JOURNAL OF ENVIRONMENTAL GEOGRAPHY
Journal of Environmental Geography 6 (1–2), 9–19.
DOI: 10.2478/v10326-012-0002-4
ISSN: 2060-467X

STUDIES OF OXFORD STONE AS A CONTRIBUTION TO ENVIRONMENTAL GEOMORPHOLOGY

Mary J. Thornbush

School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, West Midlands B15 2TT, United Kingdom
e-mail: m.thornbush@bham.ac.uk

Research article, received 12 December 2012, published online 15 April 2013

Abstract

Much scientific research has been conducted on Oxford stone, of which the historical buildings of central Oxford, UK are comprised. This paper reviews all published literature to-date specifically for Oxford stone, compiling an inventory of studies. The context for this review is in the application of environmental geomorphology to the more recent studies by physical geographers. Overall findings across published studies assist with an understanding of current trends in the conservation of Oxford's historical buildings. Early observations remain generally representative of the findings, although the more recent literature has employed modern methodologies in science and technology that were not available in the late 1940s. Some indication of remaining research gaps are identified and forthcoming research presented. Last is a discussion of current practice in the cleaning and replacement of building stone that briefly considers the authenticity of Oxford stone, which is relevant for heritage conservation. The contribution of such studies to environmental geomorphology is addressed.

Keywords: limestone, historical buildings, soiling, human-environment relations, photogeomorphological approach, conservation, authenticity

INTRODUCTION

The search for contextual similarities between traditional landscape analyses and heritage-orientated research

Much research has been published over the years on Oxford stone that has contributed to a better understanding of the degradation and deterioration of building stone. Geologists and geomorphologists at the University of Oxford have examined the various types of limestone comprising Oxford's historical buildings. The emphasis shifted from a focus on the stone and different types of limestones and their sources from local quarries (in Oxfordshire, but also further afield in Leicestershire and Gloucestershire, etc.) to environmental geomorphological studies of the impacts of air pollution on weathering and the condition of the buildings. Most recently, a photogeomorphological approach was taken up (Thornbush, in press a), where the buildings were depicted as they appeared in photographs from archival and recent records.

This paper reviews the more prominent published studies for Oxford stone. It begins from the earlier work of the geologist W.J. Arkell, who was a Senior Research Fellow of New College in 1933-1940, and continues with more recent works, including by physical geographers, such as by H.A. Viles since 1996, when geomorphologists began to examine Oxford's historical buildings in the context of heritage conservation. These later studies are considered to be exemplar of environmental geomorphology, as a subfield of geomorphology that is within an applied geomorphology (*Fig. 1*). This has two branches connected with environmental geomorphology, and specifically human-environment relations, comprising physical (natural) and human (cultural) components of landscapes.

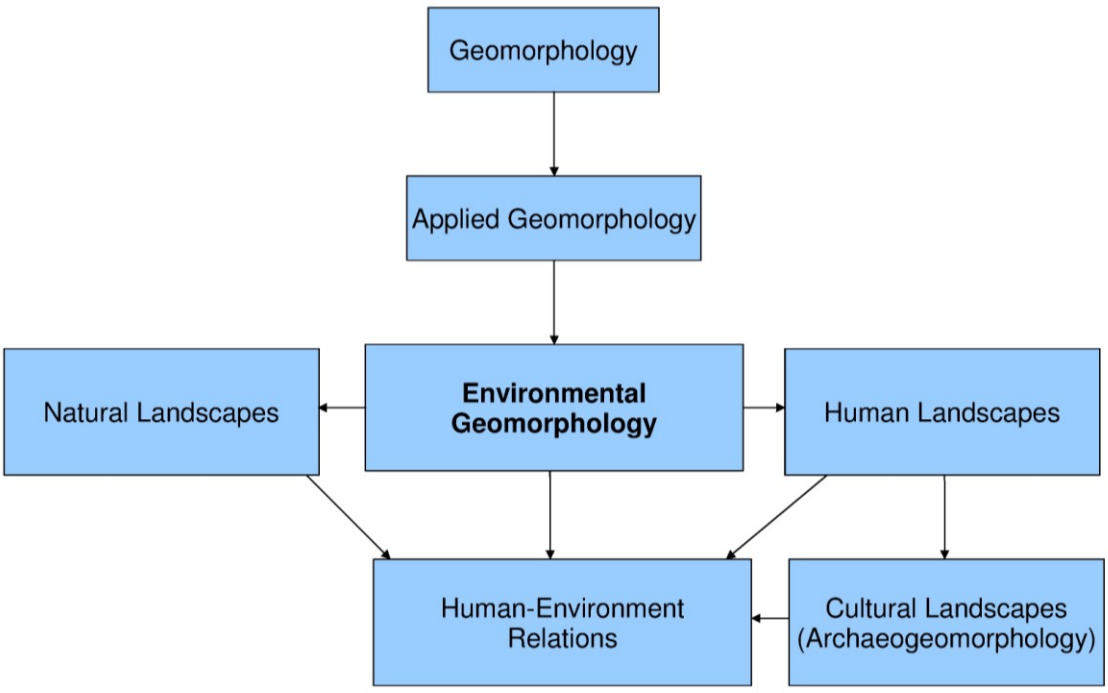
The geologist Coates (1971) introduced environmental geomorphology as part of the then emerging field of environmental geology. According to him, environmental geomorphology '...is very broad and diverse, and includes [humans] and [their] role in terrain activities'. This breadth complicates the task of fully covering the topic. Papers contained within the compilation had been presented at the Environmental Geomorphology Symposium held in the Department of Geology, State University of New York at Binghamton on 16-17 October 1970. He presented the subject content in three parts: 1) watershed planning; 2) regional and local studies; and 3) societal and educational perspectives. This was to commemorate the 'Environmental Decade' (of the 1970s), and the conference was devoted to examining the role of the geomorphologist in environmental studies. He argued that '...during these times of urban renewal and suburban sprawl, the growing population with its accompanying displacements, the rapid expansion of highway networks, and various terrain distortion activities, the geomorphologist has all too often been passive or played only a subsidiary part in any planning or decision-make process'. This stance was developed from the address of interdisciplinary approaches to water resources, as at a drainage basin in southern New York, and the emergence of environmental research in geomorphology. Pending on this and other developments, environmental geomorphology was born out of environmental geology, which itself addresses: '1. Physical data on the terrain itself; 2. Data for management and disposal of wastes; 3. Data for water resources development; and 4. Data on the full range of usable rock and mineral materials and subsurface fluids' Coates (1971). He finally defined the subfield as follows:

> Environmental geomorphology is the practical use of geomorphology for the solution of problems where [humanity] wishes to transform landforms or to use and change surficial processes. Obvious candidates for this study, interpretation, and planning include land-fill operations, ground-water mining and subsidence, streamflow regime upsets, and hillslope modifications. In addition, environmental geomorphology includes extraction of surficial materials, and protection of certain landscapes, such as beaches, which benefit [humanity]. The goal for geomorphic environmental studies is to minimize topographic distortions and to understand the interrelated processes necessary in restoration, or maintenance, of the natural balance.

