistent; freezing events are generally less frequent, shorter in duration, and less severe under ivy relative to exposed stonework. Whilst this should mean that construction materials covered with ivy experience less physical damage from frosts, analysis of temperature data alone do not provide direct evidence of this. An experiment was therefore undertaken to simulate ivy's influence of frosts in the laboratory. This follows a long tradition in weathering science and materials durability testing to simulate environmental conditions in the laboratory, where the variables of interest can be more easily controlled than when using field observations (e.g., Matsuoka, 1990; Goudie and Viles, 1995; Warke and Smith, 1998; Ingham, 2005).

Samples (5 cm cubes) of Elm Park limestone, the same stone used to construct the test wall, were exposed to realistic freezing cycles in an environmental cabinet. Instead of using living ivy in the experiment, temperatures simulating 'with' and 'without' a cover of ivy were recreated based on the microclimate data collected at the Wytham Woods test walls and using meteorological observations. One batch of samples was exposed to conditions representing exposed walls (the 'bare stone' experiment) and a second batch was exposed to the same conditions having been adjusted for ivy cover (the 'ivy-covered' experiment).

For the 'bare stone' experiment, freezing cycles between +9°C and -5°C were simulated. This represented the warmest and coldest 25% of daytime and night-time temperatures, respectively, for 100 frost events recorded in central Oxford during the harsh winter of 2012/13. The experiment therefore simulated 'harsh but realistic' winter conditions for central southern England. For the 'ivy-covered' experiment the cycle was adjusted to reflect thermal buffering by ivy as recorded at the Wytham Woods test wall. Ivy's measured influence on the frequency, duration and severity of freezing events (described above) was accounted for (Table 3-5). Moisture was applied to the stone samples during both simulations, in exactly the same way, using a spray bottle. By keep moisture application the same, the thermal influences of ivy on frost damage could be tested in isolation.

Table 3-5. Freezing regimes used to simulate the influence of ivy on stone deterioration by frost

'Bare stone' conditions reflected frost events recorded in central Oxford during winter 2012/13. 'Ivy-covered' conditions were adjusted to reflect thermal buffering as recorded at the Wytham Woods test wall.

	'Bare stone' conditions (based on meteorological data)	'Ivy-covered' conditions (adjusted based on test wall measurements)
Frequency of freezing cycles	4 cycles per 48 hours	3 cycles per 48 hours
Duration of freezing cycles	6 hours freezing	4 hours freezing
	6 hours thawing	8 hours thawing
Severity (magnitude) of freezing cycles	Freezing at –5°C	Freezing at –2°C
	Thaw at +9°C	Thaw at +8°C

Time was accelerated during the experiments so that two complete freeze-thaw cycles occurred every 24 hours. Both the 'bare stone' and 'ivy-covered' simulations were run for a 6-week period, representing a total of around 85 and 63 individual freezing events, respectively. Alongside visual observations, deterioration of the stone was assessed as a loss of mass (in grams) and as a change in surface hardness measured using an Equotip device (see Section 3.6 for details of this technique).

Can frost buffering by ivy reduce stone deterioration rates?

The freezing cycles were sufficient to cause physical deterioration of the Elm Park limestone cubes. Whilst all samples lost weight during the experiments, stone subject to the 'bare' conditions lost significantly more weight over the course of the experiment than under 'ivy-covered' conditions (Figure 3-8a, $p = 0.01$). Material loss (by weight) was reduced by 27% under 'ivy covered' conditions. Similarly, the surface hardness of 'ivy-covered' stone did not change whereas hardness of 'bare' stone was significantly reduced. On average, softening of stone exposed to 'ivy-covered' conditions was reduced by more than 60% compared to 'bare' conditions over the course of the experiment (Figure 3-8b, $p = 0.02$).

These observations provide the first experimental evidence that the buffering influences of ivy on the frequency, duration and severity of freezing events can reduce rates of stone deterioration. Furthermore, these observations reflect the influence of ivy on temperature alone, in isolation of any influence on stone wetting during rainfall events. Given that shielding of walls from rainfall by vegetation is known to occur (e.g. Hanssen and Viles, 2014), frost protection by ivy may be even greater where it reduces the likelihood of materials being wet during periods of freezing weather.

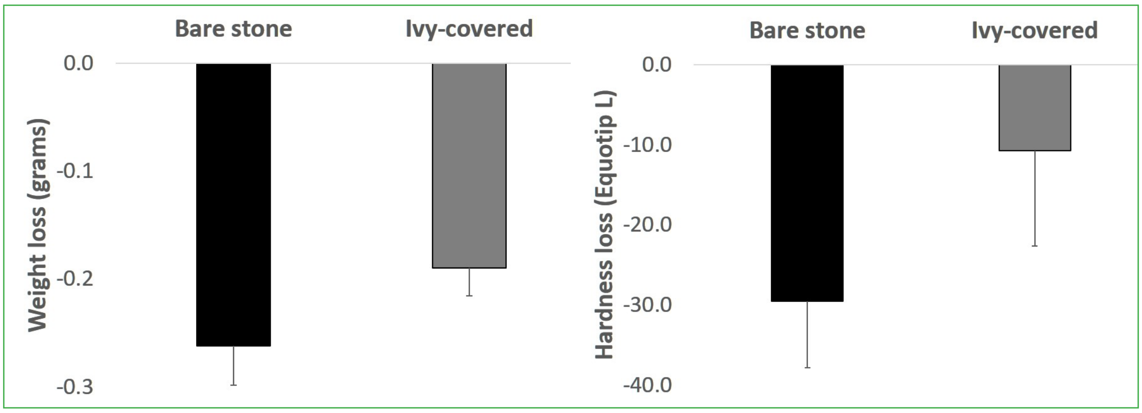


Figure 3-8: Deterioration of Elm Park limestone as a result of freezing cycles simulated in an environmental chamber representative of 'bare stone' and 'ivy-covered' conditions: (a) loss of mass (average + SD, n = 5) and (b) change in surface hardness after a 6-week simulation.

3.4 Ivy influence stone surface soiling and discolouration

Particulate pollution contributes to the deterioration of building materials through chemical reactions, such as the formation of blackened gypsum crusts on limestone (Grossi et al., 2003). In urban areas most pollution comes from vehicle exhausts, deposited on walls and buildings through dry and wet depositional processes. As well as contributing to the physical and chemical deterioration of stone, surface discolouration from pollution and microbial colonisation (particularly algal greening) are management issues for historic buildings for aesthetic reasons (Brimblecombe and Grossi, 2005). The influence of vegetation cover on stone soiling is therefore of interest for conservation but has been largely unstudied.

Ivy is particularly tolerant of common urban pollutants such as sulphur dioxide (Bannister, 1976) and dust (Grime et al., 1988) making it a good candidate for an effective pollution buffer on walls. To examine this, observations were made of airborne particulates accumulating on ivy foliage in areas of Oxford during this research, summarised below and described in detail by Sternberg et al. (2010). Long-term monitoring was also undertaken at the Wytham Woods test wall to examine whether stone discoloured more or less with a cover of ivy, and how this might vary between aspects and at different heights on walls.

3.4.1 Evidence for ivy filtering airborne particulates

Ivy leaves were collected from three sites in Oxford, one experiencing high traffic volumes (London Road), one having medium traffic flow (Walton Street) and one rural site with a low level of traffic (Wytham Woods). At London Road and Walton Street, leaves were sampled from the outer and inner parts of the canopy. Small (1 cm^2) sections of leaves were examined under a Scanning Electron Microscope at magnifications ranging from 100x to 500x. Microphotographs were taken of the leaf surfaces in order to determine the number, size and density of particles present.

Results of the study are described in detail by Sternberg et al. (2010). A range of particles were identified, including those associated with diesel and coal combustion. Most particles were present on leaves from the site with the highest traffic volume (up to 30 thousand particles per mm^2) whereas leaves from the rural site had the fewest particles (as few as 60 particles per mm^2). In areas of high-traffic flow, leaves from the inner part of the canopy (closest to the wall face) had significantly fewer particles than leaves from the outer part (Figure 3-9, $p = 0.02$). This shows that ivy acts as a filter in polluted urban areas, reducing the delivery of particulates to the walls and buildings it grows on. The filtering effect was less clear in areas of medium traffic flow (Figure 3-9).

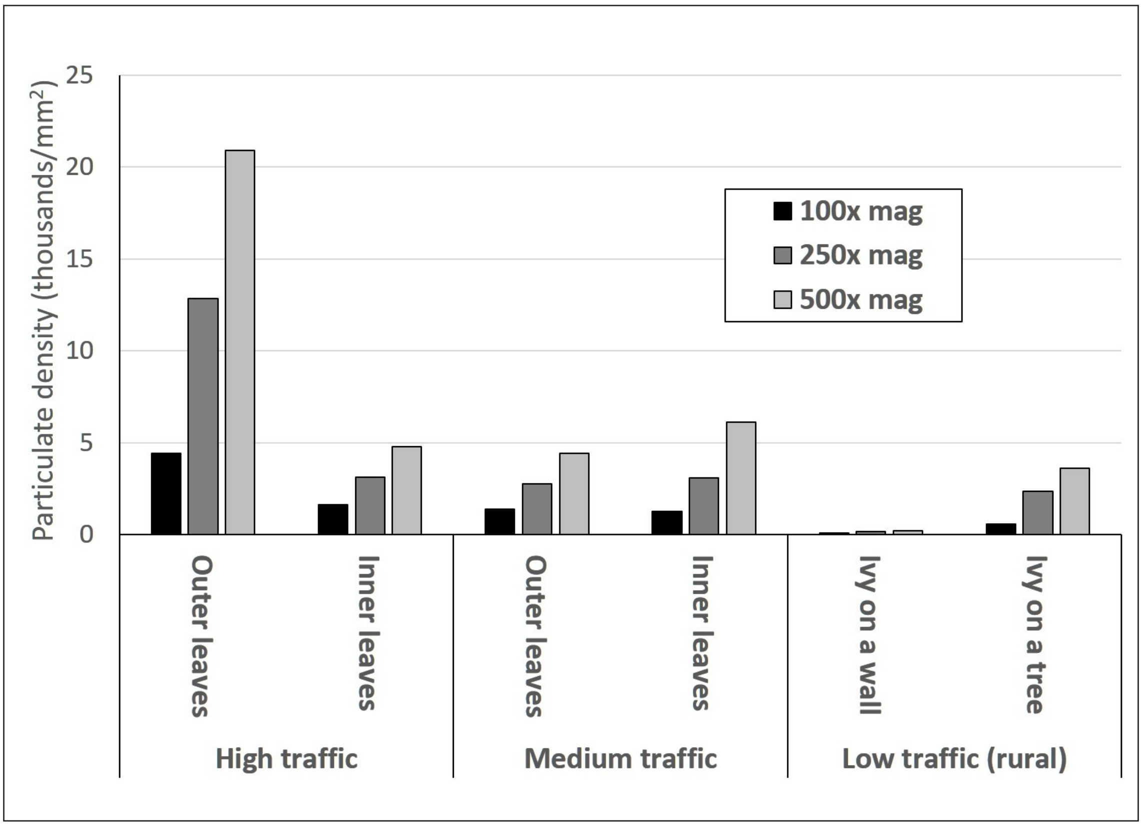


Figure 3-9: Densities of airborne particulates on leaves taken from the outer and inner parts of ivy canopies growing on walls in Oxford: high traffic volume = London Road; medium traffic volume = Walton Street; low traffic volume = Wytham Woods. Counts were made at three different magnifications (100x, 250x and 500x). Average values of four different leaves from each site are shown. (Produced using data from Sternberg et al., 2010)

The effectiveness of vegetation in filtering pollution from the air will depend on many factors such the size and shape of leaves, whether leaves are waxy or covered in hairs, and the structure of the plant (e.g., Speak et al., 2012; Janhäll, 2015; Lundholm et al., 2015; Abhijith et al., 2017). English ivy appears to be an effective pollution sink in urban areas (Sternberg et al., 2010, Figure 3-10). A cover of ivy will reduce the amount of particulate pollution reaching the face of walls and buildings, particularly in busy roadside settings. This may act to reduce deteriorative processes (including discolouration) involving reactions between stone minerals and airborne pollutants. The broader environmental benefits of airborne pollution filtering by vegetation on buildings are increasingly being recognised, including improved human health (Dover, 2015).

Figure 3-10: Ivy foliage can capture a remarkable amount of airborne pollution in urban areas with high traffic flow. This example is from London Road, Oxford (taken in February 2007, ©Alan Cathersides).

3.4.2 The influence of ivy on stone discolouration

To examine the influence of ivy cover on stone surface soiling and discolouration, quantitative colour measurements were made at the Wytham Woods test wall using a spectrophotometer (CM-700d). This device uses standardised measures of colour (L*a*b* colour space) making it possible to differentiate different types of colour change such as blackening and greening. As well as being relevant to the aesthetic deterioration of historic stonework, changes in the colour of building materials give an indication that weathering is occurring (Viles & Gorbushina, 2003). As the test site at Wytham Woods is a relatively unpolluted area, away from main roads, changes in stone colour more reflect microbial growth and chemical alteration of the stone surface in reaction with rainwater.

Spectrophotometer measurements were made in areas with and without a cover of ivy, at three different heights (top, middle and base) on four wall aspects (N, E, S, W). Measurements were repeated (in the same spots) every two to three months so that changes over time could be assessed relative to the start of the study (April 2013). Change in the lightness of the stone (L*) was used as a measure of soiling or blackening of the surface, and change in the colour of the stone (C*ab) was used as a measure of discolouration or greening.

Changes in stone lightness and colour are summarised in Figure 3-12 and Figure 3-13, respectively, for the first year of monitoring. The overall trend was for a reduction in lightness (i.e., blackening) and an increase in colour (i.e., greening) over time. An overall influence of ivy on stone lightness was noticeable on the four aspects, but this was not statistically significant when averaged across the year ($p = 0.11$). Time of year (season) had a strong influence however, as seen in Figure 3-12. For example, exposed stone was significantly darker than ivy-covered stone in January ($p = 0.001$) and was noticeably darker in November ($p = 0.05$) and May ($p = 0.05$). Overall differences in colour (greenness) between ivy-covered and bare stone was significant ($p = 0.005$) but this also varied considerably between seasons (Figure 3-13). Exposed stone had discoloured more in November, January and March compared to adjacent ivy-covered areas. These patterns corresponded to cooler and wetter months of winter and spring (November to March). Seasonal growth of microorganisms on stone is known to be sensitive to water and thermal stress for example (Viles and Cutler, 2012; Cutler et al., 2013).

The influence of wall height on stone discolouration was also examined in combination with ivy cover using data collected in July 2015. Overall, the tops of walls had darkened significantly more than the middle and bottom sections ($p = 0.01$). Exposed stone had also darkened significantly more than ivy-covered stone ($p = 0.04$), but the strength of this effect varied with wall height (Figure 3-14a). For example, on all four aspects the tops of walls had discoloured more without a cover of ivy ($p = 0.01$) whilst there was less of a difference on the lower sections. Ivy appeared to have limited darkening at the tops of the walls, which may otherwise occur relatively quickly where more directly exposed to moisture (rainfall) and sunlight. Similarly, wall height had a significant effect on greening ($p = 0.007$), with greater colour change at their tops compared to lower sections (see Figure 3-11). The influence of ivy on greening was not clear in July when these measurements were taken, and in some cases stone was more discoloured under the ivy canopy (particularly the east-facing wall, Figure 3-14b).

Figure 3-11. Photographs illustrating the influence of wall orientation (aspect) and height on stone discolouration at the Wytham Woods test wall. Note the greening towards the top of the north-facing wall relative to other areas of stone.

These measurements highlight an interacting influence of wall orientation and height and, in particular, seasonal effects on stone soiling and discolouration over time. The greatest differences between ivy-covered and exposed stone occurred during the wetter/cooler winter and spring months, probably in association with the growth of microorganisms. Shading of stone by ivy foliage, and its influence on stone surface microclimates, may mediate microbial growth to some extent, particularly at the tops of walls but this requires further research.

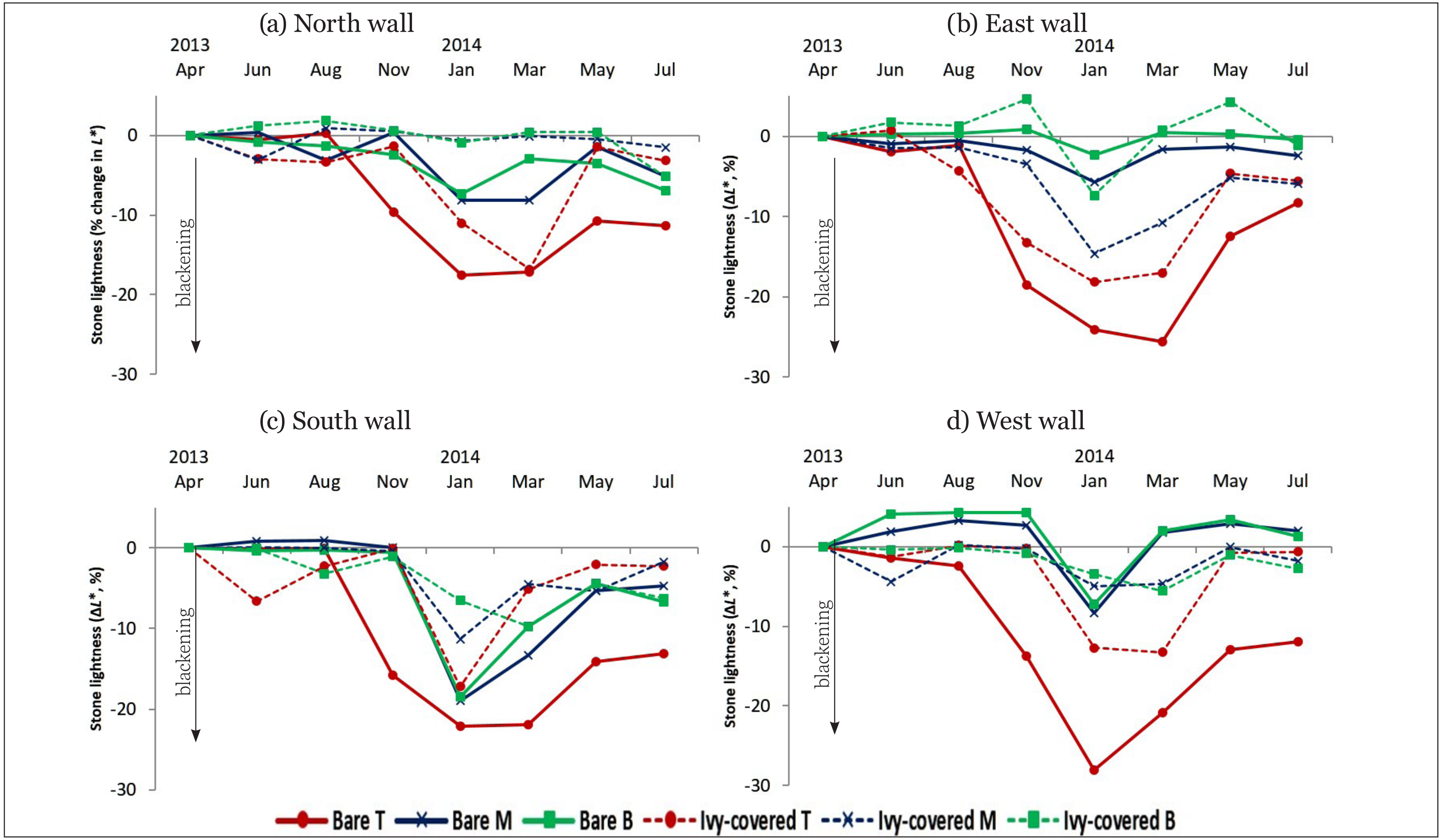


Figure 3-12. Changes in the lightness of stone at the Wytham Woods test wall (T = top, M = middle, B = base). Lower values indicate surface blackening.

