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Road Salt Damage to Historical Milestones Indicates Adaptation of Winter Roads to Future Climate Change May Damage Arctic Cultural Heritage

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Abstract: There is no doubt that anthropogenic global warming is accelerating damage to cultural heritage. Adaptation measures are required to reduce the loss of sites, monuments and remains. However, little research has been directed towards understanding potential impacts of climate adaptation measures in other governmental sectors on cultural heritage. We provide a case study demonstrating that winter road salt, used to reduce ice related accidents, damages historical iron milestones. As the climate warms, road salt use will move north into areas where sites have been protected by contiguous winter snow cover. This will expose Artic/sub-Arctic cultural heritage, including Viking graves and Sami sites, to a new anthropogenic source of damage. Research and planning should therefore include the evaluation of secondary impacts when choosing climate adaptation strategies.

Keywords: cultural heritage; climate change; corrosion; degradation; adaptation; planning processes

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1. Introduction

In his 1991 Nature commentary, George Burns highlighted increasing levels of damage to cultural heritage, calling for a deeper understanding of the processes involved [1]. Direct anthropological causes, including vandalism, accidents, and war are easier to identify than the unintentional effects of other human activity, such as maintaining a transport infrastructure. Similarly, damage through natural causes may range from the direct effects of earthquakes and eruptions to the indirect consequences of environmental change [2]. Climate change increasingly threatens cultural heritage [3], even where Arctic conditions have previously favoured preservation [4], and adaptation measures are required to preserve sites [5]. Climate change also affects transport infrastructure, both in terms of mobility [6] and road safety [7], and adaptation measures are required. The consequences of these road safety measures, are, however almost never studied with respect to their potential impacts on cultural heritage. De-icing road salts, whilst reducing accidents and saving money [7,8], damage the natural environment [9]. Their effects on cultural heritage have, however, only been assumed from the study of theoretically equivalent situations [10]. To date, there are almost no studies testing these assumptions [11], despite the possibility of damage having been raised some time ago [12,13]. There is now indisputable evidence that road salt does not remain on the road surface [14–16]. Sodium chloride (NaCl) is the most common road de-icing agent [17] and in 2005 18–23 million tonnes were spread in the US alone [14,18].

In this paper, we use a semi-quantitative survey of 18th century cast-iron milestones in Sweden to assess the potential impact of road salt on the preservation of metal heritage objects. On the basis of the results from this small, but culturally important sample, we discuss the degradation of cultural heritage in the context of winter road maintenance and climate change. This pilot-study is, to our knowledge, the first to look at the relationship between road salt and cultural heritage outside of the built environment.

2. Materials and Methods

Milestones were introduced in Sweden with the advent of the 1649 Innkeeper Ordinance [19]. They enabled the royal administration of the then European great power to more accurately oversee the payment of travel allowances to its officials during tax collection and similar activities. Milestones were made of wood, stone or cast iron and were placed along the main roads at every quarter of an old Swedish mile (10,688 metres). Although many have disappeared, still more than 7000 are preserved [19,20], but only 288 of these are made of cast iron [21].

We applied a semi-quantitative approach to the assessment of damage to a subset of these milestones with respect to the presence of road salt, distance from the road, and compass orientation. Studying cultural heritage often entails unavoidable limitations which might be considered unacceptable in the physical or experimental sciences. Many historical phenomena do not exist in sufficiently large numbers within a given geographical or climatic region for large statistical analyses to be possible. There is, for example, only one Stonehenge [22] and the earliest presence of humans in Northern Europe was represented by a single set of footprints now lost to rising sea levels [23]. These examples are the basis for a considerable part of our understanding of European prehistory. Much of our knowledge of the past, and indeed the fossil record itself, would be considered as statistically insignificant if subject to the requirements of experimental design and p-values. In some respects, the analysis of a necessarily limited set of cultural heritage objects could be considered as equivalent to a pilot study, in other words a "small-scale methodological test conducted to prepare for a main study" [24,25]. In this context, the subsequent 'main study' would then need to proceed with an extended scope, including additional object types or a wider geographical region, in order to test the general applicability of the results of the pilot study.