In this way, Coates established human-environment relations conceptually within his notion of an environmental geomorphology. He followed this up with a subsequent publication (Coates, 1972), wherein he identified various issues and themes concerning environmental geomorphology. These specifically included the following: '1). The study of geomorphic processes and terrain that affect [humanity], including hazard phenomena such as floods and landslides. 2) The analysis of problems where [humanity] plans to disturb or has already degraded the land-water ecosystem. 3) [Humanity's] utilisation of geomorphic agents or products as resources, such as water or sand and gravel. 4) How the science of geomorphology can be used in environmental planning and management'.

There was much response to Coates's (1972) Environmental geomorphology and landscape conservation, especially volumes II (on urban areas) and III (nonurban regions). Dury (1975), for instance, found the second volume to be better than the first (which is mostly unaddressed in book reviews and editorials), even though he found that contribution to be mainly representative of the urban theme in the USA (for example, California) and, hence, fails to address problems on a global scale. There is also a lack of address of karst development for urban areas. Jacobs (1977) was more impressed by the 75 pages written by the editor, comprising Coates's overview, text, and references that were considered to be more helpful than the collection of articles. For the latter volume (III), Gregory (1974) acknowledged an awareness of contemporary problems deriving both directly and indirectly from human activity (as presented more recently in Panizza's (1996) model of the relationships between the geomorphological environment and humans; refer to his Fig. 1). The author also appreciates the temporal span of articles represented in the volume, since 1900 (with volume I covering the literature before 1900). He also remarks on the 10% of content written by the editor that effectively outlines the content of the papers, with introductions provided for the three main sections (organised according to the following topics: terrain degradation; soil conservation; and landscape

Fig. 1 The placement of environmental geomorphology within geomorphology



management). The volume contains some rare papers and brings together relevant studies for the subject matter, such as concerning landscape management. Ofomata (1974) considered this anthology to be the most important as it fills a gap in the literature; however, it did not completely portray nonurban environments through the exclusion of the African (for which papers are mainly written in French and should have been translated and included in this volume) and Latin American continents. Again, the volume is dominated by American studies, with some additional coverage of Australia, China, Israel, Japan, and Russia.

Panizza (1996) recognised the contribution of Verstappen (1983) for definition of environmental geomorphological issues. Like Briggs (1981), Panizza (1996) envisioned environmental geomorphology to encompass human-environment relationships from a geomorphological perspective, with the environment approached from an ecological sense. He subdivided geomorphological components into: '...geomorphological resources [(raw materials relevant to geomorphological processes and landforms)]; and geomorphological hazards [(associated with geomorphological instability)]'. Within this environmental component, humans represent: '...Human activity [(identified as '...hunting, grazing, farming, deforestation, utilisation of natural resources and engineering works')]; and Area vulnerability [(occurs due to human intervention, such as '...population, buildings and structures, infrastructures, economic activity, social organisation and any expansion and development...')]'.

Around this time, Coates (1982) also published in the book Applied geography: Selected perspectives. His paper on Environmental geomorphology perspectives addressed its potential contribution to land-water ecosystems and focussed on food, population, and energy. Subsequent books included Developments and applications of geomorphology, where Fisher (1984) discussed coastal environmental geomorphology in applied coastal research. Environmental and dynamic geomorphology included a paper on environmental geomorphology in Hungary by Pécsi (1985), as a part of applied geomorphological research. Geomorphology and environmental changes in tropical Africa was a special publication that included a paper on the fluvial environment of the Tana River, Kenya by Ojany (1986) that addressed environmental geomorphology. Physical geography and geomorphology in Hungary also contained a paper by Pécsi (1986) that comprised of problems involving the utilisation of the environment.

In addition to these earlier books on environmental geomorphology, papers were also disseminated explicitly as part of international conference proceedings. For instance, the Proceedings of IGARSS '84, Strasbourg, France, where environmental geomorphological studies in the Himalaya, India were based on the analysis of aerial photographs and satellite images and gave consideration to the degeneration of environment (Prasad et al., 1984). Prasad (2008) subsequently published a book on Environmental geomorphology that defined it as '...the scientific study of morphological process and landforms with respect to nature' (preface). He stipulated that the subdiscipline is primarily concerned with surficial physical features of Earth history. However, he acknowledged that these Earth processes and landforms are influenced by human interactions, what he referred to as 'eco-culture' or 'physico-cultural phenomena', which is particularly prevalent in the 'techno-scientific era'. At this time, humanity has destroyed nature due to its constructions and contributed to 'eco-degradation' hazard, ensuing on what he terms an environmental disaster that has challenged scientific research and spurred the need for 'eco-protection', causing geomorphology to meet with environmental science. The author mentioned relevant problems, such as the protection of environmental diversity, establishing ecological balance, and 'eco-development' as part of conservation. Environmental geomorphology's connection with the Earth sciences also brings into question natural resources and land use. Further to this, derived from the first international geomorphological conference held in Manchester, UK, was Environmental and dynamic geomorphology: Case studies in Hungary edited by Pécsi (1985), which portrayed environmental geomorphology in Hungary. Most recently, *Zeitschrift für Geomorphologie* published the proceedings of the second international conference on geomorphology: Geomorphology and geoecology held in Frankfurt am Main, Germany in 1989 and included perspectives of environmental geomorphology by Coates (1990).

There have also been journal articles published as part of environmental geomorphology in various different languages. The *Natural Sciences Journal of Hunan Normal University* published a paper in Chinese by Deng (1986) that placed the role of environmental geomorphology (along with regional and applied geomorphology) as a practical approach to territorial adjustment. The *Boletim de Geografia Teoretica* published a paper by De Barros Goes (1988) in Portuguese that was an application of environmental geomorphology at Rio de Janeiro. Timofeev (1991) examined the object, aims, and tasks of environmental geomorphology in an article published in *Geomorfologiya* in Russian. The author approached environmental geomorphology as a new trend in science at the interface between geomorphic systems and human ecology. *Zeitschrift für Geomorphologie, Supplementband* published an article by Pécsi (1993) on environmental geomorphology in Hungary, which advocated that this new research trend was born of practical topographic assessments (similar to the earlier practical approach to territorial adjustment by Deng, 1986). Importantly, he delineated the subject and goals of environmental geomorphology as different from geomorphology at large because of its focus on the consequences of human intervention, as in the development, change, and state of landforms from a practical perspective. *Sbornik Ceske Geograficke Spolecnosti* published a paper by Ivan (1993) in Czech that considered the cultural landscape and discussed environmental geomorphology as comprising research problems associated with cultural and disturbed landscapes.

