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Update on the call for data on inventory and condition of stock of materials at United Nations Educational, Scientific and Cultural Organization cultural heritage sites

The current status of air pollution effects on materials and United Nations Educational, Scientific and Cultural Organization world cultural heritage sites in Europe

Report by the International Cooperative Programme on Effects of Air Pollution on Materials, including Historic and Cultural Monuments

Summary

The present report summarizes recent available information on the current status of air pollution effects on materials in Europe. Air pollutants, in combination with climatic parameters, are key factors in the corrosion and deterioration of several metallic and non-metallic materials. This reduces the operating life of technical materials and threatens objects of cultural heritage, an important component of our individual and collective identity.

Findings from the exposure of material specimens performed in the network of test sites of the International Cooperative Programme on Effects of Air Pollution on Materials, including Historic and Cultural Monuments (trend analysis) and assessments made on historic and cultural monuments, particularly the information gathered during the recent call for data on inventory and condition of stock of materials at United Nations Educational, Scientific and Cultural Organization cultural heritage sites are used in order to assess the current impact of air pollutants on the atmospheric corrosion and soiling of various materials, including materials used in objects of cultural heritage.

The observations go hand in hand to indicate that, although the degradation of materials in Europe is today significantly reduced, mainly due to the reduction of sulphur dioxide pollution, the current rates of corrosion and soiling of materials are still unacceptably high. This is reflected in an increased potential risk of corrosion and soiling of built cultural heritage. This causes massive economic losses through protective measures, substitution of

degraded materials, cleaning, maintenance and restoration work on buildings and historical and cultural monuments exposed outdoors.

Contents

I. Introduction

1. The present report was prepared by the Co-Chairs of the International Cooperative Programme on Effects of Air Pollution on Materials, including Historic and Cultural Monuments (International Cooperative Programme Materials) for consideration by the Working Group on Effects and the Steering Body to the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe at their fifth joint session, to be held in Geneva from 9 to 13 September 2019. The present report is a summary of recent International Cooperative Programme Materials findings in trend analysis and assessments made for United Nations Educational, Scientific and Cultural Organization (UNESCO) sites.

II. Background and key questions

2. Air pollutants in combination with climatic parameters are key factors in the corrosion and deterioration of several metallic and non-metallic materials. This reduces the operating life of technical materials and threatens objects of cultural heritage, an important component of our individual and collective identity. The present report aims to address the following policy-relevant science questions:

(a) What improvements in corrosion and soiling of materials can be observed?;

(b) Considering the improvements, are there still differences in corrosion and soiling between polluted and non-polluted areas?;

(c) What are the main pollutants responsible for corrosion and soiling of materials and can the most recent dose-response functions predict corrosion and soiling in the current multi-pollutant situation?;

(d) What is the current situation of the predicted corrosion and soiling of materials of historic and cultural monuments at UNESCO world cultural heritage sites?;

(e) What are the main pollutants responsible for the predicted corrosion and soiling of materials of historic and cultural monuments at UNESCO world cultural heritage sites?;

(f) What is the role of anthropogenic activities in determining the levels of pollutants affecting the studied UNESCO sites and thus the damage to the materials of which these objects are built?;

(g) What improvements in the predicted corrosion and soiling of materials of historic and cultural monuments at UNESCO world cultural heritage sites can be estimated?;

(h) What is the cost of damage due to air pollution to materials of these works of art and historic buildings?;

(i) What errors, if any, are introduced by using Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe data in dose-response functions for estimating corrosion and soiling of materials of historic and cultural monuments?

3. Each of the above questions are addressed individually below. Answers to questions (a) to (c) are taken from International Cooperative Programme Materials Report No. 76,[1] which summarizes the most important findings. An updated trend report (1987–2018) is expected in 2020. Answers to questions (d) to (i) are mainly taken from report No. 77,[2] which describes findings from a pilot study on the inventory and condition of stock

[1] International Cooperative Programme on Effects of Air Pollution on Materials, including Historic and Cultural Monuments (International Cooperative Programme Materials), "Trends in pollution, corrosion and soiling 1987–2012", Report No. 76 (Stockholm, Swerea KIMAB AB, 2014).

[2] International Cooperative Programme Materials, "Pilot study on the inventory and condition of stock of materials at risk at United Nations Educational, Scientific and Cultural Organization (UNESCO)

of materials at risk at United Nations Educational, Scientific and Cultural Organization (UNESCO) cultural heritage sites and from Reports Nos. 80,[3] 83[4] and 86[5] describing the findings from the call for data on inventory and condition of stock of materials at risk at UNESCO cultural heritage sites launched in October 2015, which involve the six following Parties to the Convention: Croatia, Germany, Italy, Norway, Sweden and Switzerland.

III. What improvements in corrosion and soiling of materials can be observed?

4. Corrosion has decreased substantially, to around 50 per cent of the original values measured in 1987. In recent years, however, the improvements in corrosion and soiling have been minor. For real cultural heritage objects made of metals the decreases are instantaneous, responding rapidly to decreasing pollution levels. For stone materials, however, there is a substantial time lag, 20 years or more, before improvements can be seen. The main detailed findings are:

(a) For measured pollution concentrations (sulphur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), nitric acid (HNO_3) and particulate matter (PM) deposition) trends at International Cooperative Programme Materials test sites do not contradict findings on trends reported by the European Environment Agency;

(b) The data show no clear trends for the climate variables;

(c) Maximum corrosion of carbon steel (first year exposure) has decreased from 70 µm in 1987 to 20 µm in 2000. No major changes are subsequently observed. Weathering steel shows similar results after one year of exposure since the beneficial properties of this material emerge only for longer exposure periods;

(d) Maximum corrosion of zinc (first year exposure) decreased from more than 5 µm in 1987 to about 2.5 µm in 1989, and to just over 1 µm in 2000. No major changes are subsequently observed;

