Climate change and the deteriorating archaeological and environmental archives of the Arctic

Jørgen Hollesen[1,*], Martin Callanan[2], Tom Dawson[3], Rasmus Fenger-Nielsen[4], T. Max Friesen[5], Anne M. Jensen[6], Adam Markham[7], Vibeke V. Martens[8], Vladimir V. Pitulko[9] & Marcy Rockman[10]

The cold, wet climate of the Arctic has led to the extraordinary preservation of archaeological sites and materials that offer important contributions to the understanding of our common cultural and ecological history. This potential, however, is quickly disappearing due to climate-related variables, including the intensification of permafrost thaw and coastal erosion, which are damaging and destroying a wide range of cultural and environmental archives around the Arctic. In providing an overview of the most important effects of climate change in this region and on archaeological sites, the authors propose the next generation of research and response strategies, and suggest how to capitalise on existing successful connections among research communities and between researchers and the public.

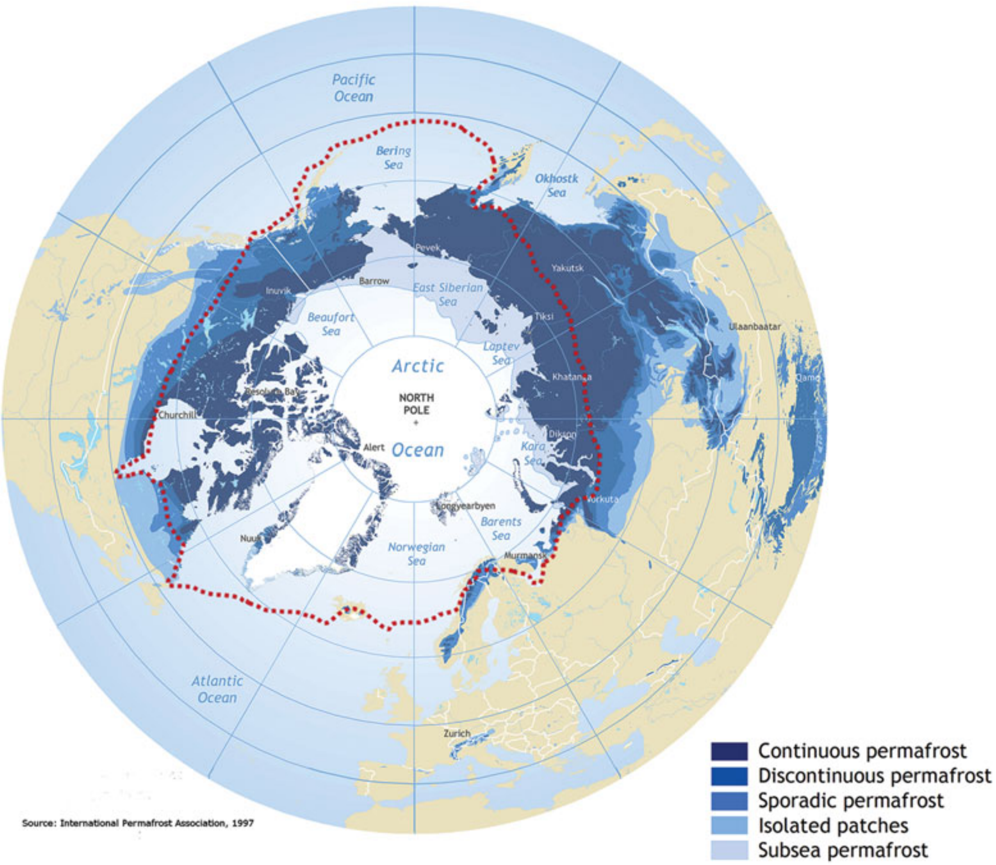
Keywords: Arctic, climate change, conservation, heritage management, archaeological mitigation strategies

Introduction

The past decade has witnessed growing global concern about the accelerating impact of climate change on archaeological sites (Colette 2007; see online supplementary material

[1] *Department of Conservation and Natural Sciences, National Museum of Denmark, IC Modewegsvej 1, 2800 Lyngby, Denmark*
[2] *Department of Historical Studies, Norwegian University of Science and Technology, Gunnerushuset, A284, Kalvskinnet, Erling Skakkes Gate 47B, 7491 Trondheim, Norway*
[3] *School of History, University of St Andrews, St Katharine's Lodge, The Scores, St Andrews, UK*
[4] *Center for Permafrost (CENPERM), University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen K, Denmark*
[5] *Department of Anthropology, University of Toronto, 19 Russell Street, Toronto, Ontario M5S 2S2, Canada*
[6] *Department of Anthropology, University of Alaska Fairbanks, 303 Tanana Loop, Bunnell Building Room 405A, Fairbanks, 99775-7720 AK, USA*
[7] *Union of Concerned Scientists, 2 Brattle Square, Cambridge, 02138-3780 MA, USA*
[8] *Norwegian Institute for Cultural Heritage Research (NIKU), Storgata 2, 0155 Oslo, Norway*
[9] *Institute for the History of Material Culture, Russian Academy of Sciences, 18 Dvortsovaya nab, St Petersburg, Russia*
[10] *National Park Service, 1849 C Street NW, Washington, DC 20240, USA*
* *Author for correspondence (Email: joergen.hollesen@natmus.dk)*

ANTIQUITY 92 363 (2018): 573–586 https://doi.org/10.15184/aqy.2018.8



Source: International Permafrost Association, 1997

Figure 1. Circum-Arctic map of the distribution of permafrost. The focus area of this article is located north of the +10°C July isotherm (dotted red line) (map by Brown et al. *1997).*

(OSM) 1, references 1–4). An increasing number of ancient sites and structures around the world are now at risk of being lost. Once destroyed, these resources are gone forever, with irrevocable loss of human heritage and scientific data. Often defined as the territory north of the +10°C July isotherm, the Arctic (Figure 1) is a bellwether for current large-scale repercussions of climate change, and for the future changes predicted to occur around the world. The Arctic has warmed at a rate of more than twice the global average since the 1980s (Stocker *et al.* 2013). While some historical changes in climate result from natural causes and variations, the strength of current trends indicate clearly that human influences have become a dominant factor (ACIA 2004; Stocker *et al.* 2013). Due to increasing concentrations of greenhouse gasses in the Earth's atmosphere, currently observed climatic trends are predicted to accelerate (ACIA 2004; Stocker *et al.* 2013).