There is a lack of theoretical development in environmental geomorphology in more recent years. For this reason perhaps, some studies do not claim to be a part of this subdiscipline even though the work is essentially environmental geomorphological in scope. For instance, Martín Duque et al. (1998) performed a landscape reclamation study representative of environmental geomorphology; however, the authors do not refer to environmental geomorphological explicitly within the article outside of the keywords. They did, however, instigate a methodological application. More recently, *Environmental Geology* approached hazardous wastes from an environmental geomorphological approach, arguing that environmental geomorphology normally lacks detailed environmental impact assessment (Yesilnacar and Cetin, 2008). These authors also presented a predominantly methodological study that is typical of environmental geomorphological research, with its emphasis on the development of methodology over theory. Finally, Mahaney (2012) most recently examined the implications of extreme heating events for an environmental geomorphology in a paper published by *Geomorphology*. This paper similarly focussed on a methodological approach based on rock weathering in a geological investigation that was essentially driven by material testing (methodology, as through the use of scanning electron microscopy or SEM) rather than aimed at a greater theoretical framework. Nevertheless, another paper published recently by Garcia et al. (2012) based a study of the Dam Rio Verde-Parana in Brazil on an environmental geomorphology, with its aims reflecting concepts within the subfield, including the identification of both its environmental compartments as well as regional geology and physiography and human impacts in the area. These authors discovered an intense human influence, such as of urban growth, natural hazards (including mass movements and flooding), and a fragility of the landscape created by agricultural land use.

Perhaps the most unifying principle of environmental geomorphology is its emphasis on the practical use of geomorphology in order to solve problems associated with surficial processes and materials that may appear as landforms. As part of an applied geomorphology, environmental geomorphology could also abide by the principles and practice of an applied geography, as outlined by Briggs (1981) as part of a problem-orientated discipline. Specific problems identified by the author include: '...pollution, damage to wildlife, destruction of habitats, soil erosion and resource depletion; the problems of human deprivation and inequality'. In this way, he conveyed problems associated with both natural (physical) and cultural (human) landscapes (see *Fig. 1*). Moreover, his article has a more developed section on the method of applied geography than when addressing the subject matter of applied geography, which is similar to other published studies relevant to the subdiscipline. Panizza (1996), for instance, differentiated a model of the geomorphological environment and humans (with active and passive branches), affecting impact and risk (refer to his Fig. 1).

This practical subdisciplinary approach often targets human-environment relations and is apparent in several recent studies in the literature. For example, a geoarchaeological study of Australia considered past human-environment interactions, focussing on influences of human behaviour as distinguished from environmental impacts on key topics (Holdaway and Fanning, 2010). 'Human-made landforms' are referred to in terms of human-environmental interactions in mountain regions, including the Sudetes Mountains, Poland (Latocha, 2009). These (human-made landforms), comprising more persistent types in the landscape, for example agricultural terraces, as well as disappearing anthropogenic features, such as field roads, are differentiated from natural landforms (Latocha, 2007). Other authors have developed a history of human-environment interactions (in the Late Holocene), noting some important (anthropogenic) events, such as the onset of agriculture in the Yame' River valley on the Bandiagara Plateau of Dogon country, Ounjougou Mali, and the increasing role of human-set fires and food production (Ozainne et al., 2009). Since hydrology affects the livelihoods of rural communities and is an integral variable affecting desertification (Huber-Sannwald et al., 2006), rivers have received much attention within an environmental geomorphology; as for example, tracking the evolution of the Yellow River in China in consideration of the physical components of the landscape (geological structure, climate) in addition to the human environment (Li et al., 2003). Such human-environment interactions have been regarded as relevant for study by natural scientists and are used to diagnose social and cultural change (Rapp and Jing, 2011). Human land use has been central to approaches advocating human-environment interactions in conjunction with process geomorphology (e.g. Enters et al., 2008), many stipulating sustainable land use (e.g. assessments of natural versus ecoenvironmental vulnerability, as in the Apodi estuarine in northeast Brazil; Boori and Amaro, 2010, 2011).

The purpose of this study is to present (known) published works for Oxford stone in order to develop a discussion of this research that has implications for conservation policy and practice. The overarching aim is to delineate the different works in order to arrive at a current understanding of this record of historical buildings in the context of environmental geomorphological studies. Specific objectives are to review scientific research by various authors who have made a contribution over the years to studies of Oxford stone, and discuss the future of Oxford's historical buildings. This paper outlines the state of the art and critically discusses directions taken in science and technology and its implications for stone conservation policy and practice. Ultimately, this is a contribution to the literature in environmental geomorphology by placing studies of Oxford stone as part of an applied geomorphology within the specific jurisdiction of environmental geomorphology (as denoted in *Fig. 1*), as part of cultural landscapes within a more human facet of the subdiscipline that engages with the conservation of cultural landforms and landscapes.

Oxford stone

The published book by Arkell (1947) Oxford stone made the first significant contribution to an understanding of the variety of limestones comprising Oxford's historical buildings. His geological perspective is captured in this book, with much emphasis on the different types of limestones and where they were quarried, except for the final chapter on The decay, repair and maintenance of Oxford buildings, where he focussed more on the condition of buildings during his time. In his Chapter 8, Arkell (1947) made several observations about Oxford stone, which he accounted was transformed due to much refacing in Bath and Clipsham stones. For instance, Bath stone needed replacement every 200 years, with large-scale renewal occurring in 1850-1860 at various colleges, including Queen's, Exeter, Jesus, All Souls, and Balliol Colleges. The majority of restorations occurred in 1900-1912 with the introduction of Clipsham stone, a durable variety of stone. Buildings were observed to be thickly covered with ivy and creeper, such as Magdalen (cloisters), Exeter (quadrangle), and Balliol (west front) Colleges until some 20 years before the publication of his book, with Christ Church (meadow buildings) being loaded with greenery still in his time. Then, some buildings still retained some of their original stone, where stone decay could be studied at the Sheldonian Theatre, Radcliffe Camera, Bodleian (lower stages), Christ Church (library, Canterbury quad and gate), Trinity (chapel), Pembroke (chapel), Worcester, Corpus Christi (fellows building), and the old observatory. Elsewhere, Arkell (1947) noted that buildings had been modified through patching, scraping and even the use of preservatives. In his chapter, Arkell (1947) considered the various weathering processes and features evident then, including encrustation, blistering and exfoliation; warts; cavernous decay; weathering along bedding planes and granular disintegration; solution of the fine matrix as well as chemical decay along contacts (of limestone with sandstone); fracturing due to the use of iron cramps and dowels; vibration from road traffic on High Street; creepers as well as lichens and algae; and last is his address of the future of Oxford stone.