(e) Maximum corrosion of copper (first year exposure) decreased from 3.4 µm in 1987 to just over 1 µm in 2000. No major changes are subsequently observed;

(f) Maximum surface recession of limestone (first year exposure) decreased from 20 µm in 1987 to 10 µm in 2000. No major changes are subsequently observed;

(g) Studies performed at St. Paul’s Cathedral in London between 1980 and 1985 showed recession rates of limestone of around 50 µm $year^{-1}$ and a reduction in the rate of erosion to 25 µm $year^{-1}$ during the period 1990 to 2000. The results suggest a time lag of about 20 years between the reduction in SO_2 and the benefit being seen in the existing building stone;

(h) Measurements of soiling of modern glass (Haze) started in 2005 and since then there has been no improvement;

cultural heritage sites. Part IV: The relationship between the environment and the artefact”, Report No. 77 (Rome, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, 2015).

[3] International Cooperative Programme Materials “Call for Data ‘Inventory and condition of stock of materials at UNESCO world cultural heritage sites’. Part I – Status Report”, Report No. 80 (Rome, National Agency for New Technologies, Energy and Sustainable Economic Development, 2017).

[4] International Cooperative Programme Materials, “Call for Data ‘Inventory and condition of stock of materials at UNESCO world cultural heritage sites’. Part II – Risk assessment”, Report No. 83 (Rome, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, 2018).

[5] International Cooperative Programme Materials, “Call for Data ‘Inventory and condition of stock of materials at UNESCO world cultural heritage sites’. Part III – Economic evaluation”, Report No. 86 (Rome, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, 2019).

(i) Corrosion at non-polluted (rural sites) has also decreased since 1987 and the percentage decrease is about the same as for urban and industrial sites.

IV. Considering the improvements, are there still differences in corrosion and soiling between polluted and non-polluted areas?

5. The differences between polluted and non-polluted areas are not as considerable as in the 1980s but are still significant. At the most polluted sites, 2020 targets are exceeded. The main detailed findings are:

(a) For most metallic materials (carbon steel, weathering steel and zinc) there are clear differences between polluted and non-polluted areas. High pollution levels result in elevated corrosion levels exceeding 2020 targets;

(b) For copper there are a few “low-polluted” sites (rural areas) with high corrosion values after one year of exposure, most likely related to elevated O_3 levels. It is expected that this is an effect that shows up primarily for shorter exposure times;

(c) For limestone, high values are shown for highly polluted sites but also for some sites with high precipitation levels. This is related to the effect of pure rain (karst effect) and is not expected to level off with increasing exposure times. Instead, at these sites with high levels of precipitation, surface recession of limestone cannot be lowered below the present target levels by only decreasing pollution;

(d) For soiling of modern glass, calculations show that a threshold is exceeded after 90 days for a traffic site, 110 days for an industrial site, and 130 days for urban sites, whereas it is reached after one year for a rural site.

V. What are the main pollutants responsible for corrosion and soiling of materials and can the most recent dose-response functions predict corrosion and soiling in the current multi-pollutant situation?

6. In terms of corrosion, SO_2 is still the most important pollutant, while wet acid deposition no longer makes a large contribution. Other pollutants of importance in the multi-pollutant situation are PM and HNO_3. The current dose-response functions for corrosion can be improved, especially for limestone, where natural processes such as dissolution in neutral rainwater and freeze-thaw cycles now are relatively more important.

7. For soiling, particulate matter, SO_2 and NO_2 are the main pollutants included in recently developed dose-response functions and there is no reason to improve these functions in the near future.

8. The main detailed findings are as follows:

(a) SO_2 is included in dose-response functions for all materials and is, despite the lower levels, still one of the main pollutants;

(b) Acid rain has changed from being a very important contributor to the corrosion rate, to now contributing around 20 per cent and typically much less to corrosion for many of the test sites;

(c) HNO_3 is important for a few materials, in particular zinc but also for some extent limestone;

(d) PM is important because it attracts water and it is included in dose-response functions for carbon steel, zinc and limestone;

(e) The dose-response function for weathering steel overpredicts current corrosion values of steel;

(f) The dose-response function for copper underpredicts current corrosion values of copper;

(g) The dose-response function for zinc does not show any systematic errors but its predictive ability is poor;

(h) The dose-response function for limestone fails to predict the high corrosion levels observed at some rural sites. It is suggested that any development of dose-response functions for limestone should be undertaken taking into account karst geology and natural weathering of carbonate rocks;

(i) For soiling of modern glass, recent dose-response functions have been developed including the parameters SO_2, NO_2 and fine particulate matter with a diameter of 10 micrometres or less (PM_{10}) and the functions have been benchmarked against models based on neural networks. The only drawback of these functions is that they do not include the influence of climate, but there are no plans at the current stage on how to involve these effects.

VI. What is the current situation of the predicted corrosion and soiling of materials of historic and cultural monuments at United Nations Educational, Scientific and Cultural Organization world cultural heritage sites?

9. In recent years, the risk of corrosion and soiling due to air pollution has been assessed for unique monuments that are part of UNESCO world cultural heritage sites in the framework of the pilot study on the inventory and condition of stock of materials at risk at UNESCO cultural heritage sites (5 cultural objects) and based on data collected in the scope of the call for data on inventory and condition of stock of materials at UNESCO world cultural heritage sites (2015–2017) (21 cultural objects). The assessment was based on information on environmental parameters and involved the use of dose-response functions established by International Cooperative Programme Materials. The main identified risks were corrosion of limestone and copper and soiling of limestone and modern glass.

