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MAPPING THE SPATIAL DISTRIBUTION OF PRECIPITATION, BIOLOGICAL SOILING, AND DECAY ON MONUMENTS IN NORTHERN IRELAND: TOWARDS UNDERSTANDING LONG-TERM STONE RESPONSE TO MOISTURE

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Abstract: The Natural Stone Database for Northern Ireland was constructed to address the paucity of information available to stone conservation practitioners. Almost 2000 listed buildings, 260 monuments and 118 quarries were surveyed over three years to produce an interactive GIS database for the Northern Ireland Environment Agency. This contains information on stone sources, together with details of stone condition and decay processes and is complimented by a website available to the general public. This paper uses elements of this GIS to link annual rainfall data for Northern Ireland with information on the biological soiling, and decay of stone monuments across the province to examine the relationship between moisture and availability on these processes. Results suggest that biological soiling is indeed strongly influenced by moisture availability (i.e. precipitation), with higher levels of biological soiling evident in the wetter North-West of Northern Ireland where annual precipitation is higher in response to a strong Atlantic signal. This compares to lower levels of biological soiling evident in the more rain-sheltered South-East of the province. Stone deterioration appears to be less influenced by climate and more closely related to the geology characteristics with higher levels of decay often observed on sandstone monuments and lower levels of decay associated with areas in which low porosity stone types such as basalt predominate. The results have clear implications for future patterns of soiling in light of projections for regional climate change that indicate increased winter wetness, but they also demonstrate the multifactorial nature of the controls on stone decay and highlight the need for careful and thorough analysis before any generalizations are proposed.

Keywords: Building stone; Biological soiling; Decay; Climate Change; Stone Database; Northern Ireland

1. Introduction

Northern Ireland has a rich stone-built heritage, including buildings and monuments ranging from the medieval to the contemporary. Many of these were constructed using sandstone (as a primary stone type or as stone dressing)– a stone that is often aesthetically pleasing and easy to work, but also one that is prone to decay. Northern Ireland has a variety of local Carboniferous and Permo-Triassic sandstones (Tab. 1), many of which were historically used for construction, particularly in the case of older monuments, where the nearest available stone would have been accessed due to transport limitations. The Natural Stone Database Project was a first step in addressing some of the lack of information available for stone conservation in Northern Ireland. The project developed as a unique partnership between industry and research in Northern Ireland that combined the research knowledge of the Stone Weathering Research Group at Queen's University Belfast with the practical experience of Consarc Design Group (an architectural practice with a specialist conservation branch). The project comprised an extensive two and a half year programme of surveying, stone sampling and analysis which was used to produce an interactive, database of listed buildings, monuments and stone quarries 'The Natural Stone Database' and 'Guidance Notes' for the Northern Ireland Environment Agency and a website (www.stonedatabase.com) providing information on local buildings, quarries and stone types, and fully accessible by the public (Hyslop et al., 2009).

Table 1. Summary of Northern Ireland's main local sandstone varieties, adapted from www.stonedatabase.com

Sandstone Type	Age	Porosity (%)	Description
Ballycastle Sandstone	Carboniferous	2,79	Ranges in colour from pink, grey and yellow to white, fine to coarse-grained bedded sandstone. Decays by scaling and granular disintegration
Cookstown Sandstone	Permo-Triassic	n/a	Ranges in colour from pale pink to red and weathers by flaking, scaling and bedding-plane erosion. Thin section analysis shows it to be more calcareous than Scrabo Sandstone
Dungannon Sandstone	Carboniferous	4.44-17.10	Fine-to medium-grained with colours ranging from cream, greyish-white, and grey to yellow. In polluted environments this sandstone soils rapidly and develops black crusts which when breached rapid decay occurs through scaling and granular disintegration
Dungiven Sandstone	Carboniferous	18,9	Vast range of colours from buff, white, yellow to pink. Individual pebbles and beds of coarser material are often visible in blocks. Stone faces generally show granular disintegration, differential weathering along bedding planes, and occasional pitting of stone surfaces
Fermanagh Sandstone	Carboniferous	1,29	Pale grey to buff in colour, very durable, rarely exhibiting pitting
Scrabo Sandstone	Permo-Triassic	21-24	Ranging in colour from buff to pink or red. Clay-rich, bedded sandstone which weathers rapidly with flaking, scaling up to cavernous decay