Of the 288 remaining milestones made of cast iron our case study represents a small but significant number located in a delimited geographic area with similar environmental conditions. We studied 37 cast iron milestones in Södermanland County, Sweden dating from the 1760s and 1770s [19] (Figure 1). Seven are located along former road sections, now farm tracks without thoroughfare traffic and not treated with road salt. The other 30 are located along winter salted roads that, prior to the construction of motorways (1973–1994), were used as the main roads south of Stockholm. In 1994, all milestones were restored and repainted with period-typical linseed-oil paints in the 1770s colour scheme. This provides a baseline date from which we can measure the effects of road salt induced corrosion. High resolution close-up photographs were taken of the milestones in October 2019 and September 2020. Each milestone has a relief text panel with a royal crown and insignia, a quarter mile indication and the initials of the county governor. The majority have King Gustav III (reign 1771–1792) emblems, but King Adolf Fredrik's (reign 1751–1771) emblem is also represented.

The milestones are registered in both the National Heritage Board's antiquities register [21] and the Swedish Transport Administration's register of historical road remains (MWL). The latter is not publicly accessible, and we were provided with access for the purpose of this project. The roads included in this study have almost complete milestone series, with very few gaps (Figure 1). The recorded history of these milestones, before their repainting in 1994, is fragmentary. Older photographs at Södermanland's museum show that some of them have previously been painted black, and this colour was visible beneath the new paint on some of those studied. Two further milestones in the area north of Nyköping were excluded from the analysis as they had more recently been repainted.

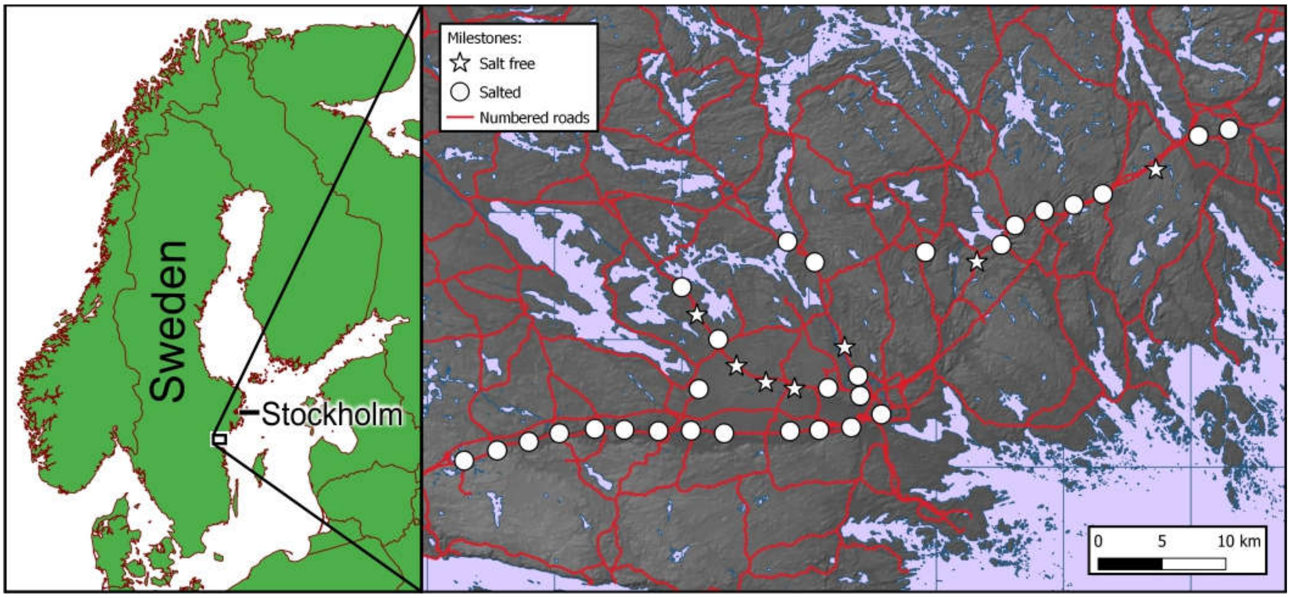

Figure 1. Map of milestones in this study. Circles are on main roads with winter salting, stars are on older stretches of road without through traffic or winter salting (Basemap data ©Lantmäteriet, Sweden).