10. The estimated recession rate of limestone and corrosion rate of copper after one year of exposure (figure I) are well above the background corrosion rate (3.2 µm $year^{-1}$ for limestone and 0.32 µm $year^{-1}$ for copper) and generally close to the target set by International Cooperative Programme Materials for the year 2050 (6.4 µm $year^{-1}$ and 0.64 µm $year^{-1}$) or even higher. In some cases, these values are close to the targets set for 2020 (8.0 µm $year^{-1}$ and 0.8 µm $year^{-1}$, respectively). Among the cultural objects examined in the context of the call for data, limestone corrosion could be an issue for monuments in Italy (i.e. the Leaning Tower of Pisa, Palazzo Madama and the Royal Palace of Caserta) and Germany (Würzburg Residence and the Gatehouse of Lorsch Abbey). Copper is mainly present as a roof material (Speyer Cathedral, Porta Nigra and Bremen Town Hall, Germany, and the towers of the cathedral of the Abbey of St. Gall, Switzerland) or as copper details (Hercules Monument, Germany, and Nederluleå church, Sweden). Copper corrosion seems to be an issue for several monuments.

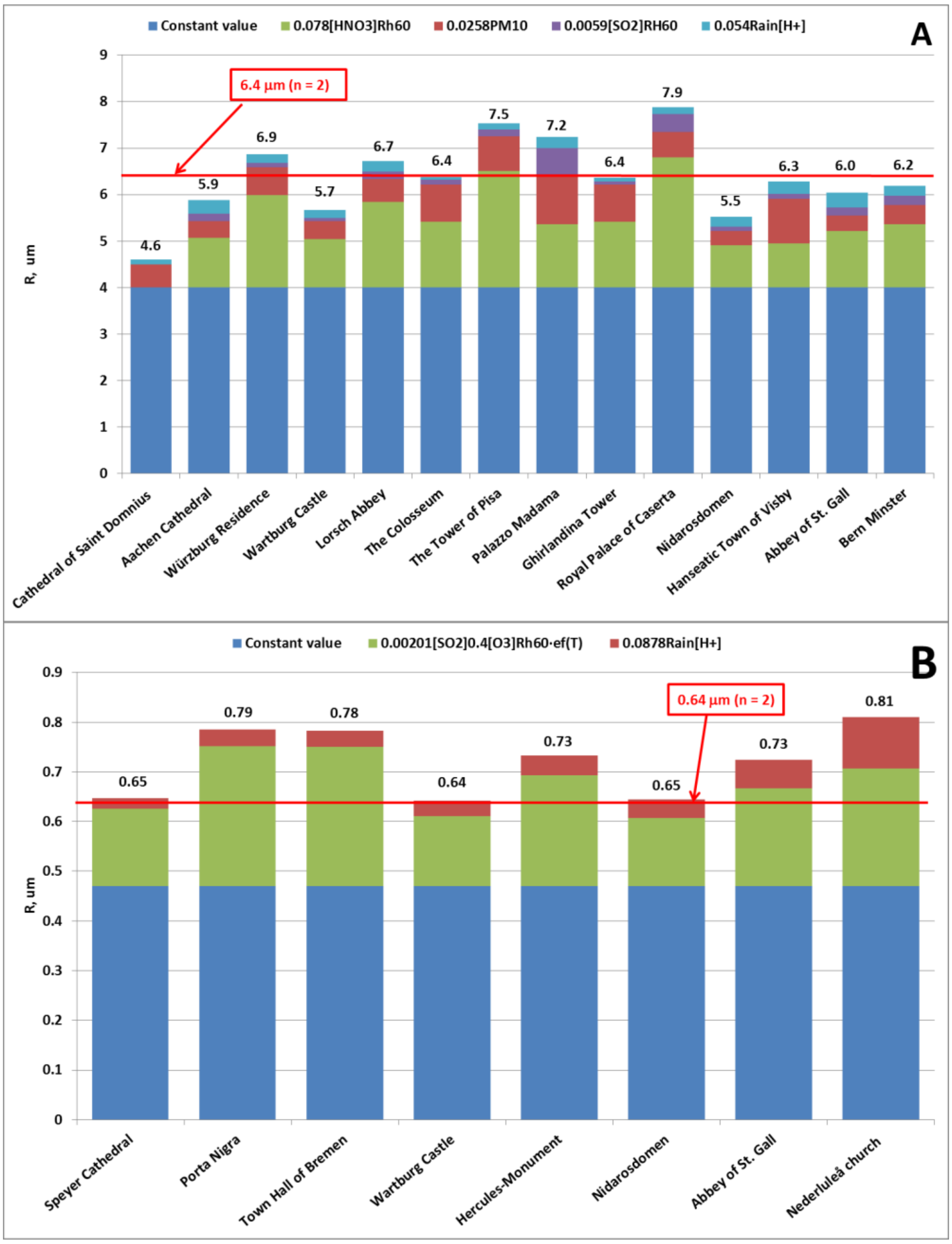
11. Sandstone and bronze were not identified as at risk of corrosion at any of the monuments investigated. Bronze is quite sensitive to SO_2 and the decrease in levels of SO_2 during recent decades has caused a substantial decrease in bronze corrosion. As for sandstone, the effect of the two main risk factors for limestone, HNO_3 and PM_{10}, could not be quantified because the only available dose-response function for the corrosion of sandstone was from the SO_2 dominating situation. However, as surface recessions of limestone and sandstone are highly correlated, as indicated by previous parallel exposures of the two materials in the International Cooperative Programme Material programme, it is not possible to exclude risks to sandstone monuments coming from HNO_3 and PM_{10}, even if the risk could not be quantified with the present methodology.