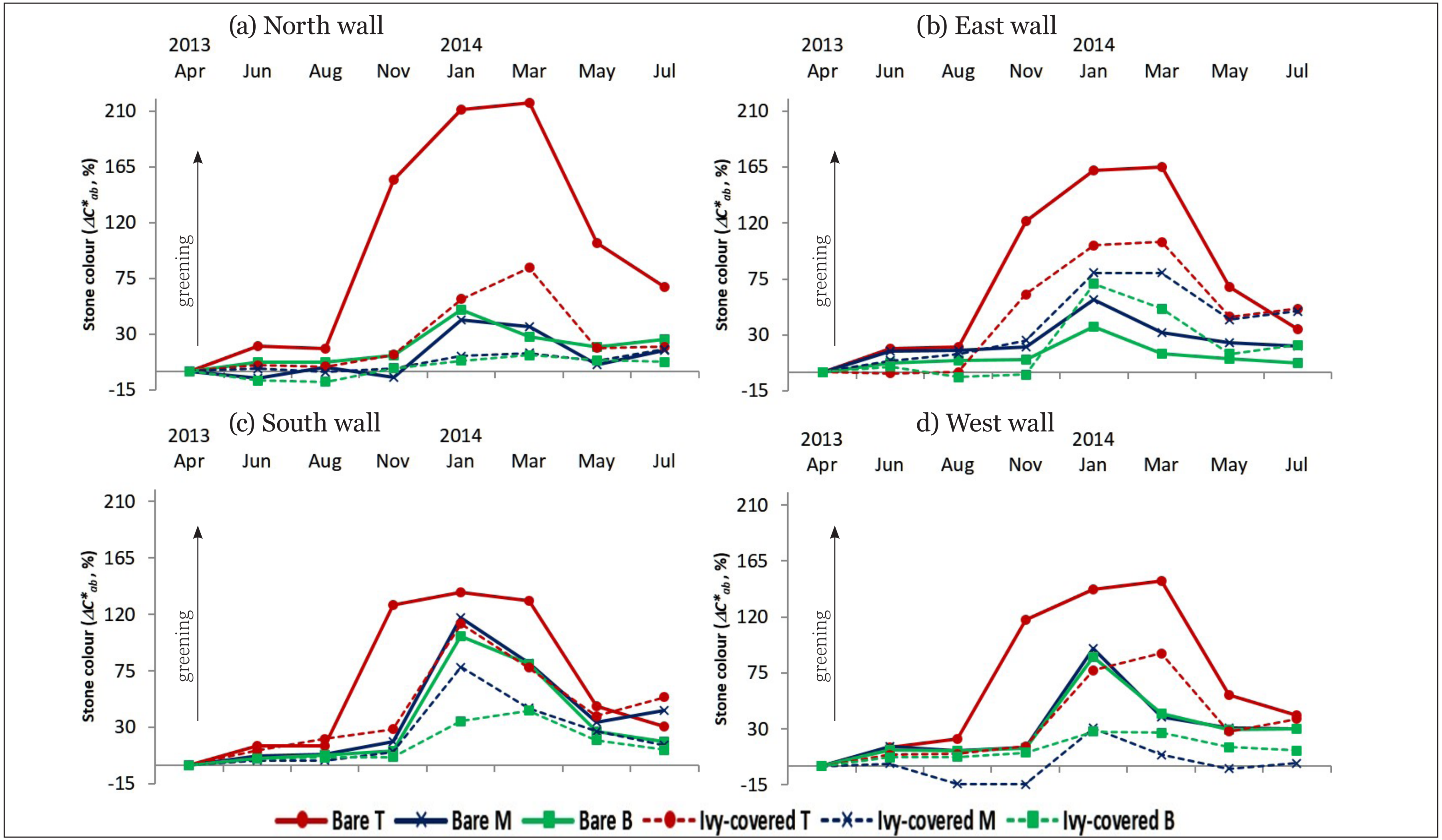


Figure 3-13. Changes in the colour of stone at the Wytham Woods test wall (T = top, M = middle, B = base). Higher values indicate discolouration.

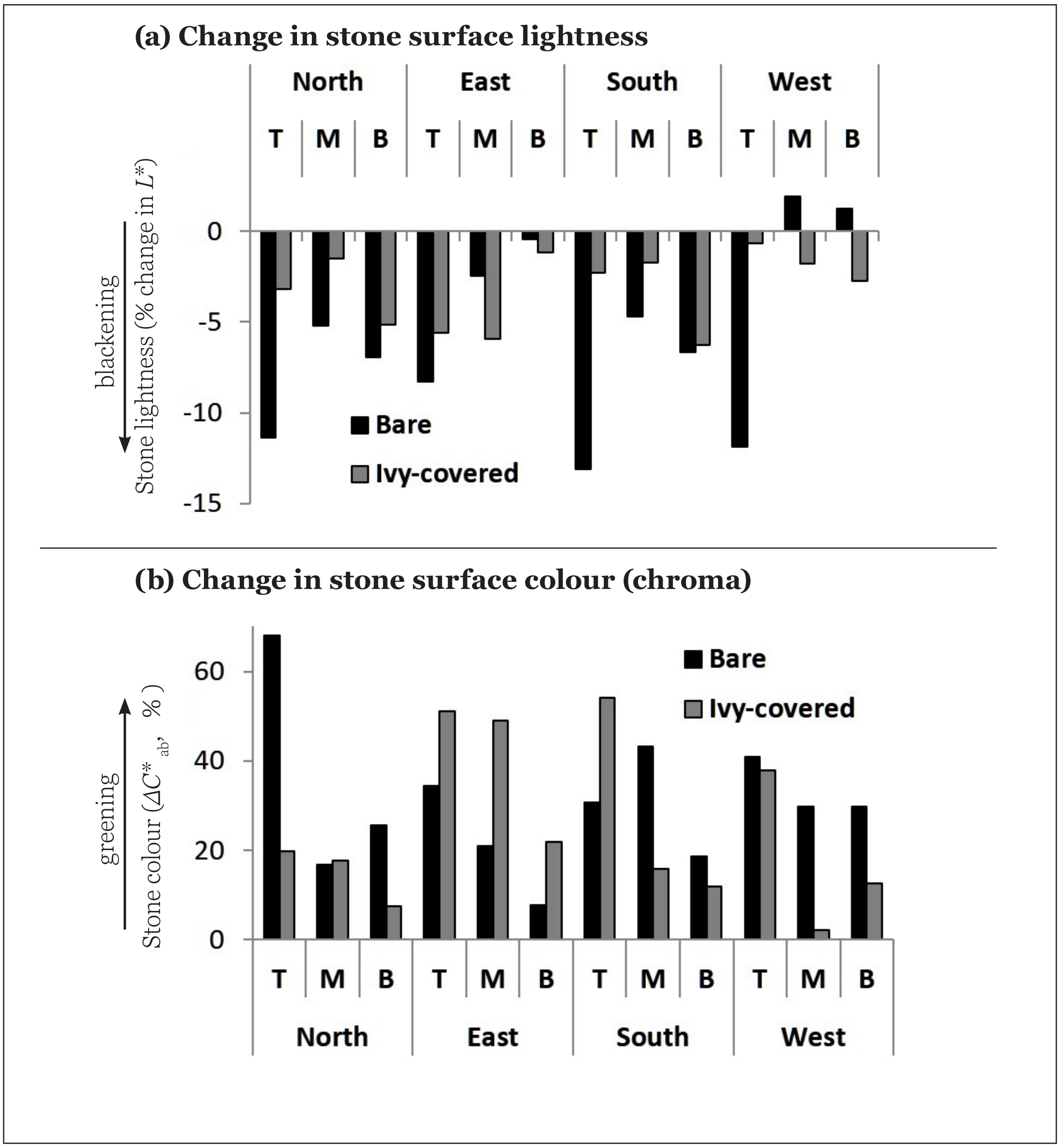


Figure 3-14. Stone surface (a) darkening and (b) discolouration at the Wytham Woods test wall recorded in July 2015 relative to baseline measurements (April 2013). Four wall aspects and three wall heights were measured (T = top of wall, M = middle of wall, B = base of wall).

3.5 Ivy influences on stone moisture and damp

Moisture is a critical factor in many deteriorative processes affecting stone and brick masonry (Table 3-1). Damp is associated with microbial growth (notably algae, fungi and moulds) and the movement of moisture into and within masonry can lead to chemical decay, and the mobilisation and penetration of damaging salts. Factors affecting how wet materials are, and where moisture is within a structure, are also varied and complex. However, any form of covering over a wall is likely to affect moisture by changing inputs (such as rainfall hitting the wall) and outputs (through evaporation) of water. Vegetation growing on walls has the potential to influence moisture dynamics within masonry materials, yet evidence of this is generally lacking.

Measurements at field sites have given some conflicting results, with some walls being wetter under ivy and some drier (see Viles, 2011). These differences probably result from variations in wall aspect, type of construction, the extent of ivy cover (including canopy thickness), and local sources of moisture, all of which are difficult to control in the field. The test wall at Wytham Woods has therefore given a unique opportunity to compare moisture in stone with and without a cover of ivy, when all other variables are controlled for as far as possible.

Two approaches were taken to monitoring moisture at the test wall, each described in the follow sections. First, surface and near-surface measurements (a few centimetres depth) were made every month using hand-held moisture meters (a Protimeter and CEM type, as described by Eklund et al. 2013). Readings were compared between aspects, heights (top, middle, base) and between ivy-covered and bare stone. Secondly, to gain a picture of deeper-seated moisture (up to 20 cm depth), a two-dimensional geoelectrical technique was used (GeoTom Electrical Resistivity Tomography, ERT) that is useful for visualising moisture in historic walls (e.g., Sass and Viles, 2006; Sass and Viles, 2010). These measurement techniques, which are entirely non-destructive, work on the principle that the electrical conductance and resistance of porous materials are influenced by the presence of moisture. Variations in the values obtained in different areas, and over time, can therefore help identify patterns of moisture within masonry materials. Although the difficulties of making quantitative assessments of moisture contents with handheld moisture meters are well known, they can be used with caution to investigate relative changes in moisture values over time and across relatively homogeneous walls.

3.5.1 Surface and near-surface moisture (hand-held moisture meter surveys)

Monthly moisture measurements obtained using a CEM and Protimeter type meter are shown in Figure 3-15 and Figure 3-16, respectively. These devices detect moisture (measured on an arbitrary scale) in slightly different ways and at slightly different depths, meaning that values obtained from each are not directly comparable. However, both devices were useful for making relative comparisons between wall aspects and between areas with and without ivy cover.

Clear seasonal patterns in stone surface moisture were detected using both devices. Moisture readings were lower during the summer months (June-September) and higher during the rest of the year, particularly in late winter and early spring (February-March). This corresponds to moisture inputs (which are greatest in wetter months and least in drier months) and outputs (greatest in warmer months and least in cooler months). The seasonal patterns were generally consistent between the wall aspects (Figure 3-15 and Figure 3-16).

Differences in stone moisture were observed between ivy-covered and exposed sections of wall. This was most pronounced using the CEM meter (which measures slightly deeper into the stone), with higher values recorded under ivy on almost all months of the year (Figure 3-15). These differences were generally small, however, less than 10% in most instances. Measurements made using the Protimeter also tended to be higher under a cover of ivy, but this was less consistent (Figure 3-16). The difference between ivy-covered and exposed sections of wall tended to be greatest during the warmer months of the year. This may be reflect reduced evaporation under a cover of ivy due to solar shading, supported by cooler conditions measured under ivy during summer, see Section 3.3).

The influence of ivy cover on moisture varied between aspects and between different heights on the wall. For example, moisture content measured using the CEM meter was significantly different between aspects ($p = 0.002$) and between different wall heights ($p < 0.001$) across the year. The greatest differences between ivy-covered and bare stone occurred on the east- and north-facing walls (Figure 3-17a). Differences were also greatest at the tops and bases of walls, with much less difference on middle sections (Figure 3-17b). These general patterns were supported by the Protimeter measurements, but were not found to be statically significant due to the lower precision of this device (Figure 3-17c-d).

Overall, the influence of ivy cover on stone surface and near-surface moisture at the test wall was to increase readings by an average of between 3% and 8%. Importantly, this was much less than natural variations caused by seasonal patterns of wetting and drying over the course of the year, which caused variations in stone moisture in the order of 13% to 32%. These data show that whilst consistently higher moisture readings were obtained under a cover of ivy (probably caused by slightly reduced evaporation from shaded stone), this difference was generally very small. Variations in aspect, wall height, seasonal weather, and other sources of moisture are therefore likely have a greater influence on overall patterns of moisture and damp in historic walls. An important challenge in interpreting moisture data is that the timing of measurements (e.g., time since last rainfall) is likely to reflect the degree of difference measured between ivy-covered and bare sections. Given that measurements cannot in taken in very wet weather using these devices, all measurements were made during relatively dry conditions. The likely shielding influence of ivy cover during heavy, driving rain was not therefore reflected in these data.

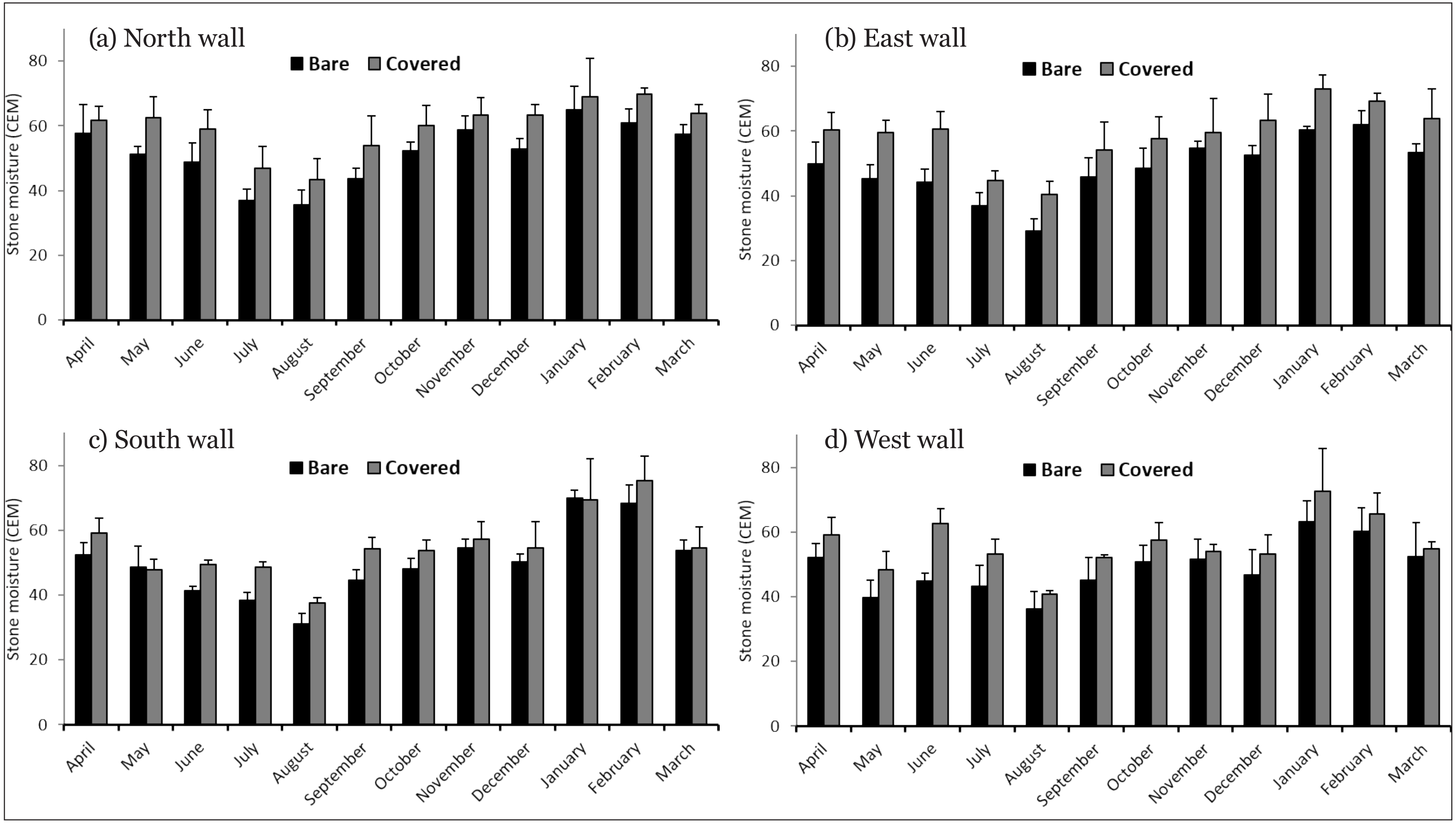


Figure 3-15. Surface moisture data (CEM meter) for Elm Park Limestone at the Wytham Woods test wall, in areas with and without a cover of ivy. Average values are shown by month, error bars indicate variation across different heights (April 2014-April 2015). NB. Values are on a relative, arbitrary scale.