One of the key underlying controls on stone decay is moisture content and migration (Turkington et al., 2002). Moisture can cause damage directly - dilatation and contraction can take place in sandstones due to moisture changes. For most sandstones, hydric dilatation is in the range of 500μm/m, but clay-rich sandstones can reach 5000μm/m (Snethlage and Wendler, 1996). However, because moisture is an underlying control, it also acts indirectly through other decay agents. For example, it is in the presence of soluble salts that moisture is most often considered most destructive, with salts re-crystallizing to push apart grains as damp stones dry (Smith and McGreevy, 1988; Goudie and Viles, 1997). Moisture availability will also be key in determining the nature and extent of biological colonization on rock surfaces. Thus, Caneva et al. (2008) considered the quantity and availability of water to be the main determining factors for the speed at which a surface is colonized.

The aim of this paper is to begin to understand stone response, in terms of biological soiling and decay, to the variable current precipitation across Northern Ireland. It investigates the influence of wider environmental factors without delving into specific monument macro-environmental influences (though it recognizes the importance of these). Once a greater level of understanding of the effects of current precipitation regimes on stone has been gained, implications for climate change and wetter winter conditions are discussed.

2. Methods

Investigating the biological soiling of monuments
A total of 247 monuments, which were surveyed as part of the Natural Stone Database project were included for GIS. Soiling information for each monument on the database was expounded using information from the original monument survey sheets to include the biological soiling information for each façade. Each monument was then given a corresponding score (1 or 2) according to whether all existing façades had >50% biological soiling or did not. The GIS map was then queried for all monuments where every existing façade had a value of 2 (>50% soiling). The GIS was then also queried for all monuments where sandstone was the primary stone type.

The rainfall raster shows annual rainfall in millimetres as an average value for the years 1961-1990. The MET office isohyet map was digitised to Irish grid to include 14 values ranging from 750-1800mm; this was then converted from polyline to a raster surface with a spatial resolution of 500m.

2.1. Assessing stone characteristics and condition

All monuments had previously been surveyed as part of the stone database project and given a stonework condition score for each façade (and overall) based on the UAS staging system devised by Warke et al. (2003). The building and monument surveys provided an indication of the overall

Table 2. Definitions of the level of decay and extent of intervention required for each of the four main decay stages in the UAS staging system. Adapted from Warke et al. (2003)

Stage	Extent of intervention required
Stage 1	- No active intervention may be required - Or localized remedial treatment of individual stone blocks - Periodic reassessment advised
Stage 2	- Relatively limited section specific remedial action
Stage 3	- Significant intervention - Up to 50% of total façade showing deterioration - Appropriate intervention should prolong life expectancy of the structure
Stage 4	- Serious deterioration affecting >50% of façade - Considerable intervention required - If not of historic/architectural merit consider palliative rather than restorative treatment

condition assessment of the stonework of each façade of a building and ranged from: Stage 1 (best condition) to Stage 4 (poorest condition), stages 1 to 4 are described in table 2. Each elevation was surveyed according to the 'Staging System' which records and assesses the type, nature and extent of weathering of the stonework, the condition assessment score for each elevation was then averaged to produce an overall value for the building or monument. A staging score of 2110 (a lower stage 2) was chosen as an indicator as it represented a medium level of decay. A stage 2 building is described in Warke et al. (2003) as one where "section specific remedial action would be required but the extent of intervention should be relatively limited because of the lack of distant involvement within the façade boundaries" i.e. there is some spreading stone decay but this is currently limited to localised areas. A stage 2 building may be considered to be bordering on "acceptable" decay with limited intervention required, whereas stage 3 and 4 buildings will require considerable restoration work. Therefore the GIS map was queried for all monuments where at least 50% of façades demonstrated a score of 2110 or greater i.e. a medium level of decay or above.

Stone porosity values were derived from Open Porosity and Apparent Density (BS EN 1936) testing carried out as part of the stone database project using blocks collected from both contemporary and historical quarries.