12. Soiling can be an issue for both non-transparent and transparent materials, represented here by limestone and glass, respectively. PM_{10} is the main risk factor for soiling of limestone. A risk is indicated if the calculated theoretical maintenance time, triggered by a

decrease in reflectance greater than 35 per cent, is shorter than 10 years. In the most unfavourable cases (the Colosseum, the Leaning Tower of Pisa, Palazzo Madama and Ghirlandina Tower, Italy, and the walls of the Hanseatic town of Visby, Sweden), the required maintenance interval to remedy a soiling of limestone that is no longer tolerable is about 4 to 6 years. For cultural heritage objects, a period of 10 to 15 years seems appropriate and therefore periods shorter than this could be considered not tolerable. Only in one of the cases studied, Nidarosdomen, Norway, can a cleaning interval higher than 15 years be estimated.

Figure I

Estimated recession rates for limestone, first year of exposure (A) and corrosion rates for copper, first year of exposure (B) for selected cultural heritage objects in Europe



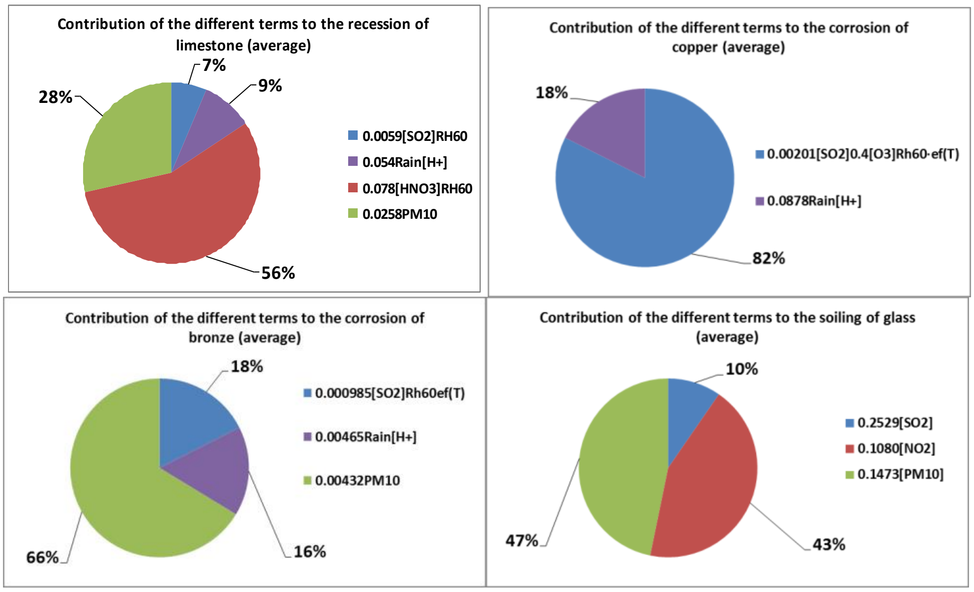
Source: International Cooperative Programme Materials, “Call for Data ‘Inventory and condition of stock of materials at UNESCO world cultural heritage sites’. Part II – Risk assessment.”, Report No. 83 (Rome, National Agency for New Technologies, Energy and Sustainable Economic Development, 2018).

13. Glass is an important material of historical and cultural buildings and soiling is a potential issue at almost all locations in Europe if glass is present in sufficient amounts. For glass, optical damage (soiling) is preferably expressed as haze, which takes into account the loss of transparency due to both absorption and scattering of light. Haze above 1 per cent causes visual discomfort and aesthetical impairment perceived by human eyes leading to the feeling of a "dirty" glass plate. For most of the cultural objects, the estimated cleaning interval for glass, i.e. the time necessary for the haze to reach a value of 1 per cent, ranges between four and seven months. During this period of time the glazing of the cultural heritage object can remain without cleaning without generating the perception of a degradation no longer tolerable. In the most unfavourable case, Palazzo Madama, Italy, the estimated soiling of glass is so fast that the tolerable level is reached in about three months.

VII. What are the main pollutants responsible for the predicted corrosion and soiling of materials of historic and cultural monuments at United Nations Educational, Scientific and Cultural Organization world cultural heritage sites?

14. The main risk factors (pollutants) for the different risks (corrosion/soiling) were extensively studied under the call for data on Inventory and condition of stock of materials at UNESCO world cultural heritage sites and are represented in figure II and the table below for different materials. PM_{10} was identified as a risk factor both for corrosion and soiling of limestone, while HNO_3 was identified as a risk factor only for corrosion. The combined effect of SO_2 and O_3 was identified as a risk factor for copper, and PM_{10} and NO_2 were identified as risk factors for soiling of glass. SO_2 is still an important deterioration agent for some materials used in cultural heritage but is no longer the dominant factor. Moreover, the acidity of precipitations seems to have a small impact on the degradation of materials in the current situation.

Figure II
Risk factors (pollutants) determining the recession of limestone, the corrosion of copper and bronze and the soiling of glass



Source: Elaboration of data from International Cooperative Programme Materials, "Call for Data 'Inventory and condition of stock of materials at UNESCO world cultural heritage sites'. Part II – Risk assessment", Report No. 83 (Rome, National Agency for New Technologies, Energy and Sustainable Economic Development, 2018).

Risk factors (pollutants) for different risks to materials constituting the artifacts (+ low impact; ++ medium impact; +++ high impact). An empty square indicates that the specific risk/pollutant combinations was not included in the dose-response function used. Therefore, the impact level could not be estimated.

Risk	*SO_2*	*NO_2*	*HNO_3*	*SO_2*O_3*	*PM_{10}*	*pH*
Limestone corrosion	+/++		++/+++		++	+
Sandstone corrosion	+/++					+
Copper corrosion				++/+++		+
Bronze corrosion	+				++	+
Limestone soiling					+++	
Glass soiling	+/++	++/+++			++/+++	

Source: International Cooperative Programme Materials, “Call for Data ‘Inventory and condition of stock of materials at UNESCO world cultural heritage sites’. Part II – Risk assessment”, Report No. 83 (Rome, National Agency for New Technologies, Energy and Sustainable Economic Development, 2018).

