



The influence of aspect on the biological colonization of stone in Northern Ireland



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ABSTRACT

The rate and type of biological colonization of stone is influenced by a wide array of environmental factors in addition to substrate characteristics. A series of experiments was designed to compare the rate and type of biological colonization of stone at varying locations over a 21-month time period. Exposure trials were set up at nine different sites across Northern Ireland that covered a wide variety of environmental conditions. To determine aspect-related differences in colonization, blocks of Peakmoor sandstone and Portland limestone were placed on the north- and south-facing sides of purpose-designed exposure racks. Colorimetry and visual analysis were carried out on collected samples at increasing time intervals. Results showed significantly different rates of darkening and greening over time between north-facing and south-facing blocks, for both sandstone and limestone. This difference is likely to be representative of the fact that in Northern Ireland's wet climate and northern-latitude position, the north face of a building will receive less direct sunlight. Therefore north-facing blocks, once wet, will remain damp for much longer than blocks on other façades. This slow-drying phenomenon is much more hospitable for biological colonization and continued growth than the hostile environment of rapid wetting and drying cycles experienced on the south face.

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1. Introduction

It is a widely accepted axiom that biological growth varies with orientation. In the northern hemisphere more luxuriant biological growth appears to occur on north-facing surfaces, whether that be the northern slope of a mountain, side of a tree trunk, or façade of a historic building. Within Northern Ireland, the authors have frequently observed large differences in the quantity (and variety) of biological colonization between north- and south-facing building façades (supported by anecdotal evidence from conservation practitioners). North-facing surfaces in the northern hemisphere will naturally receive little to no direct sunlight during the day (particularly in winter) in comparison with those that are south-facing. This will lead to differences in (a) surface temperatures and solar radiation and (b) the moisture retention of the substrate. The term 'aspect' will be used throughout this paper to refer to spatial orientation i.e., the north, east, south or west-facing façades of a building or exposure rack.

Biological colonization on stone can generally be attributed to two main groups of contributing factors: those relating to the

properties of the substrate, i.e., the bioreceptivity of the stone, and environmental controls. The latter group of factors is the focus of this work, with bioreceptivity factors controlled to a certain extent by the use of one relatively homogenous stone type as the primary substrate throughout.

1.1. Environmental controls on biological colonization

Halsey et al. (1998) investigated the effects of aspect on the Lichfield Cathedral tower, in Staffordshire, England, measuring temperature, relative humidity, and the frequency of heating–cooling cycles. Results showed that the north face did not rise as much in temperature as the other faces, reaching a maximum of around 15 °C as opposed to 18–20 °C for the other three façades. The north face also demonstrated fewer heating–cooling cycles per month and fewer wetting–drying cycles. The lower frequency of environmental fluctuation may suggest less deterioration on this side from physical weathering (through, for example the crystallization or hydration/dehydration of soluble salts), but it also presents much more stable, and therefore less environmentally extreme conditions that are more suitable for colonization and continued growth.

The amount of solar radiation reaching a façade will also have an impact on the biodiversity of the substrate. Cyanobacteria have

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protective pigments and sheaths that protect them from ultraviolet radiation at levels that would be inhibitory to other microorganisms (Garcia-Pichel et al., 1993), whereas algae appear to be sensitive to solar radiation and are therefore more commonly located in shaded and moist areas (Lyalikova and Petushkova, 1991; Gaylarde and Morton, 1999). This was demonstrated on a more global than microclimatic scale by Gaylarde and Gaylarde (2005), who compared the microbiological diversity of 230 microbial biofilm samples taken from building exteriors (including stone, brick, concrete, mortar, and paint) in seven Latin American and six European countries. They found that in Latin America cyanobacteria were the dominant biomass, followed by fungi, whereas in Europe algae were the prominent biomass on all substrates, followed by cyanobacteria, with coccoid autotrophs being the most common form of organism overall. García de Miguel et al., 1995, in a study of biodeterioration on the Great Jaguar pyramid, in Guatemala, also found that cyanobacteria were the most prominent organisms and that eukaryotic algae were absent from most samples.

Caneva et al. (2008) considered the quantity and availability of moisture to be “the main determining factors for the speed at which a surface is colonized.” A stone surface can be an inhospitable environment for organisms, with rapid changes in surface temperature and variation in moisture availability. This is particularly true for vertical stone surfaces, where precipitation may not directly impact the stone face and any that does will run off rapidly. This accounts for the higher levels of colonization on angled or horizontal stone surfaces on a building (such as string courses and buttress capstones) where water gathers or runs off less rapidly, allowing sufficient moisture to be retained for colonization to occur. Young and Urquhart (1998) state, “vertical façades seldom support much biological growth unless they are in regions of high humidity or are often wetted.” Ortega-Calvo et al. (1993) also commented, “algae are commonly found on buildings in humid places, growing in cornices, in holes and crevices or beneath crusts where water is retained and evaporation is low.” Different species of microorganism will have variable tolerances for lack of moisture; however, those species adapted for life in desert or consistently low-moisture conditions are in the minority, and a mild and humid or wet climate will inevitably encourage more biological growth than an arid region. Gillatt and Tracey (1987) have also stated that “algae are more frequent on moist than on dry sites.”

As discussed, some previous research, e.g., Halsey et al. (1998), has demonstrated the difference in conditions and the potential impacts on stone weathering on differing aspects. Robinson and Williams (1996) state that “the issue of whether stone deterioration on buildings varies with aspect has rarely been discussed in any detail and remains under-researched.” They also go on to comment that “where thermal changes are responsible for the deterioration one would expect to find significant differences in amounts of weathering between the north and south sides of buildings but little, if any, differences between the east and west sides.”