3. Results

3.1. Biological soiling

Figure 1 shows a map of annual rainfall overlain with monuments (those showing heavy biological soiling are highlighted in black, sandstone monuments are signified with an X). A total of 107 monuments out of 247 were selected by query as having over 50% biological soiling on all existing façades. It was immediately evident that a higher proportion of the monuments selected were located in the North-West of Northern Ireland. This was confirmed by percentage values (Tab. 3) which demonstrate that, proportionately, just under double the amount of monuments in the North-West of the country have heavy biological soiling on all existing façades as compared with the South-East. There is clearly a higher number of monuments that have sandstone as a primary stone type in the North-West of Northern Ireland, however this does not appear to correspond directly with heavy biological soiling as a higher number of non-sandstone monuments have high biological soiling.

Table 3. Showing percentage values of monuments with over 50% soiling on all existing façades or monuments with a condition score of 2110 or over on at least 50% of façades, divided by region i.e. North-West or South-East of Northern Ireland

Area of Northern Ireland	Monuments over 50% soiled on all existing façades (%)	Monuments with a condition score of 2110 or over on at least 50% of façades (%)
North-West	53	39
South-East	28	16

3.2. Stonework condition

Figure 2 shows a map of annual rainfall overlain with monuments (those with a condition score of 2110 on >50% of façades are shown in black, sandstone monuments are signified with an X). A total of 74 monuments were found by query to have a condition assessment score of 2110 or over on at least 50% of the existing façades, and again a larger proportion of these (Tab. 3) were located in the North-West portion of Northern Ireland – 39% of monuments in the NW compared to 16% in the SE.

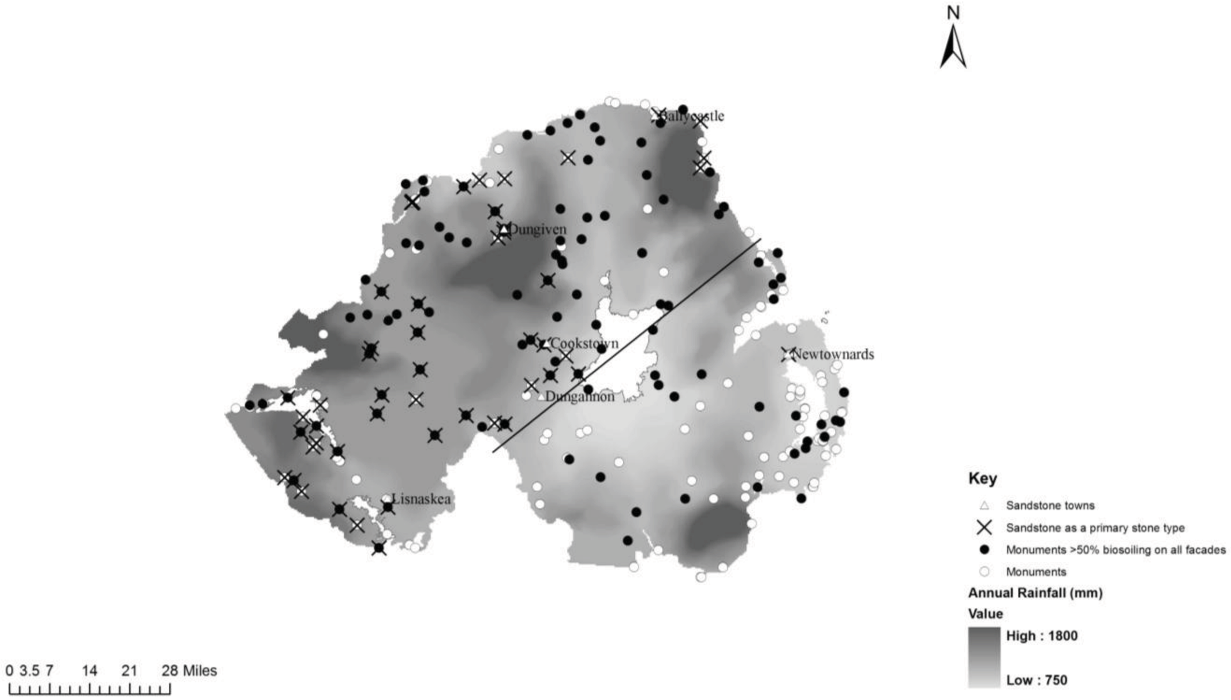

Fig. 1. GIS map showing annual rainfall (mm) overlaid with monuments (white circle), and monuments where all façades demonstrate over 50% soiling (black circle). Monuments where sandstone is the primary stone type are highlighted with an X and towns located near major sandstone quarries are noted.