15. When looking at individual pollution levels of HNO_3 and PM_{10} in the selection of the investigated sites, there is a strong correlation, except for in the case of some sites with high levels of PM_{10} that do not have correspondingly high levels of HNO_3. On the other hand, there are no sites in this selection with low levels of PM_{10} and high levels of HNO_3. PM_{10} is important both for corrosion and soiling of limestone, while HNO_3 is important only for corrosion. When there is a risk for limestone, both corrosion and soiling can be an issue (high levels of PM_{10} and HNO_3). There are also some cases where only soiling can be an issue (high levels of PM_{10} and low levels of HNO_3) but no cases with a risk of limestone corrosion without simultaneous risk of soiling (low levels of PM_{10} and high levels of HNO_3).

16. The main risk factor for copper is the combined effect of SO_2 and O_3. However, development of corrosion products is quite different in areas with high SO_2/low O_3 compared to areas with low SO_2/high O_3. Therefore, it is important to investigate the protective properties of the patina in order to assess whether the short-term risk of corrosion, as determined in the present study, remains a risk even after prolonged exposure of these monuments to high levels of O_3 combined with low levels of SO_2 or if the formation of, for example, dense layers of cuprite will result in a significant decrease of corrosion rate with time.

VIII. What is the role of anthropogenic activities in determining the levels of pollutants affecting the United Nations Educational, Scientific and Cultural Organization sites studied and thus the damage to the materials with which these objects are built?

17. Most of the UNESCO sites studied are located in the heart of European cities. In these urban areas, several air quality problems are present, mainly related to NO_2 and PM_{10}, two pollutants that currently seem to play a prominent role in determining damage of limestone (corrosion due to PM_{10} and HNO_3, an oxidation product of nitrogen oxides (NO_x), and soiling due to PM_{10}) and soiling of glass (mainly attributable to NO_2 and PM_{10}).

18. Road traffic is an important source of both pollutants. Road transport was the most important sector for urban emissions of NO_x in three cities investigated during the pilot study on the inventory and condition of stock of materials at risk at UNESCO cultural heritage sites when assessing the impacts on three outstanding historic buildings (the Parthenon, Athens, the Klementinum, Prague, and the Neues Museum, Berlin). Road transport was also among the top three sectors for emissions of PM_{10} in these metropolitan areas. Additional large sources are energy production and distribution, incomplete biomass combustion for heat

production, for example, in domestic boilers, wood stoves and fireplaces, and, in some case, industry production and harbour activities.

19. NO_x, together with atmospheric oxygen, hydrocarbons and volatile organic compounds, are involved in a cycle that leads to the generation of ozone. O_3, a secondary pollutant, is a powerful oxidiser that exerts a direct corrosive effect on various materials, particularly copper. Ozone precursors are largely emitted by motor vehicles, fossil fuel power plants, oil refineries, the agricultural sector and a number of other industries.

IX. What improvements in the predicted corrosion and soiling of materials of historic and cultural monuments at United Nations Educational, Scientific and Cultural Organization world cultural heritage sites can be estimated?

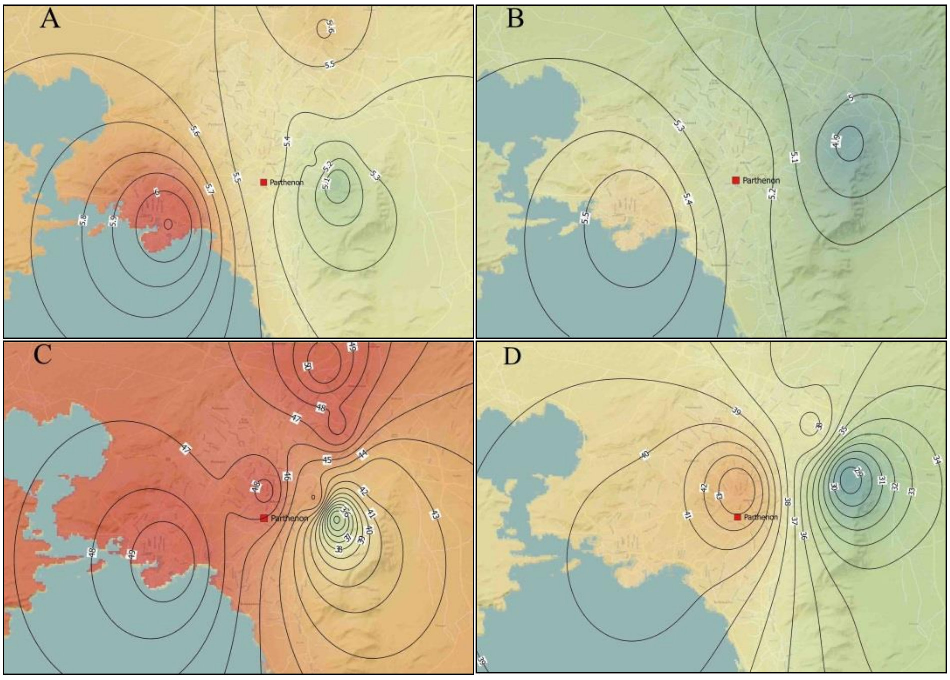
20. The improvement in the estimated corrosion and soiling rates of materials of historic and cultural monuments was investigated for limestone during the pilot study on the inventory and condition of stock of materials at risk at UNESCO cultural heritage sites for the period 2000 to 2010. The improvement of air quality between 2000 and 2010 in the three cities that host the UNESCO sites studied (the Parthenon, Athens, the Klementinum, Prague and the Neues Museum, Berlin) produced a small but quantifiable decrease in the predicted recession rate for limestone, first year exposure, which included practically most of the metropolitan areas. The decrease in the recession rate of limestone of the UNESCO sites studied was about 5 to 8 per cent. It is generally agreed that relative change of degradation rates is more representative than absolute values.