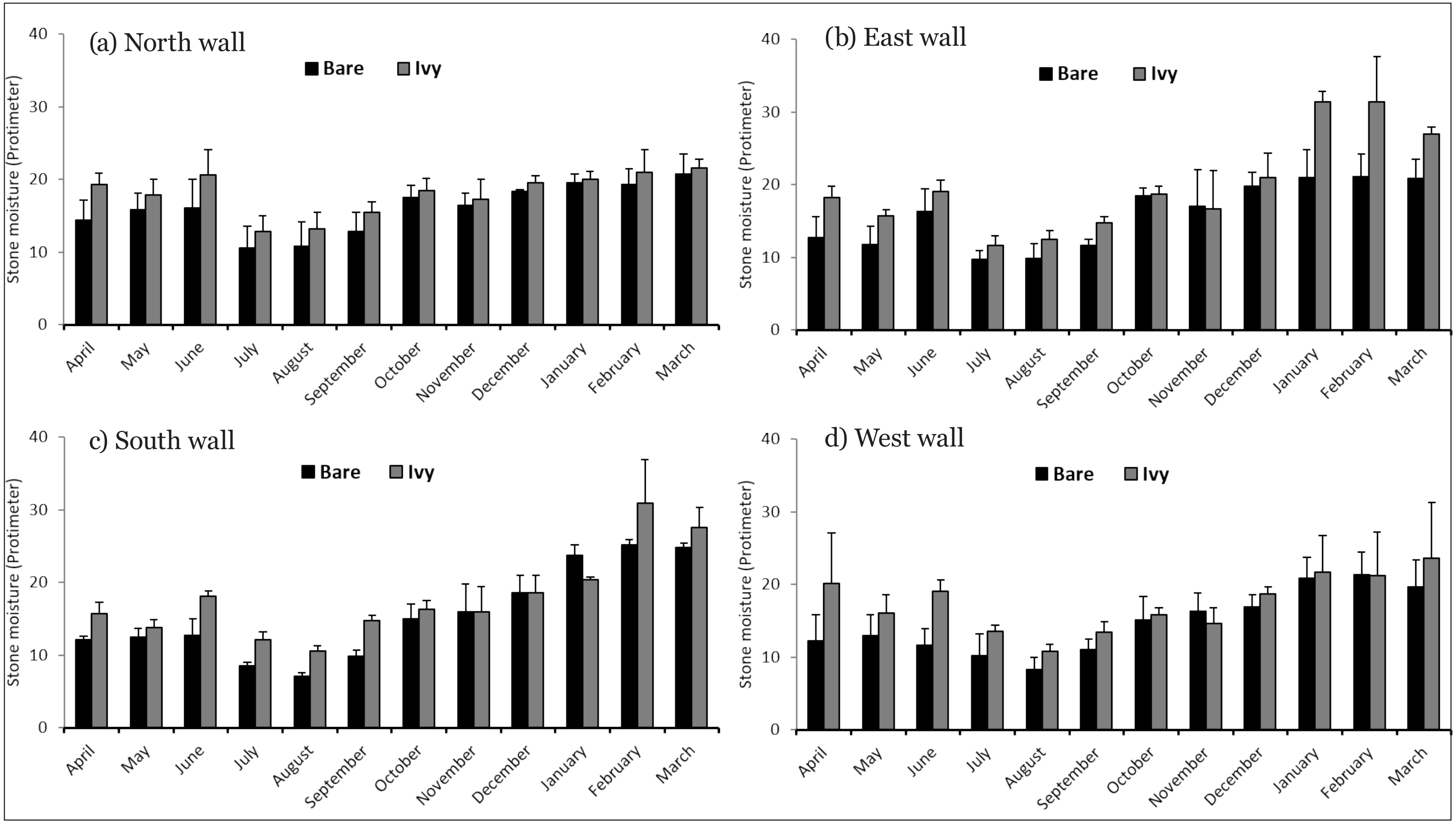
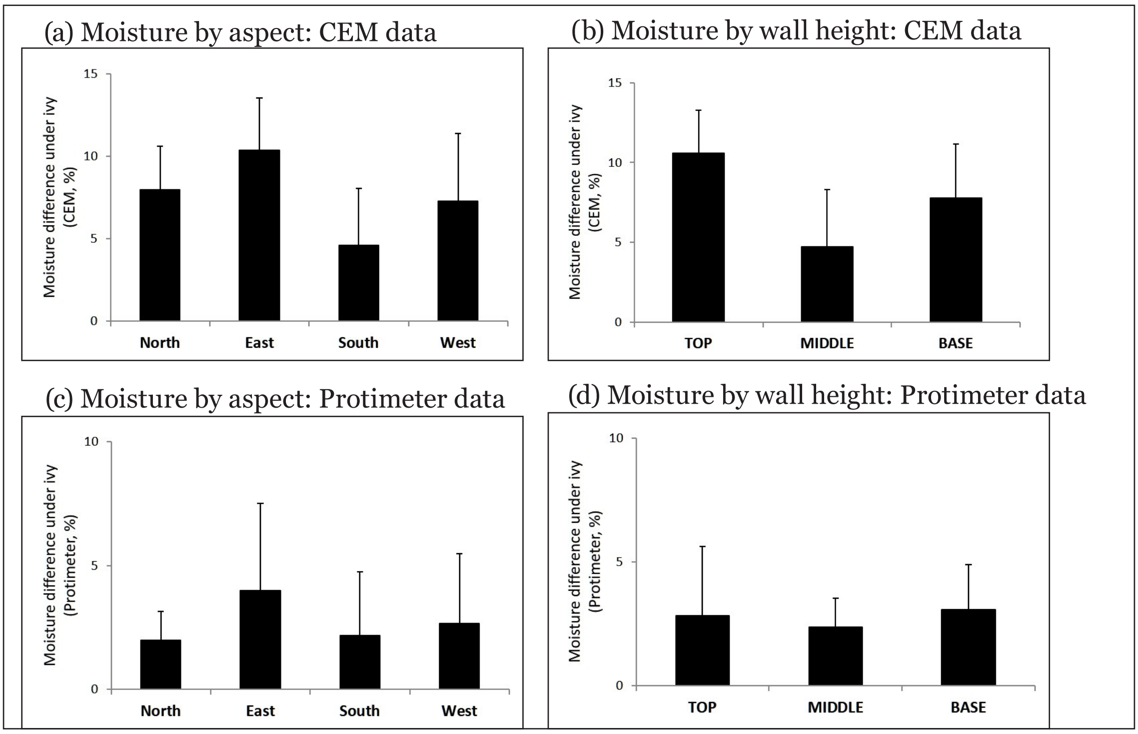


Figure 3-16. Surface moisture data (Protimeter meter) for Elm Park Limestone at the Wytham Woods test wall, in areas with and without a cover of ivy. Average values are shown by month, error bars indicate variation across different heights (April 2014-April 2015). NB. Values are on a relative, arbitrary scale.

Figure 3-17. The influence of ivy cover on stone surface moisture (annual average difference between ivy-covered and exposed stone) for different aspects and at different heights on the Wytham Woods test wall. Data collected using two different hand-held meters are shown for comparison (Protimeter and CEM type). Error bars indicate variation across 12 consecutive months (April 2014-2015).



3.5.2 Sub-surface moisture (ERT survey)

To visualise deeper-seated moisture using ERT survey, ECG electrodes were attached to each wall aspect in a horizontal transect at a height of 0.91 m above the ground. Each transection included ivy-covered and bare halves of walls (Figure 3-18). A current was applied (automatically chosen by the GeoTom device) and electrical properties of the materials were recorded, interpolated and visualised using specialist computer software.

Data obtained using ERT are shown visually in Figure 3-19. Bluer colours indicate relatively higher levels of moisture (areas of lower electrical resistance). The general pattern shows a drier zone (orange and red colours) towards the surface of the walls and relatively wetter zones (bluer colours) at depth. Surface patterns reflected the spacing of stone blocks and recessed mortar joints, particularly on the south- and east-facing walls. The average wetness was nevertheless generally similar between the four aspects at the time of survey. Ivy had not made the walls consistently wetter or drier beyond the surface, although there was some evidence that the structure was drier under a cover of ivy, at least on the west wall and possibly the east wall (Figure 3-19). This may reflect surface shielding from rain to some extent (Hanssen and Viles, 2014). Differences may, of course, be more pronounced during wetter months of the year when rain-shielding by vegetation will be greatest. However, overall the survey indicated that ivy has had little influence on deep-seated moisture in the test wall and is not, therefore, enhancing possible deterioration associated with damp.

Figure 3-18. Geoelectrical survey being conducted at the Wytham Woods test wall in July 2014. Electrodes were placed in horizontal transects across ivy-covered and exposed sections of each aspect.

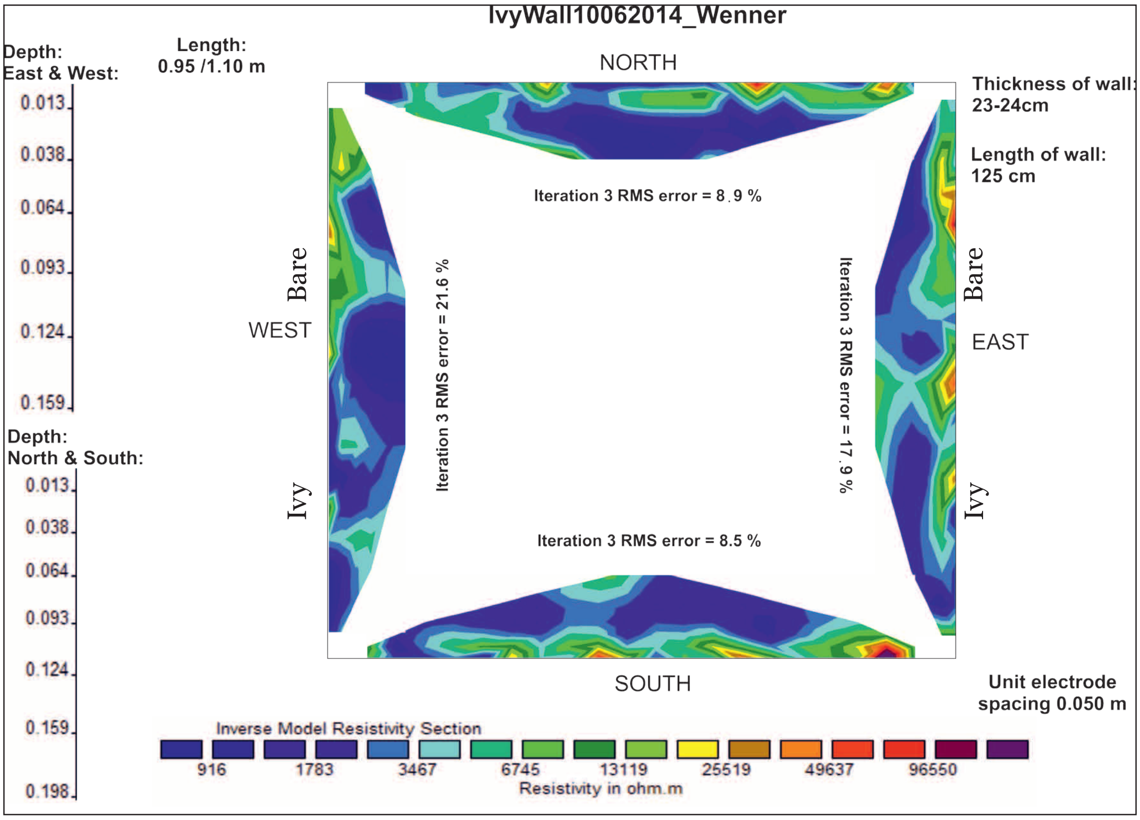


Figure 3-19. Electrical resistivity (ERT) profiles (Wenner configuration) for the Wytham Woods test wall (July 2014). Blue colours are indicative of higher moisture. Each wall has one side covered with ivy and one without any ivy side, as indicated.

3.6 Ivy influences on stone hardness

As masonry materials weather over time their physical properties change, including their hardness. Both the softening and hardening of stone can indicate that physical and/or chemical alterations are taking place, providing a useful tool for diagnosing deterioration. For this research a type of impact hammer (Equotip 3 Surface Hardness Tester, Type D) was used to measure surface hardness at the test walls (Section 3.6.1) and field sites (Section 3.6.2), comparing the hardness (as a proxy for weathering state) in areas with and without a cover of ivy. The Equotip device fires a small tungsten carbide ball at the test surface and, depending on the amount of rebound, returns a numerical value. Higher values indicate harder materials (typically less weathered) and lower values indicate softer materials (typically more weathered) (Viles et al. 2011; Wilhelm et al. 2016).

3.6.1 Test wall evidence

As the precise history of construction and ivy cover at the Wytham Woods test wall is known, it is possible to make valid comparisons of hardness between covered and bare sections. In an attempt to monitor changes in the condition of the stonework over time, baseline hardness measurements were first collected in April 2013. Measurements were made on ivy-covered and exposed sides of the wall, at three heights (top, middle, base) and on four aspects. Measurement points were sanded prior to baseline measurements giving a comparable (i.e., smooth and intact) surface from which all subsequent measurements could be compared. Hardness (ten repeat readings in each location) was measured, in the same locations on each wall, at two to three month intervals over a two year period.

Change in stone hardness over time: Year 1

Figure 3-20 shows variations in hardness measurements for each aspect of the test wall and at each height for the first year of monitoring. Data are shown as a percentage change relative to the baseline measurements. There was little consistent trend over this period; hardness values varied above and below the baseline for each measured location, in both ivy-covered and bare locations, and at different positions on the walls. Most of the variation measured was within 10% of the baseline measurement, and was rarely above 15%. However, most of the measured areas had lower hardness values after 15 months than at the start of the project (Figure 3-20), which may reflect progressive and general softening of the stone over time.

A statistical comparison of the overall changes in stone hardness during this period confirmed that there was no difference between ivy-covered and bare sections of wall ($p = 0.905$). Measurements did vary significantly over time between months ($p < 0.001$), however. In other words, variation in measured hardness over time was significant, irrespective of ivy cover, indicating that other factors were influencing readings. This includes seasonal patterns of moisture (see Section 3.5) that can influence Equotip readings, as well as limitations in the precision and accuracy of the equipment especially where changes over time are very small.

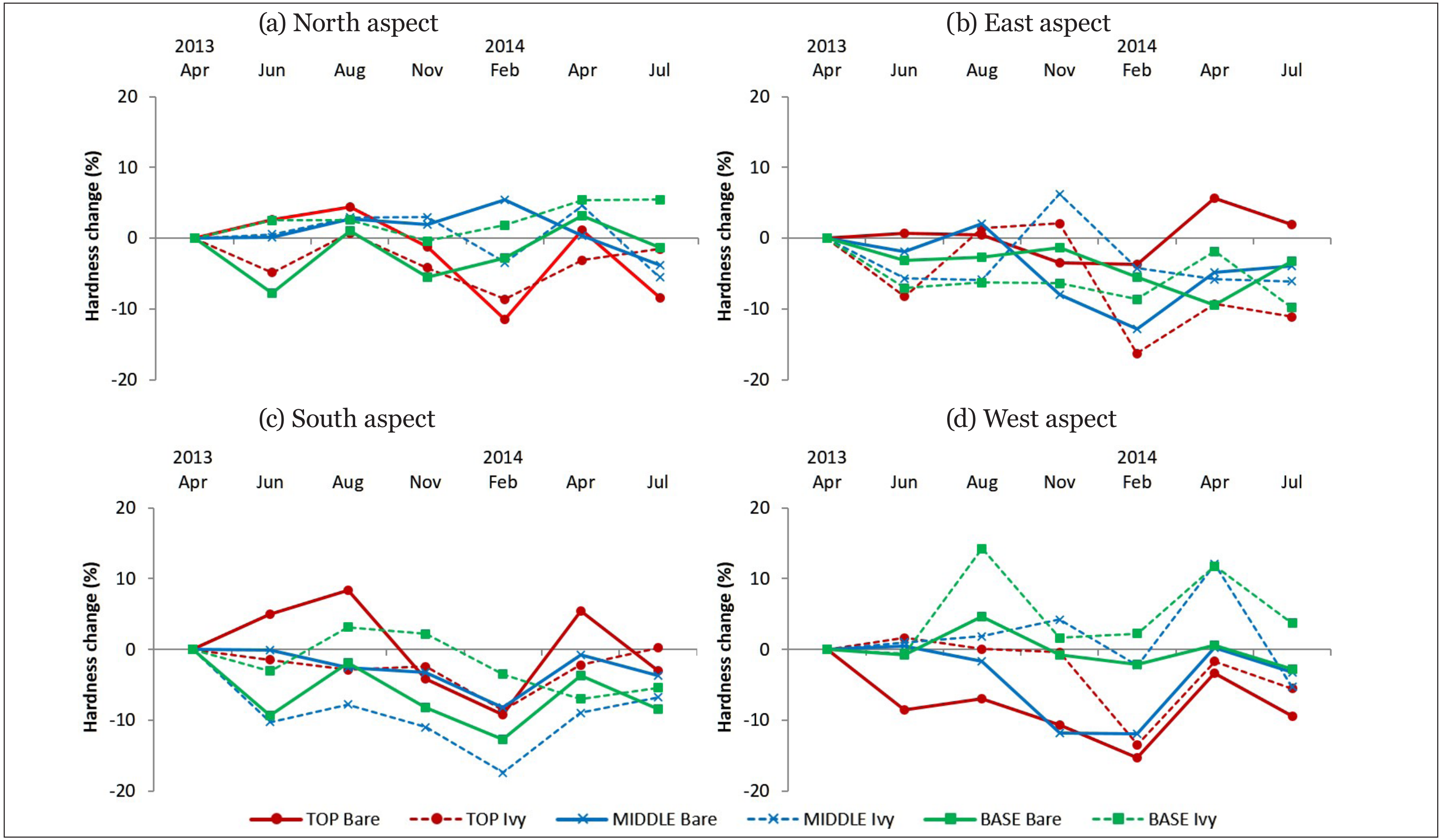


Figure 3-20. Change (%) in limestone hardness relative to baseline (Apr 2013). T = top, M = middle, B = base. Solid lines = bare stone, dashed lines = ivy-covered.

Change in stone hardness: after 2 years

Stone hardness was assessed in more detail at the test wall after 2 years, during which the bare/ivy-covered sections of each wall face were maintained by regular trimming. This comparison is useful because measurements could be compared two years apart, but at the same time of year (mid-Spring) when stone moisture was assumed to be relatively comparable to the baseline condition. Changes over this period are summarised for each wall aspect, height and ivy-cover in Figure 3-21. In the majority of cases, the average difference between baseline measurements after two full years was just 5% or less. Variation within the repeat readings was also high relative to these overall differences (indicated by the error bars in Figure 3-21).