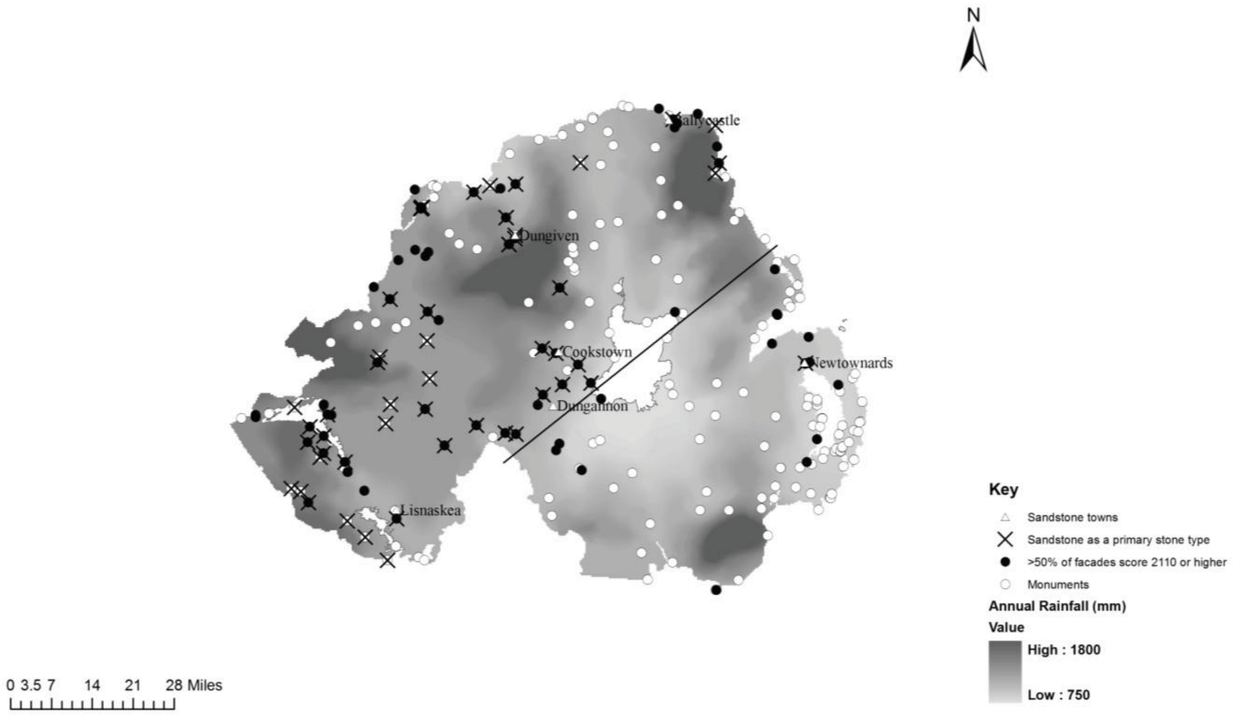

Fig. 2. GIS map showing annual rainfall (mm) overlaid with monuments (white circle), and monuments where at least 50% of façades have a condition assessment score of 2110 or greater (black circle). Monuments where sandstone is the primary stone type are highlighted with an X and towns located near major sandstone quarries are noted.

4. Discussion

There is clearly a considerable increase in both biological soiling and overall decay in the North-West region of Northern Ireland as compared with the South-East. The North-West/South-East divide line (drawn across NI in Figs. 1 and 2) was adapted from Crawford et al., 2007, who demonstrated that the NW of Northern Ireland correlated more closely with the Irish grid square predictors (because of the wetter Atlantic influence), whereas the SE of NI matched more closely with the Scottish Borders grid square. While the work of Crawford et al. (2007) was specifically related to choice of predictors for downscaling Global Climate Models to the catchment scale in Northern Ireland, it demonstrated clearly that this divide existed – a greater Atlantic signal to the NW of the line leading to wetter conditions than in the SE. The pattern of biological soiling (over 50% soiled on all existing façades) reflects this trend, confirming that one major factor that controls biological colonization is moisture supply. Ortego-Calvo et al. (1993) noted that "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. Biological soiling commonly occurs on localized sheltered or sloping areas of buildings where water does not run off as rapidly. A value of over 50% demonstrates more than the expected biological soiling (occurring on most façades in only the dampest areas) – rather, biological soiling is extended to the vertical block faces. Young and Urquhart (1998) stated that "vertical façades seldom support much biological growth unless they are in regions of high humidity or are often wetted". This again suggests that a very high level of biological soiling is present and that this is almost certainly due to high levels of moisture availability, confirmed by the greater percentage of monuments in the wetter North-West of Northern Ireland with high levels of soiling.