Damage to milestones was assessed visually in the field and from the photographs, with the 'front' of the milestone always facing the road. A four-point categorical scale was used (in Swedish) to catalogue damage. Half marks were used for intermediate cases where the degree of damage was difficult to assign to a particular category. The results were recorded as follows:

0 = No damage

Paint looks like new.

1 = Minor damage

Paint sun-bleached and (black or red) undercoat is visible.

2 = Moderate damage

Paint peeling and rust has pushed through or is visible in patches.

3 = Severe damage

Rust is visible over large parts or has deeply penetrated the surface.

Although the milestones are registered in the National Heritage Board's antiquities register [21], the accuracy of the coordinates stored in this database is variable. Distance from the road was therefore gauged on-site according to three categories:

1 = Immediately next to the road marking (<3 m).

2 = Ca 3 to 10 m from the road marking.

3 = More than 10 m from the road marking.

Only one milestone at more than 10 m from a (salted) road was included in the survey. The results are visualized in bubble plots and rose diagrams (Figure 2) created in Grapher by Golden Software™. We used the non-parametric Kendall's *tau* rank correlation coefficient [26] to test the relationship between damage on the front and back of milestones on salted and unsalted roads as well as the relationships between damage and distance from a road. Statistical analyses were undertaken in the PAST software [27].

To provide a context for the results, the number of sites and monuments in Sweden within 10 m of a road was calculated. A 10 m buffer was applied to Swedish road network data supplied by the Swedish Transport Administration, and a spatial query used to select sites (as points or polygons) from the National Heritage Board's antiquities register [21] which intersected the buffered road network. The number of sites in Northern Sweden was calculated by selecting the subset of these sites which intersected counties north of and including Värmland, Dalarna and Gävleborg. The open-source Geographical Information System software QGIS 3.10.5 was used for these calculations.