In terms of the effects of aspect on biocolonization, and therefore potentially biodeterioration, on historic buildings, the phenomenon is well accepted, yet relatively little research has been carried out to attempt to quantify the difference in colonization (particularly the early stages) between aspects on masonry. The majority of work has been based on studies of established biological growth, and in particular on lichens (Nimis and Monte, 1988; Monte, 1991; Tretiach et al., 1991; Paradise, 1997). Mottershead et al. (2003) investigated aspect-related differences on a coastal fort in England, and found that biofilms on the north aspect were thicker and more uniform than those on the south: “...stone samples from the southern wall are less pigmented and show only a slight shade of green on their surface. The biofilm is patchy in

distribution, unlike the uninterrupted layer on the surface of the north wall.” Also, Krumbein et al. (2006) refer to north-facing façades being the most conducive to biofilm formation in a report by Historic Scotland.

This study will directly investigate the differences in early biocolonization between north- and south-facing stone blocks, across nine environmentally variable sites using a set of 21-month exposure trials.

2. Materials and methods

Identical exposure trial experiments were set up at nine different sites (Fig. 1) in order to represent the wide variety of local environmental conditions (see Table 1). Care was taken not to place exposure racks in areas that were sheltered or had overhanging vegetation. All exposure racks were aligned north–south using a compass.

The exposure trials consisted of a series of investigations, consisting of specifically designed holding racks where stones were set at a 45° angle with the aim of representing slow run-off areas on historic buildings (such as buttress capstones).

The primary experiment was designed to investigate the overall rate, type, and amount of colonization on the exposed stone surfaces over time. Designated blocks at each site were collected from both aspects at intervals of 9, 13, 17, and 21 months, with additional blocks collected at 6, 11, 15, and 19 months from the north-facing sample sets only. This was due to the fact that more rapid colonization and growth was expected on north-facing blocks. All remaining blocks on both aspects were photographed using a Fujifilm A920 camera at each site visit.

Due to the accelerated initial rate of greening observed at the Omagh site, extra blocks were put out on both aspects, halfway through the exposure period (September 2010) to investigate the rate of soiling within the first few months of exposure. These then represented a set of 2- and 4-month values for the Omagh site only (Fig. 4F).

Once collected, all stones were stored at approximately 4 °C in a standard refrigerator that was used solely for these samples. The refrigerator was used (a) to prevent contamination of samples by airborne particles and (b) to slow biological degradation. All collected blocks were allowed to dry for 2–4 wk before colorimetric readings were taken.

2.1. Materials

The main type of sandstone used for the exposure trial blocks was Peakmoor sandstone, a Carboniferous, non-calcareous, quartz sandstone that is still actively quarried near Matlock, England. Peakmoor sandstone is used throughout the UK and has been used in Northern Ireland in recent years for stone replacement, due to its similarity in appearance to historically used local stone types.

To compare potential aspect-related soiling differences between different stone types, two mid- and end-time (i.e., 13 and 21-month) Portland limestone blocks were placed on both the north- and south-facing samples at each site. Portland limestone is an oolitic, Jurassic limestone from England that has historically been used widely throughout the United Kingdom for many prestigious buildings and monuments, e.g., St. Paul's Cathedral in London, and Belfast City Hall. See Table 2 for substrate characteristics for both stone types.

2.2. Colorimetry

Prieto et al. (2004) investigated the efficacy of three different methods for estimating biofilm mass on stone samples in the

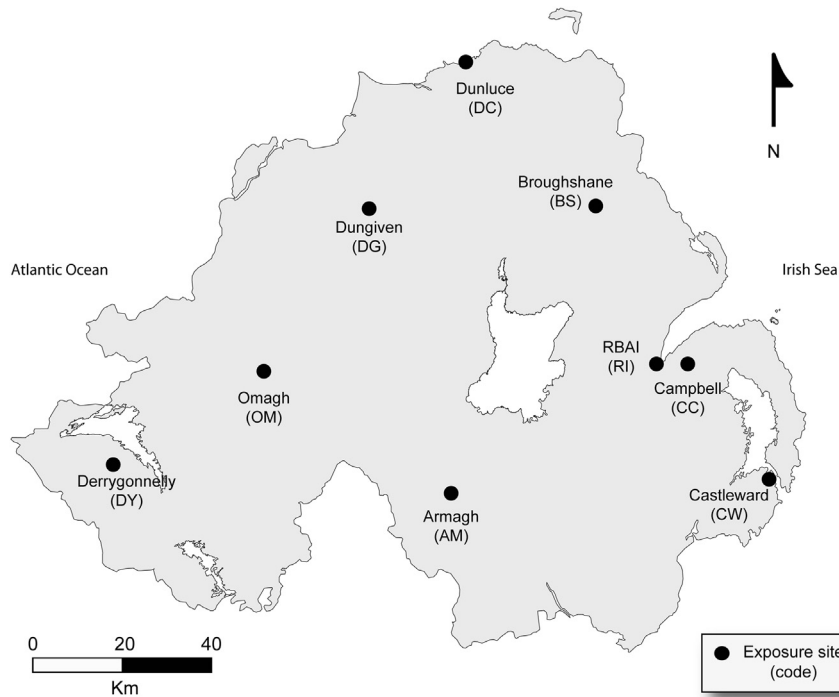


Fig. 1. Map of Northern Ireland showing all nine exposure site locations and site codes.

laboratory, on blocks inoculated with cyanobacteria. They concluded that colorimetry could be used to reliably estimate biomass with changes in colour correlating closely with cell aggregate numbers.

Colorimetry measurements were taken using a Konica Minolta Chroma-Meter CR-410 colorimeter. A total of six measurements per block were taken and averaged to give one set of $L^*a^*b^*$ values per block; this allowed for a more representative overall block value, taking into account whether soiling was uniform or patchy. Baseline readings were taken for all stone types using the same method, averaged for three blocks as opposed to one. The L^* portion of the $L^*a^*b^*$ scale measures luminance from 0 to 100, 100 representing the lightest end of the scale, and 0 the darkest. Therefore a shift toward the negative end of the scale represents darkening. A measurement on the a^* chromatic scale provides a value located on the green-to-red axis; values range from the greenest end of the scale (-50) to the reddest end ($+50$). Therefore a shift toward the negative end of the scale represents greening.