This current study does not take into account the crucial role of local and micro-environmental factors, which may vary considerably between individual monument sites. For example, one obvious question might be: why do some monuments in the SE not conform to the trend, showing over 50% biological soiling on all façades? The answer may often be related to specific macro-environment rather than the wider environmental influences explored in this paper. Thus, monuments which are overhung by trees or are near bodies of freshwater are evidently more likely to have higher biological soiling than those which are more exposed to the elements, due to a nearby source of both moisture and potential colonizing species (particularly algae). A proportion of the monuments found to have heavy biological soiling are counted as such due to heavy ivy growth, this has little bearing on local rainfall levels but rather is an issue of monument maintenance. This is indeed the case for several of the monuments in the South-East e.g. Killarsey Church, Killyleagh and Templecraney Church, Portaferry. The type of biological soiling is also not taken into account in the current study – this will be unpacked in future work. Thus, some façades may be heavily soiled by a mixture of algae, lichen, and mosses, whilst others will be colonized almost entirely by lichen or algae alone. The types and species of organism colonizing a surface may give an indication of the reason why soiling is heavy on that particular façade and in the case of lichen, the length of time the façade has been colonized. Heavy algal soiling is more likely to be linked to climate and time of substrate wetness, whereas lichens once established can survive periods of drought by reducing metabolic activity (Purvis, 2000). Therefore it might be expected that lichen will colonize monuments throughout Northern Ireland (with species-specific variation, but regardless of the NW/SE wetness gradient) whereas algal growth is more likely to be more prominent in the NW, correlating with the wet Atlantic influence. Lichen may indeed grow in size more rapidly in wetter localities but this is difficult to gauge for organisms that can live for several hundred years.
A smaller number of monuments are located in towns or cities and are more likely to be soiled by pollution which will likely inhibit biological growth, particularly that of lichens. Lichen are well recognized as bioindicators due to their high sensitivity to sulphur dioxide. Hawksworth and Rose (1976) developed an air pollution scale for England and Wales based on which lichen species were present on tree bark in cities. This indeed appears to be the case for the 8 monuments (Londonderry's historic gates and walls) located within Londonderry city centre (NW NI). The majority of these façades have a high pollution-soiling index (i.e. over 50% soiled) and a low biological-soiling index, suggesting that biological growth is inhibited by heavy pollution soiling. Therefore, both monument specific environments and the wider geographical distribution of rainfall highlighted in this paper both have important roles to play.

Substrate porosity is often considered to be one of the prime influences for biological colonization. Guillitte and Dreeson (1995) stated that bioreceptivity was controlled mainly by surface roughness, initial porosity and the mineralogical nature of the substrate. Studies by Viles (1988), Pentecost (1992), Tiano et al. (1995) and Warscheid and

Braams (2000) also found surface roughness and porosity to be linked to more rapid biological colonization. The influence of porosity or surface texture on colonisation is inextricably linked back to the availability of moisture. Crispim et al. (2003) states that "the porosity of the substrate is related to the penetration and retention of water, which in turn affects microbial colonisation". Other factors to consider are substrate permeability i.e. the interconnectivity of the substrate pores, and the influence of tooling dimension stone i.e. artificially enhancing surface roughness. However, while substrate porosity may indeed have some level of influence, it does not appear to be the major control in the case of biological soiling. Northern Ireland has a diverse underlying geology, the most porous and rapidly decaying stone type that was commonly used as dimension stone in Victorian times was Scrabo Sandstone which was sourced from quarries near Newtownards at the north end of Strangford Lough. Scrabo Sandstone porosity ranges from 21-24% and often exhibits severe decay on buildings, displaying flaking and scaling with occasional cavernous decay. Despite this, very few monuments surrounding Strangford Lough display heavy soiling, and none in the immediate Newtownards area. In contrast the North-West of the country displays heavy soiling in all areas despite having some of the least porous and most durable stone types i.e. Antrim and Londonderry Basalt (0.84-2.8%), Fermanagh Carboniferous Limestone (0.33-1.25%), Fermanagh Carboniferous Sandstone (1.29%) and Claudy Schist (1.21-6.72%) in County Londonderry. The information used also does not take into account any potential cleaning or maintenance work carried out on monuments. One of the key points presented by McCabe and Smith (2009) is that how a stone responds to biological colonization (in terms of decay) is dependant on lithological characteristics. Therefore some durable/non-porous stone will actually provide good stable surfaces for growth and thus exhibit heavy soiling (especially in areas of high rainfall), while the less durable/higher porosity stones often lose surface material as a result of biological decay – the surface is unstable, so soiling seems less severe (but active decay is greater).