Climate change will cause wide-ranging alteration to the Arctic, with some impacts already observable. Rising air temperatures, permafrost thaw, fluctuations in precipitation, melting glaciers and rising sea levels are just some of the changes affecting the natural system (ACIA 2004), and causing physical and chemical damage to archaeological sites and materials. The potential scale of this threat to archaeological sites has led to growing concern among polar archaeologists (Blankholm 2009; see OSM 1, references 1 & 5). The subject has, however, received limited attention within the wider research community, and little is known about how sites are being, and will be, affected. Here we present the first broad synthesis on the most significant climate change impacts on the Arctic, and describe how these changes are currently affecting archaeological sites. We also give examples of current management strategies and mitigation measures, including awareness-raising initiatives. Finally, we propose the next generation of research and response strategies, and suggest how to capitalise on existing successful connections among research communities and between researchers and the public. Focusing on Alaska, northern Canada, Greenland, northern Norway (including Svalbard) and northern Russia (Figure 1), we also draw parallels with archaeological sites from outside the region.

Arctic archaeological potential

The Arctic's cold and wet conditions have led to the extraordinary long-term preservation of archaeological material, including both artefacts and environmental evidence. The lack of modern development has also left many sites relatively undisturbed. Researchers therefore have unique opportunities to learn about past environments and cultures, many of which connect directly to modern indigenous cultures. Arctic archaeological sites often provide concrete connections to cultural heritage that language and other intangible aspects of culture cannot. Furthermore, they provide an ideal medium through which to engage younger generations with local heritage and culture (Lyons 2016). Spectacular finds and surviving structures have provided many novel contributions to the understanding of our common cultural history (Figure 2). Recent methodological advances are providing new results (e.g. Lee *et al.* 2018; see OSM 1, references 6–8). The archaeological deposits also contain a diverse range of animal, plant and insect remains, and anthropogenic soils and sediments that enable us to move beyond the human-mediated aspects of the environmental system to address questions within other research fields (Pitulko & Nikolskiy 2012; see OSM 1, references 9–15). Causey *et al.* (2005), for example, used avifauna from multiple archaeological sites in the Aleutian Islands to model the impact of climate change on regional ecosystems.

As there is no official record of the total number of archaeological sites in the Arctic, we collected data from national cultural heritage databases and found that ∼180 000 sites are currently registered (Table 1; OSM 2). This approximation is, however, somewhat uncertain due to a lack of official site numbers in the Russian Arctic and differences in how 'sites' are defined from country to country. Regardless of total number, very few of the sites have been excavated, and we anticipate that many more sites await discovery in those parts of the Arctic yet to be surveyed. Thus, archaeological sites in this region continue to offer great potential for further spectacular discoveries and novel scientific contributions.

Figure 2. Examples of some of the extraordinary archaeological finds from the Arctic: A) ivory owl effigy toggle from Nuvuk, Alaska (photograph by Anne M. Jensen); B) pre-contact driftwood house floor from Kuukpak in the Mackenzie Delta, Canada (photograph by Max Friesen); C) human remains from Qilakitsoq, Greenland (photograph by National Museum of Denmark); D) preserved medieval textiles from Andøy, Nordland, Norway (photograph by Mari Karlstad); E) 31 000-year-old decorated ivory scoop from the Yana site, Arctic Siberia (photograph by Vladimir Pitulko).

Table 1. The number of archaeological sites registered in the focus area of this article. Methods used to provide the numbers are described in OSM 1.

Region	Number of registered sites	Population	Area (km^2)	Population/km^2
Alaska	34 500	741 894	1 718 000	0.4
Canada (Arctic)	30 301	164 800	4 365 128	0.04
Greenland	5538	55 860	2 166 000	0.03
Norway (Arctic)	108 000	471 415	108 961	4.3
Russia (Arctic)	1600	2 338 604	3 701 921	0.6
Total	**179 939**	**3 772 573**	**12 060 010**	**0.35**

These archaeological sites may, however, be under serious threat from climate change, which is influencing a range of processes that can accelerate site destruction. The following overview is based on a detailed compilation and review of published articles and publicly available reports that identify impacts of climate change on archaeological sites in the Arctic, or that provide information about archaeological resources already damaged by climate change.

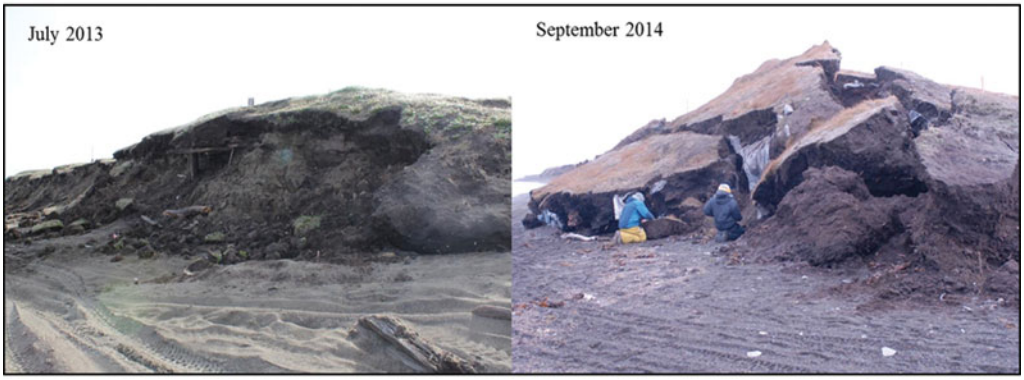


Figure 3. Examples from Walakpa in Alaska of newly exposed archaeological layers that are quickly degrading due to multiple processes (permafrost thaw, frost/thaw processes, microbial degradation and wave action during storms) (photograph by Anne M. Jensen).