Figs. 2–4 show actual block values, and Figs. 5 and 6 show block readings with baseline values deducted to show changes from the baseline, i.e., quarry-fresh blocks, from the same batch of stone. The Dunluce Castle site sandstone values have not been included due to the fact that the rack was blown down in a severe storm within

a few months of exposure. The rack was re-erected but several blocks had rust staining from the metal roof they were resting on prior to reassembly.

3. Results

3.1. Timeline

Table 3 shows the order of appearance (visibility with the naked eye) of green algae and lichens on the north- and south-facing sandstone blocks at all nine exposure sites. Within six months, eight of nine sites had green algal growth on the north-facing blocks, as opposed to three of nine for the south-facing. By 11 months all exposure sites had green algae on north-facing blocks, whereas six of nine sites had green algae on south-facing blocks. Green algae were not visibly present on south-facing blocks at all sites until 17 months.

The first visible occurrence of lichens was on north-facing blocks of one site at 11 months; these appeared on the first south-facing site block at 13 months. At 15 months seven of nine sites had visible lichens on north-facing blocks; for south-facing blocks the tally was five of nine. By the end of the 21-month exposure period seven of nine sites had lichens present on north-facing, and six of

Table 1

Environmental profiles of all nine exposure sites, elevation data gathered using a Garmin eTrex, rainfall data from MET weather stations.

Site No.	Name	Urban/Rural	Distance from coast (km, approximate)	Elevation (meters)	Nearest weather station (km, approximate)	Rainfall (mm) during exposure period
1	Broughshane	Rural	16	173	3	2826.3
2	Dunluce Castle	Rural	0	51	5	2256.1
3	Dungiven	Urban	21	94	5	2282.0
4	Omagh	Urban	34	81	1.6	2053.9
5	RBAI School	Urban	1.6	16	3	1904.2
6	Campbell College	Suburban	2.4	42	1.6	1578.2
7	Derrygonnelly	Rural	21	67	1.6	2557.83
8	Armagh Observatory	Urban	40	78	1.6	1521.9
9	Castleward	Rural	0	13	6	1976.8

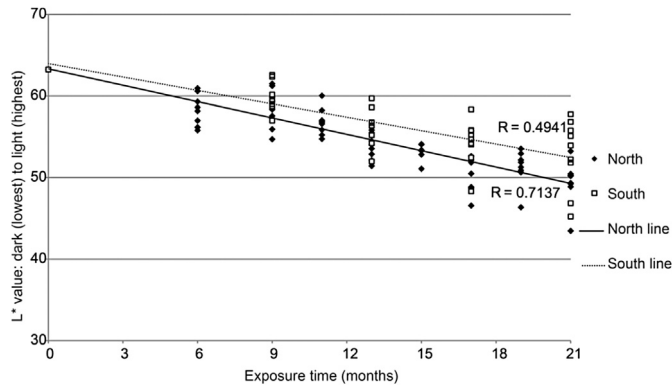


Fig. 2. Surface darkening (actual L^* values) of all north- and south-facing blocks over time; i.e., decreasing value signifies a shift toward the dark end of the L^* scale.

nine on south-facing blocks. The urban and suburban Belfast city sites had no lichens present on either the north- or south-facing blocks by the end of the experiment.

3.2. Darkening

Fig. 2 shows L^* values for all north- and south-facing blocks at all sites over the exposure period. There does appear to be difference in the rate of block darkening between aspects, with north-facing blocks darkening consistently more rapidly than south-facing samples. There is more variation among south-facing blocks, as demonstrated by the R^2 value (0.4941 on the south, 0.7317 on the north). There was a statistically significant difference ($P = 0.00004$) between L^* values on north and south-facing aspects, as confirmed by a paired two-tailed t -test ($df = 34$). It appears that the gap between north- and south-face soiling is greater at some sites than for others, and there is a wider variety of soiling rates on south-facing compared to north-facing samples between sites, particularly by the end of the 21-month exposure period.

3.3. Greening: aspect

Fig. 3 demonstrates a clear difference in greening rates between north- and south-facing blocks. At nine months, all sites but one show more greening on the north-facing samples than on the south-facing. The site with the most greening shows an a^* value of 0.68 on the north-facing block, as opposed to 1.73 on the south-facing sample (change from a baseline a^* value of 2.04; negative change reflects a shift toward the green end of the scale). In the case

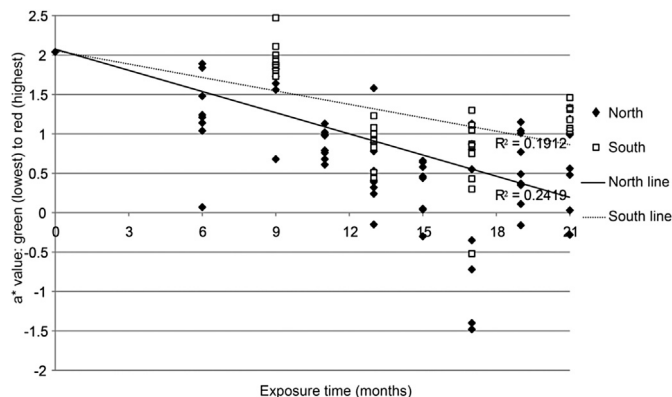


Fig. 3. Surface greening (actual a^* values) of all north- and south-facing blocks over time; i.e., decreasing value signifies a shift toward the green end of the a^* scale.

of the one site (Derrygonnelly), which showed similar greening on the south-facing samples, the a^* values were 1.82 (north) and 1.81 (south).