21. The estimated decrease in the recession rate for limestone was mainly attributable to a significant reduction of air concentration of SO_2, which nearly halved in the time period investigated. By contrast, air concentrations of NO_2, HNO_3 and O_3 were basically stagnant, with small increases or decreases depending on the particular site, and therefore with little effect on the overall recession rate.

22. The modest decrease in atmospheric concentrations of PM_{10} between 2000 and 2010 had slightly improved the environmental conditions by reducing the rate of limestone soiling of a few percentage points. As an illustration, figure III shows the corrosion maps for limestone, first year of exposure, and the soiling maps, expressed as loss of reflectance after five years, for the metropolitan area of Athens estimated for the years 2000 and 2010, respectively.

Figure III

Limestone corrosion map (µm year^{-1}) for the city of Athens in the year 2000 (A) and 2010 (B) and limestone soiling map (per cent loss in reflectance after five years) for Athens in the year 2000 (C) and 2010 (D)



Source: International Cooperative Programme Materials, "Pilot study on the inventory and condition of stock of materials at risk at United Nations Educational, Scientific and Cultural Organization (UNESCO) cultural heritage sites. Part IV: The relationship between the environment and the artefact", Report No. 77. (Rome, National Agency for New Technologies, Energy and Sustainable Economic Development, 2015).

X. What is the cost of damage due to air pollution to materials of these works of art and historic buildings?

23. The cost of damage due to air pollution to the different materials constituting objects of UNESCO world cultural heritage sites has been extensively evaluated in the framework of the call for data on inventory and condition of stock of materials at UNESCO world cultural heritage sites. As a part of this exercise, twenty-one cultural objects of outstanding universal value were considered. Taken together, these cultural heritage objects have a total external surface area of about 430,000 m^2. Main materials present in these cultural objects are natural stones (60 per cent), artificial stone materials (17 per cent), glass (6.5 per cent), copper (3 per cent) waterproof materials (2.5 per cent), painted surfaces (2 per cent), bronze and others. A detailed description of these materials of historic and cultural monuments at UNESCO world cultural heritage sites can be found in International Cooperative Programme Materials Report No. 80.[3]

24. Maintenance, repair and restoration work is carried out on the external surfaces of buildings and monuments exposed to the outdoor environment because the materials that compose them undergo a continuous degradation process due to natural causes that is aggravated by atmospheric pollution. These works are intended as direct interventions on a cultural asset in order to maintain it over time and recover its material integrity. The aim is to preserve its functional identity and efficiency in such a way that it can be offered to collective knowledge and enjoyment and passed down to future generations in the best condition that can be achieved with today's technology.

25. Working under the assumption that the entire cost of maintenance, repair and restoration work is to be attributed to degradation due to atmospheric agents (pollution and meteorological conditions), and using the methodology developed as a part of the European

Union Rationalized Economic Appraisal of Cultural Heritage project,[6] the costs of the damage due to pollution above the "background" can be calculated.

26. An estimation of material deterioration costs at UNESCO sites showed that the annual cost of damage attributable to air pollution under the current condition range, depending on the pollution level and the meteoclimatic conditions, is from €3.1 to €20 per square metre of surface per year (€ m^{-2} $year^{-1}$) for the recession of limestone, from €5.1 to €9.8 m^{-2} $year^{-1}$ for the corrosion of copper, from €0 to €52.1 m^{-2} $year^{-1}$ for the soiling of limestone surfaces and from €0 to €11.7 m^{-2} $year^{-1}$ for the soiling of glazing. These costs add to the cost in background areas, estimated at €4.4 m^{-2} $year^{-1}$, €3.5 m^{-2} $year^{-1}$, €25 m^{-2} $year^{-1}$ and €6.8 m^{-2} $year^{-1}$, respectively, for limestone recession, copper corrosion, limestone soiling and glass soiling.

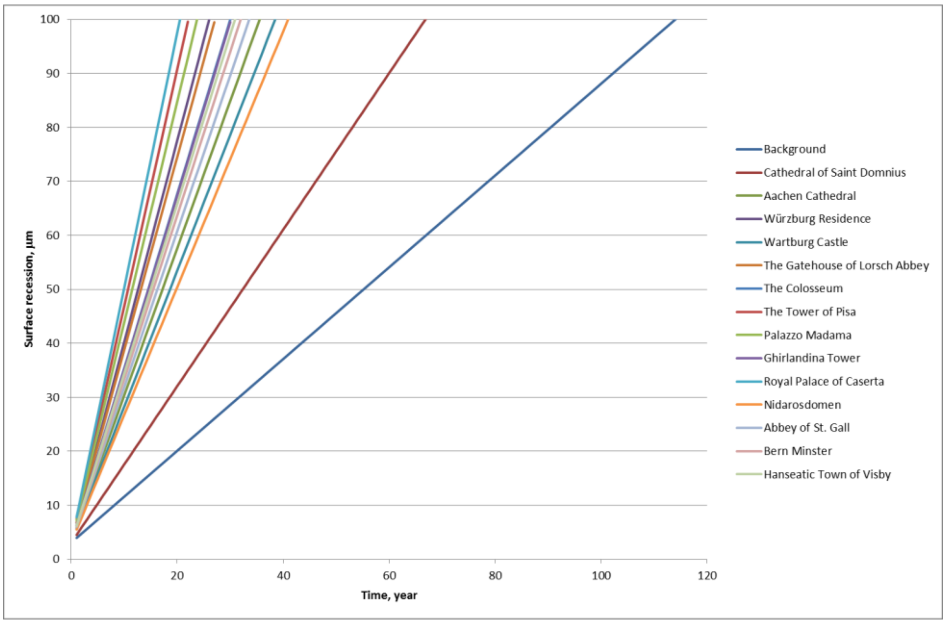
27. The additional costs due to air pollution above the costs that would occur in a background scenario derive from the fact that, in the presence of pollution, the degradation rate is higher and consequently the time between two maintenance interventions (or lifetime for the material), defined on the basis of a pre-established tolerable damage, decreases. This is illustrated in figure IV where, as an example, the evolution of the limestone recession over time in the background scenario is compared to the recession of limestone surfaces of the objects of cultural heritage considered in the call for data exposed to the local environmental conditions. According to the time-dependent dose-response function for limestone in the multi-pollutant situation, with a background corrosion rate of 3.2 μm $year^{-1}$, first year of exposure, the tolerable recession depth before action for limestone of 100 μm is reached after 114 years. At the current concentrations of pollutants, the same tolerable corrosion depth before action of 100 μm is achieved, for the different cultural objects, in a time period ranging from 20.5 to 67 years.