Statistical comparisons between the three wall heights and between bare and ivy-covered sections showed that there were no significant differences; after a two year period of ivy cover, stone was no softer or harder compared to bare stone on the north ($p = 0.59$), east ($p = 0.58$), south ($p = 0.98$) and west ($p = 0.11$) facing aspects. Height on the walls made no difference to this finding. Although not statistically significant, there was a trend for bare stone to be slightly softer than adjacent ivy-covered areas on the west wall, and this was consistent at three different heights (Figure 3-21d). This may indicate some protective influence of ivy (in slowing down deterioration relative to bare stone) on this aspect. Interestingly, this corresponds to evidence of drier conditions under ivy on the west-facing wall relative to adjacent bare stone (see Figure 3-19). However, this pattern was not found for the other walls after the two-year monitoring period.

Whilst longer-term monitoring may reveal clearer differences in stone deterioration rates with and without a cover of ivy (measured here using hardness as an indicator of stone condition), data collected during the course of this research showed that ivy had had no significant influence on the physical condition of the stonework, either positive or negative.

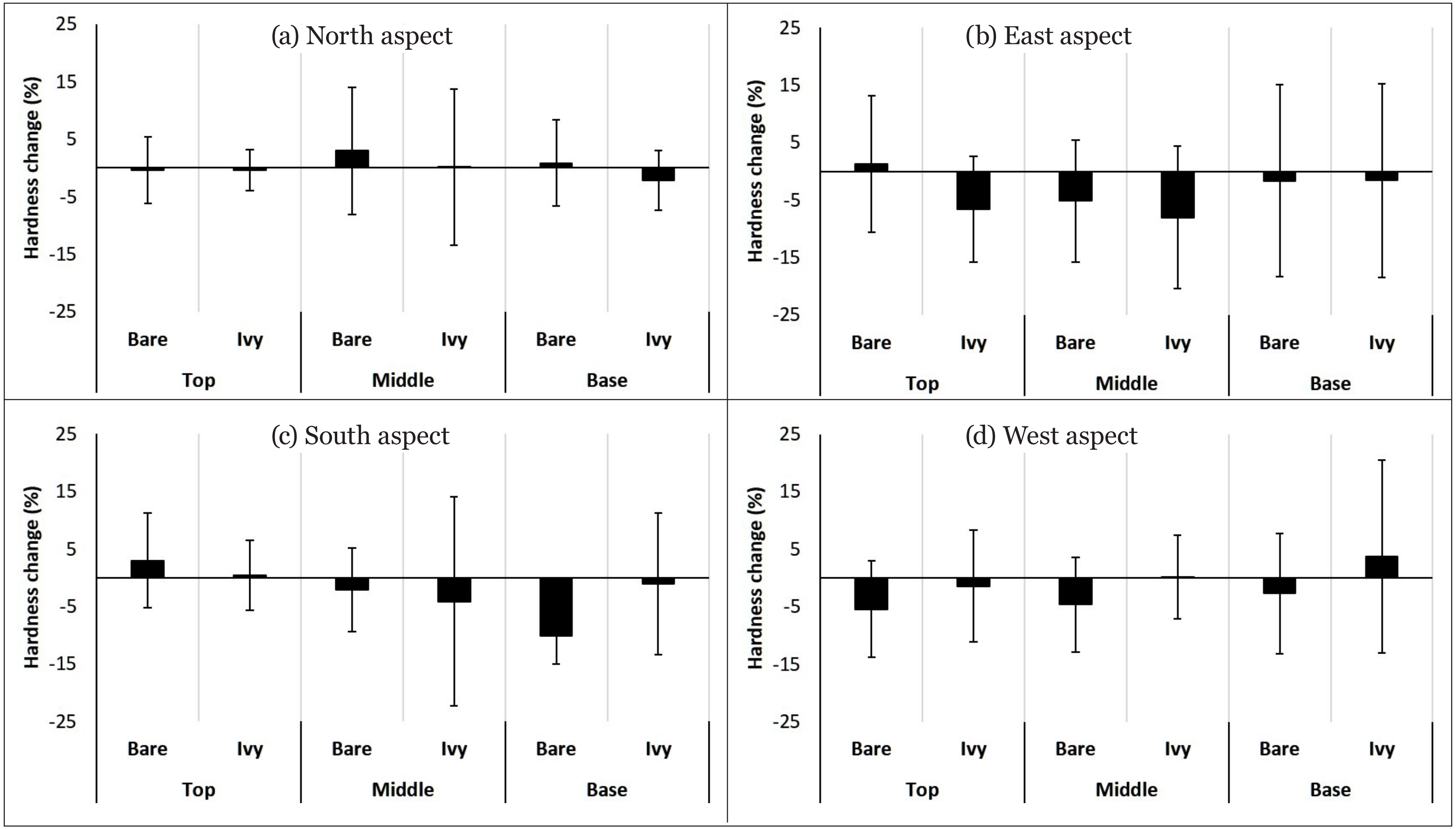


Figure 3-21. Change in stone hardness after 2 years (in March 2015) for bare and ivy-covered sections of the Wytham Woods test wall, at three different heights (top, middle, base). Average change (% relative to April 2013 baseline) ± standard deviation (n = 10).

3.6.2 Field evidence

Holywell Cemetery, Oxford (limestone wall)

Holywell Cemetery in central Oxford is surrounded by a limestone masonry wall constructed with lime mortar. The oldest parts of the cemetery date back to 1847. Older sections of wall are in a generally poor condition, with chemical crusting and blistering of stone common, whereas others have been more recently repaired (in the last 5 to 10 years) via repointing and block replacement. Ivy is growing over much of the perimeter wall although growth is generally patchy.

To assess whether stonework was harder, softer or no different under ivy cover, blocks of limestone were measured on a north-west facing wall on the eastern side of the cemetery in September 2014. What was believed to be an original section of wall (without repairs) with patchy ivy cover was chosen. The hardness of five exposed blocks and five adjacent blocks with a well-established cover of ivy (15-20 cm thickness of foliage) was measured using the Equotip. A total of 400 readings were made across covered and bare areas and data are summarised in Figure 3-22.

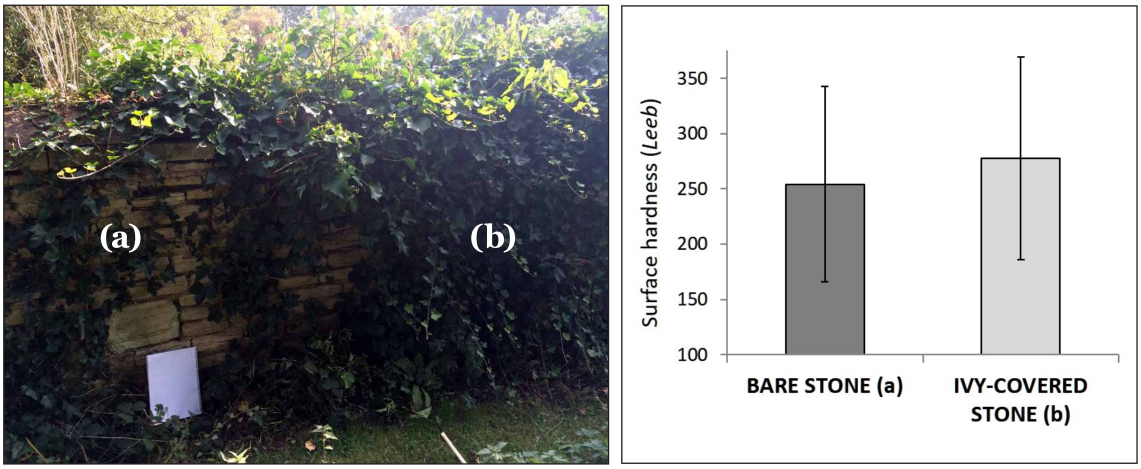


Figure 3-22. Surface hardness of poor-condition limestone with and without a cover of ivy, Holywell Cemetery, Central Oxford (mean values ± SD, n = 200). Data are for 21-Sep-2014, A4 notepad for scale).

The hardness of the ivy-covered stone was on average 9% higher than adjacent exposed stone. Although a relatively small difference, this was very consistent between repeat measurements and was statistically significant ($p = 0.002$). The bare stone was therefore significantly softer than adjacent areas covered with ivy, which may be the result of faster deterioration of the exposed stone. This difference could not be attributed to (surface) moisture, which was not found to differ between two sections of wall on the survey day. Moisture reaching the wall may vary during wet conditions however, given the covered part of the wall was completed shrouded in ivy foliage. These data indicate that the condition of the stone is poorer in areas without a cover of ivy, but given that the precise history of this wall is not known the measured differences cannot be conclusively attributed to protection by ivy.

4 CASE STUDIES

This section of the report details observations, both qualitative and quantitative, at a range of case study sites that have been undertaken during the course of the research. The case studies included here are only a selection of the sites that have been studied (see Table 1-3) but have been chosen to illustrate the nature of observations made, the challenges of researching and managing ivy on historic stone and buildings, and to support core findings presented in other sections of this report. A range of additional case study information can be found in the Phase 1 seminar report: http://www.geog.ox.ac.uk/research/landscape/rubble/ivy/

Case studies included in the following sections are:

1. **Walton Street cottage, Worcester College, Oxford**
   Observation of ivy removal and influence of ivy cover on damp in brick and stone.

2. **Thomas-a-Becket churchyard, Ramsey, Cambridgeshire**
   Removal of ivy and assessing the condition of gravestones under very dense ivy cover.

3. **Garden wall, Warnham, West Sussex**
   Observation of removal of extensive ivy growth on a brick masonry wall, and assessment of ivy influence on brick moisture and deterioration.

4. **St. Mary's Church, Marston-on-Dove, Derbyshire**
   Observation and management of ivy growing within stone masonry walls.

5. **Gleaston Castle, Cumbria**
   Observations of damage caused by extensive ivy growth within masonry walls.

4.1 Walton Street cottage, Worcester College, Oxford

This case study is used to illustrate:

- The challenges of substantial ivy allowed to grow unchecked on domestic buildings and roofs
- Evidence of ivy's influence on damp in stone and brick masonry, and how this can vary between materials, aspect and height

4.1.1 Site description and research activities

Considerable ivy growth up the side of a stone cottage (limestone construction with brick side extension) was investigated within the grounds of Worcester College in central Oxford. Growth had become a concern after reaching roof level and covering windows, with some stems starting to grow under roof tiles. The substantial outward growth of the canopy was also of concern, presenting risk of additional weight and possible wind-sail effects (Figure 4-1a). The plant was growing in a corner formed by one of the original west-facing stone walls and a north-facing brick extension wall. The main stem was growing against the brick, with additional stems and foliage extending up both the brick and stone masonry.

The ivy management strategy of the College gardeners had been to cut and remove a section of stem towards the base, and leaving the plant to die back without further removal. This could be seen on another section of the same building where ivy had been cut the previous year (Figure 4-1b). Conversations with the gardeners suggested this had worked well in the past (but see Section 2.4.4 and Section 5.1 regarding cutting ivy at the base).

In October 2013, ivy foliage was cleared away from the base of the brick wall so that sections (roughly 30 cm in length) could be removed from the main ivy stems using a hand saw (Figure 4-1c-d). The main 'trunk' of the plant was 13 cm in diameter at its widest point, and tree-ring analysis gave a minimum age of 11-12 years. Once cut, the mat of smaller stems growing against the wall could be easily lifted away and was subsequently also removed. When completed, all stems and foliage had been removed from the base of the walls to a height of around 1 m above ground level (Figure 4-1e-f). This left sections of exposed brickwork and stone from which ivy had been removed, and adjacent areas that had always been clear of ivy (Figure 4-2).

This presented an opportunity to examine the influence of ivy cover on damp. For this, moisture readings were made on sections of the brickwork and painted limestone using a Protimeter moisture meter (see Section 3.5). This was done roughly 2 hours after removal was completed. Whilst the removal and moisture measurements were made in relatively dry weather, the preceding week had been overcast with frequent rain showers. Ten readings were made in the centre of different bricks and stone blocks at 10 cm, 50 cm and 100 cm above ground level, in areas where ivy had been removed and adjacent bare areas (where ivy was never growing).


Figure 4-1. Photographs of ivy and its management on a stone and brick cottage, Walton Street, Oxford.

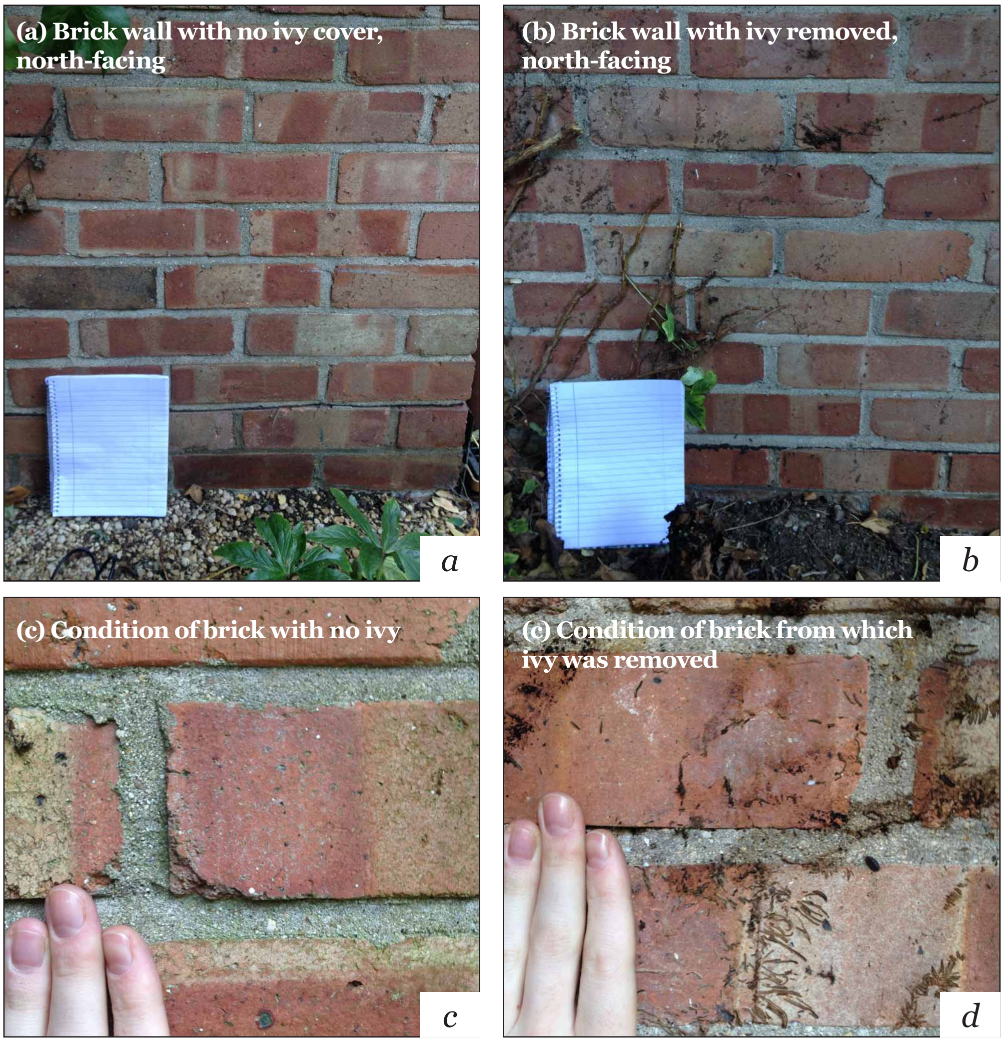


Figure 4-2. Areas of brickwork on which surface moisture readings were taken: (a) and (c) an area without any previous ivy cover; (b) and (d) adjacent area from which a complete cover of ivy has been removed.

4.1.2 Findings: was there any evidence of ivy influencing damp?

Moisture data are summarised in Figure 4-3. Significantly higher readings were made towards the base of the brick wall compared to higher up ($p < 0.001$). This is common where the ground is a source of moisture in walls, via capillary rise for example. Moisture readings also tended to be higher in areas where ivy had been removed from the brickwork, but this effect was very small (Figure 4-3a). These observations are comparable with those made at the test walls (Section 3.5).

In comparison with the brick, moisture readings for the limestone masonry were always higher, especially for the section with no history of ivy cover, which was quite damp (Figure 4-3b). Moisture patterns on this limestone wall were complicated, being influenced by a combination of both height and ivy cover. However, the overall difference between bare and ivy-removed sections was significant; the stone was significantly drier where ivy had been removed, irrespective of height above ground level ($p < 0.001$) (Figure 4-3b).

4.1.3 Key observations and implications

- Marked differences between adjacent brick and stone walls highlights the complicated nature of moisture patterns in buildings; aspect may explain some of the difference, as prevailing winds could have delivered more moisture to the west-facing limestone wall compared to the north-facing brick wall. The brick wall was also partially shielded by the rest of the cottage, which likely limits the amount of rainfall hitting this wall. Porous natural stone like limestone is also inherently more vulnerable to damp (including rising damp from ground level), although damp can be a problem for all masonry materials.

- There was little evidence of any influence of ivy cover on moisture in the brick wall, whereas height on the wall was most important.

- For the limestone wall, stone was significantly drier in areas where ivy had been removed relative to adjacent bare areas.

- The large difference that ivy cover appears to have had on the limestone wall indicates that ivy has either (1) acted as a rain-shield in the wet days prior to its removal or (2) ivy roots have been effective at removing water from the soil locally (especially if ground moisture is the main source of damp in this wall), or a combination of the two.

- The rain-shielding influence of ivy on walls may be most effective for aspects that receive most driving rain under prevailing winds.