The gap between north and south-facing greening continues to widen with time; this is observable in Fig. 3 despite the variation in environmental conditions between sites.

Fig. 4 shows north- and south-facing greening levels by site for six of the nine exposure sites. Two things are clear from the site-specific greening charts—first, that for the majority of sites, greening is consistently more intense on north-facing blocks, and, second, that greening patterns vary between sites over the 21-month period. It is also true that for all sites except Derrygonnelly and Omagh (Fig. 4D and F), the greening pattern on the south-facing samples mirrors that of the north-facing samples but at a lower intensity.

The Derrygonnelly site appears to be an exception, with greening generally increasing over time, but to a lesser degree than at other sites and with much more fluctuation. The south-facing values are also very similar to the north-facing values, with greening actually marginally higher on the south-facing blocks at 13 months.

The Omagh site (Fig. 4F) follows the pattern of the majority of sites for the first half of the exposure period, with greening higher on north-facing samples. However, between 11 and 15 months this pattern appears to shift to one more similar to that of Derrygonnelly, i.e., there are similar values on north- and south-facing samples. Fig. 4F also demonstrates the rapidity with which greening can occur, with considerable greening occurring in only two months of exposure at the Omagh site. The difference between aspects is also already distinguishable at the two-month point.

Overall there was a statistically significant difference ($P = 0.0002$) between a^* values on north- and south-facing aspects as confirmed by a paired two-tailed t -test ($df = 34$).

3.4. Darkening and greening: synthesis

There are two patterns in relation to the synthesis of greening and darkening—the first demonstrated by Fig. 5A–B, where darkening and greening both follow the same pattern throughout the exposure trial, and the second demonstrated by Fig. 5C–D, where greening and darkening are not synchronized.

3.5. Limestone

Fig. 6A–B shows changes in greening from the baseline average at each site and for both aspects at 13 and 21 months. Fig. 6A shows a very clear increase in greening on north-facing blocks as opposed to south-facing, and this is the case for all sites. The largest differences in greening between aspects can be observed at Derrygonnelly, Dunluce, and Castleward, the lowest at RBAI, Armagh, and Dungiven.

At 21 months (Fig. 6B) there is much less difference between aspects; greening appears to have continued to increase on the south-facing blocks, but has decreased on those that are north-facing. At 13 months five out of nine sites have a negative a^* value shift of 0.6 or more for south-facing samples, at 21 months seven of nine sites show a change of 0.6 or more. On the north-facing samples at 13 months, seven of nine sites have an a^* value change of 0.8 or over, while at 21 months only four sites are over 0.8.

4. Discussion

There can be no doubt that soiling (and particularly greening) occurred more rapidly and continued to be more intense on north-facing blocks (see Fig. 7). North-facing blocks

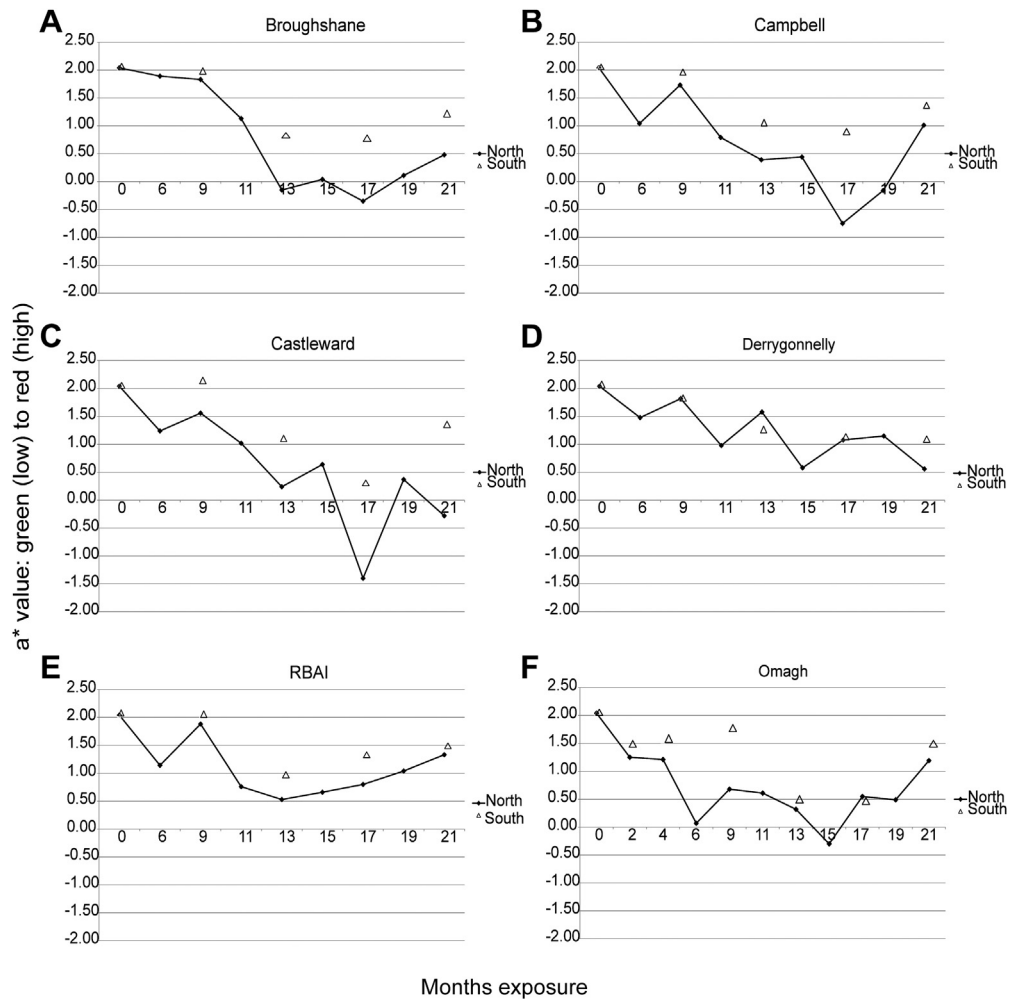


Fig. 4. Greening (a^*) values over time for six individual exposure sites (north and south), A–F: Broughshane, Campbell, Castleward, Derrygonnelly, RBAI, and Omagh.