The impact of climate change on archaeological sites

Coastal erosion

Sea-level rise, the lengthening of open-water periods due to sea-ice decline and a predicted increase in the frequency of major storms are all expected to intensify erosion of the Arctic coastline (Lantuit *et al.* 2012). Coastal erosion poses a widespread threat to many archaeological sites in this region due to the predominantly coastal lifeways of Arctic people. The permafrost coasts of north and north-west Alaska and the western Canadian Arctic are characterised as one of the largest areas of high-sensitivity shoreline in the circumpolar Arctic (Lantuit *et al.* 2012). While not a new phenomenon in this area, coastal erosion is currently widespread and is greatly affecting the archaeology in the region (Jones *et al.* 2008; Friesen 2015; Gibbs & Richmond 2015; Jensen 2017; O'Rourke 2017; see OSM 1, references 16–22). Jones *et al.* (2008), for example, focused on a stretch of the Beaufort Sea coastline near Drew Point in north Alaska, and found that three out of four known archaeological sites had disappeared, with the remaining site heavily damaged by erosion. Furthermore, the coastlines near Barrow on Alaska's North Slope, having been inhabited by semi-sedentary Alaska Natives for at least 4000 years, are quickly being lost to erosion and thawing permafrost (Figure 3). Twenty years ago, rapidly eroding coastal bluffs began exposing human remains at Nuvuk, a key site for understanding the Thule migration across the North American Arctic (Jensen 2017; see OSM 1, references 20–21). Since then, sea-level rise, fierce coastal storms and permafrost thaw have removed over 100m of land. This has destroyed several Ipiutak structures, and has heavily eroded a cemetery containing over 100 individuals (Figure 3).

The most important archaeological sites of the Inuvialuit—the aboriginal inhabitants of north-westernmost Canada—are endangered by erosion (Friesen 2015; O'Rourke 2017). In the Russian Arctic, erosion is severe along the Laptev and East Siberian Seas (Figure 1) (Lantuit *et al.* 2012; see OSM 1, references 23–24), although how this is affecting archaeological sites is virtually unknown. Erosion rates of 5–6m per year have, however, been measured over a 10-year period at the archaeological site of Yana (Pitulko 2014). This site represents the earliest-known occupation in the Arctic region (25 000 kya) and is a key site for understanding the first peopling of the Americas. Although the Chukchi shorelines (north-west of the Bering Strait) are considered less vulnerable, erosion is still removing local archaeological sites (Dikov 1977; Gusev 2010; Lantuit *et al.* 2012). The coastlines of the Canadian Archipelago, Greenland and Svalbard are considered stable due to their predominantly rocky nature, the persistence of sea ice throughout the summer season (for the Canadian Archipelago) and because of a strong post-glacial rebound (rise of land) (Lantuit *et al.* 2012). Nevertheless, erosion on a local scale may still be a major threat to archaeological sites, such as Fort Conger on northern Ellesmere Island in Canada, Iita in north-west Greenland and Herjolfnes in south Greenland, where the remains of a Norse settlement are threatened by coastal erosion (Dawson *et al.* 2015; see OSM 1, references 25–27). Several sites in northern Norway and Svalbard have also been categorised as threatened by coastal erosion (Flyen 2009; see OSM 1, references 28–31).

Permafrost thaw and microbial degradation

Large parts of the exposed land surface of the circumpolar north contain permafrost (perennially frozen ground) (Figure 1). Permafrost often preserves organic archaeological materials, as cold temperatures and high saturation levels slow the decay of organic materials (Hollesen *et al.* 2017). Model predictions show that a warmer climate will affect both the spatial extent of permafrost and the depth of the active layer, which thaws during summer (Slater & Lawrence 2013; Hollesen *et al.* 2015). An increase in active layer depths in response to warmer temperatures is significant because it exposes the previously frozen soil layers to accelerated erosion, to wet/dry and freeze/thaw cycles and to increased microbial activity (Hollesen *et al.* 2017). Studies from north-western Canada, northern Alaska and Siberia show that permafrost destabilisation is leading to severe erosion and landscape change, with dramatic effects on the preservation of archaeological sites (e.g. Solsten & Aitken 2006; Jones *et al.* 2008; Pitulko 2014; Andrews *et al.* 2016). In Auyuittuq National Park Reserve, Nunavut, Canada, 24 out of 48 archaeological sites are categorised as being at high risk of soil disturbance (Solsten & Aitken 2006). In Russia, the speed of slope erosion (up to 10m per year) is shown to be highly dependent on the ice content of the soil, mean summer temperature and the amount of incoming solar radiation (Pitulko 2014). Clear evidence of hydro-thermal erosion has also been reported in Greenland (Hollesen *et al.* 2017).