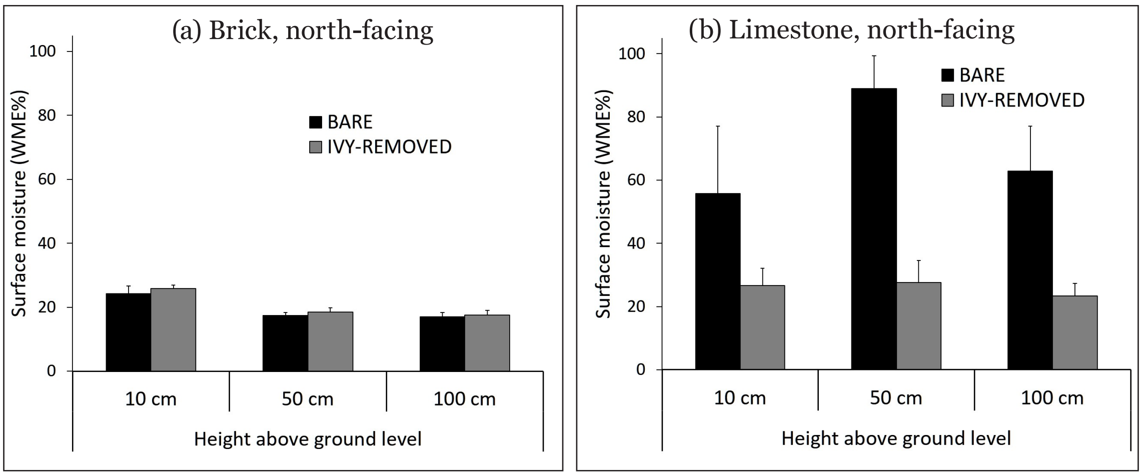


Figure 4-3. Surface moisture of a brick and limestone wall in areas where ivy had recently been removed, and adjacent areas free of ivy growth, Walton Street, Oxford. Average + SD of ten measurements in each location made using a Protimeter.

4.2 Thomas-à-Becket churchyard, Ramsey, Cambridgeshire

This case study is included to illustrate:

- What difficulties may be expected when removing a dense, well established, but not rooted in, covering of ivy
- What surface damage might be expected under dense ivy cover
- Implications for site management

4.2.1 Site description and research activities

St Thomas-à-Becket Churchyard, Ramsey, Cambridgeshire, contained extensive and unusual ivy growth. The churchyard contained a remarkable, probably unique, number of gravestones completely encased in ivy growth. Individual stones, and in some cases whole rows of stones, were encased, often with neighbouring stones fully exposed (Figure 4-4). In March 2008 the project team were brought in to assess the impact of the ivy on gravestones. All ivy was removed from three gravestones and partially removed from a fourth to serve as a demonstration.

Although gravestones may seem somewhat removed from the building walls which were the main focus of this research, there are useful parallels to be drawn from ivy's impact on gravestones and stone wall surfaces. The need to avoid damage to the stone surface and carved features during removal, and the state of stone conservation beneath the ivy could help to inform other projects where ivy removal is necessary.

Figure 4-4. St Thomas-à-Becket churchyard, Ramsey, Cambridgeshire ©Alan Cathersides.

Ivy covered stones were first categorised into 4 classes:

- **Juvenile** - stones with young growth/s of ivy growing up one or both sides, but where individual ivy stems were very clear and a large proportion of the gravestone was visible (Figure 4-5a).
- **Shroud** – stones which were completely covered with ivy, with very little, if any, stone showing on either side and ivy growths cascading down from the top increasing the thickness of the cover, but with no flowering/arboreal growth present (Figure 4-5b).
- **Shrub** – stones as above, but where the woody flowering stems of ivy had been produced over the whole structure, from ground level up to and above the top of the stone (Figure 4-5c).
- **Shrub & Shroud** – similar to 'shroud' but where the woody flowering stems had been produced at the top of the stone only, not all the way down to the ground (Figure 4-5d).

Ivy was removed completely from one example each of 'Shrub', 'Shroud' and 'Shrub & Shroud' types.

(a) Juvenile | (b) Shroud | (c) Shrub | (d) Shrub & Shroud

Figure 4-5. Four types of ivy cover: (a) Juvenile; (b) Shroud; (c) Shrub; (d) Shrub & Shroud. Ramsey, March 2008 (all ©Alan Cathersides).

Removal was carried out using hand tools only – secateurs, loppers and hand saws (Figure 4-6a) to reduce the risk of damage to the gravestones beneath. In each case work began at the outer extremities of the ivy growth, with shoots cut and removed in easily handled lengths. Care was taken to remove only freely-cascading growth first (Figure 4-6b) and, where stems were entangled, to cut them free before removal to avoid pulling too sharply and risk damaging gravestone features. In this manner the growth was gradually removed until the framework of main stems affixed to the gravestone were fully exposed (Figure 4-6c).

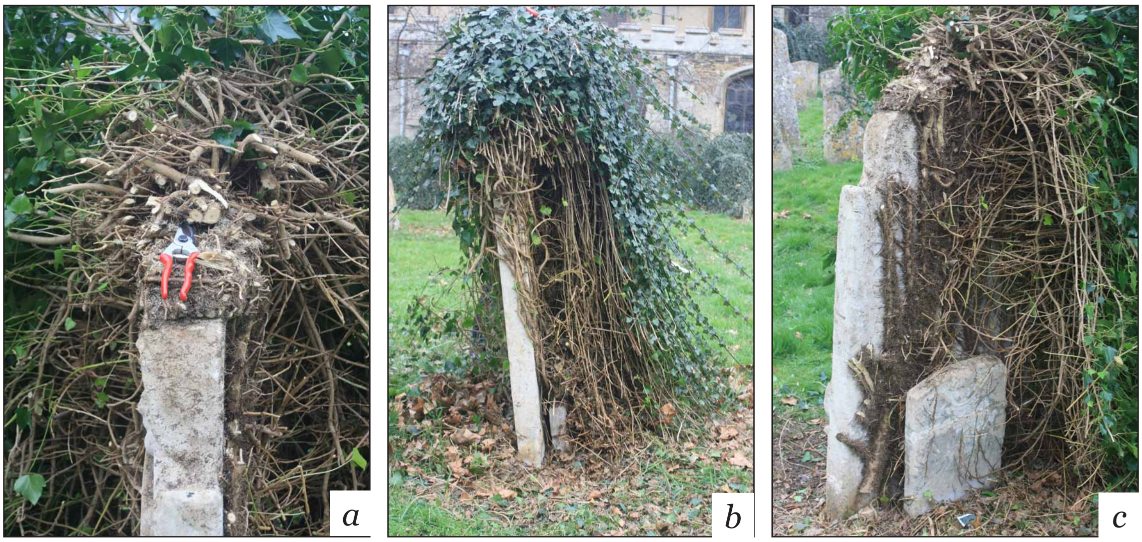


Figure 4-6. Ivy removal: (a) sample of tools used for ivy removal; (b) removal of cascading ivy first; (c) framework of main stems, Ramsey, March 2008 (all ©Alan Cathersides).

4.2.2 Findings

Difficulties and considerations when removing a dense, well established, but not rooted in, cover of ivy included:

- Once the top of gravestones had been cleared and the stems running down the sides were cut, the rest of the framework proved surprisingly easy to simply peel away from the face of the gravestone (Figure 4-7a).

- Juvenile stems of ivy were found to be harder to remove than older stems. This indicates that ivy depends on the initial adhesion of aerial rootlets from a young stem to stay in place and that the adhesion mechanism is not continually refreshed on older stems (Figure 4-7c). This supports observations of plants 'releasing' from walls slightly as they age (Section 2.2).

- Ivy removal by hand is advisable when dealing with unknown factors such as fragile or intricate features (Figure 4-7e). Two people working methodically and carefully to prevent damage and record the process could remove ivy from heavily covered, large gravestone in 45 to 60 minutes.

- It might be worth considering whether ivy removal during the cold winter months is advisable, as the sudden exposure of stonework might be more damaging via thermal shock. Ivy removal at other times of the year when stone can acclimatise more gradually might be a better option. Uncovering already damaged stonework could result in increased damage by exposing already vulnerable surfaces to weathering agents (Figure 4-7f). Conversely, a dense covering of ivy can prevent detection of serious flaws.

Figure 4-7. (a) main framework of stems peeling away from stone surface; (b) growth between gravestones and 'footstones'; (c) juvenile stems adhered more firmly to the surface than older stems; (d) example of ivy 'hedge' behind row of uncovered stones; (e) removal of ivy from fragile or intricate features needs to be undertaken with care; (f) flaws or previous damage may be protected by a covering of ivy but put at risk if exposed; (g) aerial rootlet marks left once stems are removed; (h) and (i) brown staining on gravestones. Ramsey, March 2008 (all ©Alan Cathersides).

What evidence of surface damage was found under the ivy?

There was little evidence that ivy coverings had caused any physical damage on the four gravestones uncovered. The aerial rootlets had not penetrated into the stones and in most places did not appear to have any marked impact on stone surfaces. However, in some cases these aerial roots left clear marks. These marks were not visibly etched into the stone but were probably the result of aerial rootlets shielding part of the surface whilst the surrounding area was exposed to weathering (Figure 4-7g). On two of the uncovered stones there was clear evidence of brown staining directly associated with the branch network (Figure 4-7h and Figure 4-7i). This did not appear to be associated with the ivy stems/branches, but with the accumulation of organic matter above branches which can begin to decay and release humic acid. This staining may disappear over time as the stone continues to weather.

4.2.3 Key observations and implications

- In each case ivy stem/s were close to, or wedged between, the main gravestone and smaller 'footstones'. This had presumably been done to make maintenance easier but had inadvertently provided a spot for ivy seedlings to establish protected from strimmers and mowing (Figure 4-7b).

- All stems which touched the ground layered – producing proper roots from leaf nodes. In this location it had led to some rows of stones effectively becoming ivy 'hedges' as the low stems between gravestones layered (Figure 4-7d). Contact with soil and moisture from the ground are key triggers for true root initiation as opposed to the aerial 'climbing' rootlets (see Section 2.4.1).

- Nesting birds commonly use thick ivy cover. Removal should be undertaken outside the nesting period (Mar–Aug) where possible. If this is not feasible, ivy should be checked to ensure there were no nesting birds and work stopped if necessary. Under the Wildlife and Countryside Act 1981 it is an offence to 'take, damage or destroy the nest of any wild bird while that nest is in use'.

- Sections cut from main stems showed it can take as little as 7 years for unchecked ivy to completely cover a gravestone.

- There was no clear evidence such massive growths of ivy on individual gravestones have a de-stabilising effect. In the case of the 'shroud' types of growth, ivy may even have a stabilising effect by making a tall narrow object only slightly taller but much wider. This may also apply to the 'shrub' growth type. Arboreal, flowering ivy growths do make gravestones notably taller, however. The 'shrub and shroud' type of cover, with large amounts of flowering growth atop gravestones, may make them 'top heavy' and will have an additional 'windsail' effect. There was only one example of a toppled gravestone which was covered in ivy, but it was impossible to determine whether the stone itself had a pre-existing flaw or whether vandalism was involved.

4.3 Garden wall, Warnham, West Sussex

This case study is included to illustrate:

- The efforts required to remove well-established ivy from brick masonry
- Qualitative observations and quantitative evidence for the influence of extensive ivy growth on the condition (moisture content and hardness) of brick masonry

4.3.1 Site description and research activities

An opportunity arose for the project team to attend and assist in the removal of extensive ivy growth from a domestic, free-standing brick masonry wall in the village of Warnham, West Sussex. The site was first visited on 26 September 2014 when removal was undertaken by members of 'Horsham Green Gym'. The purpose of the removal was to reinstate use of a private garden (including some concern the ivy was making the wall unsafe), and to remove considerable overhang of ivy in an adjacent car park (Figure 4-8).

The wall was constructed to two heights (2.5 m and 1.5 m high sections), oriented ESE–WNW, and formed the boundary between a private garden and a car park. Conversations with owners of the adjoining properties suggested the original structure dated from *c*.1890. On closer inspection it was found that a newer brick capping had been added at an unknown date. This capping could be distinguished from the main (lower) portion of wall by being less weathered/discoloured. Once fully removed, at least two different periods of construction/extension were also identified, but these could not be dated with any great confidence. These factors were taken into consideration to ensure valid comparisons as far as was possible.

The wall itself appeared generally sound but had some degree of 'give' if pushed with the full weight of 2 to 3 people; this had given cause for concern about the additional weight of the substantial arborescent ivy growth. The purpose of the investigation was to:

1. Record the nature of ivy growth on the structure prior to removal.

2. Observe the process of removal i.e., its relative ease or difficulty.

3. Observe and record any evidence of damage to the brickwork under ivy.

4. Collect quantitative evidence of any possible influences of ivy on wall moisture and brick condition (assessed as surface hardness).

Nature of ivy growth

Ivy was growing up from the base of the south-facing side of the wall, against the taller section, with a large canopy of arborescent growth reaching at least 2 m above the wall top. The canopy overhang was 1 m on the south side and 1.5 m on the north side of the wall (Figure 4-8a-b). The middle section of the southern aspect was entirely covered (from base to top) in a dense mat of stems and foliage (Figure 4-8c). The canopy overhang on the north side extended down to 1 to 2 feet above ground level (Figure 4-8a). A section of the wall was entirely free of ivy on both sides (no climbing growth and no canopy cover) providing ideal 'control' comparisons with the covered sections of wall. A section cut from the main stem indicated that the plant was at least 23 years old.

Figure 4-8. Ivy canopy prior to removal (a) north-facing side of the wall; (b) south-facing side of the wall (c) mat of stems growing against the wall surface. Warnham, 2014.

Removal of ivy growth

The ivy was removed by a team of 8 to 10 volunteers. The strategy adopted was, first, to cut back and remove the higher canopy growth, second, to cut back the foliage of the climbing growth (against the wall), and third, to remove the root/stem mat from the wall face. This was done using a saw and garden pruning shears (and brute force) working simultaneously in two teams on both sides of the wall. Given the considerable amount of arborescent growth, care was taken to ensure that roughly equal amounts of growth were removed from both sides of the wall at the same time, to reduce the risk of toppling by uneven weight distribution (Figure 4-9).

The amount of growth removed was more than enough to fill a standard skip (Figure 4-9d), taking 4 to 5 hours of continuous work. The 'root mat' that clung to the wall face was removed in sections by sawing across the woody growth to the wall face, and using leverage with a crow-bar and blade of a garden shovel (this approach was largely under the instruction of the property owner who was adamant that all, or at least as much as possible, of the ivy should be removed). These sections were formed of dense growths of climbing shoots and aerial rootlets forming a layer against the wall up to 5 cm thick (Figure 4-9e-f).

Whereas all of the ivy canopy and most of the climbing growth was successfully removed, the section containing the main 'trunk' (including where the ivy was rooted into the ground) was exceptionally rigid and thick. Attempts to snap this growth using leverage raised concerns about the stability of the wall, and it was decided that this section of growth (the middle portion of the southern face of the wall) should be left, and that it was probably affording some degree of structural support for the wall (Figure 4-10b).

Figure 4-9. Spreading flowering stems were first removed, followed by vertical foliage covering the wall. The dense mat of stems was sawn and prised off using a crow-bar were possible.

Figure 4-10. (a) Before removal (b) post-removal (notice the section of growth including the main 'trunk' that could not be removed due to structural concerns.

4.3.2 Findings

The 'root mat' covering the wall face was levered away in large pieces leaving the underlying wall intact; removing the mat did not pull away any of the main wall fabric, although the presence of fine, light-coloured powder on the aerial rootlets was probably mortar dust. Relative to an adjacent bare section of wall, growth of aerial rootlets into mortar joints was associated with loss of the mortar, which was visibly more recessed where ivy was removed (Figure 4-11). Inspection of the underside of the root mat (the side in contact with the wall face) showed that attachment was largely superficial (via aerial rootlets) with no evidence of 'rooting-in' to the main wall fabric. The underlying pattern of pointing was clearly imprinted into the dense mat of rootlets (Figure 4-12a).

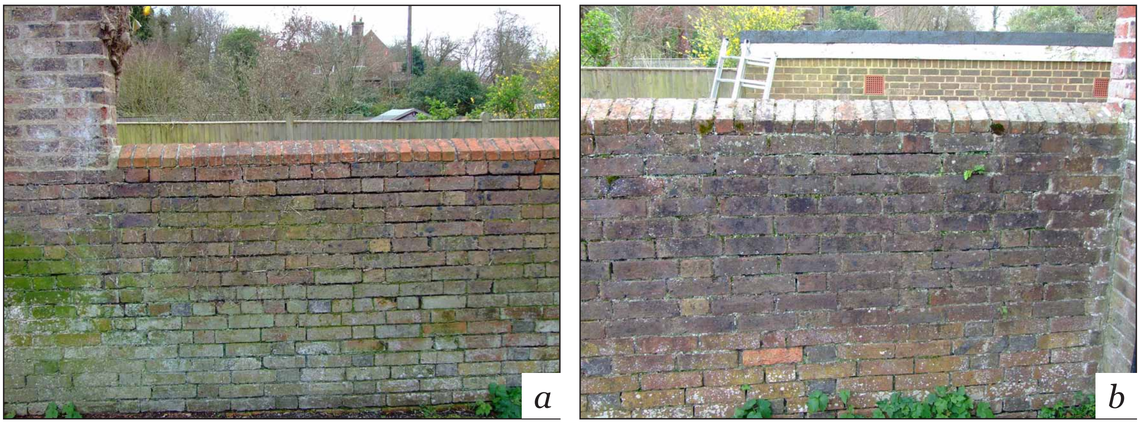


Figure 4-11. Sections of wall from which ivy was removed (a) and adjacent area without any ivy cover (b). Note slightly recessed mortar joints where ivy was removed.

The majority of the brickwork beneath was in remarkably good condition. Some individual bricks were more deteriorated than others (Figure 4-12c), but this was observed in areas both with and without ivy. This deterioration was much more likely attributable to variations in the original composition/physical characteristics of individual bricks rather than ivy cover and may have been present before the ivy grew. Numerous and clearly visible aerial rootlets were left attached to the surface of the brickwork once stems were removed, illustrating the aesthetic damage that can be caused once ivy is taken off (Figure 4-12b).

There were, however, instances where damage was likely attributable to thickening of stems growing within mortar joints. This included isolated bricks being punched out and cracking parallel to the joint orientation, possibly the result of stresses induced by thickening stems (Figure 4-13a and b).

Figure 4-12. (a) mortar joint imprint on underside of ivy root mat; (b) aerial rootlets attached to bricks after removal of stems; (c) evidence of deterioration (present in both ivy covered and bare areas).