were colonized more rapidly by both green algae and lichens, with a full six-month lag between all sites having visible green soiling on north-facing samples, and all sites having visible green soiling on south-facing samples (Table 3). In terms of greening, there was generally a larger amount of fluctuation in greening (than darkening) levels throughout the 21-month exposure period, but throughout these fluctuations a^* values for south-facing blocks

remained higher (less green) than north-facing blocks, the exceptions to this being Derrygonnelly (Fig. 4D) and the latter end of the exposure period for Omagh (Fig. 4F). The difference between the biological soiling of the two aspects is very clear when examining collected blocks. Pollutants and other non-biological sources of soiling will be airborne, deposited by precipitation or occult deposition. In the majority of cases it is probable that this will result in a more even spread of soiling, i.e., these sources will be as likely to soil the north face as the south. There may of course be potential exceptions to this rule, e.g., if one side of the rack is angled more toward a roadside than the other (it was for the purpose of avoiding such situations that racks were all placed on rooftops and no racks were placed directly on a roadside).

Table 2

Substrate characteristics for Peakmoor sandstone and Portland limestone. Open porosity, apparent density and pH testing carried out by the author. All other information derived from BRE stone list.

	Peakmoor sandstone	Portland limestone
Age	Carboniferous	Jurassic
Texture	Fine-medium-grained	Tightly grained
General mineralogy	Quartz, kaolinite	Oolites in a calcium carbonate matrix
Open porosity %	14.56	16.09
Saturation coefficient	0.68	0.70
Compressive strength (MPa)	72.5	62.7
Apparent density	2264.50	2298.48
pH	7.42	8.65

An important thing to consider is that the a^* scale measures on a green-to-red axis; therefore if both green algal and red biological staining are occurring simultaneously they will compete along the same scale. Red algae (*Rhodophyta*) are seldom found on external stone surfaces. Caneva et al. (2008) state that they are rarely represented on stone in subaerial environments, being only sporadically found in “monumental fountains or very humid hypogean environments.” In the majority of cases where algal reddening of the surface of exposure trial-blocks occurs this will have been due

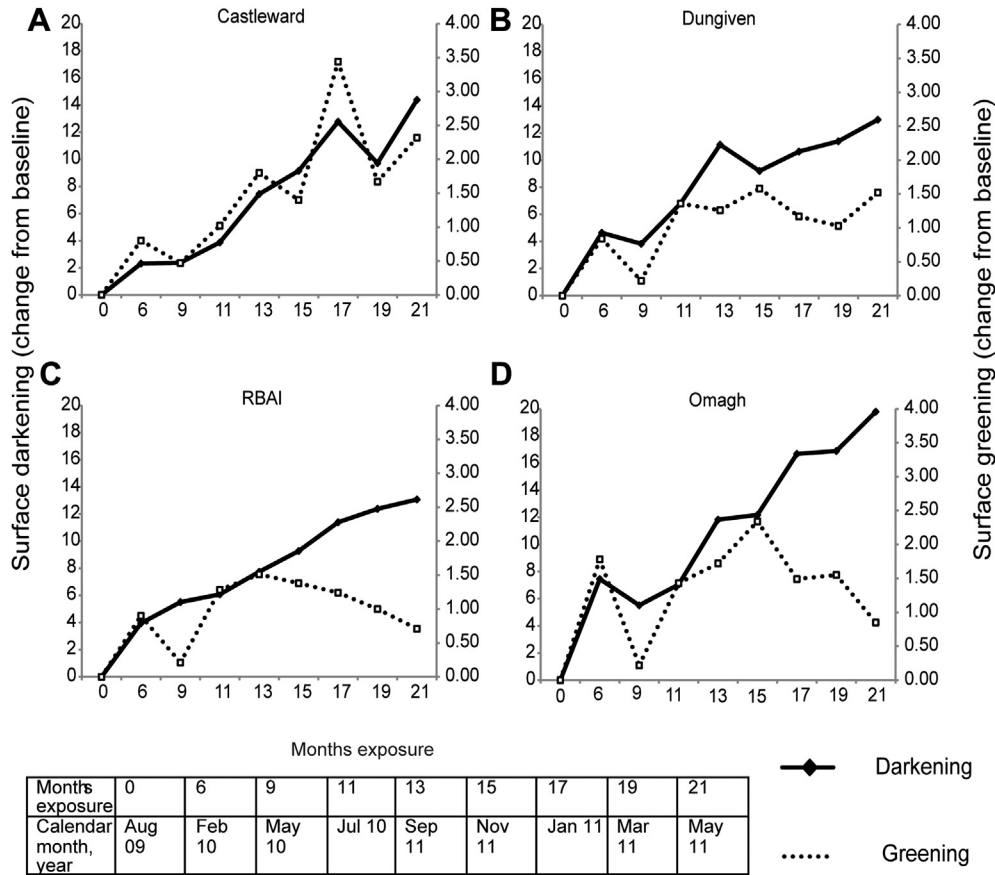


Fig. 5. Greening and darkening of individual exposure sites over time, north face only. Values show change toward dark (negative L* shift) or green (negative a* shift) from baseline readings.

to the presence of the green algal genera *Trentepohlia* and *Haematococcus*, which contain high levels of carotenoid pigments and are therefore orange to red in appearance. It is the occurrence of both colors (i.e., red and green) of “green” algae that accounts for the high levels of fluctuation at the Derrygonnelly site, where red-colored algae were observed on sandstone blocks.