The physical erosion of sites is relatively easy to document by, for example, remote sensing or repeated site visits. It is, however, more difficult to discover, quantify and predict ongoing microbial or chemical degradation of archaeological deposits and similar processes in archaeological wood. These degradation processes have been scientifically documented (e.g. Mattsson *et al.* 2010; Matthiesen *et al.* 2014; Hollesen *et al.* 2015, 2016a, 2017; see OSM 1, references 32–38). The results show that microbial and fungal communities in archaeological deposits and surviving wooden structures have adapted to the cold Arctic environment; they are sensitive to increasing soil temperatures, especially when water is drained and increasing oxygen availability triggers degradation. The deterioration of

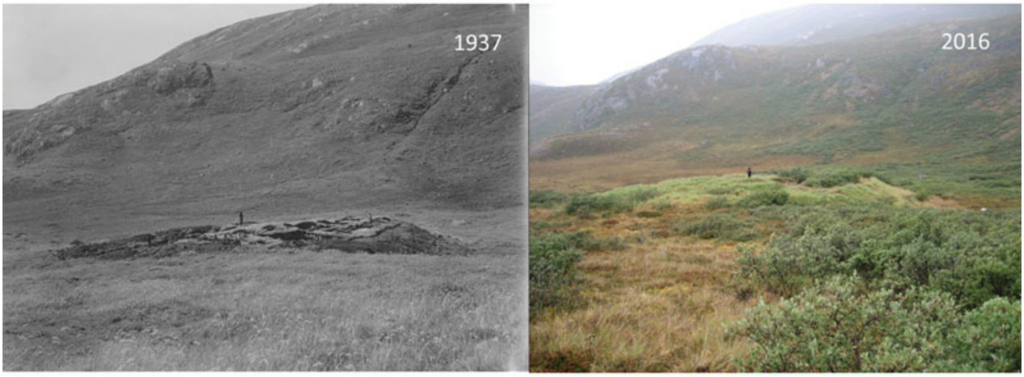


Figure 4. The project REMAINS of Greenland is currently investigating the impact of vegetation increase in Greenland. The use of historical photographs is one of the methods used to highlight changes in vegetation (photographs from Austmanndalen near Nuuk in west Greenland by Roussel (1937) and Matthiesen (2016)).

organic archaeological deposits is accompanied by high microbial heat production. In some cases, this increases soil temperatures, thereby accelerating the decomposition processes and intensifying significantly the impact of climate change (Hollesen *et al.* 2015).

Increasing soil temperatures and changes in the soil's water content are also important in areas without permafrost (Hollesen *et al.* 2016a). Recent studies of organic archaeological deposits in northern Norway indicate that a predicted air temperature increase of 3°C during the twenty-first century could accelerate the overall decay rate by ∼50 per cent (Hollesen e*t al.* 2016b; Martens *et al.* 2016). This will be highly dependent, however, on the timing of precipitation, the frequency of dry periods and on evaporation rates (Hollesen *et al.* 2016b).

Vegetation increase and tundra fires

Several studies using satellite-based remote sensing and field observations show that the circumpolar Arctic tundra has undergone a 'greening' during recent decades (e.g. Tape *et al.* 2006; see OSM 1, references 39 & 40). Over time, climate change is projected to cause a shift in vegetation zones and to promote the expansion of boreal forests into the Arctic tundra, and of tundra into the polar deserts. A direct consequence of vegetation increase is that archaeological sites will become overgrown and eventually hidden (Figure 4). Furthermore, thicker vegetation and the spread of trees will increase summer evapotranspiration (Swann *et al.* 2010), which may lower the soil's water content and contribute to the decay rate of organic archaeological deposits (described above). An increase in root depth may also represent a risk to sub-soil archaeology (Crow & Moffat 2005). When roots exploit the soil for water and nutrients, they may penetrate and cause physical damage to organic archaeological material, including bone and wood (Tjelldén *et al.* 2015). Additionally, roots may disturb the archaeological stratigraphy, which is crucial to site interpretations (Tjelldén *et al.* 2015). Together with the shift in vegetation, wildfire activity is expected to increase dramatically (Young *et al.* 2017; see OSM 1, references 41 & 42), with strong impacts on permafrost stability and the loss of organic material in the soil (Mack *et al.* 2011).

Tourism and the impact of local communities

Climate change is responsible for longer and more extensive seasonal sea-ice melt in the Arctic, which has increased the accessibility of the region. The Intergovernmental Panel on Climate Change (Stocker *et al.* 2013) predicts that the Arctic Ocean will be nearly ice-free during summers before the end of this century, thereby opening up new shipping routes and extending the use of those that already exist. This will probably drive an increase in the development of coastal infrastructure and cruise tourism (Larsen *et al.* 2014). Such changes will open up more archaeological sites to visitors, bringing more traffic into sensitive environments. Improved accessibility to cultural heritage sites—which are often marketed together with the natural landscape as integral parts of the wilderness experience—is already challenging resource managers to balance the use and protection of sensitive sites (Høgvard 2003; Hagen *et al.* 2012). The impacts of uncontrolled or poorly planned tourism on archaeological sites have been well documented in other parts of the world (Markham *et al.* 2016), but there is currently limited information for the Arctic. In Norway, damage to archaeological sites at Kautokeino (Finnmark) and Lake Leinavatnet (Troms County) from all-terrain vehicles, illegal campsites and hikers' paths has been documented (Blankholm 2009). Increased visitor numbers to Svalbard has caused clear damage to cultural heritage sites, such as at the early twentieth-century marble mining settlement of London (Hagen *et al.* 2012; Thuestad *et al.* 2015).

Melting ice, thawing permafrost and coastal erosion is exposing archaeological sites in the Arctic to potential damage not just from tourists, but also from commercial and non-commercial collectors. This includes some local Arctic communities who collect—often legally, but sometimes illegally—artefacts and other archaeological resources found on the ground surface or eroding from the shoreline (Staley 1993; Hollowell 2006). An increase in this type of collecting should be expected as the erosion of coastal archaeological sites accelerates and melting ice and thawing permafrost expose more remains. There is, however, also the danger of large-scale plundering of archaeological resources, as has been reported in north-east Siberia. Here, high-pressure hydraulic pumps have been used to 'mine' concentrations of mammoth remains at kill and butchery sites such as Berelekh, Yana and Buor-Khaya (Pitulko *pers. comm.*, 2014; see OSM 1, references 43–44).