His observations on the weathering of buildings were to become the basis of geomorphological research. He observed that crusts commonly developed on Oxford stone, and that this was the most serious type of weathering, particularly for Headington freestone that appeared in Oxford in 1885. The formation of these skins developed through the accumulation of gypsum (calcium sulphate) from smoke released in the burning of coal. Arkell (1947) described it as follows: 'The surface of this [Headington free-] stone on exposure to the weather forms a hard, impermeable, black crust and the skin curls up and peels off. In time a new skin begins to form and the process is repeated'. Viles (1993a) delineated a three-stage conceptual model of blistering, which concurs with his observations. Moreover, a study on the environmental pollution of Oxford confirmed that restorations were frequent when colleges were burning sulphurous coal transported by way of the Oxford canal (Viles, 1996a). The outline by Arkell (1947) of skin formation is as follows:

> The blistering of the skin, with formation of an empty cavity behind it, seems to be due to the fact that the calcium sulphate skin has different physical properties from the stone (calcium carbonate) behind it and so reacts independently to changes of temperature and moisture, until eventually it parts company. In particular the skin expands more than the stone when heated by the [S]un, and the blistering is a natural response to the conflict of forces so set up.

Studies of temperature in the formation and exfoliation of skins have been mostly neglected for Oxford apart from a study by Viles, (1993b), who examined the impact of orientation on weathering features like blistering (on south-facing walls). Moisture through walls (but not Oxford fogs or drizzle in the making of sulphuric acid) was examined by Sass and Viles (2010a), who found more moisture in locations of decay, such as under blackened crusts. Experiments using simulated driving rain showed that weathered blocks absorb more water and this occurs at a faster rate than by crusted or replacement blocks (Sass and Viles, 2010b). However, they reported that these decayed blocks also dried up faster than other blocks. Temperature may be an important variable that has not received as much attention as it perhaps should, especially since Arkell (1947) noted that blistering was worse on south walls that receive more daytime sunlight (and experience the most temperature changes); as for example, any Headington freestone still remaining in the Bodleian quadrangle. Where moisture is not the culprit, irregularities in stone hardness (as well as any nodular structure) could lead to cavernous decay, which could develop to a depth of several inches. Goudie and Viles (1997) published a book on Salt weathering hazards that addressed the occurrence of salt weathering, which has been known to include cavernous weathering. More work, however, could be done field-testing for stone hardness in order to account for the ribs or 'bars' that Arkell (1947) outlined as part of the 'toning down' process in addition to cavernous weathering. He also mentioned the mechanical etching of wind-driven rain and hail, which was examined in a study of soiling and rainwashing due to wind-driven rain from the southwest along the south side of the Ashmolean Museum by Thornbush (2010a). This was not, however, directly on etching or at Jesus College, where damage was attributed by Arkell (1947) to acidity enhanced by organic matter from the covered market. He addressed rising capillary from the water table, which affected the base of columns, as on the south side of the Clarendon Buildings. He did refer to capillary action into sandstone, which has a greater porosity than limestone, leading to the enhanced decay of sandstone along limestone-sandstone contacts, as evident on the plinth of the Ashmolean Museum. Porosity may also increase as stones decay. It would have been helpful to address the role that condensate (settling close to ground-level in a cold, humid location) will have on the weathering of limestone.

Studies have not followed up on some areas addressed in the book by Arkell (1947). Some have already been outlined, but others remain to be mentioned. For example, research has not addressed the excessive use of iron cramps and dowels to emplace Bath stone, which led to fracturing and spalling of the stone. Even though much research has addressed the impacts of traffic pollution due to the Oxford Transport Strategy and its monitoring (e.g. Viles, 1996b), the impact of traffic on vibrations, especially along busy streets like the High Street, has not been investigated. Arkell (1947) presented a study conducted in 1932 at University College to monitor vibrations on the High Street using a Milne-Shaw seismograph. It would be interesting to revisit this research and follow-up in order to test for any weathering features more predominant where there are more vibrations from traffic, such as cracks due to structural instability and damage.

In his final book chapter, Arkell (1947) addressed several biota, including creepers, lichens and algae. In his time, it appears that there was some hostility towards ivy and creepers, and their use was highly controversial. There is no doubt that this controversy continues today, when organisations like English Heritage are struggling with whether ivy should be carefully managed and have invested in research into their bioprotective versus biodeteriorative impacts. Arkell (1947) took the stance that creepers should be kept away from already weathered buildings, such as those experiencing crumbling and/or exfoliation. His concern was that the mechanical action of creepers, ivy in particular, will hasten the weathering process. For example, even the wind can pull them and move them about, potentially contributing to damage when these climbing plants pull material. However, he was of the opinion that sound buildings could withstand the use of ivy and creepers, assuming that the plants' growth is controlled (e.g. away from windows and eaves and not allowed onto roofs). He identified some advantages to such climbers, which included their ability to hold moisture to the wall and keep it damp (this could, however, evoke chemical weathering). This was also recently supported by Sternberg et al. (2011), who found higher relative humidity on ivy-covered walls relative to uncovered (exposed) walls. Arkell (1947) also observed that the leaves of these plants act like tiles, shedding off water, which offers walls some protection from rainwashing. The only similar line of research to test this latter observation was also by Sternberg et al. (2010), who advocated that ivy also protects walls from the deposition of dust particulate due to shielding by leaves. However, they did not address deleterious impacts that Arkell (1947) mentioned, for instance that the tendrils and suckers can secrete acids enhancing decay. He described that these tendrils and suckers become attached to walls and coat them with a hard woody substance, which is visible when the plant is removed. This was observed by Arkell (1947) at Exeter and Lincoln Colleges, where he attributed it to the clearance of ampelopis. He did seem to favour the greenery produced by such plants, suggesting that they improved the aesthetics of buildings, particularly those without perfect symmetry and masonry. He valued the use of controlled creepers like at Lincoln and Pembroke Colleges, and found that the plants made these places more pleasant, especially in the summer. For example, amepolopsis growing at New College is green in the summer, but turns crimson in the autumn. His concluding view, however, was that research should focus on testing for the harmfulness of ivy and creepers, for instance as was evident at Lincoln College, in places previously occupied by creeper that were subsequently decayed, with creeper as a possible cause. In this latter case, Arkell (1947) suggested keeping the wall clear of creeper. Nevertheless, he did believe that flowering plants, like wistaria, should be allowed to grow on plain walls, even if harmful. His view of lichens and algae, on the other hand, was that they offered a protective covering and showed no sign of harm to the stone. This latter point is also a point of contention in the literature on biodeterioration.

Other studies

Many publications have followed the classic volume by Arkell (1947), most of it linked to work by Viles driven by some funded research projects. The first of these projects concerned the environmental monitoring of the Oxford Transport Strategy of June 1999 (Viles, 1996b). Here, the concern was over the impact of air pollution on Oxford stone due to traffic. This project involved three strands of research, including exposure trials and photographic monitoring of walls. Sensors exposed at roadside locations were examined by Viles and Gorbushina (2003) after up to three years of exposure. They found that sensors located on busier roads became soiled faster; that all sites experienced bacterial, fungal (especially within surface hollows) and phototropic colonisation (particularly at a background site that had higher colonisation of organisms after just three years), included particulate matter deposits, and also conveyed calcite dissolution. These findings led to a detailed study of fungi on these oolitic stone sensor samples (Thornbush and Viles, 2006a). For the second strand of the project, photographic surveys were extended from 1997 to 2003 to encompass six years of monitoring (Thornbush and Viles, 2008). This photographic survey involved an integrated qualitative-quantitative approach; however, other studies quantitatively assessed soiling and decay of the building stone (e.g., Thornbush, 2008a).