This is also the explanation for the changes observed between the 13- and 21-month time periods for the Portland limestone blocks (Fig. 6). Red-colored algae appeared to preferentially grow on the exposed limestone blocks and caused visible staining at many of the exposure sites. The supposed reduction in greening occurring at the 21-month period was, in fact, not a reduction in greening but an increase in reddening on the north-facing blocks, shifting the a* readings back toward the red end of the axis, whereas on the south-facing blocks, greening had progressed and red-colored algae had not yet become established. Moses (1996) also observed red algal soiling on sheltered Portland limestone samples, exposed as part of a 3-yr stone decay exposure trial at Lough Navar, Fermanagh (located approximately 3 mi from the Derrygonnelly site). The same study found green algal soiling at blocks on the north coast of Northern Ireland (located close to the Dunluce site); however, in both cases algae were only observed on sheltered blocks, prompting the author to comment that “exposure to direct rainfall may have a limiting effect on biological growth.”

4.1. Greening: site comparison

In terms of greening (Fig. 4) there was considerable variation between sites. Some sites were slow to green in the early stages,

progressing rapidly in the later stages of exposure (e.g., Broughshane and Castleward (Fig. 4A and C)); others began to green extremely rapidly but greening decreased with time (e.g., Omagh (Fig. 4F)). Fluctuation patterns also varied considerably between sites, although several sites showed a peak in greening in January 2011 (17 months). At some sites greening appeared to correlate with real-time weather data collected from MET stations near exposure sites (this will be explored further in a future publication); however, although December 2010 and January 2011 were not months with high rainfall levels, they were months with heavy and prolonged snowfall, which would have remained on blocks for several weeks. This also clarifies that low temperatures (below freezing) do not inhibit green algal growth. Moisture availability is unlikely to be an inhibiting factor in Northern Ireland due to the generally high levels of rainfall received (see Table 1); there is, however, an observable increase in the highest rainfall areas. Adamson et al. (2010) previously highlighted higher levels of biological soiling in the northwest of Northern Ireland due to the wetter maritime influence from the Atlantic.

With regard to precipitation, all exposure racks were placed in unsheltered areas, with both north- and south-facing blocks set at the same (45°) angle. Therefore incident precipitation should have wetted both aspects of the exposure rack equally, with the exception of near-horizontal driving rain. In the case of Northern Ireland the prevailing wind direction is from the southwest; therefore, incoming rainfall would be expected to preferentially wet the south aspect, promoting greening on the south-facing blocks rather than north-facing samples, as was recorded. This supports the reasoning that it is increased incident solar radiation on the south-facing

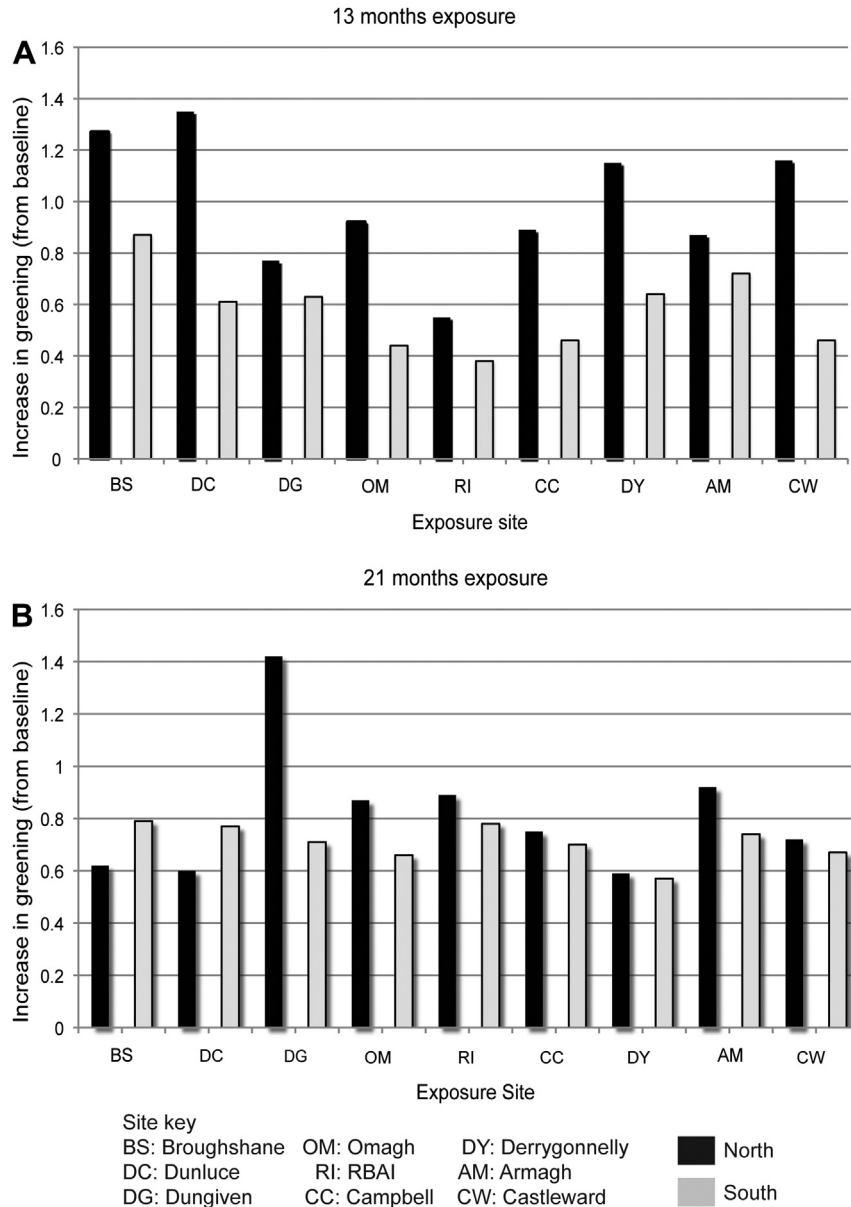


Fig. 6. Greening (change from a* baseline values) for north (black) and south (white) Portland limestone blocks at all sites at 13 (A) and 21 (B) months.