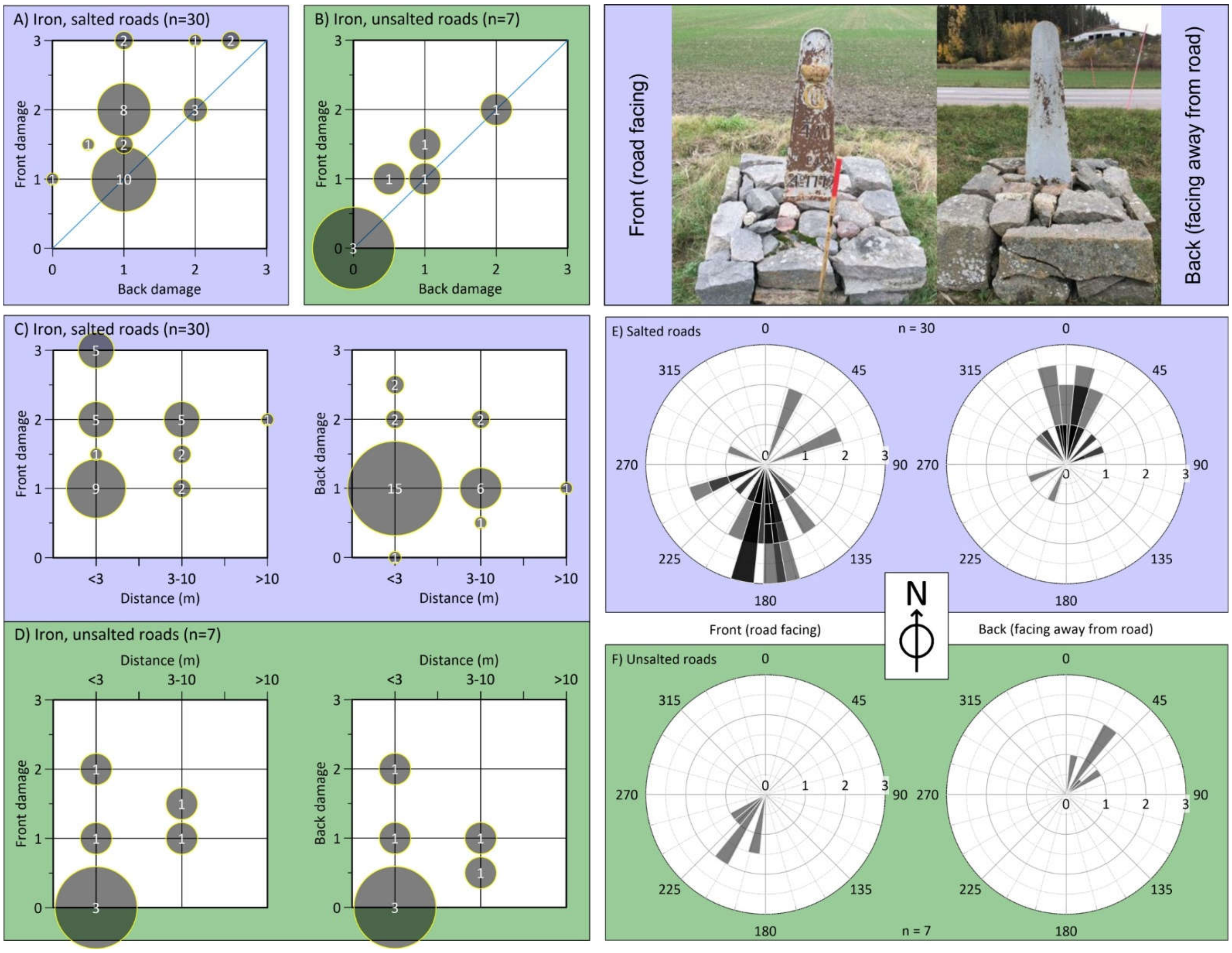

Figure 2. Bubble plots and wind rose diagrams showing milestone damage on a scale of 0 (none) to 3 (severe), with half marks where damage was difficult to classify. In the left hand panels, the radius of each bubble is proportional to the percentage of milestones in the sample group at the graph point (i.e. damage front vs damage back, damage vs distance), with actual numbers shown in the centre of the bubbles: (**A**) front and back on salted main roads; (**B**) front and back on un-salted roads; (**C**,**D**) damage in relation to distance from roads; (**E**,**F**) damage to front and back in relation to the compass direction in which each milestone faces. The upper right panel shows an example milestone with severe corrosion damage (photography by Hans Antonson 2020). (See Supplementary Data for the raw data).

3. Results

The results of the milestone damage assessment are presented in Data S1 and visualised in Figure 2A greater degree of damage was recorded on the road facing side (front) of milestones on salted roads than the side facing away (back) (Figure 2A,E). Only milestones on unsalted roads are undamaged, and those with damage exhibit similar levels on the front and back (Figure 2B,F). This pattern holds true for milestones at the edge of the road or several metres away (Figure 2C,D), for the single milestone positioned some distance from the salted road, and irrespective of orientation (Figure 2E,F).

In Figure 2A,B, bubble centres above the 45° 1:1 line indicate more damage on the front of the milestone, and points below the line would indicate more damage on the back. For the unsalted roads, the points clearly lie close to the 1:1 line (Figure 2B), indicating similar conditions (good or bad) on both sides of the milestones, three of which displayed no damage. Milestones along the salted roads demonstrated a generally higher level of damage, and the side facing the road was often more damaged than the back (Figure 2A). No milestones displayed more damage on the back than the front. In Figure 2E,F, radial bars extend from the centre of each plot in the direction in which the front and back of each milestone faces, with each milestone thus being represented by two opposing bars. The length of each bar indicates the damage to a face, with darker shading indicating more milestones facing the same direction. The results show that milestones on salted roads exhibited more damage on the front irrespective of direction, and that milestones on unsalted roads showed similar damage on the front and back.