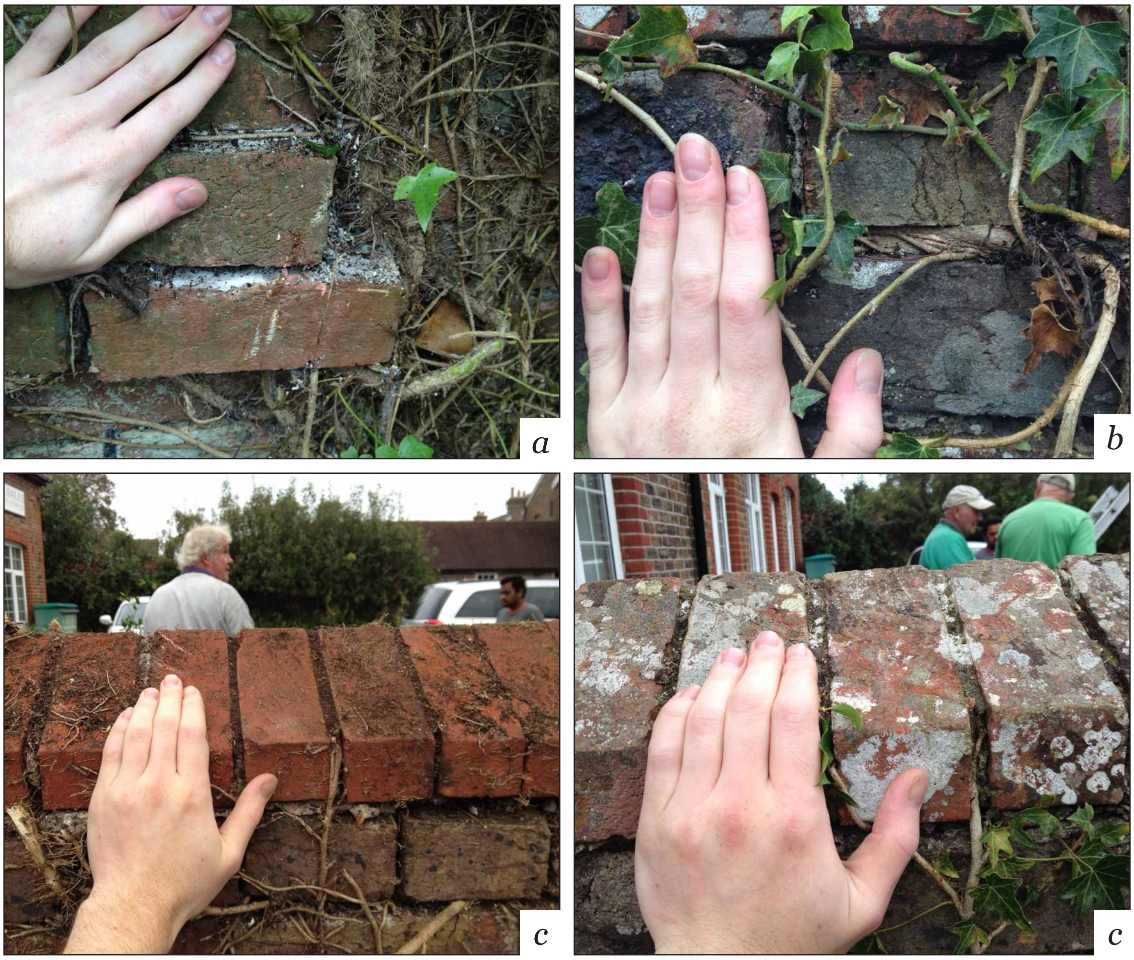


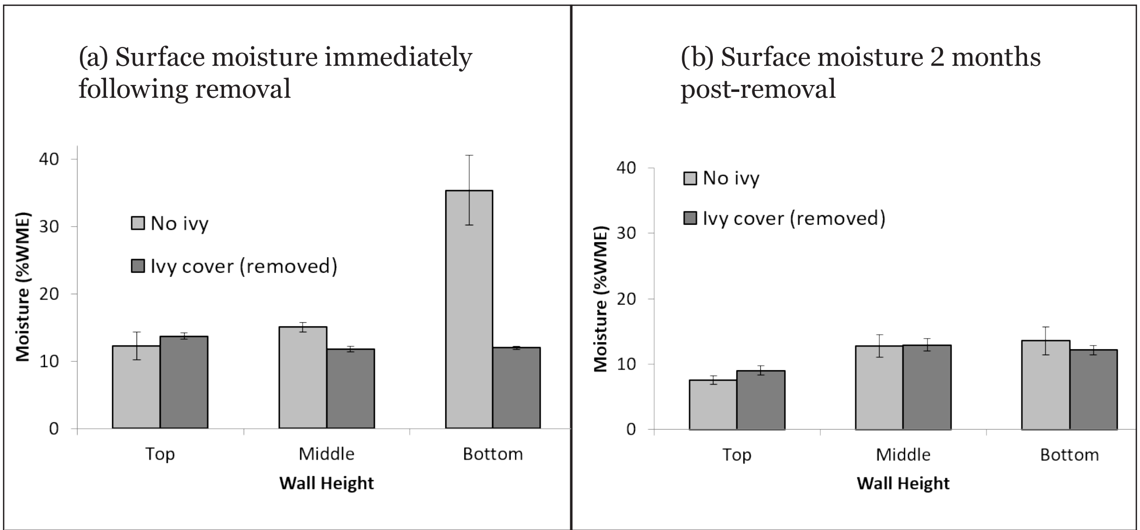
Figure 4-13. (a) Punched-out bricks; (b) evidence of stress cracking that may be caused by thickening ivy stems in mortar joints; (c) previously ivy-covered bricks clear of any other growth; (d) bricks not covered by ivy showed a wealth of lichen growth.

Ivy cover had a clear effect on colonisation by other organisms, particularly lichen. Bricks beneath the ivy canopy were notably bare of lichen compared to areas without ivy (Figure 4-13c and d). This is attributed to the canopy-forming effects of ivy foliage, excluding both light and moisture. The implications of differential lichen growth for weathering is largely unknown, but may have aesthetic implications for historic buildings.

Measurements of brick moisture

Three hand-held moisture meters were used on the wall, a Protimeter, CEM and FMW type. All three meters measure moisture in slightly different but similar ways, and are most useful when used in combination to identify relative differences in near-surface moisture content. Five different bricks were measured with each meter at the bottom, middle and top of the wall (on the southern aspect only). This was initially done on the day of removal, in areas where no ivy had ever been present and where ivy cover had just been removed.

In most cases patterns of moisture were similar in both sections of wall, irrespective of ivy cover. The overriding trend was for the base of the wall to be wetter, and the top drier. Interesting differences in surface moisture were detected using the Protimeter, however (Figure 4-14a). Whilst the tops of the walls were no different, the middle ($p < 0.001$) and in particular the bottom ($p < 0.001$) ivy-covered sections were significantly drier than adjacent bare areas (Figure 4-14a). This indicates that ivy had kept the surface of the bricks relatively dry, and also that moisture was far more consistent at different heights where covered with ivy in comparison to exposed areas of brickwork. To confirm this, moisture content was again measured in the same way, and on the same bricks, two months after initial removal of ivy. After this time the differences initially observed between bare and ivy-removed sections were no longer evident (Figure 4-14b). This very strongly indicates that when in place, ivy was acting to shield the surface from rain and keep it relatively dry (Figure 4-14a), but that this effect was no longer evident two months after removal, when the wall had equilibrated (i.e., dried and/or wetter to a similar degree) under atmospheric conditions.



** The Protimeter measures in %Wood Moisture Equivalent (%WME), used here as an arbitrary scale for relative comparisons between wall sections/ivy cover.*

Figure 4-14. Moisture readings of brick in areas with and without a cover of ivy taken (a) immediately after ivy was removed and (b) two months after ivy was removed. Measurements made using a Protimeter (average of 15 measurements, error bars indicate standard deviation).*

Measurements of brick hardness

Surface hardness was used as an indicator of weathering state for the brickwork, measured using an Equotip3 device (Viles et al. 2011). Hardness of the mortar could not be measured as the pointing was largely recessed and the surface extremely uneven (meaning that reliable data for mortar could not be obtained using the Equotip device).

Brick hardness was measured two months after initial ivy removal (in November 2014) in order to control for the possible influence of moisture content; allowing the entire wall to 'equilibrate' with respect to moisture content for a period after the ivy had been removed ensured a more reliable comparison of hardness using the Equotip (which is sensitive to moisture content). This approach meant that any differences in hardness after this time could be more firmly attributed to the weathering state of the brickwork. Hardness was measured at three heights (top, middle, bottom) taking 10 readings from four different bricks. This was repeated in two areas, one never knowingly having had any ivy cover, and one where ivy had been removed two months earlier. Hardness data are summarised in Figure 4-15, comparing 'bare' and 'ivy removed' sections of wall at the three measured heights.

The general trend was for slightly lower hardness values for the 'ivy removed' bricks. This was not statistically significant for the top and middle sections of wall, but was significant for the bottom section ($p < 0.001$). The difference in brick hardness between wall heights was also significant, regardless of prior ivy cover, perhaps indicating that other factors (such as the vertical distribution of moisture, Figure 4-14) may better explain overall patterns of deterioration.

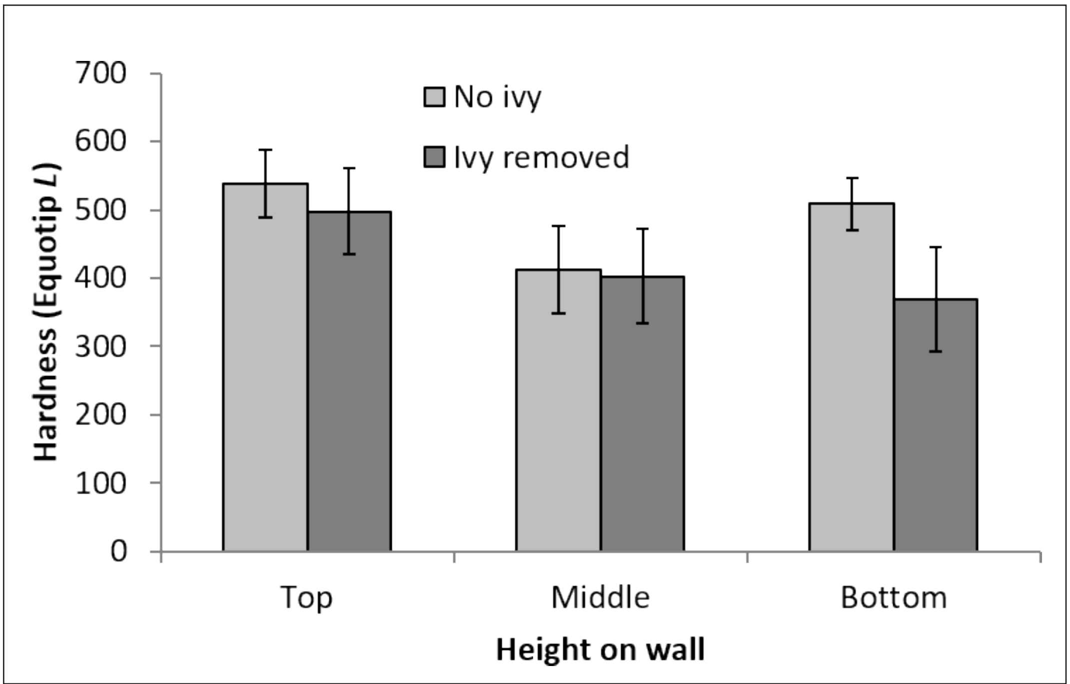


Figure 4-15. Surface hardness of brick for areas of a wall with no ivy and from which a complete cover of ivy had been removed two months earlier, at three different heights (median values ICR, n = 40).

4.3.3 Key observations and implications

- Free-standing structures can become completely engulfed with ivy where left to grow unchecked. This can pose particular problems when arboreal growth begins to overhang walls, adding significant weight to freestanding walls (and roofs and other structures).
- Removal of very well-established ivy is time consuming, and there is some danger of causing more damage to a structure if an aggressive stance is taken to its removal; if removal is necessary, approaching this in steps along with on-going assessment of the conditions/stability of the underlying structure is essential. Some growth (particularly main stems) may be impossible to remove completely, and it can be unwise to attempt to do so where this is affording some support to the structure.
- As with stone masonry, growing ivy stems can follow mortar joints in brick masonry structures, forming an extremely tight attachment to the wall surface. In this case study, removal of such growth did not cause any structural damage to the wall but did leave recessed joints exposed to the elements; repointing may be necessary where this is the case.
- Moisture patterns in this brick wall were more influenced by height (indicating a source of moisture at the base) rather than a cover of ivy. However, there was evidence that ivy had been acting to keep the base of the wall drier relative to exposed brickwork, as may be the case where ivy foliage acts as a rain shield.
- Hardness measurements gave some conflicting results, by indicating that brick was more deteriorated in areas where ivy had been removed (which were also found to be drier), but this was only true towards the base of the wall.
- Influences of ivy on the condition of masonry materials can be obscured/overridden by underlying problems, such as other sources of damp in walls. These problems, if undetected and rectified, may be enhanced where ivy is growing unchecked.
- Consistent influences of ivy cover on moisture in walls may be difficult to establish owing to context-dependent factors, such as the materials used in construction and local sources of moisture/damp.

4.4 St. Mary’s Church, Marston-on-Dove, Derbyshire

This case study is included to illustrate:

- Problems that may be caused by ivy stems growing within a wall
- Unexpected problems to consider

4.4.1 Site description and research activities

St. Mary’s Church is a Grade-I listed parish church (Figure 4-16). The main church dates from the 13th century but the porch was added later, probably during Tudor times. Concern had been expressed about ivy growth both inside and outside the church porch, which appeared to have no visible connection to the ground (Figures 4-17a, b & c).

A decision was taken to remove accessible foliage and trace the ivy stems to their point of origin, opening up sections of wall as necessary.

Figure 4-16. St Mary’s Church, Marston-on-Dove ©Alan Cathersides.

(a) External ivy growth. The newer porch wall is the redder stone on the left.

(b) Ivy growth within the porch.

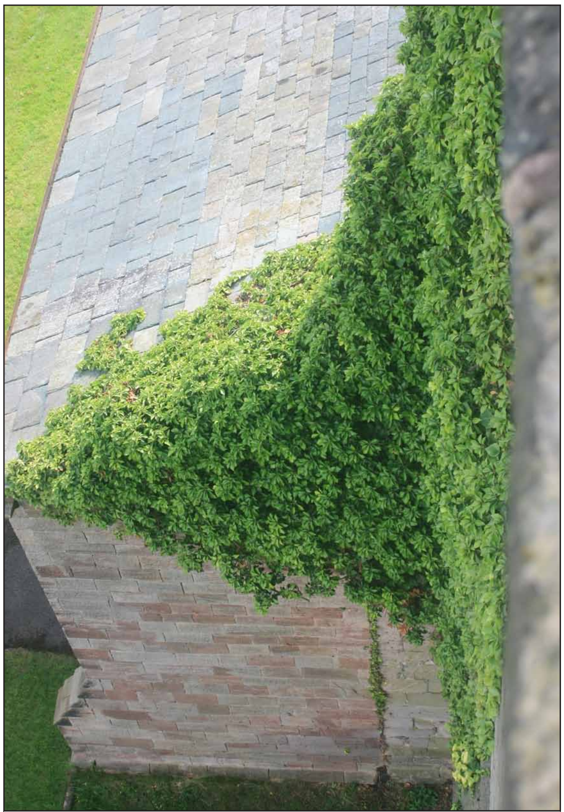
(c) External view of divide between main church and later porch (left).

Figure 4-17. Mary's Church ivy growth (all ©Alan Cathersides).

4.4.2 Findings

After the external foliage (Figure 4-18a) was cleared, it was apparent that it all originated from the join between the main church and porch (Figure 4-18b).

Stonework internally and externally was removed either side of the join (Figure 4-18c-d and Figure 4-19a) and revealed the main ivy stems growing from ground level up the crack between the main church wall and porch. Despite being rooted into the ground the ivy had, in this instance, also produced true roots. These roots had grown into the debris in the core of the wall (Figure 4-19a). As part of the investigation the ivy stems were removed from the structure and the stonework reset. A check was also made in the cramped roof space of the porch. The roof itself was in good condition and the space beneath was almost completely dark, however this space was unexpectedly found to be packed with ivy stems (Figure 4-19c).



(a) Porch from above with ivy on top of roof and growing up adjacent tower.

(b) After clearance of the extenal foliage it was clear that ivy had exploited the crack between new and old sections of the building, up its entire length.

(c) Initial removal of a single external stone revealed ivy stems and roots within the wall core.

(d) Removal of two external stones showed a mass of stems filling the crack and stems with true roots within the wall core.

Figure 4-18. Inspection of ivy growth on and within Mary's Church (all ©Alan Cathersides).

(a) Mass of ivy stems and roots within the core after removal of several layers of internal stone.

(b) Mass of compressed ivy stems removed from the base of the crack.

(c) Mass of ivy stems within the porch roof space.

Figure 4-19. Examples of damage by ivy at Mary's Church (a, b ©Alan Cathersides, c ©Jon Breckon).

4.4.3 Key observations and implications

- Close inspection of the church showed that the ivy had originally started growing externally at the base of the wall, but just inside a crack between the two sections of main church and porch. It was apparent that the ivy did not cause the crack, but was exploiting an existing and unchecked defect in the structure. With continued growth, the ivy could have made this defect worse.

- Unsuccessful attempts had been made to kill the ivy which had resulted in the accessible part of the stem being killed. However, the inaccessible parts of the plant were left alive, which then expanded further into the crack and continued to grow upwards. Stems were produced (with leaves) both internally and externally, where there was enough light to stimulate such growth.

- Growing stems had been removed were they were accessible, but at higher levels the remaining stems were clearly providing enough energy to sustain the plant's continued upwards growth.

- The mass of stems in the dark roof space was unexpected, but continued growth here was probably supported by successful growth elsewhere. Such a mass of growth could dislodge slates/tiles and in doing so make the structure more vulnerable to damage by water ingress, stimulate further growth by providing more light, and in dry conditions could also become a fire hazard.

- A key message from this case study is that regular structural inspection to identify and rectify defects is important. This should minimise the possibility of ivy taking hold where it (fortuitously) encounters these kinds of void spaces.