blocks that facilitates rapid drying and a low-moisture stone surface, less supportive of colonization on south-facing blocks. This may also explain the fact that there is less difference in greening between aspects at some of the wetter sites (such as Derrygonnelly). A total of 2557.83 mm of rain fell at Derrygonnelly over

the 21-month exposure period, compared to 1521.9 mm in Armagh; it is likely, therefore, that south-facing blocks at Derrygonnelly had less opportunity to dry between wetting events than those at Armagh, reducing the inter-aspect difference at the wetter sites.

No clear patterns in seasonality are observable in the greening data, which correlates with the fact that there appears to be no consensus in the literature on whether seasonality is a significant factor for lithobiontic organisms. Ortega-Calvo et al. (1991) state that in Europe “the season of the year in which the samples are taken does not affect the major species of algae and cyanobacteria detected”; this does not refer to biomass, however, but to the major species present. Taylor and May (1991) observed an increase in the number of bacteria during the winter months in the UK, whereas Schostak and Krumbein (1992), in a study on a German church (interior), found that the lowest numbers of bacteria were found in January, and the greatest in October.

Greening did not begin more rapidly in rural exposure sites when compared with urban locations. The most rapid greening was

Table 3

Timeline showing order of appearance (visibility with the naked eye) of green algae and lichen on north and south facing blocks at all sites. Numbers represent the number of sites (out of nine) at which the organism-type appears.

		No. of sites (out of 9) at which the organism type appears								
Time (months)		0	6	9	11	13	15	17	19	21
North face	Green algae	8	8	9	9	9	9	9	9	9
	Lichens	0	0	1	2	7	7	7	7	7
South face	Green algae	3	4	6	6	7	9	9	9	9
	Lichens	0	0	0	1	5	6	6	6	6

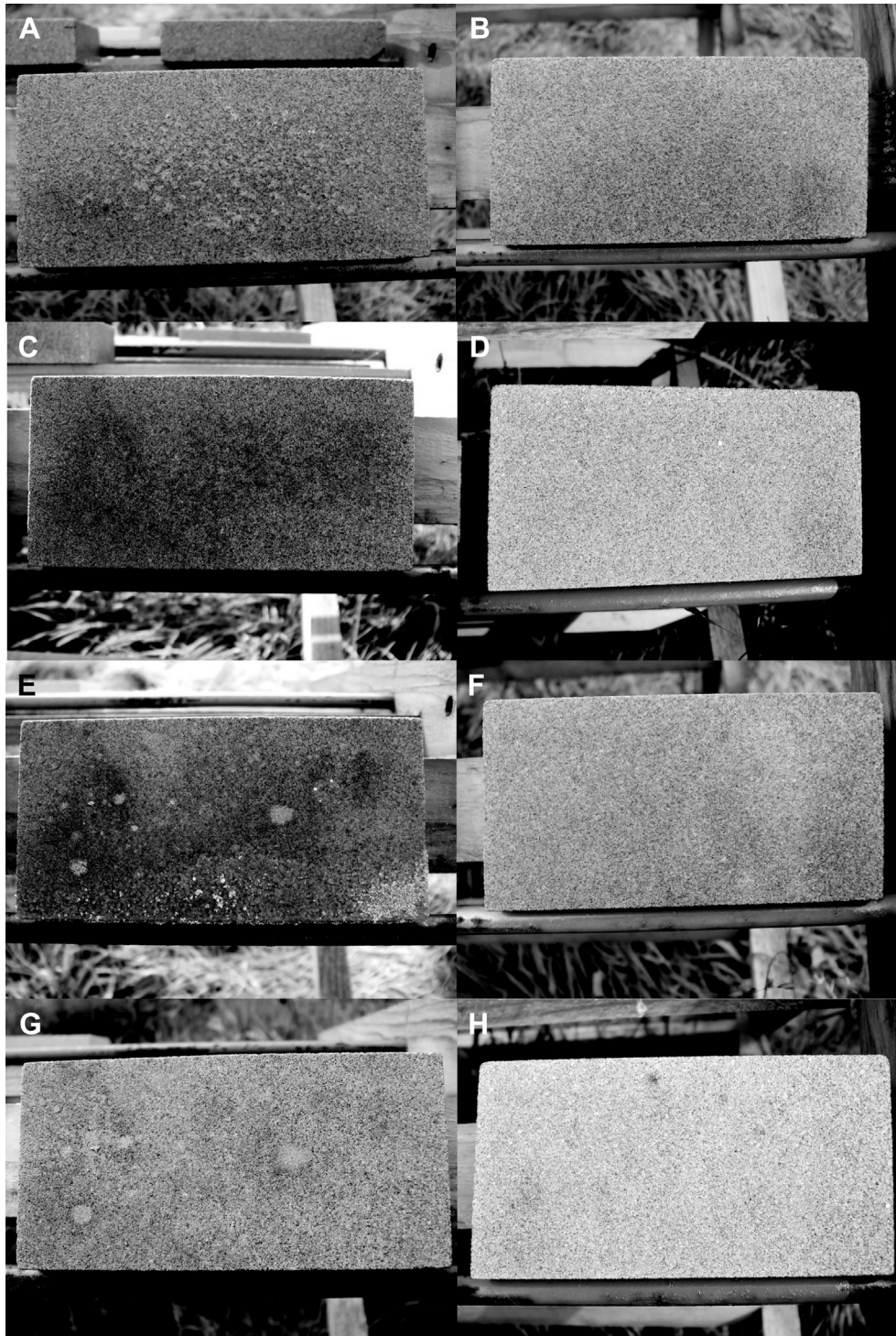


Fig. 7. Sample images from the Broughshane site at 6 (A–B), 13 (C–D), 17 (E–F), and 21 months (G–H). North-facing blocks on the left, south-facing on the right.