28. Two risk factors were associated with limestone, corrosion and soiling, and two different costs were defined. These costs are not to be added together. Maintenance and restoration work on historic buildings is a very complex operation and it is unlike that it will be carried out only to recover the soiling effects without intervening at the same time to repair any damage due to corrosion and vice versa. Soiling is a faster process than limestone corrosion. In a background scenario, the theoretical maintenance time for the soiling of limestone, triggered by a decrease in reflectance greater than 35 per cent, has been estimated at 14 years, while the theoretical maintenance time for the corrosion of limestone, triggered by a tolerable recession depth before action of 100 μm, has been estimated at 114 years. In a polluted urban atmosphere, these maintenance times become shorter and will be even shorter for those driven by soiling because of the high levels of PM_{10}, the main responsible for limestone soiling. Therefore, maintenance times and associated maintenance costs will be driven primarily by how the soiling progresses.

[6] John Watt, Ståle Navrud, Zuzana Slížková and Tim Yates, "Economic Evaluation", in *The effects of air pollution on cultural heritage*, John Watt, Johan Tidblad, Vladimir Kucera and Ron Hamilton, eds. (Springer, New York, USA, 2009).

Figure IV

Evolution over time of the recession of limestone surfaces in the objects of cultural heritage considered in the call for data



Source: International Cooperative Programme Materials, “Call for Data ‘Inventory and condition of stock of materials at UNESCO world cultural heritage sites’. Part III – Economic evaluation”, Report No. 86 (Rome, National Agency for New Technologies, Energy and Sustainable Economic Development, 2019).

29. Annual cost of damage attributable to air pollution and above the background atmosphere under current condition may seems small if expressed in € m^{-2} $year^{-1}$. However, the total annual cost of restoration work attributable to air pollution for a given type of material and a specific object of cultural heritage depends on the stock in m^2 of material at risk. This total cost may be significant. For example, total annual cost of maintenance work from soiling of the limestone surface of the Colosseum in Rome (19,450 m^2) was estimated at about €680,000 $year^{-1}$, the annual cost due to the corrosion of Speyer Cathedral’s copper roof (7,800 m^2) in Germany was estimated at €39,900 $year^{-1}$ and the cost of cleaning the glazing of the Royal Palace of Caserta in Italy (17,400 m^2) was estimated at about €94,000 $year^{-1}$.

30. Cost estimates are, however, subject to uncertainty due to the assumption in estimating lifetimes of materials and maintenance costs. In addition, these costs only include the expenditures to remediate the damaged surfaces of the object of cultural heritage. These actions have a market price and involve market transactions. An additional component of the costs associated with the degradation of a cultural asset is the so-called loss of amenity, for example, the decrease in aesthetic appeal and the consequent reduction in the number of visitors to the site with the potential impact on the local economy. In addition, there is the obvious consideration that looking at a dirty and degraded building reduces the value of the visitor's experience. These losses do not have a well-defined monetary value as they are not traded in markets. According to a simple approach, the costs of amenity loss are approximately equal to the cost of cleaning and repair.[7]

[7] Ari Rabl, “Air pollution and buildings: an estimation of damage costs in France”, *Environmental Impact Assessment Review*, vol. 19, No. 4 (1999), pp. 361–385.

XI. What errors, if any, are introduced by using Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe data in dose-response functions for estimating corrosion and soiling of materials of historic and cultural monuments?

31. The main weakness of the approach followed in assessing the damage caused by air pollution to materials of these works of art and historic buildings and the associated costs is that degradation rates are estimated with dose-response functions, where the estimation can differ substantially when compared to the measured degradation rate determined by placing materials on a rack for one or several years.