The interpretation of Figure 2A,B is supported by the results of the correlation analysis (Table 1). Kendall's *tau* shows a higher significant positive association between front and back damage on unsalted roads (0.94) than salted roads (0.49). This indicates an almost linear relationship between damage on the front and back of milestones on roads without salt, but a less cohesive relationship between damage on the front and back on salted roads. The correlation between distance and damage is weak for salted roads (0.04 and −0.06), and medium for unsalted roads (0.38 and 0.23). For the salted roads, there is a high probability of distance and damage being uncorrelated, but with the small dataset and lack of data from milestones away from the edge of the road these results should be interpreted with caution.

Table 1. Kendall's *tau* rank correlation coefficient for damage on front and back of milestones and in relation to distance from roads. A value of *tau* closer to 1 indicates a higher correlation between the variables indicated in the first column, with a value of 0 indicating no correlation. The 'Prob. uncorrelated' column shows the two-tailed probabilities that the variables are uncorrelated, with a value closer to 1 indicating a higher probability of a *lack* of correlation, and a value closer to 0 indicating a lower probability of the variables being uncorrelated.

	Kendall's *tau*	**Prob. Uncorrelated**
Salted roads		
Front: back	0.49	0.00
Front: distance	0.04	0.76
Back: distance	−0.06	0.65
Unsalted roads		
Front: back	0.94	0.00
Front: distance	0.38	0.23
Back: distance	0.23	0.47

4. Discussion

This study provides empirical evidence of damage to historical cast iron monuments being caused by the application of road salt for improving road safety and mobility. Anthropogenic airborne pollutants, especially acid rain, have a documented destructive effect on historical monuments, built cultural heritage, buried artefacts and organic materials [28–31]. Sulphur dioxide deposition from acid rain has been particularly damaging to stone [29,32,33] and iron and steel [34,35], but emissions have dropped by 80% in Europe since the peak in 1980 [36–38]. Naturally occurring factors also cause damage, and airborne salt in sea winds causes structural failure in porous stone [39], and the propagation of cracks and flaking over freeze-thaw cycles [40]. Salt also corrodes metal and, consequently, corrosion is generally more prevalent in coastal areas [34]. This is reflected in the lower frequency [10] and higher degree of degradation of prehistoric bronze artefacts close to the Swedish west coast than in other parts of southern Sweden [41] (the Baltic Sea on Sweden's east coast being brackish). In museum collections, prehistoric metal artefacts excavated before the mid-20th century in Germany and Sweden also appear to be less corroded than those excavated more recently, suggesting the acceleration of decay since the 1950s [13,42].

Previous research has assumed [41] that de-icing salt contributes to the corrosion of cultural-historical iron objects, but no unequivocal evidence has been provided. The presence of atmospheric pollutants and acid rain typically make it difficult to isolate the specific cause of corrosion. Södermanland county, where our study is located (Figure 1), is inland and was never hit as hard by acid rain as coastal regions in the south and west of Sweden [37]. Furthermore, acid rain had decreased considerably in Scandinavia by the time the milestones in this study were restored in 1994. The potential for corrosion is dependent on the concentration and volume of the pollutant hitting the object. The latter can be assumed to decrease with distance from its source, in this case vehicle tires on the road surface splashing liquid away from the road. Whilst our current data are insufficient to conclusively demonstrate a distance decay relationship between the degree of damage and the distance of the milestones from roads, the highest levels of damage were observed on milestones closest to the road (Figure 2C), and especially on the front of milestones on salted roads. The dataset for unsalted roads is, however, too small to use as a control for establishing whether mechanical splash damage could be a factor in this.