Participation in a newly funded project on catastrophic decay in building limestones led to more published work on Oxford's oolitic limestones. When Smith and Viles (2006) compared limestone with sandstone building stone, they discovered a patchiness and contagiousness in the former that was connected to catastrophic decay. Gomez-Heras et al. (2010) more recently published a paper on 'Oxford stone revisited' in the fashion of Arkell (1947) that examined the diversity of building limestone in the historical buildings. Most recently, English Heritage funded a project Ivy on Walls that generated some research into the bioprotective versus biodeteriorative effect of keeping ivy, in particular, on walls. Two studies by Sternberg et al. (2010, 2011) were already mentioned, but some work was also performed by Thornbush (2008b, 2012a) based on photoarchival searches in college archives, including at Trinity and Pembroke Colleges.

Some studies have presented new methods or approaches for use on Oxford stone. Soiling was examined at various scales from stone sensors exposed during the environmental monitoring of the Oxford Transport Strategy using the integrated digital photography and image processing (IDIP) method by Thornbush and Viles, (2004a, b) to entire blocks on the boundary wall of Worcester College with the decay mapping in Adobe Photoshop (DMAP) approach developed by Thornbush and Viles (2007a). A novel technical approach was taken with the application of portable X-ray fluorescence to the same wall (2006b), finding high levels of iron on newly replaced stone blocks that possibly conveyed weathering through iron migration to the stone surface (rather than iron deposits). An earlier study by Inkpen et al. (2001) used geographic information systems (GIS) to map decay derived from a time sequence based on old photographs taken of Oxford stone. Later, Inkpen et al. (2008) presented an integrated database and GIS that was used to record and monitor Oxford stone degradation. Sun et al. (2010) designed a new optical fibre humidity sensor for monitoring building stone deterioration.

DISCUSSION AND CONCLUSION

Much has been learned about the soiling and decay of Oxford stone. Even though Arkell (1947) did not systematically test his observations, making only qualitative judgements of stone weathering in his final chapter, what he did observe has been generally supported by scientific research. However, not all of his observations have been tested, for instance algal cover is still not yet addressed in the published literature for Oxford, except for a quantitative study by Thornbush (in press b). Lichens have been examined through rooftop experiments in Oxford by Carter (2002) and Carter and Viles (2003). More research needs to be conducted with aspect (wall orientation) in mind, which will affect microclimate (temperature in particular) and the development of lichens and algae. (Thornbush is currently working on a lichen study that quantifies lichen distribution across a string course in the Oxford city centre, where she considers microclimatic effects, including aspect).

Further microclimatic studies are still needed to examine the weathering features found on historical buildings in central Oxford. The use of a climatic chamber (as by Thornbush and Viles (2007b), who tested for the dissolution of weathered versus unweathered surfaces in differently concentrated solutions of carbonic acid) would be ideal for this kind of work in order to support any field experiments. Temperature, as well as moisture, variations should be considered in these studies. Needless to say, more research is needed to address any potential harmful effects of ivy on walls, including physicochemical analyses that test for chemical secretions and their acidity. This is relevant because decaying plant matter also generates acids that could be harmful to Oxford stone even in nonacidic (clean) air. This is considered in detail by Thornbush (in press c) in a recent publication that addresses the biodegradation and biodeterioration of limestone surfaces covered with vegetation (climbing plants in particular). More attention to the archival record for past use may be beneficial to understanding the use of climbing plants at Oxford colleges, including case studies at Christ Church, Exeter, and Lincoln Colleges. It is also relevant to investigate the different impacts of evergreen (ivy) versus deciduous (creeper) varieties. This would provide a cross-temporal context similar to the study by Thornbush (2010b), which reexamined a selection of buildings included in restoration photographs taken by the Oxford Historic Buildings Fund between 1957 and 1974. More recently, Thornbush (2012b) has devised a simple photo-based weathering index, namely the S-E index, for classifying soiling and decay damage to historical limestone based on a laneway in central Oxford, where a majority of buildings have not been cleaned or refaced in recent years. This classification system takes into account physical, chemical, and biological weathering processes and is based on the quantification of visible weathering forms. It has been applied most recently at churchyards located centrally in Oxford by Thornbush and Thornbush (in press a).

The conceptual framework for this paper is based on environmental studies performed in urban environments. They have encompassed studies employing a variety of both quantitative and qualitative methods, as outlined in *Table 1*. Moreover, these studies within an environmental geomorphology address both human and natural (physical) landscapes as well as human-environment relations. Topics have included land use (urbanisation, conservation); pollution (from energy production, such as from coal fires and transport); and microclimate (temperature, moisture). These main themes have, respectively, produced works addressing vegetation cover; acid rain; and aspect.

Perhaps one of the greatest contributions of the current research is its use of photography. Such a photogeomorphological approach taken initially by Viles (e.g. 1994) in her photographic monitoring and taken up and developed by M.J. Thornbush since 2004, is an advantage because of its contribution to an expanding photographic record, which could be used cross-temporally by various workers to develop new methods to examine the degradation and deterioration of Oxford stone. Some Oxford colleges also house extensive archives that could help extend the temporal photogeomorphological record back to the middle of the 19th century. These enable longer term studies that examine the visual appearance of Oxford stone, including any weathering features (especially if visible close-up). For example, as in the cross-temporal study of traffic congestion and stone decay that was conducted using archival material (including photoarchival) at Magdalen College (Thornbush and Viles, 2005).

Table 1 Methods used in Oxford studies

Method	Chronology of references
Vibrations (seismograph)	Bowen in Arkell (1947)
Field surveys	Viles (1993b); Smith and Viles (2006); Thornbush (in press c); Thornbush and Viles (2008)
Exposure trials	Viles (1996b); Carter (2002); Carter and Viles (2003)
Mapping and GIS	Inkpen et al. (2001, 2008)
Scanning electron microscopy (SEM)	Thornbush and Viles (2006a); Viles and Gorbushina (2003)
Portable X-ray fluorescence (PXRF)	Thornbush and Viles (2006b)
Simulation experiments	Thornbush and Viles (2007b)
Computer processing	Thornbush (2008a, 2010a, in press b); Thornbush and Viles (2004a, 2004b, 2007a)
Archival studies	Thornbush (2008b, 2012a); Thornbush and Viles (2005); Viles (1996a)
Petrographic analysis	Gomez-Heras et al. (2010)
2-D resistivity surveys	Sass and Viles (2010a, 2010b)
iButtons	Sternberg et al. (2010; 2011)
Optical fibre humidity sensors	Sun et al. (2010)
(Re)Photographic surveys	Thornbush (2010b, 2012b, a); Thornbush and Thornbush (in press a, in press b); Viles (1993a, 1994)

Thornbush and Thornbush (in press b) are currently working on a book entitled Photographs across time that portrays physical and cultural landscape change in urban settings, including Oxford, in a rephotographic approach.