Discussion

Our research has reviewed 46 articles and reports that identify impacts of coastal erosion, permafrost thaw, vegetation increase, tundra fires and increased accessibility to archaeological sites in the Arctic (OSM 3). That 42 of these articles are published after 2000 demonstrates the recent increase in evidence of damage to Arctic archaeological sites. The increase may be due partly to a rising awareness of the issues, but it also signals a real increase in the number of sites that are being damaged. In light of both the damage already documented and predicted (Stocker *et al.* 2013), we should prepare for a new reality where archaeologists and heritage managers must deal with a growing number of vulnerable and degrading sites. An effective response to this emerging situation requires the development of new methods and strategies to detect, monitor and mitigate vulnerable sites, and, where necessary, to prioritise between them.

Detecting vulnerable sites

The Arctic contains at least 180 000 archaeological sites (Table 1). Very few of these sites have been investigated and we know little about their current state of preservation. It is often assumed that the remoteness and the climate associated with these sites provide protection enough. As the examples highlighted here demonstrate, however, climate change means that this may no longer be the case. Paradoxically, remoteness now compounds the problem: sites far from population centres or popular travel routes cannot be visited often, and may be damaged or disappear completely before being documented. As it is impossible to visit and survey all the sites in the Arctic, new methods to detect and quantify site changes on a regional scale must be developed. This will allow for more effective and targeted site inspection and monitoring or mitigation efforts in the future. Studies have shown that the impact of sea-level rise on archaeological sites can be assessed at a regional scale, using techniques such as remote sensing (e.g. unmanned aerial vehicles or satellite imagery) combined with geographic information systems (GIS) (e.g. Solsten & Aitken 2006; see OSM 1, references 45–46). The value of such methods is highly dependent upon the quality of the input data. This can be highly variable for the Arctic, large areas of which remain poorly mapped, with positions and elevations of archaeological sites often inaccurately recorded. This has serious negative consequences for the development of predictive models and assessments that are so vital for effective prioritisation between sites. Reliable estimates for impact rates of erosion, permafrost thaw, vegetation increase and human access are also currently lacking. To a certain extent, however, such estimates have been advanced for the modelling of the natural environment (e.g. Lantuit *et al.* 2012; Slater & Lawrence 2013), but the resolution is often too low to be useful for the monitoring of archaeological sites. Furthermore, the physical and chemical composition of archaeological deposits is very different from the natural soils for which such estimates were originally developed. Increased research effort is therefore required to investigate how archaeological sites and artefacts are being affected by ongoing climate change.

Monitoring and mitigation

Monitoring vulnerable sites in the vast and remote Arctic (Table 1) presents an enormous challenge, especially considering the limited number of archaeologists working here. One method to increase capacity in response to this challenge is to work with local people. Scotland's Coastal Heritage at Risk Project (SCHARP), for example, asked volunteer citizen scientists to use a smartphone and tablet applications to assist with the identification and monitoring of vulnerable sites (Dawson 2015). Several other studies have also used vulnerability protocols to monitor the state of archaeological sites (e.g. Daly 2014; see OSM 1, references 47–48). If future archaeological surveys in the Arctic were equipped with a standard protocol for evaluating site vulnerability, the systematic data collected could serve as baselines for monitoring change. Observations by archaeologists or local informants will determine the necessity of establishing more detailed environmental monitoring of relevant parameters. The collected data will help to provide a stronger knowledge base for protection and mitigation strategies (Rytter & Schonhowd 2015; Sidell & Panter 2016). We currently lack a full understanding of which parameters have the most effect on preservation conditions and therefore of how to set threshold values for when to respond (Martens 2016). Although there are many examples of different mitigation measures being applied to protect archaeological deposits from erosion, microbial degradation and vegetation increase (e.g. Rytter & Schonhowd 2015), such strategies have seldom been applied in the Arctic. This is probably due to the high costs and significant logistical challenges of applying such protective measures here. In some cases, however, low-tech mitigation measures could be an option to slow the degradation processes. Snow fences, for example, could be used to increase the soil-water content, and soil covers could be used to insulate the ground surface. These measures would buffer against variations in soil-water content, and may also prevent erosion, although such measures would require thorough testing before large-scale application.

Rescue and prioritisation of sites

The erosion processes occurring along the north coasts of Alaska, the western Canadian Arctic and in parts of Siberia are already so frequent and destructive that immediate action is needed. Excavations in both Alaska and Siberia demonstrate that anything not excavated will be lost within a few years of exposure (Jensen *pers. comm.*; Pitulko *pers. comm.*). Excavations in the Arctic are often more challenging than those in other regions and hence can be very expensive and time-consuming. The existing mechanisms for response—including rescue excavations—are already regularly overwhelmed, and pressures will become more acute in years to come. In addition, conventional science funding models are insensitive to the rate at which sites are now being destroyed. In Alaska, it is already impossible to manage all threatened sites using existing resources. It is therefore essential to find effective methods of evaluating the significance and potential of sites in order to prioritise those that should be excavated and those that must be allowed to decay. Existing methods of prioritising eroding coastal sites in Scotland (Dawson 2013) could be adapted for the Arctic.