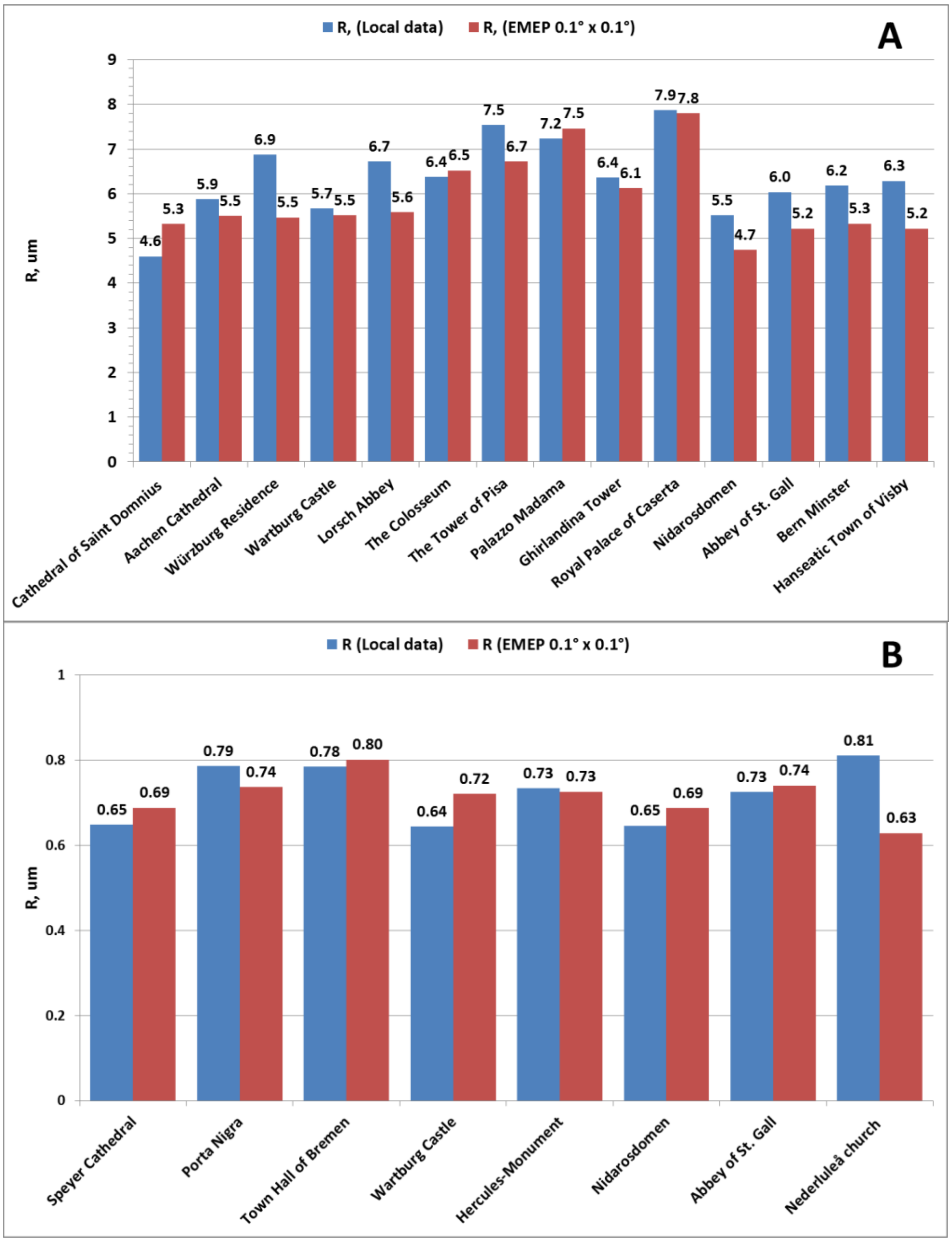
32. Another weakness is the representativeness of the measuring stations with respect to the air quality in the immediate surroundings of the cultural objects, which has an impact on the materials from which they are built. Many cultural and historical monuments are located in cities and, at the micro-scale level, the concentrations of pollutants can vary according to the distance from the dominant sources of pollutants (i.e. distance from the kerbside) and the topography of the city (i.e. street configuration).

33. Often, the values used as input data for the dose-response functions are obtained from monitoring stations that are located at a distance from the cultural object that can generally vary from a few hundred metres to a few kilometres. Continuous measurement in the immediate surroundings of the cultural objects, which could give an accurate representation of air quality, requires extensive resources that often unavailable. This limits the accuracy of estimates of exposure to pollutants of the materials of historic and cultural monuments.

34. Corrosion and soiling of the materials of individual cultural objects, calculated with the local environmental parameters collected during the call for data on inventory and condition of stock of materials at risk at UNESCO cultural heritage sites, were compared with those obtained by using the data available as output of the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe /Meteorological Synthesizing Centre-West model for the year 2015 at the new resolution of 0.1° x 0.1° (longitude-latitude). The objective of this comparison was to ascertain whether the output data of the Cooperative Programme model at this resolution can be used to obtain estimates of degradation rate of materials comparable to those obtained from the local data. Overall, a relatively good agreement was observed between the two sets of data and within the uncertainties associated with the use of dose-response functions (figure V), suggesting that the Cooperative Programme model data at this resolution level could reasonably be used in future for similar risk assessments. The same level of agreement would not have been possible with the old Cooperative Programme model resolution of 50 km x 50 km due to the lower resolution.

Figure V

Comparison of estimated degradation rates using local data (blue) and Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe model data (red) for: recession rate of limestone (A), corrosion rate of copper (B)



Source: International Cooperative Programme Materials, "Call for Data 'Inventory and condition of stock of materials at UNESCO world cultural heritage sites'. Part II – Risk assessment", Report No. 83 (Rome, National Agency for New Technologies, Energy and Sustainable Economic Development, 2018).

XII. Conclusion

35. The current status of air pollution effects on materials in Europe, including materials used in objects of cultural heritage, has been assessed using information from the exposure of material specimens performed in the network of test sites of International Cooperative Programme Materials (trend analysis) and evaluations made on historic and cultural monuments, particularly the information gathered during the recent call for data on inventory and condition of stock of materials at risk at UNESCO cultural heritage sites.

36. Despite the fact that degradation of materials in Europe is today significantly reduced due to the reduction of atmospheric pollutants, mainly SO_2, the current rates of corrosion and soiling of materials are still unacceptably high. This is particularly relevant to the built cultural heritage, an important component of our individual and collective identity. This causes massive economic losses through protective measures, substitution of degraded materials, cleaning, maintenance and restoration work on buildings and historical and cultural monuments exposed outdoors.

37. Although the number of cultural heritage objects taken into account (5 in the pilot study and 21 in the call for data) is small compared to the number of objects in UNESCO world cultural heritage sites located in countries that are Parties to the Convention, they provide a good overview of the identified risks of air pollution damage to outdoor cultural heritage materials and show the most important pollution risk factors in Europe today. These risks vary in extent and severity depending on the material, the levels of air pollutants and climate parameters.