Another major contribution of these studies is as exemplar of environmental geomorphology within an applied geomorphology in the realm of heritage science conservation. Since this geomorphology subfield has already been delineated in earlier works (such as Panizza (1996) in an introduction to environmental geomorphology), the current review encapsulates Oxford stone as part of this applied geomorphology, providing a further case study to supplement the published Hungarian case studies. The current case study also aligns well with the multidisciplinary approach comprising geomorphic systems and human ecology outlined by Timofeev (1991), as well as the emphasis on cultural landscape advocated by Ivan (1993). It also supports recent frameworks developed by the author (Thornbush, 2012c), who recently outlined the inclusion of archaeogeomorphology as a subfield of an applied geomorphology that examines cultural landscapes. Environmental geomorphology would encompass archaeogeomorpholgoy, and cultural landscapes with a human-oriented geomorphology (in addition to more traditional (physical) landscape geomorphology), and would in turn be an applied (practical) geomorphology (see *Fig. 1*). More specifically, as denoted by several other authors (Fisher, 1984; Pécsi, 1985, 1993) environmental geomorphology is a practical (applied) geomorphology. As such, for Oxford, it provides a framework for studies in the degeneration of the (built) environment (Prasad et al., 1984). It also encapsulates practical problems of utilising the environment in these urban settings conveyed by Pécsi (1986) and the consideration given by Coates (1990), conveying environmental geomorphologists as scientists who are concerned with solving societal problems, including where natural surface processes have affected the built environment (installations and properties) as well as where they are changed by human activity, such as the the deterioration of Oxford stone through (among other reasons) exposure in a polluted environment due to combustion.

This paper does not consider either the variety of limestones used in Oxford's historical buildings, nor does it consider methods of repair and maintenance in any detail. However, it does pick up on the discussion by Arkell (1947) of the future. At the end of his Chapter 8, he conveyed that in the past Oxford colleges employed their own masons, but that the trend now is to contract out the work. In his time, only Magdalen, Wadham, and Exeter Colleges still employed their own mason. Today, however, some colleges do keep clerks-for-works or architects. The problem of keeping the latter, however, is that architects are not necessarily stone conservation experts. Arkell (1947) recognised Oxford's historical buildings as a national heritage, which should be upheld by an advisory panel:

> For that same Fellow will readily agree that Oxford is a national heritage. And if the university as a whole is a national heritage so are the individual buildings that compose it. The university, acting through its advisory panel of architects, university officers, scientific experts, and chosen representatives of the colleges, would seem none too large an authority to take responsibility for the components of such a heritage.

The office of the panel would have many responsibilities, including reporting to the Government Building Research Station. He suggested that the panel obtain its own portable cleaning outfit that would be made available for regular cleaning and treatment of buildings that could promote regular inspections of decay and keep an up-to-date dossier of each building. However, to the author's knowledge, an advisory panel is still missing from the university's administration, which could, as Arkell (1947) suggested, help to bring together different experts and supports within the university, including individual colleges and schools (including laboratories).

The current practice of conserving Oxford stone requires the replacement of blocks that have suffered from cavernous weathering (blowouts) once crusts have been breached and the more friable material beneath collapses. This was evident relatively recently after cleaning at various locations, such as at the boundary wall surrounding Magdalen College along Longwall Street in central Oxford. Cleaning of the stonework does reveal decay features, such as is still evident on the plinth of the Ashmolean Museum even after it was restored recently. Although cleaning brightens the stonework, it does not conceal stone decay damage, which can only be patched-up or replaced. For example, replacement blocks are still evident at the boundary wall of Worcester College, although they are now darkening and less conspicuous. Outside Exeter College facing onto Turl Street, blocks have been (noticeably) replaced on the façade. The Sheldonian Emperors' Heads are another example of replaced Oxford stone that brings into question the authenticity of the fabric of Oxford's historical buildings. Cleaning and restoration works are performed piecemeal by storey, as is evident recently at the Bodleian Library, whose upper storey was restored recently and the middle level cleaned. This practice (of piecemeal cleaning and replacement) makes it difficult to perform temporal studies of stone decay for Oxford's historical buildings. It is also difficult to control the lithology of the type of limestone used even across one façade, as for example at the Ashmolean Museum, which comprises different varieties of limestone in addition to sandstone. Oxford's buildings are often hidden behind scaffolding, which has become an expected part of this urbanscape. Its historical buildings are now a mere cast of what they once were because of various 'face-lifts' over the years, including since the time of Arkell (1947). Even though stone decay has been studied and tested, science cannot solve the problem of Oxford stone's plight with time.

This takes one back to the beginnings of environmental geomorphology and specifically the original work by Coates (1971), with its portrayal of this geomorphology subfield as being conjunctant to landscape conservation. Moreover, the work by Prasad et al. (1984) addressed the degeneration of environment, which suits this examination of studies of Oxford stone. The historical buildings of central Oxford are part of a cultural landscape that needs to be conserved and as a cultural heritage resource that needs to be sustained. By examining how cultural stoneworks change due to exposure in certain environments, such as in polluted urban settings, it is possible to work towards their conservation rather than piecemeal replacement and replication. These studies make a contribution to environmental geomorphology as cultural heritage that is susceptible to (passive) human activities that enhance an area's vulnerability (Panizza, 1996), leading to risks associated with the conservation of this cultural landscape and affecting the sustainability of this resource. By examining human-environment relations within environmental geomorphology, it is possible to better connect the human (cultural) and physical (natural) branches of the environment. This includes considerations of human landforms, as in a built-up urban setting in the current study, rather than just traditional notions of physical landforms previously addressed by geomorphologists.

References

Arkell, W.J. 1947. Oxford stone. London: Faber and Faber Limited

Boori, M.S., Amaro, V.E. 2010. Detecting and understanding drivers of natural and eco-environmental vulnerability due to hydro geophysical parameters, ecosystem and land use change through multispectral satellite data sets in Apodi estuarine, Northeast Brazil. *International Journal of Environmental Sciences* 1 (4), 543–557.

Boori, M.S., Amaro, V.E. 2011. A remote sensing approach for vulnerability and environmental change in Apodi Valley region, Northeast Brazil. *World Academy of Science, Engineering and Technology* 50, 501–511.

Briggs, D.J. 1981. The principles and practice of applied geography. *Applied Geography* 1 (1), 1–8.