4.5 Gleaston Castle, Cumbria

This case study is included to illustrate:

- Problems that may be caused by ivy stems even when not rooted into walls

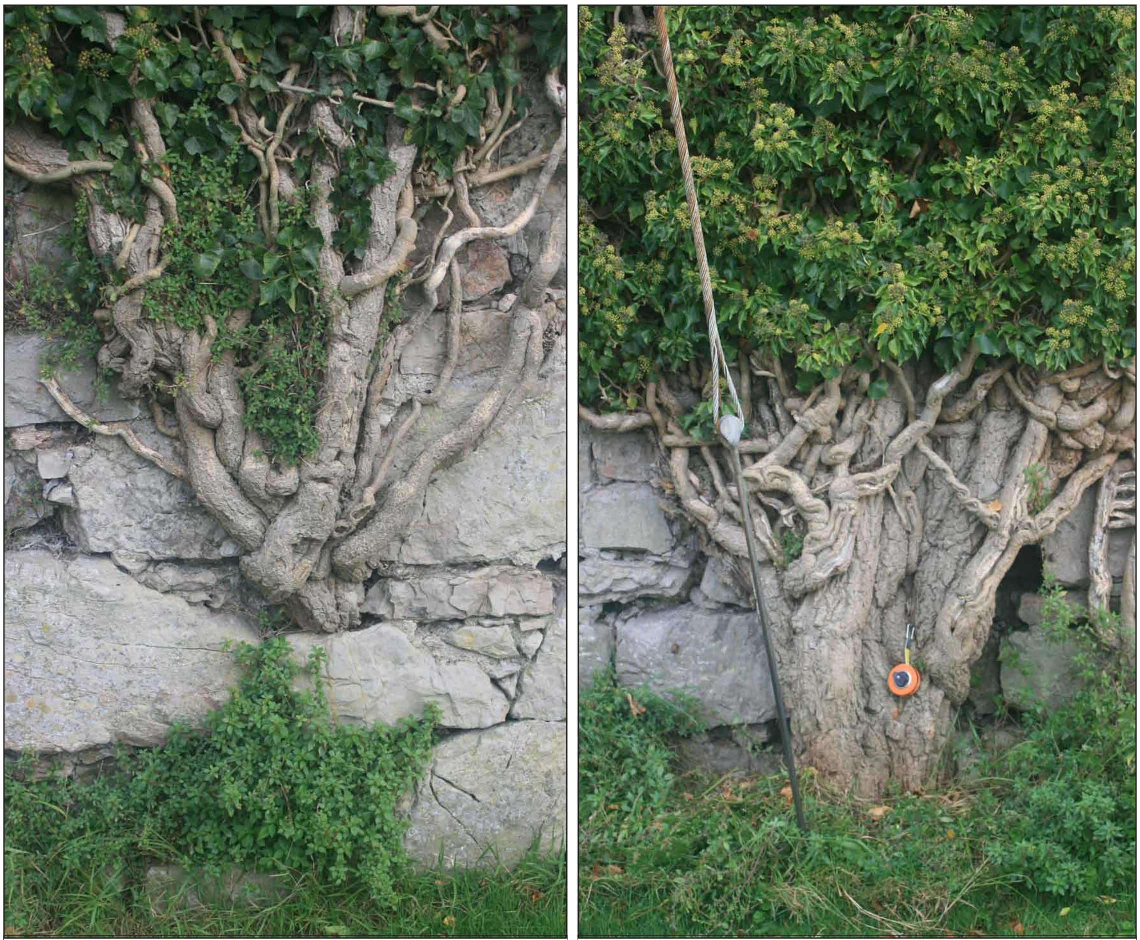
4.5.1 Site description and research activities

Gleaston Castle in Cumbria was built in the 14th century and is both scheduled and listed (Grade I). The ruins consist of several sections of curtain wall and the remains of two towers and the keep, which is still quite substantial (Figure 4-20). The nature of ivy growth and its interaction with the wall masonry structure was inspected in 2009.

4.5.2 Findings

There was a mix of vegetation over most of the remains and some sections had ivy clearly rooted into the structure (Figure 4-21a). However, most of the ivy on the keep originated from a very large (approx. 1 metre diameter) ivy plant rooted into the ground at the base of the keep (Figure 4-21b). Beyond the base, there was no indication that the stems from this plant had rooted into the walls over which they were growing.

Figure 4-20. Main tower of Gleaston Castle ©Alan Cathersides.



(a) Ivy rooted into structure of curtain wall. (b) Ivy at the base of the keep.

Figure 4-21. Ivy rooting into walls and the ground, Gleaston Castle (both ©Alan Cathersides)

Damage had been caused, however, by ivy stems following eroded mortar joints between the stones (Figure 4-22a). This mode of growth is quite regularly seen (Figure 4-22b-c) and may be associated with automatic 'tropisms' particularly in relation to touch (see Section 2.3) or to avoid water loss by keeping out of the wind and taking advantage of shade in recessed joints.

Initially, stem growth within mortar joints will not cause any problems, but as the stems increase in size stones or bricks can be pushed apart or, as was found at Gleaston Castle, stones can be levered out of the structure altogether (Figure 4-22d, also see Section 2.1.3 and other relevant sections in this report).

(a) Ivy stems following eroded mortar lines at Gleaston Castle.

(b) Ivy stems following eroded mortar lines at Dover Western Heights.

(c) Ivy stems following eroded mortar lines at Thornton Abbey.

(d) Stones at Gleaston Castle dislodged by expanding ivy stems.

Figure 4-22a-d. Features of damage by ivy growth along eroding mortar joints (all ©Alan Cathersides)

4.5.3 Key observations and implications

- Careful examination of all the issues is necessary. Rooting into a structure may not be the only cause for concern.
- Growing ivy stems that take advantage of channels created by missing or eroded mortar can cause damage as they get older and thicken. Where this is considered to be potential problem, removal at an early stage is advisable.
- This may only happen where structures are in poor condition to begin with (where mortar is eroding for example), but the force which expanding plant stems can exert should not be underestimated.

5 CONCLUSIONS AND RECOMMENDATIONS

A large amount of information has been gathered during the course of this research. This section uses the information collected in three ways: First, in section 5.1, to address the initial perceptions of ivy identified early on in the project (see Table 1-1). This is done in Table 5-1 which revisits the perceived benefits and problems of ivy and demonstrates how our research has refuted or confirmed these. Second, in section 5.2, to address the key research aims of the project by summarising the findings in Table 5-2. Third, in section 5.3, the findings are used to make some practical recommendations for managing ivy on historic sites.

5.1 Addressing perceived benefits and problems of ivy

Table 5-1 illustrates how our research findings support or refute the perceptions of ivy's impacts gleaned from a survey of clerks of works/ maintenance managers and gardeners at the start of the research project. Where we were able to collect objective data to address the issues, the colour shading exemplifies the level of confidence we have in the research findings.

Table 5-1. Research findings in relation to perceived benefits and problems of ivy noted by a sample of clerks of works/ maintenance managers and gardeners.
Green = high confidence; yellow = medium confidence. See Table 5-2 for more details.

Perceived benefits	Research findings to support or refute these perceived benefits
Keeps old walls sound	Ivy is an effective microclimate buffer, reducing extremes of temperature and relative humidity Ivy buffers against damaging frosts Ivy is an effective filter of airborne particulates
Provides a security barrier	Not covered by this research
Can help with weather-proofing (shields walls from driving rain)	Some evidence that ivy does shield walls from rain, at least towards the surface
Can give colour and texture to a building	Subjective observation Not directly covered by the research
Easy to grow	Extensive observation at numerous sites has shown that in most places ivy grows very easily
Can cover an unsightly building	Subjective observation. Not directly covered by the research
Can enhance the appearance of buildings	Subjective observation Not directly covered by the research
Good habitat for birds and insects	Not directly covered by this research; however, birds were often found to be nesting in ivy at a range of field sites The benefits of ivy for shelter and food provision for a range of birds and insects (including bees and butterflies) is well known (e.g., Thomas, 2010; Couvillon et al., 2015)

Table 5-1. Research findings in relation to perceived benefits and problems of ivy noted by a sample of clerks of works/ maintenance managers and gardeners. Green = high confidence; yellow = medium confidence. See Table 5-2 for more details.	
Perceived problems	**Research findings to support or refute these perceived problems**
Roots damage stone, mortars, pointing	Depends on whether there are pre-existing defects in the wall – ivy can exploit defects not create them
Triggers security lights	Not directly covered by this research; however, this problem can be solved by regular management of ivy growth.
Can cause damp/ maintains moisture on wall surface	Some conflicting results: some evidence that ivy cover reduces evaporative water loss and may keep wall surfaces wetter than non-ivy covered areas; this effect appears minimal
Rootlets leave marks on the stonework	Yes, when stems are removed. These marks are superficial
Can grow onto other people's property	Indisputable. However this can solved by regular ivy management.
Lifts copings and slates	Ivy can exploit cracks and spaces between slates and coping stones, but not create them.
Grows into glass windows	Not directly covered by this research Ivy cannot actively break through glass, but it can enter through existing cracks/holes This problem can be minimised/solved by regular management of ivy growth
Can encourage insect infestations	Not covered by this research
Can grow up gutters and hoppers and get into drainpipes	Indisputable; however, this can also be solved by regular ivy management
Rootlets remove moisture and 'suck cement out of mortar'	No evidence found Ivy aerial rootlet attachment is entirely superficial

5.2 Addressing the research aims

Table 5-2 summarises the six main research questions posed at the start of the research project and the key findings derived from the field experiments at Wytham Woods, laboratory investigations and experiments, and the work carried out on the case study sites. The relevant sections of chapters 2 and 3 which contain the key results are cross referenced in this table.

Table 5-2. Summary of original research aims and key findings from this project

Research question	Summary of findings	Evidence
How does ivy respond to wall defects as it grows, and under what circumstances does it cause damage?	• The potential for ivy to cause damage to walls is primarily controlled by the presence and physical characteristics of defects, which varies depending on the general condition of the structure. • Ivy can only grow into walls where defects and internal cavities are already present. Ivy cannot actively 'bore' into masonry. • Climbing juvenile stems grow upwards in response to gravity and will, in most cases, 'exit' defects into order to continue upwards were it is possible to do so. The exception to this is where a stem grows into a small defect (such as a hole or crack) and is unable to exit due to a lack of space to turn. In such instances, stems will either die or continue to grow into the wall if internal cavities already exist. • The growth of stems along contours of walls and in mortar joints means that thickening as the plant ages can cause damage if growth is constricted. The extent of such damage will depend on the type of construction materials (i.e., their physical strength) and the condition of wall (i.e., whether mortar has deteriorated and been lost). • Arboreal (adult flowering) growth often occurs when ivy reaches the top of the structure it is growing on. This form of growth is spreading rather than clinging/climbing. Adult growth may prove problematic if left unmanaged, due to additional weight and possible wind-sail effects.	Section 2.1, p10 Section 2.2, p20
When does ivy root into walls?	• The formation of true roots from ivy stems growing on walls can cause considerable structural damage, but this process is complicated and not well understood. • Ivy stems growing on the surface of walls, and the majority of stems growing in existing defects, will not produce true roots. However, moisture, darkness and the presence of fine weathered material (protosoil) can favour root initiation.	Section 2.4, p31
How do aerial rootlets affect vulnerable building materials?	• Aerial rootlets are covered in microscopic hairs that secrete a glue-like substance. Deformation of the hairs within surface microtopographical features braces rootlets tightly against the surface. Microscope observations show that this attachment is entirely superficial – aerial rootlets do not penetrate into the materials they are attached to, and they do not extract moisture or nutrients. • Attachment is remarkably strong and attempts to remove stems from walls will leave marks that may be an aesthetic problem. Forceful removal from weak and deteriorating walls can also cause damage by pulling off pieces of masonry along with stems.	**Section 2.5, p38**

Table 5-2. Summary of original research aims and key findings from this project

Research question	Summary of findings	Evidence
Does a cover of ivy influence stone deterioration/ weathering rates?	• Ivy is an effective microclimate buffer, reducing extremes of temperature and relative humidity, and limiting the frequency and range of variations over time. This may limit the efficacy of some weathering processes. • Ivy buffers against damaging frosts (the frequency, duration and magnitude of freezing events are reduced under ivy). Laboratory experiments have shown that this influence can reduce rates of stone deterioration relative to exposed stone. This effect will depend on the general climate in which a wall is situated (frost protection may be greatest in northern England for example). • These influences on microclimate and frost seem consistent between different walls, but the strength of the buffering effect is affected by wall aspect to some extent. • Long-term monitoring of stone surface hardness (used as an indicator of deterioration) shows that ivy has had no influence over a period of a few years. Stone was neither harder nor softer under ivy compared to adjacent areas of exposed stone.	Section 3.3, p50 Section 3.6, p78
Is stone soiling reduced under a cover of ivy?	• Ivy is an effective filter of airborne particulates. A cover of ivy reduces the amount of airborne pollution reaching the face of walls, which can otherwise be involved in chemical deterioration and soiling of masonry. This effect is greatest in areas of high traffic volume. • In less polluted areas, discolouration of stone is primarily driven by seasonal patterns of moisture, temperature and light, which affect the growth of microorganisms. Wall aspect and height on a wall also influence patterns of stone darkening and greening. Ivy cover has a relatively limited influence on discolouration relative to these seasonal effects, but may slow down discolouration via shading effects.	Section 3.4, p64
Does a cover of ivy affect the moisture content of walls?	• Field observations show conflicting evidence of ivy's influence on wall moisture. Some walls appear wetter under ivy and some drier. This may depend on the materials and type of construction, as well as the dominant source of moisture getting into walls. • A cover of ivy probably shields walls from rainfall, limiting entry of moisture into the wall face. • Where ground-level moisture is a source of damp in walls, a cover of ivy may limit evaporative water loss due to elevated relative humidity and (in summer) cooler temperatures that occur beneath ivy foliage. • Long-term monitoring at test walls showed that near-surface moisture in stone masonry was consistently higher under a cover of ivy relative to bare walls; however, this difference was small and well within the typical range of seasonal variations in moisture. • ERT surveys of test walls showed that ivy probably has very little influence on deeper-seated moisture in masonry walls.	Section 3.5, p72

5.3 Managing ivy on historic walls

The research presented in this report shows that there can be positive benefits in having ivy growing on a structure, however it is also very clear that there are situations where ivy can be very damaging. The aim of this final section is to help owners and managers identify the different possibilities and enable them to prioritise where work may or may not be necessary in order to ensure that resources are used appropriately. Ivy should not be removed simply because it is there, or just because it looks untidy or because someone has an personal dislike of it as a plant. It should only be removed when there is good reason to do so and the effects of removal have been considered carefully.

In all cases the wildlife value of ivy should be taken into account (both positive and negative) and whenever complete removal, partial removal or management are undertaken these should be timed to avoid disturbing wildlife, particularly nesting birds.

5.3.1 Management options

Complete removal

There are some very clear situations where ivy should be removed. In all cases, the need for repairs such as re-pointing, re-setting stones or even partial rebuilding after ivy removal should be considered. In these situations ivy can be considered similar to other woody plants such as trees and shrub because damage will be caused by the continual increase in size of stems and/or roots.

Situations where complete ivy removal is advised include:

- Where the ivy is rooted into the structure. This may be obvious if the main stem originates from the wall, or closer inspection may be needed where the main ivy stem is rooted into the ground but has also sent 'true' roots into the structure.
- Where ivy stems are growing within the core of a wall, or through cracks/gaps/holes within the wall.
- Where ivy stems are utilising channels between bricks or stones, either caused by mortar erosion or building design with stones set forward of mortar joints
- Where stems are growing around or over protruding stones such as capping stones.
- Where stems are growing between faults, cracks or similar defects in a structure, even if still clearly only rooted into the ground.

Complete removal may also be considered important for the presentation of a monument or a particular aspect of it.

Partial removal

Partial removal of ivy growth may be an option to consider under certain circumstances. This can be particularly useful in helping to fully assess whether the ivy is damaging or not, where there are limited funds available or where a temporary 'holding operation' is required. With partial removal it is important to ensure the juvenile (climbing) stems are fully removed from the cutting point forwards to the growing tip. Ivy will regrow from the cut point, but this does not encourage the formation of 'true' roots which grow into the structure. Any portion of stem left between the cut point and the growing tip may, however, sprout 'true' roots (see Fig. 2-16a). The arboreal stems, which may grow in excess of three metres in length can be cut back to any point along their length and will regrow from this point.

Situations where partial removal may be advisable include:

- Where the arboreal (flowering) stems of ivy are growing outwards and rubbing against sections of the structure when moving in the wind.
- When the mass of ivy stems, particularly the arboreal stems, threatens to destabilise a structure.
- Where the structure needs to be inspected (removal of some growth, particularly dense arboreal growth may uncover enough of the structure for inspection, but this will not always be the case).
- Where the ivy is encroaching on particularly vulnerable or visually important parts of a structure.
- Where ivy is entering roof spaces or growing over gutters/downpipes or starting to cover windows, entrances or similar.

Management

Ivy growth can be managed in the same way as any plant growth. Regular cutting back of growing stems or arboreal growth as described above can be undertaken without detriment to the plant or the structure it covers. Management in this way needs to be undertaken on a regular, though not necessarily frequent, basis. Adopting a regime of pruning is an option if the partial removal of ivy has shown that it is not causing obvious deterioration of the structure. Regular management may be annually, biennially or even longer, as the scale of the work and vigour of the plant dictates.

Situations where management may be advisable include:

- Where the arboreal (flowering) stems of ivy are growing outwards and begin to rub against sections of the structure.

- Where it is necessary to maintain the mass of ivy stems, juvenile and/or arboreal, to a size which cannot de-stabilise a structure.

- Where the ivy needs to be kept away from a vulnerable or visually important parts of a structure.

- Where ivy must be prevented from entering roof spaces or growing over gutters/downpipes, windows, entrances or similar.

No action

There may be times when neither removal, partial removal nor management are appropriate and in these situations there can be advantages to leaving ivy in place both as a 'bio-protective shield' as described in this report, and where the covering is dense – as a measure to prevent more damaging tree or shrub species from establishing. This option is only advisable where the ivy is growing over a structure and is not rooted into it.

Situations where no action may be advisable:

- Where there are no funds for conserving and presenting any structures uncovered.

- Where the fabric of the structure is fragile and would be subjected to further deterioration if left exposed.

- Where ivy is growing on/in extremely fragile structures and removal would be detrimental to stability.

- Where a screen of vegetation could help protect the structure from the attention of vandals.

- Where there are no presentational issues for the site.

5.3.2 Considerations for the removal of Ivy

When ivy removal is considered the best option the following tips should assist the successful completion of the work:

Where ivy is not rooted into the structure

- Start the work from the top and outer edges of the growth. This has two advantages. First, if work has to stop for any reason there will be no problems, if it has started at the bottom, severing the stems from the roots, and work stops for any time the stems that are left may root into the structure. Secondly, the younger stems are generally the most difficult to remove, and once these have been taken off the older stems become progressively easier.