Road salt is used for two main reasons: (1) anti-compaction to prevent snowfall from sticking to the road surface and being packed, and thereby becoming difficult to remove by physical measures (e.g., snowplough), and, (2) anti-icing to prevent frost formation or condensation from creating a layer of black ice on the road surface. Anti-compaction salt use is predicted to decrease in Sweden with climate change (higher temperatures), whilst anti-icing salt is likely to increase—especially in the north of Sweden and other arctic, colder, parts of the globe [43]. The use of road salt reached its peak in Sweden during the early 1990s (c. 300,000 tonnes/year) [44,45], but has now been reduced through better planning, to around 150,000 tonnes (2018/2019). Sweden has 42,706 registered sites and monuments within 10 m of roads, and of these 7028 are in the northern half of Sweden, where winter snow cover is more persistent. Although some regional assessments of climate change heritage risks are available [46,47], no systematic survey of the preservation status of sites along roads has been undertaken. Similarly, there is no national system for prioritising the preservation of sites at risk of being damaged by the effects of future climate change [48]. The milestones studied in this paper are far from the only type of cultural heritage object made of cast iron. There are many other types of transport infrastructure heritage, and other metal objects potentially at risk include bridges, lamp posts, boundary markings and the numerous metal attachments to buildings. These objects are not only inherently valuable as cultural heritage objects, but also in terms of their potential for providing information on past iron production techniques, the location of past communications networks, and the social and environmental context of these phenomena. Whilst the context of creation and use of the milestones is at least partly documented in the historical record [19,20], there are large numbers of iron objects which predate the written record. Many of these are under the soil surface (e.g., spearheads or boat rivets in Viking Age gravemounds [49,50]), and risk being destroyed if nearby roads are salted [51].

There is a difficult challenge in, on the one hand, reducing accidents and travel times (e.g., commuting, just-in-time deliveries), and on the other hand, protecting cultural heritage. In many countries, both are regarded as national interests, but the ethics of 'balancing' lives against cultural heritage is most often only discussed in the context of war [52,53] and disasters [54], not transport planning [55], despite the greater ubiquity of the latter. Measures have been implemented to reduce salt induced corrosion on iron in vehicles [56,57] and on traffic infrastructure [56]. Similarly, transport planning should include measures for protecting cultural heritage at risk from damage by changes in the use of winter de-icing salt. Climate change research suggests that increasing temperatures will change the geography of winter road maintenance in the future [58], and areas now with permanent or contiguous winter snow cover, and thus not treated with salt, may be exposed to heavy salt loads for the first time.

Climate change impacts cannot be reliably studied without consideration of human behaviour [59], and the consequences of adaptation measures need to be considered with a broader perspective than just their capacity to manage the effects of climate change. Climate change adaptation needs to be monitored [60], evaluated [61], and considered in terms of its sometimes unpredictable [62] consequences [63]. Cultural heritage should be included in this cycle (Figure 3), and alternatives to salting (e.g., speed limit reduction, sanding or gritting without salt, alternative road surfaces [64]), or additional protection for cultural heritage (e.g., barriers, alternative traffic planning), should be considered where the objects may be damaged, above or below ground. This is by no means a simple equation—building barriers or lowering speed limits costs money [65] and calculating the economic or societal value of hidden cultural heritage is far more complex [66] than calculating the cost of periodic re-painting of milestones. Calculating a monetary value for cultural heritage is also extremely problematic [67]. Evaluating these interests requires not only interdisciplinary science, but also a cross-sectoral approach, linking university research and the cultural heritage sector with transport authorities and industry as well as the general public [68]. Failing to do so presents us with considerable potential for conflicts, or negative trade-offs, between several Sustainable Development Goals [69], including 11.4 "Strengthen efforts to protect and safeguard the world's cultural and natural heritage", 11.2 " . . . access to safe, affordable, accessible and sustainable transport systems for all, improving road safety . . . " and the now overoptimistic 3.6 "By 2020, halve the number of global deaths and injuries from road traffic accidents".

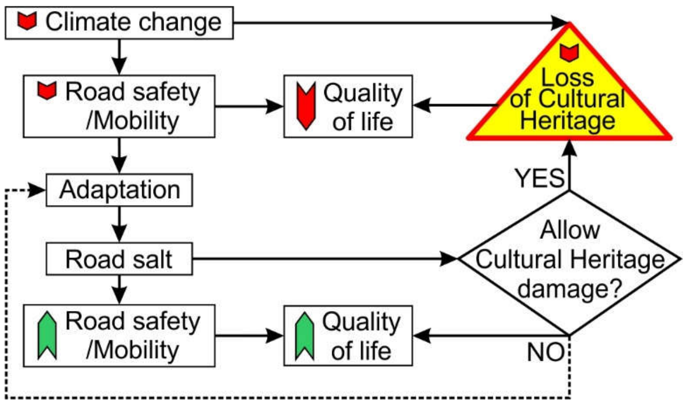

Figure 3. The insertion of cultural heritage into a simplified decision chain for road salt use. Coloured up or down arrows inside the text boxes indicate positive or negative trends or effects. Road salt decisions should include consideration of cultural heritage damage (the diamond) and a mechanism for feeding (dotted line) back into road safety climate change adaptation strategies. Institutional preconditions (barriers) may affect decision processes at any point in the model.