Carter, N.E.A. 2002. Bioprotection explored: Lichens on limestone. Unpublished doctoral thesis. Oxford: School of Geography and the Environment, University of Oxford

Carter, N.E.A.,Viles H.A. 2003. Experimental investigations into the interactions between moisture, rock surface temperatures and an epilithic lichen cover in the bioprotection of lichen. *Building and Environment* 38, 1225–1234.

Coates, D.R. (ed.) 1971. Environmental geomorphology. Binghamton: State University of New York

Coates, D.R. (ed.) 1972. Environmental geomorphology and landscape conservation. Stroudsburg: Dowden, Hutchinson and Ross

Coates, D.R. 1982. Environmental geomorphology perspectives. In: Applied geography: Selected perspectives. New Jersey: Prentice-Hall, 139–169.

Coates, D.R. 1990. Perspectives of environmental geomorphology. *Zeitschrift für Geomorphologie, Supplementband* 79, 83 –117.

De Barros Goes, M.H. 1988. Environmental impact and risk areas related to the urbanisation process in the Baixada de Sepetiba, Rio do Janeiro. *Boletim de Geografia Teoretica* 18 (35-36), 39–73.

Deng, M. 1986. Preliminary study of geomorphology and territorial readjustment. *Natural Sciences Journal of Hunan Normal University* 9 (2), 77–82.

Dury, G.H. 1972. Some current trends in geomorphology. *Earth-Science Reviews* 8 (1), 45–72.

Dury, G.H. 1975. Book reviews: The environment. *Earth-Science Reviews* 11 (4), 365–366.

Enters, D., Dörfler, W., Zolitschka, B. 2008. Historical soil erosion and land-use change during the last two millenia recorded in lake sediments of Frickenhauser See, northern Bavaria, central Germany. *Holocene* 18 (2), 243–254.

Fisher, J.J. 1984. Regional long-term and localized short-term coastal environmental geomorphology inventories. In: Costa, J.E., Fleischer, P.J. (eds.) Developments and applications of geomorphology. Berlin: Springer-Verlag, 68–96.

Garcia, C.M. Carrijo, B.R., Sessegolo, G., Passos, E. 2012. Environmental assessment of the area surrounding Dam Rio Verde-Parana / Brazil. An overview of environmental geomorphology. *Journal of Environmental Biology* 33 (Suppl. 2), 289–291.

Gomez-Heras, M., Smith, B.J., Viles, H.A. 2010. Oxford stone revisited: Causes and consequences of diversity in building limestone used in the historic centre of Oxford, England. *Geological Society Special Publication* 333, 101–110.

Goudie, A.S., Viles, H.A. 1997. Salt weathering hazards. Oxford: Wiley

Gregory, K.J. 1974. Geomorphology. *Earth-Science Reviews* 10 (3), 228–229.

Holdway, S.J., Fanning P.C. 2010. Geoarchaeology in Australia: Understanding human-environment interactions. *Geological Society Special Publication* 346 (1), 71–85.

Huber-Sannwald, E., Maestre, F.T., Herrick, J.E., Reynolds J.F. 2006. Ecohydrological feedbacks and linkages associated with land degradation: A case study from Mexico. *Hydrological Processes* 20 (15), 3395–3411.

Inkpen, R.J., Fontana, D., Collier, P. 2001. Mapping decay: Integrating scales of weathering within a GIS. *Earth Surface Processes and Landforms* 26 (8), 885–900.

Inkpen, R., Duane, B., Burdett, J., Yates, T. 2008. Assessing stone degradation using an integrated database and geographical information system (GIS). *Environmental Geology* 56 (3-4), 789–801.

Ivan, A. 1993. Relief of the landscape as part of the environment and its man induced disturbances. *Sbornik Ceske Geograficke Spolecnosti* 98 (3), 179–189.

Jacobs, P. 1977. Environmental geomorphology and landscape conservation. *Urban Ecology* 2 (3), 286–288.

Latocha, A. 2007. Human impact on the environmental changes in the Eastern Sudetes. *Acta Universitatis Wratislaviensis, Studia Geograficzne* 80, 1–215.

Latocha, A. 2009. Land-use changes and longer-term human-environment interactions in a mountain region (Sudetes Mountains, Poland). *Geomorphology* 108 (1-2), 48–57.

Li, B., Ge, Q., Zheng, J. 2003. Evolution of the Inner-Mongolia reach of the Yellow River and its response to the environment in the past 2000 years. *Proceedings of SPIE – The International Society for Optical Engineering* 4890 (2), 604 –611.

Mahaney, W.C. 2012. Extreme heating events and effects in the natural environment: Implications for environmental geomorphology. *Geomorphology* 139-140, 348–359.

Martín Duque, J.F., Pedrazaa, J., Díez, A.,Sanza, M.A., Carrasco, R.M. 1998. A geomorphological design for the rehabilitation of an abandoned sand quarry in central Spain. *Landscape and Urban Planning* 42 (1), 1–14.

Ofomata, G.E.K. 1974. Non urban landscape. *Landscape Planning* 1, 378–380.

Ojany, F.F. 1986. Tana River delta and other deltaic rivers in Kenya; a contribution in fluvial and environmental geomorphology. In: Kadomura, H. (ed.) Geomorphology and environmental changes in tropical Africa. Sapporo: Hokkaido University, Graduate School of Environmental Science, 165–178.

Ozainne, S., Lespez, L., Drezen, Y.L., Eichhorn B., Neumann K., Huysecom E. 2009. Developing a chronology integrating archaeological and environmental data from different contexts: The late Holocene sequence of Ounjougou (Mali). *Radiocarbon* 51 (2), 457–470.

Panizza, M. 1996. Environmental geomorphology. In: Panizza M. (ed.) Environmental geomorphology. Amsterdam: Elsevier.

Pécsi, M. 1985. Environmental geomorphology in Hungary. In: Pécsi, M. (ed.) Environmental and dynamic geomorphology: Case studies in Hungary. Contribution to the First International Geomorphology Conference, September 1985, Manchester, UK. Budapest: Akademiai Kiado, 3–15.

Pécsi, M. 1986. Environmental geomorphology in Hungary. In: Pécsi, M., Lóczy, D. (eds.) Physical geography and geomorphology in Hungary. Budapest: Hungarian Academy of Sciences, Geographical Research Institute, 117–122.

Pécsi, M. 1993. Environmental geomorphology in Hungary. *Zeitschrift für Geomorphologie, Supplementband* 87, 1–11.

Prasad, G. 2008. Environmental geomorphology. New Delhi: Discovery Publishing House PVT. Ltd.

Prasad, G., Sundriyal, R.R., Verma, V.K. 1984. Studies in environmental geomorpholgoy of Dudhatoli Ridge, Garhawal, Himalaya, India. IGARSS '84. Remote sensing – From research towards operational use. Paris: European Space Agency, Scientific and Technical Publications Branch, 289–294.

Rapp, G., Jing, Z. 2011. Human-environmental interactions in the development of early Chinese civilization. *Geological Society Special Publication* 352, 125–136.