The way forward

Awareness of the climatic threats faced by cultural heritage around the world is increasing. A range of 'bottom-up' initiatives, such as IHOPE and the Pocantico Call, have emerged (see OSM 3), and several national initiatives aimed at monitoring and responding to the impacts of climate change on cultural heritage have also been developed. The US National Park Service (NPS) established one such approach in 2009. The NPS Climate Change Response Program recognises the need to address the impact of climate on cultural heritage, and to learn from cultural heritage for all areas of climate response (Rockman 2015; see OSM 1, references 49–50). As archaeologists and cultural resource managers produce strategies to handle this growing problem, however, it must be understood that it cannot be engaged effectively by any single organisation or nation. It is therefore crucial that knowledge is shared between cultural resource managers, researchers and those engaged in international projects dealing with the issue of climate effects on heritage. Current scientific projects, such as the Arctic CHAR Project (Canada), REMAINS of Greenland, NABO (Greenland), InSituFarms (Norway) and SPARC (Norway), focus on how archaeological sites and materials are, and will be, affected by climate change in the Arctic (see OSM 3). Financially stretched regional and national research-oriented funding agencies, however, cannot bear the burden of supporting the large-scale, sustained response required to face these challenges. New funding models, staff education and recruitment, public engagement and research must be developed and implemented. Archaeologists and allied scientists must also publicise research on climate threats to cultural heritage, both in scientific journals and in more popular forms. Media coverage, especially in the Arctic, has a key role to play in creating awareness and increasing the public pressure required to direct resources to research and mitigation.

Conclusions

Coastal erosion, permafrost thaw, increasing vegetation, tundra fires and increased accessibility are all part of the broad picture of climate change, with significant implications for the continued preservation of archaeological sites in the Arctic. Each type of impact has different effects, causing damage at timescales varying from days to decades, or even centuries. Consequently, some sites are in immediate danger and others are safe, at least for now. How many sites fall into each of these categories is unknown, so we must develop methods to detect the most vulnerable sites. Methods are also required for effectively managing sites currently characterised as vulnerable. In some areas, it should be possible to monitor sites through the combined use of citizen science projects, vulnerability protocols and environmental monitoring programmes. We must also acknowledge the particular challenges of monitoring such sites, given the size and remoteness of the Arctic. Given that very little has been done to develop methods for mitigation, excavation may seem to be the only currently applicable solution for managing archaeological deposits at risk of degradation. Excavations in permafrost regions are, however, expensive and time-consuming, and archaeologists are already overwhelmed. With the climate continuing to change, this situation will undoubtedly deteriorate. As natural processes are causing the damage, most jurisdictions have no designated funds or programmes for archaeological mitigation. This must change if we are to respond in a serious and efficient manner to the problem of natural threats to heritage. Concurrently, we must be realistic and acknowledge that it will be necessary to prioritise between sites in order to direct limited resources to the most valuable sites.

The current situation in parts of the Arctic clearly demonstrates that we are poorly prepared to respond to a scenario where system-wide, natural processes affect thousands of archaeological sites at once. There are no easy solutions, but the longer we wait, the more difficult the challenges will become.

Acknowledgements

Hollesen and Fenger-Nielsen thank VELUX FONDEN (33813) and the Danish National Research Foundation (CENPERM DNRF100) for financial support, as well as colleagues at the National Museum of Denmark and

Greenland National Museum. Callanan thanks the Norwegian Research Council (Miljø 2015) for post-doctoral funding. Dawson thanks Historic Environment Scotland. Friesen wishes to thank the following: Sylvie LeBlanc, Tom Andrews, Susan Lofthouse, Greg Hare, Martha Drake, Stephen Hull and Jamie Brake. Jensen thanks Jeffery Weinberger for his assistance; and the North Slope Borough and Ukpeaġvik Iñupiat Corporation for financial support for work at Walakpa. Markham thanks the J.M. Kaplan Fund, the Barr Foundation and the Rockefeller Brothers Fund. Martens thanks The Research Council of Norway for funding project 212900. Pitulko thanks the Russian Science Foundation for supporting project 16-18-10265-RNF.

Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.15184/aqy.2018.8

References

ACIA. 2004. *Impacts of a warming Arctic: Arctic climate impact assessment. ACIA overview report*. Cambridge: Cambridge University Press.

Andrews, T.D., S.V. Kokelj, G. Mackay, J. Buysse, I. Kritsch, A. Andre & T. Lant. 2016. Permafrost thaw and Aboriginal cultural landscapes in the Gwich'in Region, Canada. *APT Bulletin* 47: 15–22.

Blankholm, H.P. 2009. Long-term research and cultural resource management strategies of climate change and human impact. *Arctic Anthropology* 46: 17–24. https://doi.org/10.1353/arc.0.0026

Brown, J., O.J. Ferrians Jr, J.A. Heginbottom & E.S. Melnikov (ed.). 1997. *Circum-Arctic map of permafrost and ground-ice conditions* (Circum-Pacific Map Series CP-45, scale 1:10,000,000, 1 sheet). Washington, D.C.: U.S. Geological Survey in Cooperation with the Circum-Pacific Council for Energy and Mineral Resources.

Causey, D., D.G. Corbett, C. Lefèvre, D.L. West, A.B. Savinetsky, N.K. Kiseleva & B.F. Khassanov. 2005. The palaeoenvironment of humans and marine birds of the Aleutian Islands: three millennia of change. *Fisheries Oceanography* 14(s1): 259–76. https://doi.org/10.1111/j.1365-2419.2005.00365.x

Colette, A. 2007. *Case studies on climate change and world heritage*: 52–63. Paris: UNESCO World Heritage Centre.

Crow, P.G. & A.J. Moffat. 2005. The management of the archaeological resource in UK wooded landscapes: an environmental perspective. *Conservation and Management of Archaeological Sites* 7: 103–16. https://doi.org/10.1179/135050305793137512

Daly, C. 2014. A framework for assessing the vulnerability of archaeological sites to climate change: theory, development, and application. *Conservation and Management of Archaeological Sites* 16: 268–82. https://doi.org/10.1179/1350503315Z.00000000086

Dawson, P., M. Bertulli, L. Dick & L. Cousins. 2015. Heritage overlooked and under threat: Fort Conger and the heroic age of Polar exploration, in P.F. Biehl & C. Prescott (ed.) *Identity and heritage: contemporary challenges in a globalizing world*: 107–15. New York: Springer. https://doi.org/10.1007/978-3-319-09689-6_11

Dawson, T. 2013. Erosion and coastal archaeology: evaluating the threat and prioritising action, in M.Y. Daire, C. Dupont, M. Baudry, C. Brillard, J.M. Large, L. Lespez, E. Normand & C. Scarre (ed.) *Ancient maritime communities and the relationship between people and environment along the European Atlantic coasts* (British Archaeological Reports International series 2570). Oxford: Archaeopress.