From the point of view of the general public, balancing lives, and from the point of view of industry, just-in-time deliveries, against cultural heritage may seem a simple equation weighted strongly in favour of lives and service provision. However, at the national or regional planning level things are not so simple [5,48]. Resources are limited and spending must be prioritized within and across different sectors. Cultural heritage is just one of many aspects of society which must be balanced against funding public safety, healthcare, the arts and railways, etc. Similarly, the selection of cultural heritage (and landscapes) for conservation or excavation requires an evaluation and decision-making process. Prioritization has been identified as a common institutional barrier in planning climate adaptation for cultural heritage and landscapes, and it is intertwined with the need for systematic monitoring of the effects of climate change on cultural heritage [70]. Similarly, lack of communication "among heritage institutions, academic researchers, and the local community" can act as an institutional barrier affecting the feasibility of implementing frameworks for boosting cultural and natural heritage conservation [68]. Institutional barriers could, in theory, negatively affect the implementation of any of the decisions implicit in our simplified decision chain model for road salt use (Figure 3).

Whilst the Swedish Heritage Act simply emphasises the importance of protecting heritage for its intrinsic value [71], there are more explicit arguments expressed in the scientific literature [51]. Cultural heritage is fundamental to human identity [72], and provides empirical evidence of long-term human activity and its interaction with the environment [73]. This has been expressed most clearly in the context of archaeological sites, which provide windows into " . . . long-term social processes such as migration, population dynamics, human security, and health, [making] contributions that are unobtainable by other social scientists working within the constraints of an instrumented climate record that is only a century or two in length . . . " [74]. This is a well-established argument in cultural heritage research [73] which has been gaining wider relevance in the context of the climate and biodiversity crisis [75]. The relevance goes beyond research into the objects themselves as archives of past events and changes, and into the use of cultural heritage to " . . . support conversations about values of place, identity, and story in the development of sustainable and just climate adaptation" [74].

5. Conclusions

In this pilot study, we have demonstrated that climate change related damage to cultural heritage may come from not only inaction, but also deliberate actions for adapting other sectors to climate change. The study of 37 cast iron milestones has brought novel insights into the risk of de-icing road salt damaging cultural heritage. The results have wider implications for studying the secondary impacts of climate change on cultural heritage, both in terms of other monuments made of iron and metal objects in buried contexts such as graves. Conservation practice needs to be aware of all potential risks to cultural heritage, including those caused by the actions of other government agencies in attempting to mitigate the effects of climate change in other social contexts.

The study also demonstrates the value of conducting a pilot study on a limited set of heritage objects to test an assumption or demonstrate proof of concept. Further analyses, on more objects and in other parts of the world, will help increase our understanding of the degree to which historically significant iron objects are threatened by human actions in relation to climate change. These analyses should include the use of more advanced methods for documenting monuments and assessing damage, such as hyperspectral imaging and laser scanning [76]. Such methods not only provide for a more empirically robust assessment than ocular methods, but also facilitate the easier integration of site-specific data into landscape models derived from LiDAR and other remote sensing techniques. The data and models may then also be used for virtual reconstructions for educational purposes or prior to restauration [77,78].

The milestones in this pilot study are one small part of the extremely small percentage of the products of past human activities which survive to the present day. If we lose these objects to corrosion, then we will irreversibly lose immeasurable parts of our cultural history. To return full cycle to George Burns, "Unless the situation is recognized and action is taken, future generations may look back at the present time as that when the cultural heritage of the human race was most extensively damaged" [1].

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/cli9100149/s1, Milestones measurement data. (Excel file). Results of the milestone survey, including an explanation of the data columns on a second worksheet.

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Conflicts of Interest: Authors declare that they have no competing interests.

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