Sass, O., Viles, H.A. 2010a. Two-dimensional resistivity surveys of the moisture content of historic limestone walls in Oxford, UK: Implications for understanding catastrophic stone deterioration. *Geological Society Special Publication* 331, 237–249.

Sass, O., Viles, H.A. 2010b. Wetting and drying of masonry walls: 2D-resistivity monitoring of driving rain experiments on historic stonework in Oxford, UK. *Journal of Applied Geophysics* 70 (1), 72–83.

Smith, B.J., Viles, H.A. 2006. Rapid, catastrophic decay of building limestones: Thoughts on causes, effects and consequences. In: Fort, R., Álvarez de Buergo M., Gómez-Heras, M.,Vázquez-Calvo C. (eds.) Proceedings of the international conference on heritage, weathering and conservation, 21-24 June 2006, Madrid. London: A.A. Balkema Publishers, 191–197.

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, 162–168.

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.

Sun, T., Grattan, K.T.V., Smith, B.J.,Srinivasan, S., Basheer, P.A.M., Viles, H.A. 2010. Optical fibre humidity sensor design for building stone condition monitoring. *Proceedings of the IEEE Sensors,* 1135–1139.

Thornbush, M.J. 2008a. Grayscale calibration of outdoor photographic surveys of historical stone walls in Oxford, England. *Color Research and Application* 33 (1), 148–154.

Thornbush, M. 2008b. Postcards used to track environmental history. *Environmental History* 13 (2), 360–365.

Thornbush, M.J. 2010a. Measurements of soiling and colour change using outdoor rephotography and image processing in Adobe Photoshop along the southern façade of the Ashmolean Museum, Oxford. In: Smith, B.J., Gomez-Heras, M., Viles, H.A., Cassar, J. (eds.) Limestone in the built environment: present-day challenges for the preservation of the past. London: Geological Society Special Publication 331, 231–236.

Thornbush, M.J. 2010b. Photographic surveys of building exteriors in central Oxford, UK. *International Journal of Architectural Heritage* 4 (4), 351–369.

Thornbush, M.J. 2012a. Tracking the use of climbing plants in the urban landscape through the photoarchives of two Oxford colleges, *Landscape Research*, 1861–1964.

Thornbush, M.J. 2012b. Developing a weathering scale for limestone walls in central Oxford, UK. *Geosciences* 2, 277–297.

Thornbush, M.J. 2012c. Archaeogeomorphology as an application in physical geography. *Applied Geography* 34, 325–330.

Thornbush, M.J. in press a. Photogeomorphological studies of Oxford stone – A review. *Landform Analysis*

Thornbush, M.J. in press b. Digital photography used to quantify the greening of north-facing walls along Broad Street in central Oxford, UK. *Géomorphologie: Relief, Processus, Environnement*

Thornbush, M.J., in press c. The use of climbing plants in heritage bioconservation. In: Horizons in Earth Science Research, Volume 10. Hauppauge, New York: Nova Science Publishers

Thornbush, M.J., Thornbush, S.E., in press a. The application of a limestone weathering index at churchyards in central Oxford, UK. *Applied Geography*

Thornbush, M.J., Thornbush, S.E., in press b. Photographs across time. Sharjah, U.A.E.: Bentham Science Publishers

Thornbush, M., Viles, H. 2004a. Integrated digital photography and image processing for the quantification of colouration on soiled surfaces in Oxford, England. *Journal of Cultural Heritage* 5 (3), 285–290.

Thornbush, M.J., Viles, H.A. 2004b. Surface soiling pattern detected by integrated digital photography and image processing of exposed limestone in Oxford, England. In: Saiz-Jimenez, C. (ed.) Air pollution and cultural heritage. London: A.A. Balkema Publishers, 221–224.

Thornbush, M., Viles, H. 2005. The changing façade of Magdalen College, Oxford: Reconstructing long-term soiling patterns from archival photographs and traffic records. *Journal of Architectural Conservation* 11 (2), 40–57.

Thornbush, M., Viles. H. 2006a. Changing patterns of soiling and microbial growth on building stone in Oxford, England after implementation of a major traffic scheme. *Science of the Total Environment* 367 (1), 203–211.

Thornbush, M.J., Viles, H.A. 2006b. Use of portable X-ray fluorescence for monitoring elemental concentrations in surface units on roadside stone at Worcester College, Oxford. In: Fort, R., Álvarez de Buergo, M., Gómez-Heras M., Vázquez-Calvo, C. (eds.) Proceedings of the international conference on heritage, weathering and conservation, 21-24 June 2006, Madrid. London: A.A. Balkema Publishers, 613–619.

Thornbush, M.J., Viles, H.A. 2007a. Photo-based decay mapping of replaced stone blocks on the boundary wall of Worcester College, Oxford. *Geological Society Special Publication* 271, 69–75.

Thornbush, M.J., Viles, H.A. 2007b. Simulation of the dissolution of weathered versus unweathered limestone in carbonic acid solutions of varying strength. *Earth Surface Processes and Landforms* 32 (6), 841–852.

Thornbush. M.J.. Viles. H.A. 2008. Photographic monitoring of soiling and decay of roadside walls in central Oxford, England. *Environmental Geology* 56 (3-4), 777–787.

Timofeev, D.A. 1991. Environmental geomorphology: Its subject, aims, and tasks. *Geomorfologiya* 1, 43–48.

Verstappen, H.Th. 1983. Applied geomorphology: Geomorphological surveys for environmental development. Amsterdam: Elsevier.

Viles, H.A. 1993a. The environmental sensitivity of blistering of limestone walls in Oxford, England: A preliminary study. In: Thomas, D.S.G., Allison, R.J. (eds.) Landscape sensitivity. Chichester: Wiley, 309–326.

Viles, H.A. 1993b. Observations and explanations of stone decay in Oxford, UK. In: Thiel, M. J. (ed.) Conservation of stone and other materials: Causes of disorders and diagnosis. London: E. and F.N. Spon, 115–120.

Viles, H.A. 1994. Time and grime: Studies in the history of building stone decay in Oxford. Research Paper No. 50. Oxford: School of Geography, University of Oxford

Viles, H. 1996a. "Unswept stone, besmeer'd by sluttish time": Air pollution and building stone decay in Oxford, 1790-1960. *Environment and History* 2 (3), 359–372.

Viles, H.A. 1996b. Monitoring the effects of the Oxford Transport Strategy on building stone decay and soiling. In: Riederer, J. (ed.) Proceedings of the 8th international congress on deterioration and conservation of stone, 30 September-4 October 1996, Berlin, 831–834.

Viles, H.A., Gorbushina, A.A. 2003. Soiling and microbial colonisation on urban roadside limestone: A three year study in Oxford, England. *Building and Environment* 38 (9-10), 217–1224.

Yesilnacar, M.U., Cetin, H. 2008. An environmental geomorphologic approach to site selection for hazardous wastes. *Environmental Geology* 55 (8), 1659–1671.