– 2015. Taking the middle path to the coast: how community collaboration can help save threatened sites, in D. Harvey & J. Perry (ed.) *The future of heritage as climates change*: 248–68. London: Routledge.

Dikov, N.N. 1977. *Arkheologicheskiye pamyatniki Kamchatki, Chukotki i Verkhnei Kolymy* [*Archaeological sites in Kamchatka, Chukotka, and the upper reaches of the Kolyma*]. Moscow: Nauka.

Flyen, A.C. 2009. Coastal erosion—a threat to the cultural heritage of Svalbard?, in J. Holmén (ed.) *Polar research in Tromsø 2009*: 13–14. Tromsø: University of Tromsø.

Friesen, T.M. 2015. The Arctic CHAR Project: climate change impacts on the Inuvialuit archaeological record. *Les nouvelles de l'archéologie* 141: 31–37.

Gibbs, A.E. & B.M. Richmond. 2015. National assessment of shoreline change—historical shoreline change along the north coast of Alaska, U.S.–Canadian border to Icy Cape. *U.S. Geological Survey Open-File Report* 2015-1048. Santa Cruz (CA): U.S. Geological Survey. https://doi.org/10.3133/ofr20151048

GUSEV, S.V. 2010. 'Whale Alley': past, present, future (eastern Chukotka), in O.V. Belova (ed.) *Studia anthropologica. A festschrift in honour of Michael Chlenov*: 486–512. Moscow: Gesharim.

HAGEN, D., O.I. VISTAD, N.E. EIDE, A.C. FLYEN & K. FANGEL. 2012. Managing visitor sites on Svalbard; from precautionary approach to knowledge-based management. *Polar Research* 31: 1–17. https://doi.org/10.3402/polar.v31i0.18432

HØGVARD, K. 2003. *Miljøovervåking av ferdselsslitasje—Grønland, Island og Svalbard.* [*Environmental monitoring of human use effects—Greenland, Iceland and Svalbard*]. Aarhus: Nordic Council of Ministers.

HOLLESEN, J., H. MATTHIESEN, A.B. MOLLER & B. ELBERLING. 2015. Permafrost thawing in organic Arctic soils accelerated by ground heat production. *Nature Climate Change* 5: 574–78. https://doi.org/10.1038/nclimate2590

HOLLESEN, J., H. MATTHIESEN, A.B. MØLLER, A. WESTERGAARD-NIELSEN & B. ELBERLING. 2016a. Climate change and the loss of organic archaeological deposits in the Arctic. *Scientific Reports* 6: 28690. https://doi.org/10.1038/srep28690

HOLLESEN, J., H. MATTHIESEN, A.B. MØLLER & V.V. MARTENS. 2016b. Making better use of monitoring data. *Conservation and Management of Archaeological Sites* 18: 116–25. https://doi.org/10.1080/13505033.2016.1182750

HOLLESEN, J., H. MATTHIESEN & B. ELBERLING. 2017. The impact of climate change on an archaeological site in the Arctic. *Archaeometry* 59: 1175–89. https://doi.org/10.1111/arcm.12319

HOLLOWELL, J.J. 2006. St Lawrence Island's legal market in archaeological goods, in N. Brodie, M.M. Kersel, C. Luke & K.W. Tubb (ed.) *Archaeology, cultural heritage, and the antiquities trade*: 98–132. Gainesville: University Press of Florida.

JENSEN, A.M. 2017. Threatened heritage and community archaeology on Alaska's North Slope, in T. Dawson, C. Nimura, E. López-Romero & M.-Y. Daire (ed.) *Public archaeology and climate change*: 126–37. Oxford: Oxbow.

JONES, B.M., K.M. HINKEL, C.D. ARP & W.R. EISNER. 2008. Modern erosion rates and loss of coastal features and sites, Beaufort Sea coastline, Alaska. *Arctic* 61: 361–72.

LANTUIT, H., P.P. OVERDUIN, N. COUTURE, S. WETTERICH, F. ARE, D. ATKINSON, J. BROWN, G. CHERKASHOV, D. DROZDOV, D.L. FORBES, A. GRAVES-GAYLORD, M. GRIGORIEV, H.W. HUBBERTEN, J. JORDAN, T. JORGENSON, R.S. ODEGARD, S. OGORODOV, W.H. POLLARD, V. RACHOLD, S. SEDENKO, S. SOLOMON, F. STEENHUISEN, I. STRELETSKAYA & A. VASILIEV. 2012. The Arctic coastal dynamics database: a new classification scheme and statistics on Arctic permafrost coastlines. *Estuaries and Coasts* 35: 383–400. https://doi.org/10.1007/s12237-010-9362-6

LARSEN, J.N., O.A. ANISIMOV, A. CONSTABLE, A.B. HOLLOWED, N. MAYNARD, P. PRESTRUD, T.D. PROWSE & J.M.R. STONE. 2014. Polar regions, in V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.B. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea & L.L. White (ed.) *Climate change 2014: impacts, adaptation, and vulnerability, part B: regional aspects: working group II contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*: 1567–612. New York & Cambridge: Cambridge University Press.