observed at Omagh (the western urban site), with the a^* value dropping from the baseline of 2.04 to a value of 0.06 within six months. Despite this initial rapid greening phase, greening began to decrease, with Omagh ending the 21-month period as the second least green site, with the Belfast city centre site (RBAI) as least green. It is possible that the levels of pollutants at both these sites began to inhibit the initially rapid algal growth. Omagh is classed as a large town, with a population of just under 20,000 in the 2001 census, as opposed to the Belfast Metropolitan Urban Area, which

had a population of 580,000 (NINIS, 2012). However, the blocks collected at Omagh were visibly much more soiled than the Belfast blocks; this is due to the fact that Belfast, unlike Omagh, is a designated smokeless fuel zone (DEFRA, 2012). The blocks collected from Omagh had large amounts of black flyash (particularly coal) particles embedded in the biofilm within six months.

There are therefore clearly two types of soiling occurring on the observed blocks, although in a colorimetry sense they are inter-linked on the L^* (darkening) scale. Green soiling can be attributed

almost entirely to green algae, cyanobacteria, and, to a much smaller degree, lichens. Darkening of blocks, however, can be contributed to by a wide variety of sources, both inorganic and organic (green algae, fungi, lichens, cyanobacteria, etc.).

Due to the fact that the L^* portion of the $L^*a^*b^*$ system measures the degree of luminosity, i.e., darkness to lightness of a given surface on a scale of 0–100, there will be a degree of overlap between the “greenness” data and the surface darkening data; i.e., if the surface darkening of a particular sample was composed of entirely green algae then the changes in L^* and a^* should be proportionally the same (as observed in Fig. 5A–B), whereas if the surface darkening was mostly composed of non-green soiling, e.g., flyash or fungal growth, with very little green algae, the change in L^* and a^* should follow different patterns of change (demonstrated by Fig. 5C–D). The two scales are not comparable in a quantitative sense, since they are measured on different axes, L^* 0–100 and a^* –50 to +50; however, changes in pattern will show whether changes occur in the same direction over the same time period. This is indeed observable with the exposure sites.

While identification of species or genera involved would have been a very beneficial exercise (and will in fact be carried out in the near future for a limited selection of sample blocks), the main focus of the experiment was to investigate the rate (and general type) of change observed on freshly exposed blocks in settings representative of those experienced by dimension stone exposed across Northern Ireland. It is well known that only a small proportion of the organisms present on a stone surface can be cultured and identified; e.g., Dubosc et al. (2001) conclude that culture on different nutrient media is inappropriate for determining the dominant organisms because it favors the growth of more non-representative organisms such as bacteria and fungi. Garcia-Vallès et al. (1997) comment that some of the most persistent rock fungi are not culturable with routine techniques, and cultures can be overgrown with airborne fungi that are not typical rock flora. Several authors have concluded that 99% of the microorganisms present in such a sample cannot be cultivated (Amann et al., 1995; Pace, 1997; Herrera et al., 2009). The majority of lithobiontic organisms are also genera that are considered ubiquitous (Ariño and Saiz-Jimenez, 1996), often varying little even between continents. While the use of DNA/RNA identification techniques has made identification more efficient, the species needs to be in the existing databases (i.e., previously sequenced) to be identified; almost every study appears to find species that are new to the database, and large amounts of taxonomic debate have arisen from their naming and grouping. In addition, where adhesive-tape sampling or surface scraping is used, only organisms that reside on the outer surface will be identified, excluding any organisms residing in pores or between stone grains.

5. Conclusions

Where previous studies featuring aspect comparison have focused on established biological growth (predominantly lichens), this study has allowed for a comparison of biological growth between aspects at the very early stages of colonization (up to 21 months) in a natural (rather than laboratory) setting. Results show visible, measurable, and statistically significant colorimetric differences between north- and south-facing blocks, detectable from as early as two months after exposure.

Both “greening” and darkening of sandstone blocks was significantly increased on north-facing as opposed to south-facing blocks. This is assumed to be a function of increased “time of wetness” on the north face due to slower drying times, and therefore related to mainly biological soiling (whether green or otherwise).

Portland limestone blocks showed initially much higher levels of greening on north-facing blocks, but at the later stages of the exposure trial this aspect-gap decreased. This was not due to a decrease in north-face greening but to the increased levels of carotenoid-rich green algal species, shifting the a^* values back toward the red end of the green-red axis.

Northern Ireland’s wet climate lends itself to high levels of biological soiling, particularly on local higher-porosity (i.e., higher-moisture-retention-capacity) sandstones. United Kingdom and Irish conservation professionals are reporting higher levels of algal greening in recent years. This is thought to be a function of wetter exposure conditions (McCabe et al., 2011), combined with reduced atmospheric sulphur pollution, and increased nitrogen pollution from vehicles (Smith et al., 2010). Algal soiling is an esthetic nuisance and costly to remedy for building owners. Greater knowledge of the predicted patterns of biological soiling (algal greening in particular) may allow for more tailored conservation measures in the future, particularly with climate change projections suggesting warmer, wetter winters for the northwest of the United Kingdom (UKCP09, 2012). If, for example, greening is likely to occur much more rapidly on the north face of a building, building owners or conservators may find it more cost-effective to preferentially treat only (or more frequently) the north face with biocides or water consolidants.

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