As with biological soiling, higher assessment condition scores (i.e. building stone decay) also occur more prominently in the North-West of Northern Ireland. Biodeterioration of stone can indeed be caused by lichen and algae. Lichen anchor themselves to their substrate using rhizines and can release a wide spectrum of products including lichenic acids which can also cause stone deterioration . The presence of lichen and algae on a stone surface will also change the dynamics of a stone block, helping to retain moisture at the stone surface and potentially altering the albedo. In some cases these factors may lead to an overall protective effect. However for the most part biodeterioration is localized and rarely causes severe decay at full façade level.

However, in contrast with the biological soiling map, the condition assessment scoring map does appear to correspond largely with the underlying geology, in particular with local sandstone outcrops. Monuments in Northern Ireland generally range in age from 14th to 19th Century and as such were built almost entirely from stone that was available locally due to transport issues. They therefore tend to reflect closely the geology of the local area as opposed to many of the later buildings which often feature imported English or Scottish stone. Higher decay values in this case appear to correspond to sandstone outcrops across Northern Ireland, such as Scrabo Sandstone (Newtownards area), Ballycastle Sandstone, Dungannon Sandstone, Dungiven Sandstone and Cookstown Sandstone, with higher decay scores clustered around these outcrops. While not all of these higher decay scores correspond to monuments with sandstone as the primary stone type, many of these have sandstone as a secondary stone type, influencing the decay level. The pattern is somewhat different in County Fermanagh where the local Carboniferous sandstone is particularly hard-wearing and less prone to decay than other Northern Irish sandstones, thus explaining the number of sandstone buildings in this area that show low levels of decay.

UKCP (2009) climate predictions for Northern Ireland show an increase in winter precipitation varying from 6 to 34% by the 2080's (based on the high emissions scenario, ranging from the 10 to 90% probability level) and a range of decrease in summer precipitation by the 2080's of -4 to -38% (high emissions scenario, 10 to 90% probability level). Precipitation is also to increase proportionally more in the Mourne mountains area of the South-East and increase least in the central North-West (County Londonderry). This may lead to a shift in biological soiling patterns with higher algal growth in particular in parts of the South-East of the country. Species which are not capable of surviving long periods of reduced rainfall during summer may begin to die out, leading to an increase in species which are more capable of coping with more seasonal climate scenarios i.e. wetter winters and drier summers. As temperatures are also to become milder in winter this may lead to a general increase in biological soiling without low temperatures to reduce the numbers of the more temperature-sensitive species.

5. Conclusions

- The biological soiling of monuments in Northern Ireland reflects the broad NW/SE precipitation divide – the NW is dominated by the wetter Atlantic Signal and shows greater biological soiling in response, the SE is drier, with less biological soiling evident
- While these broader trends clearly exert a control on biological colonization and decay, it is clear that site-specific macro-environmental controls can override them – for example, overhanging vegetation and freshwater bodies

Although biological growth and increased moisture availability are likely to play some role in increased decay in the North-West, the extent of stone decay appears to correspond more closely to underlying geology, with monuments in sandstone areas showing more extensive decay

Biological soiling patterns are likely to change in future in response to projected climate change, with more climate-sensitive (particularly drought-sensitive) species reducing in number and an increase in species which are better adapted for periods of drought in summer and increased rainfall in winter. For example, if precipitation levels increase in the SE of NI, it might be expected that algae will become more dominant in biological soiling in this area if the country. Overall biological soiling may also increase due to milder winters as temperature-sensitive species will not be regulated by colder seasonal temperatures.

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