- Where the structure is in poor condition carefully levering the stems and aerial rootlets away from the face of the structure may be necessary to prevent loss of fabric.

- Remove the stems carefully in small sections. This is especially important if the structure is not in good condition, as any attempt to pull of large sections of stem could also bring down parts of the structure if the adhesion of aerial rootlets is stronger than the cohesion of the masonry.

- Stumps can be dug up (although this will require SMC if the area is scheduled) or left *in situ* and treated to prevent regrowth.

Where ivy is known to be already rooted into the structure

- Work may be started at any point, although starting at the edges and working back to the main stem may still be the easiest method.

- Stems should be removed in small sections and the aerial rootlets treated as above but it will also be necessary to tease true roots out of the structure. The majority of these will be found in the mortar joints with some occasionally in cracks or flaws in the masonry. Depending on how deeply-rooted the ivy is it may be possible to gently pull the whole root out, or it may be necessary to cut larger roots. All cut surfaces should be immediately treated to prevent regrowth – ivy does not re-generate from roots, but the root/stem interface (the section where root becomes stem) may have dormant buds that can regrow, and these are rarely obvious.

- The same care should be taken to avoid pulling on large sections of stem, to avoid dislodging sections of the structure.

- Where roots or stems thicker than 10 mm are cut and treated, it may be necessary to return and consolidate/re-point when the vegetation has completely died back/rotted away.

6 GLOSSARY OF TERMS

Aerial rootlets

Small protrusions produced from juvenile ivy stems for attachment to the growing surface. These rootlets do not take up moisture or nutrients from the supporting surface. In ivy these rootlets are usually produced on the stem between leaf nodes and they do not increase in size.

Arboreal growth

Adult phase of ivy growth when stems are non-clinging and woodier than juvenile stems. Leaves are non-lobed during this phase of growth. Flower and berry producing growth phase, with significance for wildlife.

Blind-ended defect

Defects in a structure which are accessible from one aspect only with no 'exit'. Shoots entering can only exit by growing round and out through the way they entered.

iButton®

A small data-logging device (the size of a pound coin) that record microclimate (hygrochrons® measure and log temperature and relative humidity at the same time).

CEM moisture meter

A hand-held moisture meter that indicates moisture content based on capacitance properties of the test surface. Data are collected on an arbitrary numerical scale.

Colorimetric

Measurement of some variable based on colour. For example, monitoring changes in stone surface greening (see 'Spectrophotometer').

Defect

Used in this context to denote an imperfection or artefact of deterioration of masonry structures.

ERT

Electrical Resistivity Tomography. A technique capable of visualising the resistivity (resistance) of a solid material to an electrical current. As resistivity is influenced by moisture, ERT is a useful method of detecting and visualising the distribution of moisture in walls.

Equotip

A non-destructive impact device that measures the hardness of a surface on a numerical scale. It works by firing a small impact body at a surface, and the level of rebound is indicative of surface hardness. Rebound values for masonry materials provide a relative indicator of condition, and can be used to track softening/hardening over time caused by different weathering processes.

Excrescence

A distinct outgrowth on a plant, here referring to nanoscopic 'bumps' on ivy root hairs that excrete glue-like substances in the attachment process of aerial rootlets.

Juvenile growth
Non-flowering phase of ivy growth characterised by climbing stems that attach via aerial rootlets.

Masonry
The collective term for blocks of stone or bricks arranged together to form a structure. Also see 'Pointing'.

Microclimate
The characteristics (pattern and variability) of temperature and relative humidity in a particular location. Microclimate can differ greatly from the climate of the surrounding area depending on local factors such as aspect and shading.

N
Used when reporting statistical tests to indicate the number of samples or measurements. For example, an average temperature where n = 10 is the average value of 10 different readings.

Nm
Nanometre (1 nm = 1000 µm).

p value
The main result from commonly-used statistical tests. A *p*-value (a number between 0 and 1) indicates the probability that variations in measured data could have occurred by chance. A *p*-value of 0.05 or less is usually taken to indicate 'significant' differences between measured groups. A *p*-value of 0.01 or less indicates high statistical significance.

Pointing
Using cement or mortar to fill the joints between masonry blocks.

Protimeter moisture meter
A hand-held moisture meter that indicates moisture content based on resistivity properties of the test surface. Data are usually collected on a %WME (percent wood moisture equivalent) scale.

Protosil
A poorly developed soil consisting of physically and partially weathering mineral debris. Protosoil is often present in cracks and crevices of deteriorating masonry walls and may be an important stimuli for ivy true root initiation.

Qualitative and quantitative
Relating to how something is judged or measured. Qualitative research often involves observation without measurement. Quantitative research involves measurement and the generation of (typically numerical) data. Quantitative data can be evaluated statistically and provides a more robust basis for making decisions. 'Semi-quantitative' research lies somewhere between the two.

R^2
A statistical term indicating the strength of a relationship between two variables. Values range between zero and 1, with values closer to 1 indicating a stronger relationship.

RH
Relative humidity. A measure of the amount of moisture in the air expressed as a percentage of the amount needed for saturation. Dependent on air temperature.

SD
Standard Deviation. Used as a measure dispersion/variation in a dataset. Typically shown as error bars or whiskers in graphs. A high SD indicates that measurements used to calculate an average have a wide range of values, whereas a small SD indicates that all measurements are relatively consistent around the average.

SEM
Scanning Electron Microscopy. An imaging technique that uses electrons rather than light to visualise a test surface. Allows observation at very high magnifications.

Spectrophotometer
A device capable of measuring reflection or transmission properties of a material as a function of wavelength. In this research the technique was used to quantify stone surface colour and darkening (soiling) over time.

Test walls
Purpose-built structures specifically for scientific research and monitoring. In this study test walls were built to replicate free-standing walls or ruined walls, on which ivy was grown and long-term monitoring undertaken.

Tropisms
A directional response of an organism (in this case growing shoots) to an external stimulus e.g., light (phototropism), moisture (hydrotropism) and touch (thigmotropism) and gravity (geo/gravitropism).

True roots (or primary roots)
Roots produced for obtaining moisture and nutrients, most commonly from the ground/soil but ivy can sometimes produce true roots within masonry structures. In ivy true roots are usually produced at leaf nodes and in suitable conditions these roots will grow larger and more extensive. See 'Aerial Rootlets' in contrast to true roots.

µm
Micrometre (1 µm = 1000 mm)

Weathering
The general term given to a range of different processes (physical, chemical and biological) that often act in combination to alter and/or break down materials like stone and brick over time.

7 REFERENCES

Abhijith, K.V., Kumar, P., Gallagher, J., McNabola, A., Baldauf, R., Pilla, F., Broderick, B., Di Sabatino, S., Pulvirenti, B. (2017). 'Air pollution abatement performance of green infrastructure in open road and built-up street canyon environments – A review'. *Atmospheric Environment* 162, 71-86. doi: 10.1016/j.atmosenv.2017.05.014

Ashbee, J. (2010). 'Ivy and the presentation of Ancient Monuments and buildings', in 'Ivy on Walls Seminar Report' (Chapter 2), English Heritage (now Historic England), 9-15.

Bannister, P. (1976). *Introduction to Physiological Plant Ecology*. Oxford: Blackwell Scientific Publications

Bartoli, F., Romiti, F., Caneva, G. (2016). 'Aggressiveness of *Hedera helix* L. growing on monuments: Evaluation in Roman archaeological sites and guidelines for a general methodological approach', *Plant Biosystems* 151, 866-877. http://dx.doi.org/10.1080/11263504.2016.1218969

Bolton, C., Rahman, M.A., Armson, D., Ennos, A.R. (2014). 'Effectiveness of an ivy covering at insulating a building against the cold in Manchester, U.K.: A preliminary investigation'. *Building and Environment* 80, 32-35.

Brimblecombe, P., Grossi, C.M. (2005). 'Aesthetic thresholds and blackening of stone buildings', *Science of the Total Environment* 349, 175-189.

Cameron, R.W.F., Taylor, J. Emmett, M. (2015). 'A *Hedera* green façade – Energy performance and saving under different maritime-temperate, winter weather conditions', *Building and Environment* 92, 111-121.

Carter, N.E.A., Viles, H.A. (2006). 'Ivy on walls: scoping report' (unpublished report to English Heritage).

Couvillon, M.J., Walter, C.M., Blows, E.M., Czaczkes, T.J., Alton, K.I., Ratnieks, F.L.W. 2015. 'Busy Bees: Variation in insect flower-visiting rates across multiple plant species', *Psyche 2015*, Article ID 134630, 7 pages.

Cutler, N.A., Viles, H.A., Ahmad, S., McCabe, S. and Smith, B.J. (2013). 'Algal 'greening' and the conservation of stone heritage structures'. *Science of the Total Environment* 442, 152-164.

Darlington, A. 1981. *Ecology of Walls*. London: Heinemann Educational Publishers.

Dover, J.W. 2015. *Green Infrastructure. Incorporating plants and enhancing biodiversity in buildings and urban environments*. Abingdon: Routledge

Dunham, C.W. (accessed 2014) 'Cloning your Ivies'. http://ivy.org/about_bv5.htm (last accessed February 2018)

Eklund, J.A., Zhang, H., Viles, H.A., Curteis, T. (2013). 'Using hand-held moisture meters on limestone: some factors affecting their performance and guidelines for best practice'. *International Journal of Architectural Heritage* 7(2), 207-224.

Esmon, C.A., Pedmale, U.V., Liscum, E., (2005). 'Plant tropisms: providing the power of movement to a sessile organism', *The International Journal of Developmental Biology*, 49(5-6), 665-674.

Fearnley-Whittingstall, J. (1992). 'Ivies', London: Chatto & Windus

Feldman, L.J., (1984). 'Regulation of Root Development', *Annual Review of Plant Physiology*, 35(1), 223-242.

Girouard, R.M. (1967a). 'Initiation and development of adventitious roots in stem cuttings of *Hedera helix*: anatomical studies of the juvenile growth phase', *Canadian Journal of Botany*, 45(10), 1877-1881.

Girouard, R.M. (1967b). 'Initiation and development of adventitious roots in stem cuttings of *Hedera helix*: anatomical studies of the mature growth phase', *Canadian Journal of Botany,* 45(10), 1883-1886.

Goudie, A.S., Viles, H.A. (1995). 'The nature and pattern of debris liberation by salt weathering: a laboratory study'. *Earth Surface Processes and Landforms* 20, 437-449.

Grime, J.P., Hodgson, J.G., Hunt, R. (1988). *Comparative Plant Ecology: A Functional Approach to Common British Species*. London: Unwin-Hyman

Grossi, C.M., Esbert, R.M., Diaz-Pache, F., Alonso, F.J. (2003). 'Soiling of building stones in urban environments'. *Building and Environment* 38(1), 147-159.

Grossi, C.M., Brimblecombe, P., Harris, I. (2007). 'Predicting long term freeze-thaw risks on Europe built heritage and archaeological sites in a changing climate'. *Science of the Total Environment* 377, 273-281.

Häder, D.-P and Lebert, M. (eds.). 2001. *Photomovement*. Amsterdam: Elsevier

Hart, J.W. (1990). *Plant Tropisms and other Growth Movements*. London: Unwin-Hyman

Hanssen, S.V. and Viles, H.A. (2014). 'Can plants keep ruins dry? A quantitative assessment of the effect of soft capping on rainwater flows over ruined walls.' *Ecological Engineering* 71, 173-179.

Huang, Y., Wang, Y., Tan, L., Sun, L., Petrosino, J., Cui, M-Z., Hao, F. and Zhang, M. 2016. 'Nanospherical arabinogalactan proteins are a key component of the high-strength adhesive secreted by English ivy', *Proceedings of the National Academy of Science of the United States of America* 113, 3193-3202.

Ingham, J.P. (2005). 'Predicting the frost resistance of building stone'. *Quarterly Journal of Engineering Geology and Hydrogeology* 38, 387-399.

Janhäll, S. (2015). 'Review on urban vegetation and particle air pollution – Deposition and dispersion'. *Atmospheric Environment* 105, 130-137.

Lundholm, J., Tran, S., Gebert, L. (2015). 'Plant functional traits predict green roof ecosystem services'. *Environmental Science & Technology* 49, 2366-2374.

Marshall, R.H., McAllister, H.A., Armitage, J.D. (2017). 'A summary of hybrids detected in the genus *Hedera* (Araliaceae) with the provision of three new names'. *New Journal of Botany,* 7(1), 2-8.

Massa, G.D., Gilroy, S. (2003). 'Touch modulates gravity sensing to regulate the growth of primary roots of *Arabidopsis thaliana*', *The Plant Journal for Cell and Molecular Biology*, 33(3), 435-445.

Matsuoka, N. (1990). 'Mechanisms of rock breakdown by frost action: An experimental approach'. *Cold Regions Science and Technology* 17, 253-270.

McAllister, H.A., Rutherford, A. (1990). '*Hedera helix* L. and *H. hibernica* (Kirchner) Bean (Araliaceae) in the British Isles'. *Watsonia*, 18, 7-15.

Melzer, B., Seidel, R., Steinbrecher, T., Speck, T. (2011). 'Structure, attachment properties, and ecological importance of the attachment system of English ivy (*Hedera helix*)'. *Journal of Experimental Botany* 63, 191-201.

Melzer, B., Steinbrecher, T., Seidel, R., Kraft, O., Schwaiger, R., Speck, T. (2010). 'The attachment strategy of English ivy: a complex mechanisms acting on several hierarchical levels'. *Journal of the Royal Society Interface* 7, 1383-1389.

Metcalfe, D.J. (2005). '*Hedera helix* L', *Journal of Ecology*, 93(3), 632-648.

Ruedrich, J., Kirchner, D. and Siegesmund, S. (2011). 'Physical weathering of building stones induced by freeze-thaw action: a laboratory long-term study'. *Environmental Earth Sciences* 63(7), 1573-1586.

Sass, O., Viles, H.A. (2006). 'How wet are these walls? Testing a novel technique for measuring moisture in ruined walls'. J*ournal of Cultural Heritage* 7, 257-263.

Sass, O., Viles, H.A. (2010). 'Wetting and drying of masonry walls: 2D-resistivity monitoring of driving rain experiments on historic stonework in Oxford, UK', *Journal of Applied Geophysics* 70, 72-83.

Speak, A.F., Rothwell, J.J., Lindley, S.J., Smith, C.L. (2012). 'Urban particulate pollution reduction by four species of green roof vegetation in a UK city'. *Atmospheric Environment* 61, 283-293.

Stafikhani, T. et al (2014). 'A review of energy characteristics of vertical greenery systems'. *Renewable and Sustainable Energy Reviews* 40, 450-462.

Sternberg, T. (2010). 'Field and laboratory results', in 'Ivy on Walls Seminar Report' (Chapter 4), English Heritage (now Historic England), 22-28. Available at: http://www.geog.ox.ac.uk/research/landscape/rubble/ivy/

Sternberg, T., Viles, H., Cathersides, A. (2011). 'Evaluating the role of ivy (*Hedera helix)* in moderating wall surface microclimates and contributing to the bioprotection of historic buildings'. *Building and Environment* 46, 293-297.

Sternberg, T., Viles, H., 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.

Takahashi, H., (1997). 'Hydrotropism: The current state of our knowledge', *Journal of Plant Research*, 110(2), 1098, 163-169.

Thomas, R. (2010). 'Ivy – an ecological perspective in relation to walls', in 'Ivy on Walls Seminar Report' (Chapter 8), English Heritage (now Historic England), 47-49. http://www.geog.ox.ac.uk/research/landscape/rubble/ivy/

Thomsit-Ireland, F., Blanusa, T., Essah, E., Hadley, P. (2016). 'Controlling ivy attachment to wall surfaces by applying paints, metal meshes and sheets'. *Journal of Living Architecture* 3, 1-14.

Trewavas, A. (2009). 'What is plant behaviour?', *Plant, Cell & Environment*, 32(6), 606-616.

Turner, C. (2010). 'Ivy removal at Godolphin Estate, The National Trust', in *Ivy on Walls Seminar Report* (Chapter 6), English Heritage (now Historic England), 36-40. http://www.geog.ox.ac.uk/research/landscape/rubble/ivy/

Viles, H.A. (2010a). 'Research methods and sites', in 'Ivy on Walls Seminar Report' (Chapter 3), English Heritage (now Historic England), 16-21. http://www.geog.ox.ac.uk/research/landscape/rubble/ivy/

Viles, H.A. 2010b. 'Interpretations and implications of our results', in 'Ivy on Walls Seminar Report' (Chapter 5), English Heritage (now Historic England), 29-36. http://www.geog.ox.ac.uk/research/landscape/rubble/ivy/

Viles, H.A., Cutler, N.J. (2012). 'Global environmental change and the biology of heritage structures'. *Global Change Biology* 18, 2406-2418.

Viles, H.A., Goudie, A.S., Grab, S., Lalley, J. (2011). 'The use of the Schmidt Hammer and Equotip for rock hardness assessments in geomorphology and heritage science: a comparative analysis'. *Earth Surface Processes and Landforms* 36(3), 320-333.

Viles, H.A., Sternberg, T, Cathersides, A. (2011). 'Is ivy good or bad for historic walls?', *Journal of Architectural Conservation* 17, 25-41.

Warke, P.A., Smith, B.J. (1998). 'Effects of direct and indirect heating on the validity of rock weathering studies and durability tests'. *Geomorphology* 22, 347-357.

Webster, E., Cameron, R., Culham, A. (2017). 'Gardening in a Changing Climate'. *Royal Horticultural Society*, UK. https//www.rhs.org.uk/science/pdf/RHS-Gardening-in-a-Changing-Climate-Report.pdf

White, A. 2010. 'Ramsey Churchyard', in *Ivy on Walls Seminar Report* (Chapter 7), English Heritage (now Historic England), 41-46. http://www.geog.ox.ac.uk/research/landscape/rubble/ivy/

Wilhelm, K., Viles, H.A., Burke, O. (2016). 'Low impact surface hardness testing (Equotip) on porous surfaces – advances in methodology with implications for rock weathering and stone deterioration research'. *Earth Surface Processes and Landforms* 41, 1027-1038. doi: 10.1002/esp.3882.

Wong, N.H., Tan, A.Y.K., Chen, Y., Sekar, K., Tan, P.Y., Chan, D., Chiang, K., Wong, N.C. (2010). 'Thermal evaluation of vertical greenery systems for building walls'. *Building and Environment* 45(3), 663-672.



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