LEE, E.J., D.A. MERRIWETHER, A.K. KASPAROV, V.I. KHARTANOVICH, P.A. NIKOLSKIY, F.K. SHIDLOVSKIY, A.V. GROMOV, T.A. CHIKISHEVA, V.G. CHASNYK & V.B. TIMOSHIN. 2018. A genetic perspective of prehistoric hunter-gatherers in the Siberian Arctic: mitochondrial DNA analysis of human remains from 8000 years ago. *Journal of Archaeological Science: Reports* 17: 943–49. https://doi.org/10.1016/j.jasrep.2016.06.001

LYONS, N. 2016. Archaeology and native northerners: the rise of community-based practice across the North American Arctic, in T. Max Friesen & O.K. Mason (ed.) *The Oxford handbook of the prehistoric Arctic*: 197–220. Oxford: Oxford University Press.

MACK, M.C., M.S. BRET-HARTE, T.N. HOLLINGSWORTH, R.R. JANDT, E.A.G. SCHUUR, G.R. SHAVER & D.L. VERBYLA. 2011. Carbon loss from an unprecedented Arctic tundra wildfire. *Nature* 475: 489–92. https://doi.org/10.1038/nature10283

MARKHAM, A., E. OSIPOVA, K. LAFRENZ SAMUELS & A. CALDAS. 2016. World Heritage and tourism in a changing climate. UNESCO and UNEP. Available at: http://whc.unesco.org/document/139944 (accessed 17 April 2018).

Martens, V.V. 2016. *Preserving rural settlement sites in Norway? Investigations of archaeological deposits in a changing climate* (Geoarchaeological and Bioarchaeological Studies 16). Amsterdam: Vrije Universiteit Amsterdam.

Martens, V.V., O. Bergersen, M. Vorenhout, P.U. Sandvik & J. Hollesen. 2016. Research and monitoring on conservation state and preservation conditions in unsaturated archaeological deposits of a medieval farm mound in Troms and a Late Stone Age midden in Finnmark, northern Norway. *Conservation and Management of Archaeological Sites* 18: 8–29. https://doi.org/10.1080/13505033.2016.1181930

Matthiesen, H., J.B. Jensen, D. Gregory, J. Hollesen & B. Elberling. 2014. Degradation of archaeological wood under freezing and thawing conditions—effects of permafrost and climate change. *Archaeometry* 56: 479–95. https://doi.org/10.1111/arcm.12023

Mattsson, J., A.C. Flyen & M. Nunez. 2010. Wood-decaying fungi in protected buildings and structures on Svalbard. *Agarica* 29: 5–14.

O'Rourke, M.J. 2017. Archaeological site vulnerability modelling: the influence of high impact storm events on models of shoreline erosion in the western Canadian Arctic. *Open Archaeology* 3: 1–16. https://doi.org/10.1515/opar-2017-0001

Pitulko, V. 2014. Potential impacts on the polar heritage record as viewed from frozen sites of East Siberian Arctic, in J. Bickersteth, N. Watson, M. Frisen & J. Hollesen (ed.) *International Polar Heritage Committee of ICOMOS conference 2014: the future of polar heritage—programme and book of abstracts*: 77–80. Copenhagen: National Museum of Denmark.

Pitulko, V. & P. Nikolskiy. 2012. Extinction of wooly mammoth in Northeastern Asia and the archaeological record. *World Archaeology* 44: 21–42. https://doi.org/10.1080/00438243.2012.647574

Rockman, M. 2015. An NPS framework for addressing climate change with cultural resources. *The George Wright Forum* 32: 37–50

Rytter, J. & I. Schonhowd. 2015. *Monitoring, mitigation, management. The Groundwater Project—safeguarding the World Heritage site of Bryggen in Bergen*. Oslo: Riksantikvaren.

Sidell, J. & I. Panter. 2016. How to carefully construct a hospital over a Roman boat in central London, UK. *Conservation and Management of Archaeological Sites* 18: 266–75. https://doi.org/10.1080/13505033.2016.1182761

Slater, A.G. & D.M. Lawrence. 2013. Diagnosing present and future permafrost from climate models. *Journal of Climate* 26: 5608–23. https://doi.org/10.1175/JCLI-D-12-00341.1

Solsten, B. & A. Aitken. 2006. An application of GIS techniques to assess the risk of disturbance of archaeological sites by mass movement and marine flooding in Auyuittuq National Park Reserve, Nunavut. *Géographie physique et Quaternaire* 60: 81–92. https://doi.org/10.7202/016366ar

Staley, D.P. 1993. St Lawrence Island's subsistence diggers: a new perspective on human effects on archaeological sites. *Journal of Field Archaeology* 20: 347–55. https://doi.org/10.1179/jfa.1993.20.3.347

Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P.M. Midgley (ed.). 2013. *Climate change 2013: the physical science basis. Contribution of working group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC.

Swann, A.L., I.Y. Fung, S. Levis, G.B. Bonan & S.C. Doney. 2010. Changes in Arctic vegetation amplify high-latitude warming through the greenhouse effect. *Proceedings of the National Academy of Sciences of the USA* 107: 1295–1300. https://doi.org/10.1073/pnas.0913846107

Tape, K., M. Sturm & C. Racine. 2006. The evidence for shrub expansion in northern Alaska and the Pan-Arctic. *Global Change Biology* 12: 686–702. https://doi.org/10.1111/j.1365-2486.2006.01128.x

Thuestad, A.E., H. Tømmervik & S.A. Solbø. 2015. Assessing the impact of human activity on cultural heritage in Svalbard: a remote sensing study of London. *The Polar Journal* 5: 428–45. https://doi.org/10.1080/2154896X.2015.1068536

Tjelldén, A.K.E., S.M. Kristiansen, H. Matthiesen & O. Pedersen. 2015. Impact of roots and rhizomes on wetland archaeology: a review. *Conservation and Management of Archaeological Sites* 17: 370–91. https://doi.org/10.1080/13505033.2016.1175909

Young, A.M., P.E. Higuera & F.S. Duffy. 2017. Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. *Ecography* 40: 606–17. https://doi.org/10.1111/ecog.02205

Received: 4 July 2017; Accepted: 13 December 2017; Revised: 28 November 2017